A qualitative study based on existing frameworks.
ABSTRACT

The unlimited availability of sunlight and the ability of photovoltaic (PV) cells to directly convert this radiation into electricity, makes PV a promising renewable energy technology. Five PV technologies are currently commercially available, however because the PV market is characterised by increasing returns to adoption, it is expected one dominant design will eventually emerge. This research is the first to study the factors that affect technology selection in the PV market. In the first part of this research existing frameworks on dominant designs, expert interviews and (non-)scientific literature are used to arrive at a list of 20 factors influencing technology selection in the PV market. Moreover, four additional factors were found that are in favour of the coexistence of multiple designs. In the second part, from the list of 20 factors, 13 were selected to be analysed via a questionnaire on their importance in the technology selection process of PV manufactures. Also the current status of PV technologies regarding these factors was analysed using a questionnaire. The questionnaires were structured using the Analytic Hierarchy Process (AHP) and filled in by industry experts; data was analysed using the crisp and fuzzy (logarithmic fuzzy preference programming) AHP method. Results indicate that there are only minor differences between the two data analysis methods; in both methods the category of factors standard support strategy is most important (with a relative importance of ±47%), followed by characteristics of the standard (±29%), characteristics of the standard supporter (±18%) and other stakeholders (±6%). Similarly, pricing and technological superiority are the most influential factors (±20%), and mono-crystalline silicon has the best chance to become the future dominant design (a chance of 30%). The outcomes also show that existing frameworks do not fully describe selection in the PV market, since the factors policy and law needed to be introduced.

Keywords: photovoltaic technologies, technology selection process, factors influencing the selection process, dominant designs
In February 2011 I started working on my thesis as part of my master Management of Technology. In this foreword I first explain why I made the choice to study factors influencing photovoltaic technology selection, and will end with the section in which I express my gratitude to the people that helped me during this study.

**WHY THIS STUDY?**
Currently, there is much debate on how fast we need to employ renewable energy technologies. Still, opposed to a few years ago, it is now generally recognized that continuing on this pace using fossil fuels enhances climate change with all its negative consequences. A possible negative consequence is for example the problem of rising sea levels; in western countries we will probably be able to overcome this problem, yet what will happen to those in the less developed world? One of the technologies that can help to mitigate climate change and help the world towards a low carbon economy is photovoltaic (PV) (for a description of other promising renewable technologies I refer to the book *Ten technologies to fix energy and climate* by Chris Goodall). Personally I find PV one of the most remarkable renewable energy technologies, because of its ability to directly convert radiation from the world’s main source of energy (the sun) into electricity, but also because of its (seemingly) simplicity; just lying on rooftops quietly generating electricity. Together with my bachelor’s degree in electrical engineering and the desire for a career in the sustainability/renewable energy sector, choosing PV as the central technology in my thesis seemed like a natural choice.

Still, if PV is that promising, why is its current share in electricity generation almost negligible? From an explorative literature study was found that we are currently locked into a fossil fuel based energy system (see the debate in Unruh (2000)), which makes it harder for renewable energy technologies to diffuse into the market. From this I followed the debate on socio technical change and the use of government incentives to support the transition towards renewable energies and to overcome these lock-ins. However, my desire was not to focus completely on government policies, since I also wanted to keep working on renewable technologies. Therefore I decided to focus on the success factors of PV technologies; these factors could in the end still be useful to overcome the fossil fuel based energy lock-in. For the analysis of factors I used literature on dominant designs, which contain very exciting theories, because they can be used in a wide variety of applications; they can explain why steamships became dominant over sailboats to the outcome of the much more recent video standards battle. If these theories can be used for a wide variety of applications, they can probably also deliver useful results for renewable energy technologies. This was the beginning of the thesis you are now reading.

**WITH THE HELP OF OTHERS**
I could never have brought you this thesis, having the same profundness and with the same comprehensive analysis, without the help of others. First of all I want to thank the people that I could interview and were willing to voluntarily share a moment of their time; it was amazing being able to talk to people having so much experience in working with PV. The TU Delft professors Arno (Smets) and René (Van Swaaij) helped me during the start of my research with my initial understanding of the PV market. I also want to thank Arno for his suggestion to read the book from Goodall (see above); a very interesting book. Next, I want to thank Coen (Vlek, from Solar Modules NL), Teus (Olivierse, from Solar Electricity Development) and Walter (Knulst, from LineSolar) for their time, since
although I made appointments for interviews of one hour, it always took longer than expected. I especially want to thank Walter for his comments to improve my thesis after reading a draft version. Besides the interesting interviews, I also want to thank Coen and Teus for their ride to and from the train station. Furthermore, I want to thank Arthur (Weeber, from ECN), John (Van Roosmalen, from ECN) and Wim (Sinke, from ECN) for sharing their enormous knowledge of PV technologies and the market. I want to thank Arthur for helping me to make appointments with John and Wim, and together with John he gave very useful comments to improve my thesis. Moreover, I want to thank Wim for finding a spot in his extremely busy schedule to talk to me for two hours. And finally I want to thank Jorrit (Laan) for the inspiring lunch meetings we had, but also for letting me access his Photon International account; the information from this magazine proved to be one of the most important sources of data in the analysis of this thesis.

In addition to the people I interviewed, I want to thank my supervisors for their support and comments during the process of writing my thesis. I first want to thank Geerten (Van de Kaa) for his support, as a first supervisor he helped me with any question, mainly by steering me into the right direction to answer the question myself (which I personally think is the best way to increase your understanding of a topic). Furthermore, he was the one that triggered my interest for the field of standards battles, dominant designs and technology patterns; which made me choose the specialisation innovation systems after my first year of study. From these lectures I will never forget the deadpan humour he used to present the discussed topics. Also I want to thank my second supervisor, Linda (Kamp), who is extraordinarily fast in replying her mails (record is less than 1 minute). Also she thoroughly reviewed my work and her comments have been extremely helpful for improving the readability, structure and to fine-tune my thesis. Moreover, I want to thank Jafar (Rezaei) for his help on the fuzzy analytic hierarchy process; if it wasn’t for him I would probably still be calculating matrixes. And although we only had a meeting once, I want to thank my chairman, Cees (Van Beers), for his thorough analysis of my thesis using a fresh perspective, which revealed points of concern which I had long forgotten.

Also I would like to thank my classmates and friends from the master Management of Technology who helped me with study related questions and gave me motivation while spending day and night in my second home; the library (I will never forget the wonderful coffee breaks).

Lastly, I want to thank my friends and family for supporting me in writing my thesis; helping me to focus, but also for the sometimes much needed distraction. Besides the support, I want to thank my parents for their willingness to review my paper. Similarly, I want to thank Niek (De Winter) for contacting Piet (Van der Poel) who, while working in China, also very thoroughly reviewed my thesis on both the grammar and reasoning. (These reviews have been really helpful in creating the final result!)

I hope you enjoy reading my thesis,

Allard de Winter

(Delft, 4 November 2011)
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Every year the earth receives plenty of energy from the sun to cover the world’s electricity needs; the earth receives 174 PW (petawatt, $10^{15}$ watt) from the sun each year and in 2009 only 4.8 TW (terawatt, $10^{12}$ watt) was used for electricity production (REN21, 2010; Smil, 1991). While almost all forms of energy on earth indirectly originate from the sun, photovoltaic (PV) technologies have the potential of directly converting the radiation from the sun into electricity. Since the invention of the first efficient silicon based PV cell ($\pm 6\%$) in the Bell labs during the 1950’s this technology received considerable attention from the scientific world along with governments support to provide an alternative sustainable energy source. With the rising oil prices during the 1970s, PV received increased incentives for further research and development, this triggered the introduction of a new generation of PV technologies in the market; currently multiple technologies can be produced on a commercial basis. Although PV technologies only account for 1.7% of the electricity production from all renewable sources of energy, growth rates are significant; more than 100% from 2009 to 2010 (Hirshman, 2011; REN21, 2010).

The combination of multiple available technologies and the impressive growth rates gives rise to the question which technology has the best chances to become the most widely used in the market (i.e. the dominant design). It is beneficial for a market to select a dominant design, since this focuses; research and development, manufacturing, marketing and complementary assets or industries around one single technology (Schilling, 2008). This focus makes the market more efficient, however in the PV market there is not one technology that has become dominant yet. Also no previous research has tried to predict which technology will become dominant in this market. Nevertheless, literature based on markets in which dominant designs have already emerged, resulted in lists of factors that influence the chance a design becomes dominant. These factors are for example characteristics of the technology, the strategy of a firm in supporting the design and other actors affecting the design. Using previous frameworks as a basis, this research focuses on which factors cause technological dominance in the PV market and their relative influence from the viewpoint of the individual firm. This research can be used as a basis to select the most viable design by decision makers and managers in the PV industry. Also this research serves as a practical example for previous frameworks on dominant designs.

1.1 Research Questions
The purpose of this study is to provide insight in the role of various factors and in their importance in the design selection process towards dominance of a specific photovoltaic technology within the PV market. The first and second photovoltaic generations are combined in this study since they are both commercially available. The results provide insight in the importance of these factors and are useful for investors assessing the potential of a specific photovoltaic technology, policy makers in developing the most efficient policies, scientists in better understanding of the photovoltaic market and providing direction for future research, and for photovoltaic manufactures in developing strategies.

Literature on factors influencing the technology selection process has already been extensively studied (e.g.: P. Anderson & Tushman, 1990; Clymer & Asaba, 2008; de Vries, de Ruijter, & Argam, 2011; Gallagher, 2007; Murmann & Frenken, 2006; Srinivasan, Lilien, & Rangaswamat, 2006; Suárez, 2004; Utterback, 1994). The most complete overview of these factors is found in a scientific paper by Van de Kaa (2009): this paper provides a list of twenty-nine factors that play a role in the standard dominance
process. Moreover, currently there is a lack of research in the field of renewable energy technologies on this topic; particular on factors influencing the selection process of PV technologies. The availability of different generations of PV technologies gives the perfect opportunity to compare the factors for selection in several generations. This brings us to the main research question:

Which factors influence the selection of designs in the photovoltaic cell technology market?

In order to answer the main question properly, and not to miss important technology specific characteristics that can influence this research, first a comprehensive overview of the photovoltaic market was made. This overview included information on photovoltaic technologies and their workings, also an overview of the supply chain is presented and the development cycle is described. This brings us to the first research question:

RQ1: What are the specifics of the photovoltaic technologies in the market?

Next the factors from dominant design literature were researched on their possible influence on the chances that a photovoltaic cell technology achieves dominance in the first and second generation. Moreover, the possibility of multiple designs coexisting in the market was analysed. Assessing PV technologies in relation to these factors was done by making use of existing literature and primary and secondary data. This brings us to the second research question:

RQ2: Which factors influence the chances that a photovoltaic cell technology achieves industry dominance?

The factors identified in research question two were tested on their importance in the companies decision making process via expert interviews using the analytic hierarchy process (AHP) method. This brings us to the third research question:

RQ3: What is the relative importance of factors in the decision making process of individual firms for a specific cell technology?

Finally, the factors influencing selection in the first and second generation technologies were compared with those of the new and emerging technologies from the third generation. This comparison was expected to provide insights in which aspects of the selection process are important to stimulate faster transition to the third generation photovoltaic technologies. This brings us to the fourth research question:

RQ4: Which factors influence the chances that a photovoltaic cell technology of the third generation achieves dominance?

1.2 Contributions to existing literature

This thesis uses the notion that in many markets after a phase of product innovations a single design is chosen that eventually achieves market dominance. These insights originate from scholars in the field of industrial economics. The objective in this study is to explain which factors defined in previous literature and from expert interviews, influence the technology selection process in the photovoltaic market. In addition to the analysis of factors, also the importance of factors in the selection process from the viewpoint of the firm is studied. Doing this research, contributes to various aspects of existing scientific works.
First of all, this research adds to existing scientific literature by being the first study that makes use of elaborate frameworks to analyse factors influencing technology selection processes in the PV market. This contributes to finding a common pattern of the influence factors have on technology selection, given their stage in the technology development process (Den Hartigh, Ortt, Van de Kaa, & Stolwijk, 2009; Suárez, 2004; Van de Kaa, 2009). Moreover, this study is the first in its kind to combine both elaborate frameworks on multiple designs and on dominant designs in a market characterised by increasing returns to adoption. Also because of the newness of literature on multiple designs coexisting in the market, this research also provides a practical case for theorists in this field; like de Vries, de Ruijter and Argam (2011) suggest, that more case studies are needed to confirm their conclusions and to check if the number of markets with dominant designs is decreasing.

For renewable energy technologies in general it is known that policies and regulations have an important role in the adoption process (Unruh, 2000, 2002). Currently, almost no attention is given to these elements in technology dominance literature, still this is expected to influence the adoption process of individual designs. Since multiple policy incentives can be found in the photovoltaic market, analysing this market provides the opportunity to study the effect of policies and regulations in a market characterised by increasing returns to adoption. Therefore, this research is the first step to use the policy factor into dominant designs literature.

Furthermore, this study contributes to existing literature on dominant designs by incorporating the notion of levels, which have been frequently used in other social sciences. In previous literature on dominant designs the notion of levels is not often used, while it is useful for structuring the factors on the basis of their influences in the technology selection process.

For analysing the data from the questionnaire, both the crisp AHP and the logarithmic fuzzy preference programming (LFPP) method are used. This adds to the validation of the relatively new LFPP method by providing a practical case (Y.-M. Wang & Chin, 2011), and because the crisp AHP has been often criticized it also adds to the validation of the resulting data.

In addition to benefits for the scientific community, also managers, investors and policy makers will be able to benefit from the findings in this research. Managers and investors in the photovoltaic industry can use these findings for strategic decision making and to assess the potential of a technology, since they are provided with a comprehensive list of factors influencing the success of a technology. Moreover, the comprehensive list of factors highlighting all aspects influencing the technology selection process in combination with the systematic approach of the AHP provides an easy to use framework for decision makers. Policy makers can use the results combined with existing literature on renewable energy to increase their understanding of processes and factors influencing the adoption of PV designs.

1.3 Structure of the report

After this introduction the report continues with an explanation of the background theories in which this research finds its basis to answer the research questions (chapter 2). After the theoretical part a description is given on the methods used to conduct this research in chapter 3, this chapter will also explain why these methods have been chosen.
The next four chapters do answer the subsequent research questions one to four from the previous section 1.1; starting in chapter 4 with an analysis of photovoltaics in general, with a study of the technological- and market characteristics and the selection of technologies used for further analysis. Next, chapter 5 describes the factors affecting technology selection in the photovoltaic market. The importance of factors that can be influenced by a firm in the selection process is described in chapter 6. In chapter 7 the potential of future technologies is analysed based on the insights from chapter 5 and 6.

After analysing the research questions, this report concludes in chapter 8 with the answers to the research questions, and a discussion of the findings and the used theories.
This chapter will discuss relevant literature used to analyse the research questions from the previous chapter. The chapter will start with an analysis of existing literature on dominant designs, which has been used as a basis in the analyses of this research. This section will also focus on why literature on dominant designs is applicable in the photovoltaic (PV) market. Next, the concept of levels is explained since it is used as a supplement to frameworks on dominant designs. Moreover, because policy influences the selection process of PV technologies, an analysis is made of existing policy literature related to the diffusion of renewable energies. This chapter will end with a description of the (non-)scientific literature that has been used in this research.

2.1 DOMINANT DESIGNS

A dominant design is defined as the moment a product or technology achieves “more than 50% market share among new buyers [...] in a certain product or service category for a significant amount of time” (Van de Kaa, 2009, p. 16). Or the moment when manufactures of competing designs exit the decisive battle stage (Suárez, 2004). PV technologies have a 1.7% market share in electricity production from only renewable energies, though growth rates are significant; over 100% from 2009 to 2010 (Hirshman, 2011; REN21, 2010). As a renewable energy source PV is far from dominant, however within the PV market the relative market share of first generation silicon based PV in comparison with second generation technologies is 86%; although the first generation silicon PV consists of two similar but different technologies, there seems to be a tendency for choosing a dominant product family. Historically several factors are recognized influencing this standardization process, for example the technological superiority of one technology over all others is seen to have a positive effect for adoption of that technology. The selection process of PV cells can be better understood using these factors. With the factors also a comparison can be made between the current commercially available technologies and future generations; this may provide useful insights for facilitating the success of a technology currently in the research phase.

2.1.1 LITERATURE ON STANDARDS AND DOMINANT DESIGNS

Both standards and dominant designs are used to describe the outcome of the successful process in which a technology or product is used and adopted by the largest market share, similarly the term ‘standards battle’ is used to describe the competition between two competing designs. Examples of well-known standards battles are; between the northern and southern railroad companies in the US on the size of railroad tracks during the mid-19th century (Shapiro & Varian, 1999) or the video battle between VHS (JVC), Betamax (Sony) and V2000 (Philips and others) (Rosenbloom & Cusumano, 1987). Winning or losing a battle, having developed a dominant design (e.g. with a >50% market share) or not, defines whether a complete value chain of companies and complementary goods or services is successful or not (Suárez, 2004). The process in the battle for a dominant design is uncertain, nevertheless researchers in the fields of industrial economics, institutional economics, technology management, standardization and social networks (Van de Kaa, 2009); found different factors contributing to the outcome of battles for dominance.
In technology management literature there is a discussion on the differences and similarities between standards and dominant designs (Anderson & Tushman, 1990; Gallagher, 2007; Suárez, 2004; Van de Kaa, 2009). Suárez emphasizes the similarity between the two concepts and provides an extensive overview of the terminology used to describe the “emergence of technological trajectory among several competing ones” (2004, p. 271). In the field of management the following terms are used; “dominant designs”, “technological trajectories” and “platforms” for studying technological battles. Similarly economic scholars use the concept of rational behaviour together with the terms “standards” and “technology diffusion”. Not all scholars however, accept that the concepts can be used interchangeable. Gallagher provides in his paper a clear distinction between the two concepts; he defines dominant designs to be “persistent architectures” and standards as “interface protocols” (Gallagher, 2007, p. 372). Similarly Van de Kaa (2009) describes how researchers have defined design and standard, see Table 1. Because this research largely builds on the concepts and findings from Van de Kaa (2009) and Suárez (2004), which emphasize designs and standards share the same characteristics, both standardization and dominant design literature is used.

### Table 1: Definitions of ‘design’ and ‘standard’, adopted from Van de Kaa (2009)

<table>
<thead>
<tr>
<th>Design</th>
<th>Standard</th>
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<tbody>
<tr>
<td>A product’s design specifications that define the product category’s architecture</td>
<td>Interface protocols (Gallagher, 2007)</td>
</tr>
<tr>
<td>Technical features</td>
<td></td>
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<tr>
<td>Core design concepts</td>
<td></td>
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<tr>
<td>Technological trajectory (Suárez, 2004)</td>
<td></td>
</tr>
<tr>
<td>A way of doing things which is manifested in a product</td>
<td></td>
</tr>
<tr>
<td>Entire products and/or features of products or requirements for products or services (Persistent) architectures (Gallagher, 2007)</td>
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#### 2.1.2 Characteristics related to dominant designs in the PV market

According to Schilling (2008) dominant design are selected in markets characterized by increasing returns to adoption. Increasing returns to adoption are experienced when the more a technology gets adopted, the more experience in gained by employing it, and the more the technology gets improved (Arthur, 1989). Part of the improvements comes from increased revenues when the technology gets adopted, these revenues can be used for further improvements (Schilling, 2008). Moreover, improvements in the technology and its applications come from knowledge and understanding generated when the technology is employed. This learning process comes from both the demand side, called learning by using (Rosenberg, 1982), and from the supply side of the market, called learning by doing (Arrow, 1962). Lastly, by adoption complementary assets also get developed and specialized to work with the technological design. Schilling (2008) defines the primary sources of increasing returns to be learning effects and network externalities; these are both on the demand- and on the supply- side of the market (Antonelli, 2008). The demand side experiences learning by using and network externalities, the supply side experiences learning by doing and economies of scale.
While it is not directly clear that the PV industry experiences the demand side effects, the stronger the supply side effects are present in this industry (learning by doing and economies of scale). Figure 1 shows the contributions to the cost of PV designs; in recent years a significant part of the decline in prices can be explained from learning by doing. Numbers show that learning by doing not played an important role in the years 1976 – 1986, nevertheless in recent years (1998 – 2006) these learning effects are found to be the largest cost reduction factor for PV devices (Luque & Hegedus, 2011; A. McDonald & Schrattenholzer, 2002; C. F. Yu et al., 2011). During the same period of learning effects, economies of scale are seen in the PV industry (Nemet, 2006; C. F. Yu et al., 2011). Economies of scale are the factors which cause a decline of production costs as output increases in the long run (Heather, 2003). Yu et al. (2011) argue that economies of scale in the PV market originate mainly from the higher specialization of workers and managers, and partly from the high production start-up cost and relative low marginal costs for producing an extra unit.

Because of this steep learning curve and the positive scale effects; first mover advantages are expected to have an important role in the PV industry (Schilling, 1998, 2008; C. F. Yu et al., 2011). In the case of CdTe producers for example, there have been from 2007 to 2009 only a few commercial manufacturers, from which one producer is by far the largest in the industry for the entire period (market share of >90%) (Hirshman, 2009).

The demand side factors for increasing returns to adoption are network externalities and learning by using. Network externalities can be both direct and indirect (Blind, 2004; Katz & Shapiro, 1985; Suárez, 2004); with direct network externalities the value of a product depends on the numbers of users (e.g. telephone networks). For PV it is not evident such externality exists; PV adopters do not experience increased value of their technology when the next individual adopts PV. Indirect network externalities are generated when a user needs to purchase two or more components before it can benefit from the technology. For PV technologies this type of externality is not seen, for solar panels holds a different story; without an inverter to convert the electricity these panels are as good as useless. The factor learning by using describes technological improvements from technology adoption (Rosenberg, 1982). To some extend learning by using is expected to be present in the market; for example the performance characteristics of PV modules can be optimised (e.g. lifetimes and efficiencies in hot and cold temperatures). However, no evidence is existing literature is found of the effect of learning by using, therefore this effect is expected to be negligible in the process of increasing returns to adoption.

PV technologies do experience some form of increasing returns to adoption; learning effects can be seen very clearly. Because the focus of this research is on PV technologies and not solar modules; no significant switching costs, direct and indirect network externalities, or learning by using exists. To

![Figure 1: Factors contributing to unit costs, adopted from Yu, Van Sark and Alsema (2011) *This figure only shows the most significant factors, the original version can be found in Appendix V](image-url)
ChapteR 2. Theoretical background

conclude, the PV market is characterised by what in literature is described as a market with “dominant designs”; thus it is likely that a specific technology will become the dominant design within the PV market.

2.1.3 Existing frameworks on standards and dominant designs

Literature on standards and dominant designs is in general ex-post (Anderson & Tushman, 1990; Gallagher, 2007; Tushman & Anderson, 1986); this field of study generally has no predictive abilities. However, recently an increasing number of articles describe the ex-ante process of standard formation and emerging dominant designs (Suárez, 2004; Van de Kaa, 2009). Most of this literature focuses on products with increasing returns to adoption, as described above, PV technologies are characterised by this effect; strong evidence of learning effects is found. However, no network externalities; therefore it is not evidently clear whether prior frameworks related to standards and dominant designs are applicable to the case of PV technologies. Nevertheless, especially for this industry, renewable energy, knowledge on the concepts of standards and dominant designs can be extremely useful in improving the adoption rate in this market. Also for scientific purposes, applying the case of PV technology may add to the technology management literature.

An extensive list of factors that can play a role in the adoption process of a technology can be found in the framework from Van de Kaa (2009); this research combined the findings of 127 previous publications. This framework provides a list of factors (29) that play a role in the standards dominance process. Although the framework is especially designed for standards dominance battles characterised by network externalities. In economic literature exist different types of standards (Blind, 2004) based on their economic effects; compatibility and interface-, minimum quality and safety-, variety reduction- and information standards (see the complete overview in Appendix II). Blind (2004) emphasizes that his categorization has some overlap; it is often the case a product or technology has several economic aspects from multiple categories. The framework of van de Kaa (2009) is developed for interface or compatibility standards, which are characterised by network externalities and switching costs (Blind, 2004; Schilling, 2008); this type of standard ensures a subsystem can function within other systems (e.g.: products, processes, technologies).

There are more frameworks developed on factors influencing the technology adoption process (e.g.: P. Anderson & Tushman, 1990; Clymer & Asaba, 2008; de Vries et al., 2011; Gallagher, 2007; Murmann & Frenken, 2006; Srinivasan et al., 2006; Suárez, 2004; Utterback, 1994). These frameworks generally make the distinction between factors related to; characteristics of the design supporters, characteristics of the design itself, support strategies for the design, characteristics of other actors in the industry and industry characteristics. Because PV technologies are not so much characterised by (in-)direct network externalities factors relating to network externalities will probably not influence the adoption of a specific PV technology much, consequently market characteristics are of less importance. Some other frameworks come for example from Utterback (1994) who mentions the technology dominance process in the integrated circuit (IC) market researched by Therese Flaherty (Dosi, Nelson, & Winter, 2000); in this market the technologies change from generation to generation and therefore in every generation another dominant design emerge. Utterback describes how one might think theory on dominant design has only little explanatory power for this specific case, however he also explains how results from the IC market show that for each dominant technology common characterised have been found (i.e. ‘early entry’ strategy and ‘increased production capacity’ from established firms) (Utterback, 1994).
Similarly Srinivasan et al. (2006) describes several factors that may influence the probability a dominant design emerges. In their report they define the following factors; appropriability, network effects, value net, standards-setting process, radicalness of innovation and R&D intensity. Differently from van de Kaa (2009) Srinivasan explains how network effects may only have a minor role in the emergence of a dominant design. This is an important finding for the case of PV technology since they are, like previously described, not characterised by strong network effects.

Even though the majority of researchers agrees that if a technology or product has the characteristics mentioned in section 2.1.2 then a dominant design will always emerge, there are some researchers assuming several design can coexist in one market (de Vries et al., 2011; Frenken, Saviotti, & Trommetter, 1999; Paila, 2005; Srinivasan et al., 2006). This is a relatively new field of research in comparison with literature on dominant designs; only the last few years it receives a considerable amount of attention. De Vries, de Ruijter and Argam (2011) distinct eight factors based on own and previous research contributing to a market situation in which not one but several designs coexist: “distinct features, appropriability regime, persistency and speed in development” as supply side factors and “gateway technologies, multi-channel end systems, application drives the design and price” as demand side factors. This framework from De Vries et al. (2011) is found to be the most comprehensive and complete framework to this date, since uses an up to date combination of previous literature. It should be noted that these factors in favour of multiple designs have been tested in the case of flash memory cards which is characterised by “huge fluctuations in market share” (de Vries et al., 2011, p. 17); these “huge” fluctuation seem not to be present in the PV industry. Also some of the factors will not be applicable to the case of PV. Their main findings show that recently the digitalisation of technologies and the speed of technological development are the main causes for multiple designs coexisting in the market.

2.1.4 Selected Frameworks for This Research

As mentioned in the previous paragraphs, there are several frameworks that describe factors which influence technological dominance. Currently, one of the most suitable frameworks that can be used as a basis in this research comes from van de Kaa (2009); it makes a combination of 127 previous publications. More important is that this research also makes a combination of other influential frameworks; like Suárez (2004) and Utterback (1994). Also because of time constraints for this research it is not feasible to check all existing literature individually with PV technologies; using an integrated framework saves time.

In the framework of van de Kaa (2009) 29 different factors on three levels are described; the micro (influenced by the firm), meso (the industry of the design) and macro (environmental or regulators, judiciary) level. However, there is mainly focussed on the micro and meso level. Moreover, these levels are not used as intensively as in policy literature, they are mostly used to differentiate between factors that can be affected by the firm. Factors that are applicable to the PV market are described in section 5.2, the complete list of factors can be found in 5.1.2. Furthermore, the framework targets the first “fluid” phase of a
technology/product, shown in Figure 2, when there is a period of technological discontinuity until a dominant design is emerged. This model of phases is an approach to research innovations and their dynamics. The fluid phase is characterized by technology and market uncertainty, firms are mainly focused on product innovation instead of process innovation and competition comes both from the existing technology and new entrants (Utterback, 1994). The PV market is currently in the fluid phase, still a lot of research is done and for the first generation (1G) (and sometimes second generation (2G)) there is already some focus on process innovation; however both generations are produced for the mass market on commercial basis (see also section 4.2). In the fluid phase a company can make the decision to aim for the dominant design or to focus on providing complementary goods. If the first strategy is successfully executed this will lead to the highest revenues, the framework of Van de Kaa (2009) provides a list with factors which can help to assess the chances a technology achieves dominance in the market.

The framework from Van de Kaa (2009) provides a comprehensive overview of factors ever been mentioned in scientific literature to affect the dominance of a design. This research focused on dominant designs and did an empirical study for the home network industry. Although the focus of the research was on home networks the factors influencing the dominance process came from a wide variety of industries (e.g.: video games, automobiles, PC’s, television, picture tubes, etc.) compiled from 127 papers. Therefore is expected that this list can completely explain dominance processes in the PV industry.

The factors are grouped into five categories based on the theoretical perspectives describing standard dominance:

- **Characteristics of the standard supporter**, based on institutional economics literature; these factors include the firm’s resources.

- **Characteristics of the standard**, based on technology management literature; covering compatibility of the standard, the availability of complementary goods, and technical characteristics.

- **Standard support strategy**, based on institutional economics literature; includes the strategy used by firms to promote their own strategy and prevents adoption of other standards.

- **Other stakeholders**; influential and/or affected stakeholders other than the standard supporters.

- **Market characteristics**, based on network economics literature; consists of environmental factors (a standard supporter cannot influence these factors). Because these factors are defined for products with network externalities and PV technology does not have clear network externalities; it is expected not to have a high impact on the PV adoption process.

Next to this framework on factors in favour of selecting one dominant design, there are other frameworks in favour of the coexistence of multiple designs in a single industry. It could be multiple technological designs are able to survive in the PV industry, this does not mean the analysis of factors in favour of a single dominant design is not of value since this still indicates what a successful support strategy should look like. There is reason to believe however, the market is characterised by multiple designs since; there are two technological designs (mono and multi crystalline silicon) that remained ‘stable’ over the past 40 years. To analyse whether the PV industry has characteristics to support multiple designs and not one single dominant design the framework of de Vries, de Ruijter and Argam
(2011) is adopted. Although this framework is mainly focused on technological designs that experience network effects, it is still used in this research for the reason that it provides a comprehensive overview of all factors influencing multiple design based on their own and previous research (e.g. from Srinivasan, Lilien and Rangaswamt (2006)). This framework distinguishes eight factors using a categorisation is between the supply and demand side.

2.1.5 CHANGES IN THE INFLUENCE OF FACTORS OVER TIME

This section describes in more detail the concept of Utterback (1994), that the importance of factors fluctuates according to the technology’s stage in the development process. Similarly, Ortt and Schoolmans (2004) developed the technology life cycle model on the pattern of development of a technology. This model describes how the diffusion of a technology is characterised by three phases of development after the invention of the technology, moreover it addresses a shift in relevance of factors.

The three phases of the model from Ortt and Schoolmans (2004) are:

- First, the innovation phase; in which there is increased attention for research and development to commercialize the product.
- Second, the phase of adaption; in which a market for the technology is created and in which the decisive battle for dominance is fought.
- Third, the market stabilization phase; which describes the period after dominance, in this phase there is increased attention for improvements of production processes.

![Figure 3: The three phases in the market diffusion process (Den Hartigh et al., 2009)](image)

The phases are separated by hallmarks as shown in Figure 3; first there is the invention, followed by innovation (first product) of the technology, third comes large scale diffusion of the product (industrial production) and lastly comes the market stabilisation phase after which the cycle can start over again with a new supplementary technology.
The model from Ortt and Schoolmans (2004) is useful in this research because it provides a schematic overview of the production process and it can be combined with findings from Suárez (2004); this has been done in Den Hartigh, Ortt, Van de Kaa, & Stolwijk (2009). Suárez also makes use of the notion of phases in which the characteristics of the battle shift and consequently, similar to the other frameworks, also the relevance of factors for dominance shifts. Suárez makes use of five phases, nevertheless they are similar to the model of Ortt and Schoolmans (2004).

As an example of shifts in the importance of factors, Suárez (2004) explains that during the innovation phase research and development efforts are the most important elements; since the technological design should be able to live up to the expectations of the (majority of the) adopters, and be produced on a large scale. On the other hand, during the market adaption phase in which the objective is large scale diffusion, the factors pricing, marketing communications and pre-emption of scarce assets become more important. Technological superiority may also be important, though its effect diminishes over time.

### 2.2 Levels

In previous literature many different definitions of macro, meso and micro levels can be found (e.g.: Alexander, 1987); each field of study seem to use its own definitions (Clegg, 2006). Previous literature on dominant designs also made a distinction between different levels, called the firm and the environmental level (e.g.: Clymer & Asaba, 2008; Suárez, 2004).

Similarly, in literature on emerging renewable energies the definition of sociotechnical change is often used (e.g.: Unruh, 2000). In this field of research a popular definition of levels comes from Geels (2002); he explains how niches (on the micro level) evolve into the larger market (the meso level) and eventually transform sociotechnical landscapes (on the macro level); see Figure 4.

In this research however, the notion of levels is not used to describe how PV technologies may change sociotechnical landscapes, though they are used to differentiate between influences in the technology selection process; which actors are able to influence the factors affecting this process. The existing definition of levels in dominance literature is therefore not sufficient; it does not use the notion of a macro level, and the meso level is only marginally described. Because the macro and meso levels are not described in detail, the existing definitions will not be adequate to describe situations in which; either technology specific organisations, or international- governments and institutions (indirectly) influence the technology selection process in the PV market. Therefore a new definition of levels is made, presented in Table 2.
2.2 Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
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<tbody>
<tr>
<td>Micro</td>
<td>This level consists of factors individuals or single firms can directly influence in the technology selection process.</td>
</tr>
<tr>
<td>Meso</td>
<td>Consists of factors that cannot be easily influenced by the firm; it consists of factors influenced by groups of firms (e.g. a lobby) or technology specific organisations/institutes (e.g. PV research groups at universities).</td>
</tr>
<tr>
<td>Macro</td>
<td>The level that can be influenced by international- institutes or governments (like the European Union or the United Nations).</td>
</tr>
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The new definition is partly based on earlier notions from Alexander (1987) and Turner (2003), who respectively describe levels on the basis of social interactions and social forces. Alexander (1987) describes how the micro level is characterised by patterned interactions among individuals and the macro level by interaction between groups, organisations and institutions. Turner (2003) defines how forces on the micro level are encounters and interactions between individuals and the macro level consists of institutions with their corresponding social values, ideologies and norms. On this macro level there is for example the force of regulations; regulation can be exerted through power of coordinating actions or allocating resources. Moreover, Turner defines the meso level consisting of two structural forms; a corporate and categoric unit. The categoric unit is not that useful in this study, since it consists of social characteristics like age and gender that are not used in this study; however, corporate units consisting of divisions of labour help to structure the meso level.

In the definition of levels given in Table 2; insights from Alexander (1987) are used as a basis to differentiate between single actors at the micro level and institutions at the macro level, and insights from Turner (2003) are used for further classification on the forces that play at each level and to introduce the meso level.

For firms the factors influencing the technology adoption process have a different influence given the three levels; factors on the micro level are different for every individual firm and factors on the meso and macro level will generally be the same for the complete PV industry or a line of firms related to one technological design. Nevertheless, there are some macro level factors, i.e. policy and law, that are different given the PV technology. For example CdTe and some CIGS PV cells make use of the element Cd (Cadmium), which is a by-product of zinc production and is toxic when released from its metallic bond (Bossert, Tool, van Roosmalen, Wentink, & de Vaan, 2000; de Keizer & Alsema, 2008; Razykov et al., 2011). There are strict regulations on the use of cadmium; for example in June 2010 the European Union made an exception for the use of cadmium for renewable energies (European Union, 2010), and in 2011 a law was passed which legalized the use of cadmium for solar devices (Harrison & Merrifield, 2011). However, these laws get revised every couple of years, therefore the future of cadmium usage for PV modules in certain countries remains uncertain.

Similar to notions of levels in for example Geels (2002), the innovation systems approach uses heuristics to describe the emergence of products or innovations; this approach mainly describes how influences from the macro level, institutions, affect emerging innovations (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). With this model and level, empirical studies compare different innovation systems by comparing R&D expenditures, the education systems, university–industry collaborations and availability of venture capital (Hekkert & Negro, 2009). Hekkert et al. (2009; 2007) use the TIS (techno innovation system) to make this evaluation dynamic and developed a framework for analysing key activities and dynamics of the system. Similarly Kamp et al. (2004) made an analysis of wind
turbine development in Denmark and the Netherlands; they compare the roles of learning processes in the two countries. These insights are useful for properly assessing the influence of factors like ‘regulator’ and ‘policy’, since they describe how learning processes and policy plays a role in developing specific technologies in certain countries.

2.3 Policy Incentives

Also policy can influence the selection process of PV technologies, in literature on dominance development it is widely recognized external factors of the firm do influence the chances of selection a design (e.g.: Schilling, 1998; Utterback, 1994). In existing frameworks (Van de Kaa, 2009) the factor ‘regulator’ is mentioned able to prescribe certain standards in the market, this factor seems to cover policy measures used to facilitate the transition towards renewable energies we try to explain in this section; however the definition does not cover our explanation entirely and therefore a new factor should be introduced. This factor is called ‘policy’ and will cover policy measures used to facilitate the transition towards PV. Comparing favourable policies with the rate of PV adoption per country (Brown & Hendry, 2009; EPIA, 2009; EPIA & Greenpeace, 2011; Hirshman, 2010); it is found that the rate of consumer adoption is significantly higher in countries with more favourable policies (e.g. Germany), on the other hand no such developments are found for the placement of firms’ production lines. Recently PV production capacity has shifted to Asia, although headquarters of some of the largest manufacturers are still situated in Europe or the United States (Hirshman, 2010).

Current policy favourable for the adoption of renewable energies are mostly directed and described at the upper macro level; how governments can facilitate change in the institutional landscape. Given the impressive body of literature on policy measures this is an important aspect in the transition towards renewable energies (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Breukers & Wolsink, 2007; Carley, 2010; del Río & Unruh, 2007, 2007; Foxon et al., 2005; Jacobsson & Bergek, 2004; Jacobsson & Lauber, 2006; Kern & Smith, 2008; Meza & Dijkema, 2009; Mitchell & Connor, 2004; Nill & Kemp, 2009; Peters, Ackerman, & Bernow, 1999; Smith, Stirling, & Berkhout, 2005; Stirling, 2010; Unruh, 2000, 2002; Unruh & Carrillo-Hermosilla, 2006; Verbong & Geels, 2007). These papers on the institutional level (Figure 4) mainly give insight in how policy can be best used to overcome old and promote new energy systems, and to address the negative consequences of coevolution. Common recommendations of these articles are: The need for stable subsidy programmes, instead of the current situation were in some countries the amount of government support changes every couple of years; also initiating awareness of the general public in environmental thinking; lastly ending supporting policies for fossil fuels based energy systems, which are sometimes still in place (Unruh, 2002). However, most of these policies have similar effect on the complete PV market; they do not affect individual technologies differently.

Moreover, the government subsidy programmes should not only focus on R&D but also on investment subsidies. This is found in the research on innovation systems of Kamp et al. (2004) of wind turbine development in Denmark and the Netherlands. In the article a comparison is made between roles of learning processes in the two countries. One of the most notable conclusions is R&D subsidies do not guarantee successful market development; in the case of Denmark far less R&D subsidies were at place during the early stages of the introduction of wind energy. Nevertheless, Denmark had focussed more on facilitating the knowledge transfer between researchers, consumers and producers and currently Denmark has a far larger and more developed wind energy industry in comparison with the Netherlands. Findings from this article can be used to better understand how the learning orientation of firms helps in developing a successful and dominant technology. In addition, Schilling (1998)
mentioned as one of the factors influencing the technology adoption process; the learning process of firms. She makes the distinction between core competences and absorptive capacity; especially the first aspect is related to the knowledge of employees and the importance for firms to invest in expanding their knowledge and skill base. Similarly, learning-by-doing is found to be an important aspect positively influencing emerging dominant designs (Anderson & Tushman, 1990).

2.4 Other (non-scientific) literature

Technical data and the workings of PV are not found in the other literature described in this chapter. For the basic understandings about the workings of the different types of PV technologies is made use of presentations and the syllabus of the course ET4149 “Solar Cells” from the faculty of Electrical Engineering, Mathematics and Computer Science at the TU Delft. Furthermore the following technical journals are used to find the newest technologies and advances in the PV market:

- Renewable Energy
- Energy

To find data on the current status of renewable energies in general and PV technologies specifically, papers and reports from (international) energy organisations are used. These reports are also expected to provide knowledge on national policy incentives. Examples of organisations are:

- ECN (Energy research Centre of the Netherlands)
- EPIA (European PV Industry Association)
- NEDO (New Energy and industrial technology Development Organization)
- IEA (International Energy Agency)
- NREL (National Renewable Energy Laboratory)

To ensure having the latest company information, mergers, strategies, production capacities, manufacturing innovations; i.e. all commercial industry data, is made use of the following magazine. This magazine is considered to be the leading magazine targeting specifically the PV market.

- PHOTON International (http://www.photon-magazine.com/)

Lastly data is gathered by doing interviews with industry experts; professors from universities, senior researchers from research organisations and experienced company executives.
3 Research Method

In the introduction of this report a short overview is given on how the research was conducted; this chapter will explain in more detail which methods have been used for the analysis of factors influencing technology selection in the photovoltaic (PV) market. First is explained how this research was conducted in general, followed by a more detailed description for each individual research question. Next, the data collection methods are discussed. Furthermore is explained which practices have been considered in analysing the data from questionnaires, with an extensive elaboration on how to conduct both the crisp and fuzzy analytic hierarchy process. This chapter will end with an explanation on how the research methods ensure reliability and validity of the end results.

3.1 Answering the Research Questions

This research uses a two stage process to answer the main research question: First a list of factors that influence the technology selection process is constructed, by analysis of the PV market using existing literature and three expert interviews. Secondly, the importance of factors in the decision making process of firms in the PV value chain is analysed, using six questionnaires filled in during semi structured interviews.

The analysis in the first stage was partly based on existing literature on dominant designs. Frameworks that previously have been developed provide a basic list of factors that is used to study dominance in the PV market, especially the frameworks of Van de Kaa (2009) on dominant designs, Suárez (2004) on technological lock-ins and de Vries, de Ruijter, & Argam (2011) on multiple designs coexisting in the market. To analyse the completeness and influence of the frameworks, both interviews and existing literature were used. Existing literature consisted of scientific and non-scientific sources; these are used to provide insights in the PV market, after which the role of the factors in the PV market could be analysed. To further check the completeness of the list of factors subsequent interviews were done, in which the aspects of technology selection in the PV market were discussed; similar to the Delphi-method.

Existing frameworks are used because they provide a structured way of analysing a practical case without overlooking important characteristics. In analysing which factors influence the technology selection process, existing literature on dominant designs was used; because this field of study tries to find common characteristics of successful technologies (i.e. what later become dominant designs). This research tried to find the characteristics of technology selection in the PV market, which is related to dominant designs literature, since it describes the successful strategies for technological development.

The six questionnaires in the second stage of this research have been structured using the analytic hierarchy process (AHP). Following, in order to arrive at the relative importance of factors in the firms’ decision making process, the data from these questionnaires has been analysed using both the crisp and the fuzzy AHP method. The questionnaires have been answered during semi structured interviews to ensure mutual understanding, moreover, during each interview the completeness of the list of factors from the first part has been rechecked with the experts.
The following sections describe in detail which methods have been used to answer the research questions. The first two research questions are related to what has been described as stage one in this research, the third research question is related to the second stage. Research question four on the other hand, uses insights from all three previous questions to analyse future PV technologies.

3.1.1 RQ1: WHAT ARE THE SPECIFICS OF THE PHOTOVOLTAIC TECHNOLOGIES IN THE MARKET?

Research question one is descriptive. Industry magazines and scientific literature have been used to create an overview of the PV market, primarily to make a selection of technologies that can be used for further analysis, also to serve as a basis for the analysis of existing frameworks in research question two. The following elements are discussed in this overview: a timeline with the pattern of diffusion and development, the technology and manufacturing processes and the supply chains are investigated. Scientific literature provides an overview of the latest developments of the PV technologies, while industry magazines are used for the latest market developments and opinions.

To systematically describe the timeline of development the models of Ortt and Schoolmans (2004) and Suárez (2004) have been used, they have been combined in Den Hartigh, Ortt, Van de Kaa, & Stolwijk (2009). The technologies used in this research have been selected based on their stage in the development process. This is essential since, as described by Ortt and Schoolmans (2004) and Suárez (2004), the influence of different factors on the technology selection process differs with the stage in the development process, making a selection of technologies currently commercially available reduces the risk of differences in importance between the researched technologies to a minimum.

3.1.2 RQ2: WHICH FACTORS INFLUENCE THE CHANCES THAT A PHOTOVOLTAIC CELL TECHNOLOGY ACHIEVES INDUSTRY DOMINANCE?

Research question two is investigated by conducting a case study. Based on historical PV-industry data, industry magazines (Photon International), scientific literature, literature describing the emergence of standards and dominant designs (the frameworks of Van de Kaa (2009), Suárez (2004) and de Vries, de Ruijter, & Argam (2011)), and interviews with industry experts; a list of factors is created affecting the selection process of PV technologies.

Historical industry data consist of literature that reports on the PV industry, market (shares), technologies and policies. The industry experts are asked during interviews to describe which aspects of the PV market are important in the technology selection process; the researcher provides the connection with existing dominant design models. Also it could be the case that multiple technological designs survive in the market, therefore factors influencing the existence of multiple designs (e.g.: de Vries et al., 2011) are used in the analysis as well.

The three industry experts which are interviewed for analysis of this research question have been selected from two sectors:

- Interviews with two experts from universities (professors); for fundamental understanding of technological capabilities, and the latest research- and technological developments.
- Multiple interviews with one expert from an installation company; for knowledge on consumer and demand side needs.

Furthermore, the completeness of the resulting list of factors has been rechecked during the six interviews for research question three.
Using these data sources, the large list of factors from previous frameworks is analysed for its applicability on the PV market; resulting in a smaller list of factors. The following steps have been used to check the effect of the factors in the PV market:

- First is checked whether the factors have been described in previous scientific literature on the PV market.
- Next, has been analysed whether the characteristics of the factors as described in the frameworks are present in the PV market, and can consequently be linked to the characteristics of this market; using non-scientific literature (e.g. industry magazines) and expert interviews.

3.1.3 RQ3: WHAT IS THE RELATIVE IMPORTANCE OF FACTORS IN THE DECISION MAKING PROCESS OF INDIVIDUAL FIRMS FOR A SPECIFIC CELL TECHNOLOGY?

Research question three is answered on the basis of results from research question two as well as the opinions of industry experts who are contacted to distil the influence of factors in the dominance process, and the status of these factors regarding a specific PV technology. In total six experts have been interviewed in a semi structured interview during which an AHP questionnaire was answered; three for the importance of relevant factors and three for the current status of the technologies. A larger number of interviews would have delivered more reliable results, however because the AHP method is used even one expert is essentially enough since answers can be checked on consistency.

The experts interviewed for this research question have been selected from two different sectors, research institutes and manufactures:

- Interviews with three experts from different PV manufacturing companies; for their knowledge of the commercial markets and business opportunities.
- Interviews with three experts from a semi-public research institute (ECN); for their overview of both the latest technological advances and their knowledge of the latest market developments.

Moreover, the experts from manufacturing companies have also been selected on the basis of the age of the company they are working for. Preference was given to companies that had only been recently founded (within the last two years) and consequently these companies had only just made their decision for a PV technology; two of the three selected companies had not even made their choice for a technology publicly. Selecting these kinds of companies was done to bring the possibility of a retrospective bias to a minimum. Moreover, both companies working on first and second generation technologies have been selected. The experts have been interviewed in person, which is expected to deliver better results compared to sending out questionnaires.

Using interviews in this research is necessary because of the vagueness of the theoretical concepts; speaking face to face with a person can ensure mutual understanding of the concepts mentioned. From the interviews the relative importance of the factors can be arranged from most- to least significant in the selection process using both the (crisp) Analytic Hierarchy Process (AHP) and a fuzzy AHP analysis. After the questionnaires were analysed, answers were checked on their consistency, in the case answers were considered to be (too) inconsistent respondents were contacted again to reassess their answers. The crisp AHP method has been used to check if respondents needed to be contacted
again, since this approach offers a clear indication whether answers are consistent or inconsistent (the consistency ratio).

Whether or not to adopt a specific PV technology is the choice users make and only when enough users adopt the technology it can achieve dominance. Users base their decision upon different criteria; one user may base its decision on financial revenues while the other finds it more important to prevent future climate change. The list of factors derived from the analysis in research question 2 contains multiple ratios. Also experts comparing two alternatives give more accurate judgements in comparison with comparing simultaneously all of the alternatives. With the AHP method an expert can express a relative value to assess two alternatives on different scales. Consequently the AHP method provides a simple technique of scoring to minimize complexity (Ishizaka & Labib, 2011; Saaty, 1977).

3.1.4 RQ4: WHICH FACTORS INFLUENCE THE CHANCES THAT A PHOTOVOLTAIC CELL TECHNOLOGY OF THE THIRD GENERATION ACHIEVES DOMINANCE?

For answering the fourth question mainly results from question two and three are used; the list of factors and their influence on the technology dominance process assess the chances a dominant design emerges in the third generation. Moreover, interviews and literature on the third generation technologies are consulted; one interview was conducted with an expert in third generation technologies. Moreover, the results give possible directions for which strategies decision makers can follow to successfully select and support a future dominant design.

The AHP method has already been effectively used in technology forecasting in multiple studies (W. Kim et al., 2010; Salo, Gustafsson, & Ramanathan, 2003; Vaidya & Kumar, 2006). Recently, frameworks on dominant designs describe common characteristics in the ex-ante process of standard formation and the selection of technological designs; see also section 2.1.3 (Suárez, 2004; Van de Kaa, 2009). On the other hand, there is a lot of uncertainty with the characteristics and the development process of these new technologies. Because of the pre-defined list of factors from research question two and three, the third generation technologies can be systematically studied. This is explorative research, leading to the description and better understanding of this new technology generation (Stebbins, 2001).

3.2 DATA COLLECTION METHODS

This section will describe in more detail why the choice was made for certain data collection methods. For research question one a combination of industry magazines and scientific literature has been used to generate a suitable overview of the PV market. Scientific literature has been used since others already analysed the PV market and it provided insights in the latest (technological) developments. Industry magazines are used to efficiently gather latest market developments; like novel commercial production processes, issues on which companies are currently working and sales data.

For research question two is made use of semi structured interviews, besides the sources mentioned for research question one. To be able to investigate unexpected results semi structured interviews with experts were used to answer this explorative research question (instead of structured interviews). Moreover interviews are very effective to capture the knowledge, facts and opinions of individuals; they are time efficient, have a high response rate and a wide variety of topics can be discussed in depth (Velde, Jansen, & Anderson, 2008).
For research question three a questionnaire form was filled in during the interviews. Interviews were chosen, besides for the above described advantages, to ensure mutual understanding of the topics described in the questionnaire; industry experts are not familiar with the terminology of existing frameworks. This possible ambiguity in questioning is an extensively discussed potential shortcoming of the AHP method (e.g.: Watson & Freeling, 1983) and because the questionnaire uses terminology from dominance literature, it was not certain respondents would be able to fully understand the definitions of these concepts; conducting interviews addresses this problem. The questionnaire was used because of its effectiveness with the AHP method. Although Saaty (1977, 1980) describes how the researcher can even make use of solely oral interviews to fill in the comparison matrices of the AHP method, it seems desirable for validity to let respondents themselves fill in the questionnaire under the condition that they fully understand the used terminology.

For the last research question no new data collection methods were introduced; interviews and existing literature were used. The literature consisted of both scientific and forecast reports from research institutes and governmental organisations. These sources are expected to provide the best predictions for the PV market of the future.

### 3.3 Multi-Attribute Decision Making

With the choice for a PV technology multiple, sometimes conflicting, criteria (or attributes) need to be compared. The criteria have been defined in the previous chapter as being factors influencing the dominance process. The fact that multiple factors influence the dominance process using incommensurable scales, and that from several competing alternatives (a finite number of PV designs, see 4.3.4) the best needs to be selected, makes this a multi-attribute decision making (MADM) situation.

There are many different models to evaluate, prioritise and select competing alternatives; these models can be ordered in three broad categories (Belton & Stewart, 2002):

- Value measurement models; using numerical scales to represent preferences.
- Goal, aspiration or reference level models; in which desirable levels are defined.
- Outranking models; in which alternatives are ranked pairwise.

Depending on the amount of available information decision methodologies vary from simple methods like dominance selection, minimax or conjunctive methods; to more elaborate methods in which the weight of factors are assessed on ordinal or cardinal scales (Ishizaka & Labib, 2011; J. Lu, 2007). Some of the methods from the latter category are; Simple Additive Weighting, TOPSIS, ELECTRE, MacBeth, PROMTHEE and the Analytic Hierarchy Process (AHP). Moreover, there are some evaluation methods that are not specifically developed for MADM situations, though they could be used for prioritizing factors. Examples are qualitative approaches like the Delphi method or consensus mapping. These methods try to reach consensus between experts in several interview rounds.

From the earlier mentioned categories a value measurement model was chosen as the most suitable approach for this research. This approach is expected to deliver the best possible results and makes it possible to quantify qualitative ratings (most of the factors are based on subjective criteria). Moreover, with using this approach both qualitative and quantitative can be combined in the analysis.
After a suitable approach was decided upon, a suitable method could be chosen. The AHP method, as described by Saaty (1977, 1980), was found to be most suitable for this research, because:

- The AHP method makes use of a hierarchical structure to present the decision making situation, in which a complex problem is decomposed into hierarchies. This makes it easy for respondents to understand and to have a complete overview of the decision making situation with multiple criteria and alternatives.
- The hierarchy is analysed through a series of pairwise comparisons; these comparisons are only between two alternatives, which makes the observation as free as possible from extraneous influences.
- The ability to make use of subjective criteria and to combine both tangible and intangible alternatives and attributes. Hereby, intangible aspects like experiences and intuitions of respondents can easily be incorporated in the evaluation process.
- Because of its structured nature, all alternatives and criteria receive an equal amount of attention. This is opposite of unstructured or group decisions, like the Delphi method, in which there is a tendency to focus only on the most important and least important factors and elements (R. F. Dyer & Forman, 1992).
- The method provides the ability to calculate the consistency of judgments from respondents.
- Differences between the answers of experts (for example on multiple technological generations) can easily be found and compared.
- AHP is a compensatory method; this means that it leaves room for making trade-offs, while the simpler MADM decision making methods do not offer these possibilities.

Moreover, the AHP method has proven its effectiveness in (technological) design selection (e.g.: C.-W. Chang, Wu, Lin, & Lin, 2007; Kahraman, Kaya, & Cebi, 2009; Vaidya & Kumar, 2006; Van de Kaa, 2009).

### 3.3.1 Analytic Hierarchy Process

By asking experts to rank paired comparisons, the AHP derives at a ratio scale comparing all alternatives and criteria in the decision making situation. Briefly mentioned in the previous section, the AHP method has already been used in a wide variety of applications, for example in; forecasting, evaluation, prioritizing and quality management studies. An overview of recent applications is given in Sipahi and Timor (2010) or Vaidya and Kumar (2006).

The methodology of the AHP is as follows (Saaty, 1980):

1. The AHP starts with modelling the decision making problem; by making a hierarchy (Saaty, 1990) of the overlapping goal, incentives influencing this goal and cases in which they are
applied (see also Figure 5 and Figure 22).

2. The following step is to pairwise compare the criteria on a nine point scale from 1 (equal importance) to 9 (extreme importance) (Figure 6 and Table 5), resulting in priorities.

3. With step 3 the pairwise comparisons of the previous steps are organised in a square matrix. An example is given in Table 3; it shows that financial strength is moderately more important (a factor 3) for the case of CIGS (A) than for a-Si (B). Mathematically the judgement matrix $A$ is given by (with column $j$ and row $i$):

$$
A = \begin{bmatrix}
C_1 & C_2 & \cdots & C_n \\
1 & w_{12} & \cdots & w_{1j} \\
(w_{21})^{-1} & 1 & \cdots & w_{2j} \\
\vdots & \vdots & \ddots & \vdots \\
w_{i1} & w_{i2} & \cdots & 1
\end{bmatrix}
$$

(1)

4. Now the priority vector can be calculated (i.e. the normalized eigenvector of the matrix). Thus first the matrix needs to be normalised by dividing each element with the sum of its column, mathematically:

$$
w_{ij}' = \frac{w_{ij}}{\sum_{j=1}^{n} w_{ij}}
$$

(2)

After this the principal eigenvector (or priority vector) can be calculated by taking the average of each row $i$. The eigenvector shows the normalised weight of each criteria $C$. Mathematically for vector $x$:

$$
\lambda x = Ax, \text{ with } x > 0
$$

(3)

5. The consistency of their answers can be calculated and compared with the random consistency index (Saaty, 1990); therefore it is possible to have consistent results with only one expert interview. To determine the consistency of the answers first the principal eigenvalue $\lambda_{max}$ needs to be calculated by summation of the product of each element of the eigenvector and the sum of columns of the matrix, mathematically:

$$
\lambda_{max}x = Ax
$$

(4)

Next the consistency index $CI$ can be calculated, with $n$ being the size of the comparison matrix (which equals $\lambda_{max}$):

$$
CI = \frac{\lambda_{max} - n}{n - 1}
$$

(5)

Now the consistency index can be compared with random consistency index $RI$, which is defined by Saaty (1977, 1980) as being the appropriate values for the number of criteria $n$, shown in Table 4.

**Table 4: Random Consistency Index**

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$RI$</td>
<td>0</td>
<td>0</td>
<td>0.58</td>
<td>0.9</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>
The consistency ratio $CR$ results from the dividing the calculated consistency index $CI$ by the random consistency index $RI$, mathematically:

$$CR = \frac{CI}{RI}, CR < 0.1$$

If the result is smaller than 10% the answers are considered to be consistent (Saaty, 1977, 1980).

6. Lastly a table with can be made representing the relative importance of the criteria (factors).

### 3.3.2 Criticism on the Crisp AHP Method

There is also quite some criticism on the use of the (crisp) AHP method, for example (Bhushan, 2004; J. S. Dyer, 1990; Ishizaka & Labib, 2009, 2011; Rezaei & Dowlatshahi, 2010; Tang, Ahmad, Ahmed, & Lu, 2004; Zanakis, Solomon, Wishart, & Dublisch, 1998):

1. Possible rank reversal using scale inversion when calculating the eigenvalue.
2. Nine-point scale may not always be sufficient to express the level of preference. This is addressed by filling in the questionnaire during interviews instead of sending them out; this ensures mutual understanding.
3. Categories with a large number of alternatives tend to be rated higher.
4. Number of questions becomes very large as the number of factors and alternatives increases.
5. Even when using the consistency check still inconsistent comparisons may have been made.

With regards to criticism 1 it should be noted that also with other decision making methods there exists the possibility of rank reversal (Y.-M. Wang & Luo, 2009). In general these drawbacks with using the crisp AHP method are not as great as the advantages described earlier, moreover some of the shortcomings can easily be addressed.

In order to address criticism 1 and 5 several methods have been developed, however not all researchers are convinced of the effectiveness of these new methods (see also the debate in Zanakis et al. (1998) or by Saaty and Tran (2007)). Still a lot of scientists agree that new versions of the Analytic Hierarchy Process can be seen as improvements (Ishizaka & Labib, 2011). Therefore the data from the questionnaire is both analysed using the crisp AHP approach as defined by Saaty (1977, 1980), and by using triangular fuzzy numbers in the fuzzy AHP analysis as defined by Wang et al. (2011; 2006); to address some of the above mentioned problems and to make a comparison between the two methods.
### 3.3.3 Fuzzy Analytic Hierarchy Process

The main difference of fuzzy AHP (FAHP) compared with the crisp AHP method in this research is that in FAHP expert judgments are not considered to be crisp comparisons, rather they are fuzzy evaluations of the two attributes; consequently instead of using fixed values for the comparison of attributes, intervals are used (Chan & Kumar, 2007). The already briefly mentioned method from Wang and Chin (2011; Y.-M. Wang et al., 2006) uses the logarithmic fuzzy preference programming (LFPP) based methodology; this method makes use of triangular fuzzy numbers and finds its basics in the work from Makhailov (2003). Moreover, this approach follows as a substitute of earlier work on deriving weights from fuzzy comparison matrices, e.g.; from Chang (1996) and Van Laarhoven and Pedrycz (1983). The LFPP method is proposed by Wang and Chin to overcome shortcomings from earlier frameworks for fuzzy AHP method; such as finding incorrect weights or problems with multiple optimal solutions.

The first steps of the fuzzy AHP analysis are similar to the crisp AHP method, though in the analysis of the answers from the questionnaire the fuzzy qualification of judgements is introduced. In this research we use the methods described by Wang et al. (2011; 2006); since it is found to be a robust process for analysing fuzzy comparison matrices and, as described above, it builds on existing methodologies.

The pairwise comparison uses the same definitions as the crisp AHP method, though they are linked to triangular numbers as shown in Table 5 and Figure 7. The numbers are defined by the following piecewise continuous membership function (Mikhailov & Tsvetinov, 2004):

\[ u_R(x) = \begin{cases} 
\frac{x-a}{b-a}, & a \leq x \leq b \\
\frac{c-x}{c-b}, & b \leq x \leq c \\
0, & \text{otherwise}
\end{cases} \]  

(7)

### Table 5: AHP and FAHP Rankings

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Crisp AHP (Saaty, 1977, 1980)</th>
<th>Triangular FAHP ([l, m, u])</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Extreme importance or preference.</td>
<td>9</td>
<td>{8, 9, 9}</td>
</tr>
<tr>
<td>7</td>
<td>Very strong or demonstrated importance or preference.</td>
<td>7</td>
<td>{6, 7, 8}</td>
</tr>
<tr>
<td>5</td>
<td>Strong or essential importance or preference.</td>
<td>5</td>
<td>{4, 5, 6}</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance or preference of one over another.</td>
<td>3</td>
<td>{2, 3, 4}</td>
</tr>
<tr>
<td>1</td>
<td>Equal importance or preference.</td>
<td>1</td>
<td>{1, 1, 1}</td>
</tr>
<tr>
<td></td>
<td>Intermediate values:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>{7, 8, 9}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>{5, 6, 7}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>{3, 4, 5}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>{1, 2, 3}</td>
</tr>
<tr>
<td></td>
<td>Reciprocal number (for symmetric pairwise comparison matrix)</td>
<td></td>
<td>x^{-1}</td>
</tr>
</tbody>
</table>

* \(\tilde{A}\) is defined according to the numbers in Table 5
To fully understand the (mathematical) steps of the LFPP method, first the operational laws of fuzzy number sets \(\tilde{N}_1 = (l_1, m_1, u_1)\) and \(\tilde{N}_2 = (l_2, m_2, u_2)\) are introduced, with all \(l, m, u\) being \(\{\in \mathbb{R} | > 0\}\):

**Addition:**
\[
\tilde{N}_1 \oplus \tilde{N}_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)
\]

**Multiplication:**
\[
\tilde{N}_1 \otimes \tilde{N}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \cong (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)
\]

**Division:**
\[
\tilde{N}_1 \oslash \tilde{N}_2 = (l_1, m_1, u_1) \oslash (l_2, m_2, u_2) \cong \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2}\right)
\]

The first steps of the LFPP method are similar to the crisp AHP method (section 3.3.1), the first difference comes with step 3:

3. Again the pairwise comparisons are organised in a square matrix. Mathematically the fuzzy judgement matrix \(\tilde{A}\) is given by (with column \(j\) and row \(i = 1, \ldots, n\)):

\[
\tilde{A} = \begin{bmatrix}
C_1 & C_2 & \ldots & C_n \\
(1,1,1) & \tilde{w}_{12} & \tilde{w}_{1j} \\
(\tilde{w}_{12})^{-1} & (1,1,1) & \tilde{w}_{2j} \\
\vdots & \ddots & \ddots & \ddots \\
\tilde{w}_{ij} & \tilde{w}_{ij} & \tilde{w}_{ij} & (1,1,1)
\end{bmatrix}, \quad \text{with} \quad \tilde{w}_{ij} = \{(l_{ij}, m_{ij}, u_{ij})\} \quad 0 < l_{ij} \leq m_{ij} \leq u_{ij}
\]

In \(l_{ij}; m_{ij}\) is the lower limit and \(m_{ij}\) the expected value. The reciprocal values are obtained by:

\[
\tilde{w}_{ij}^{-1} = \{u_{ij}^{-1}, m_{ij}^{-1}, l_{ij}^{-1}\}
\]

4. Because \(\ln \tilde{A}_{ij} \approx \{\ln l_{ij}, \ln m_{ij}, \ln u_{ij}\}\), the pairwise continuous membership function, as described above, can be rewritten as:

\[
u_{ij}\left(\ln \frac{w_i}{w_j}\right) = \begin{cases} 
\ln \frac{w_i}{w_j} - \ln l_{ij} & \ln \frac{w_i}{w_j} \leq \ln m_{ij} \\
\ln m_{ij} - \ln l_{ij} & \ln m_{ij} - \ln l_{ij} \\
\ln u_{ij} - \ln m_{ij} & \ln u_{ij} - \ln m_{ij} \geq \ln m_{ij}
\end{cases}
\]

Now, to determine a crisp priority vector (similar functionality like in the crisp AHP method), first the previously mentioned membership degree needs to be maximised:

\[
\max \lambda = \min \left\{\mu_{ij} \ln \frac{w_i}{w_j}\right\}, \quad \text{with} \quad i = 1, \ldots, n - 1; j = i + 1, \ldots, n
\]
This can be rewritten to the following model:

Maximise  \( 1 - \lambda \) \hspace{1cm} (15)

Subject to

\[
\left\{ \begin{array}{l}
\ln w_i - \ln w_j - \lambda \ln \frac{m_{ij}}{l_{ij}} \geq \ln l_{ij}, \quad i = 1, \ldots, n; j = i + 1, \ldots, n \\
-\ln w_i + \ln w_j - \lambda \ln \frac{u_{ij}}{m_{ij}} \geq -\ln u_{ij}, \quad i = 1, \ldots, n; j = i + 1, \ldots, n \\
w_i \geq 0, \quad i = 1, \ldots, n
\end{array} \right.
\]

However, when solving this formula the value \( \lambda \) may become negative, because not all weights will be able to meet all the judgements in the fuzzy comparison matrix \( \tilde{A}_{ij} \); to overcome this problem the nonnegative values \( \delta_{ij} \) and \( \eta_{ij} \) are introduced. This results in a model from which we calculate the values of \( x \):

Minimise  \( J = (1 - \lambda)^2 + M \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} (\delta_{ij}^2 + \eta_{ij}^2) \) \hspace{1cm} (16)

Subject to

\[
\left\{ \begin{array}{l}
x_i - x_j - \lambda \ln \frac{m_{ij}}{l_{ij}} + \delta_{ij} \geq \ln l_{ij}, \quad i = 1, \ldots, n; j = i + 1, \ldots, n \\
-x_i + x_j - \lambda \ln \frac{u_{ij}}{m_{ij}} + \eta_{ij} \geq -\ln u_{ij}, \quad i = 1, \ldots, n; j = i + 1, \ldots, n \\
\lambda, x_i \geq 0, \quad i = 1, \ldots, n \\
\delta_{ij}, \eta_{ij} \geq 0, \quad i = 1, \ldots, n-1; j = i + 1, \ldots, n
\end{array} \right.
\]

Now the weight can be determined. With \( x_i = \ln w_i \) for \( i = 1, \ldots, n \) and \( M \) is a specified constant (>1000); in order to find weights within the support intervals of the judgement and to minimize violations.

In this research the GRG (Generalized Reduced Gradient) non-linear optimization function from Excel Solver is used to find the missing values.

5. After finding the optimal solution the weights \( w_i \) are normalised by:

\[
w_i^* = \frac{e^{w_i}}{\sum_{j=1}^{n} e^{w_j}}, \quad i = 1, \ldots, n
\] \hspace{1cm} (17)

6. If \( \lambda^* > 0 \) the criteria match the priorities, also the larger the value of \( \lambda^* \) the higher the consistency. If \( \lambda^* = 0 \) the possibility of inconsistencies can be checked by calculating \( \delta^* \):

\[
\delta^* = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left( \delta_{ij}^2 + \eta_{ij}^2 \right)
\] \hspace{1cm} (18)

When \( \delta^* \neq 0 \) there consist inconsistencies in the fuzzy judgements, similar to the crisp AHP method; the larger \( \delta^* \), the higher the inconsistency. Wang and Chin (2011) do not describe a threshold like Saaty (1977, 1980) at which the comparisons become unacceptable inconsistent and should be rechecked, however in one example they calculate the value of \( \lambda^* = 0 \) and \( \delta^* = 0.2271 \) and consider this as “strong inconsistency”.
It should be noted that by using fuzzy triangular values in the comparison matrices it is very well possible to introduce some form of inconsistency in the answers (Çakır, 2008), even when the matrices are found to be consistent using the consistency ratio from the crisp AHP analysis; this is a shortcoming of the fuzzy AHP method in general. The main reason for these inconsistencies comes from the overlap that fuzzy numbers may have with each other, this is illustrated by the grey area in Figure 8.

### 3.4 Reliability and Validity

One of the steps to ensure reliability and validity in this research is to have triangulation of data; Yin (2009) defines triangulation as using two or more data sources. Moreover Patton (1987) described three other sources of triangulation, namely triangulation of different evaluators, different theories (perspectives) and methods (methodologies). In this research multiple data sources are used; expert opinions (from companies, installation companies, research institutes and universities), industry magazines and scientific literature (on both the technologies and economic/sociological theories). This research also has triangulation of evaluators by having multiple supervisors from the university as well as industry experts; data from expert interviews has after collection been checked by several experts. Moreover regarding triangulation of methodology, both the crisp AHP and the fuzzy AHP method are used. Nevertheless, although these methods use different ways of analysing data they are both based on surveys using the notion of multiple criteria decision analysis.

The results of this analysis is considered valid because it makes use of existing methods that have been successfully used to describe priorities of factors; the (fuzzy) AHP method. Therefore, this research conforms to the requirements for validity as described by Bailey (1994) of having an instrument that measures the concept and that this measurement is accurate. Secondly, there is the reliability of a research which is defined by having a consistent measurement method; results do not change when the concept being measured remains the same. One way of checking the reliability is by using two methods to measure the same concept; in this research this is tried to be achieved by using both the fuzzy and the crisp AHP method to measure the priorities of factors.

Also when using questionnaires, there are specific errors that may negatively influence reliability of a research, i.e.: double barrel questions, ambiguous wording and the level of wording, abstract versus factual questions and leading questions (influencing respondent to give specific answers) (Bailey, 1994). For this research these errors have been addressed by filling in the questionnaire while conducting a semi structured interview. According to Bailey (1994) an essential part of semi structured interviews is that the topic is predefined, though there is no predefined wording of questions or the use of predefined sub-questions. Maybe more interestingly, the interviewer studies the discussed topic in advance and adjusts the follow-up questions based on the answers of the respondent; this is why this study first investigated the state of the PV market (research question 1) and conducted the interviews and questionnaires afterwards. Also the approach of both filling in a questionnaire and doing a semi structured interview with the same respondents on the same topic ensures further reliability of the results.
The above described way of conducting questionnaires also ensured understanding of alternative judgements from experts; the different visions on the dominance process have been incorporated in the analysis as described in chapter 5. Incorporating these different, sometimes contradicting, visions is an essential part to ensure the validity of this study. Consequently the differences between different experts in filling in the questionnaire are not just averaged in the end result, they are also analysed and incorporated in the factor analysis of the PV market (chapter 5). This is important for the completeness of this research, since as described by Van de Kaa (2009, p. 94): “[…] by averaging the judgments valuable information could be lost.” This is a drawback of using the Delphi method, since in this analysis differences between expert opinions easily can get lost; due to the reuse of findings in each subsequent round.
Despite the paper in which Unruh (2000) describes governments, institutes and economic systems are locked in a fossil based paradigm due the coevolution of firms, institutions and governments around fossil fuels, photovoltaic (PV) technologies made enormous progress in terms of adoption. Also other renewables had already in 2008 a 19% contribution to global energy generation, for electricity generation 18% of the global demand came from renewable sources (REN21, 2010). However not taking into account hydropower, renewables only reached a 3% market share, from which grid connected PV accounts for 21 GW or 1.7% of the total renewable energy generation. Nevertheless, the present PV industry grows with impressive rates; in the years 2008-2009 the overall growth was 60% for installed capacity (REN21, 2010) and for production over 100% growth in 2010 (Hirshman, 2011). Similarly, the last decade the growth of second generation PV cells was 30% on average (Aberle, 2009). Especially Europe is leading in this market on research and production; there are however huge differences between European countries, the European leadership comes mainly from worldwide market leader Germany.

Already since the production of the first solar cells, crystalline silicon had the largest overall market share of shipped PV panels (EPIA, 2009). Within the first generation multi-crystalline solar cells have been the largest since 1999 (Hirshman, 2009), the latest data shows that in 2010 multi-crystalline silicon even had an estimated share of 53% within the total shipped solar cells market (Hirshman, 2011). Nevertheless, differences with the other first generation silicon design (sc-Si) are only very small, consequently one cannot say with certainty this is the dominant design.

This chapter provides an overview of the PV market in order to answer research question one: What are the specifics of the PV technologies in the market? It is necessary to create an overview to start this research for several reasons: As explained in the previous chapter, semi structured interviews are used to answer research question 2 and 3; the researcher should be well prepared for these interviews. Also explained in the previous chapter, existing frameworks have been used to analyse the PV market. The influence of factors from the framework may differ however, according to the status of technological development; see section 2.1.5. Consequently, one
should have an accurate overview of the current status of technologies.

This chapter starts with a description of the general workings of PV technologies, followed by a historical timeline of the development and diffusion of PV. Next, an overview is given of all PV technologies, from which five have been selected based on commercial availability. Lastly, the PV supply chain is described followed by a short description on PV systems.

### 4.1 Basic Operating Principles

The energy of solar radiation can be directly converted into electricity with the use of semiconductor devices, called solar cells. This process is known as photovoltaic energy conversion based on the photovoltaic effect inside solar cells. The photovoltaic effect means “the generation of a potential difference at the junction of two different materials in response to visible or other [electromagnetic] radiation” (Zeman, 2011, p. 1.8). At the junction a photon (radiation) arrives and transfers its energy to charge carriers, next these charge carriers are separated in an electron (negative) and hole (positive) and collected at the terminals of the junction. This process is explained in detail using crystalline silicon based solar cells as an example, since this is the most used design in the PV market.

First; radiation is absorbed and generates charge carriers in the absorber layer (Figure 9). The absorber layer consists of ‘p-type’ material, doped-silicon (silicon mixed with another material) in which the holes dominate the electrical conductivity and therefore can easily share an electron. The generated charge carriers consist of an electron hole pair, which need to be transported to the front and back contact. First the electron hole pair needs to be separated, see Figure 10, from which the electron (red dots) moves towards the n-layer and the hole (blue dots) towards the p++-layer (see Figure 11). The n-type layer works exactly the other way around of the p-type layer, so it has an overdose of electrons. The working of the p++-layer is the same as described above, only this layer is more heavily doped; meaning silicon with an higher concentration of another material. These n- and p++-type layers ensure the holes and electrons can move their way towards the contacts without being lost; e.g. the recombination of an electron hole pair. The process of collection is seen in Figure 11, a complete overview of the process is given Figure 12.

### 4.2 Timeline of Development

The model from Den Hartigh, Ortt, Van de Kaa, & Stolwijk (2009) is used to systematically describe the pattern of development of PV technologies and to differentiate between the phases in the diffusion process (see also section 4.3.4). This model combines earlier work from Ortt and Schoolmans (2004) and Suárez (2004). The resulting analysis forms the basis of the selection of PV technologies that are in same phase of the diffusion process. Selecting technologies from the same phase is necessary for
the later analysis on the influence of factors in the technology selection process, since the importance of factors shifts with the stage in the diffusion process.

Currently there are more than 200 manufactures of solar cells worldwide, according to the magazine Photon international (Hirshman, 2011), and there are even more manufactures of modules (see section 4.4). For silicon PV cells from the invention and discovery of the PV effect it took more than 100 years to reach the start of the 4th phase. The total production of solar cells still increases fast each year; this means that the marked stabilization is not reached yet, see Figure 30. In the timeline and its description silicon solar cells have a dominant role, since this was the first PV technology being developed which was of practical use for electricity generation.

Divided by the different phases the main actors and factors are described; from the transition from small applications like aerospace and electrifying remote (communication) stations to large grid connected electricity production. Data is gathered from multiple sources, these are shown in the timeline of Appendix VI.

4.2.1 Hallmark 1: Invention
In 1839 Antoine-César Becquerel discovers that a current is developed when exposing an electrode in an electrolyte solution to light; the first scientific writing on the PV effect. In 1873 W. Smith finds the correlation between the illumination of selenium metal and its electrical resistance while making a testing device for underwater telegraph cables. Three years later in 1876 Adams discovers that illuminating a junction between selenium and platinum produces an electric current; the PV effect, this is what all current solar cells use.

In 1883 Fritts develops the first modern solar cell; he puts a thin coating of gold on top of a selenium layer. At that time there was no theoretical explanation for the PV effect, this would last until the explanation of Einstein in 1904.

The basis of the later production method of silicon solar cells was discovered by Czochralski in 1916.

4.2.2 Hallmark 2: Innovation
The boundary between the first and second hallmark is found to be best marked by Ohl’s experiment in the 1940s. Ohl, working in the Bell Labs, conducted experiments with impurities in silicon when he discovered in 1941 that he could create the p- and n-type regions in silicon with the elements phosphor and boron.

Shockley, a colleague of Ohl at the Bell Labs, conducted further research on the p n junction effect in 1948 which resulted in better theoretical understanding. Still the manufacturing process of transistors was difficult because of impurities, researcher Teal from the Bell labs overcame this problem in 1951 by making use of Czochralski’s method for growing large, single crystals of germanium and silicon. In the same year Ohl describes efficiencies of less than 1% for multi crystalline solar cells. Later that year his colleague Pfann further optimises the manufacturing process to achieve ultra-pure semiconductor materials needed for transistors. This material would later also be used for the manufacturing of silicon solar cells.

In 1954 electrical engineer Chapin, physicist Pearson and chemist Fuller from the Bell Labs announced the first single crystalline solar cell which generated a useful amount of power, it was announced as the Bell Solar Battery and had an efficiency of 6%. This product was initially invented to overcome the problem of providing small amounts of power needed for telephone communications.
in remote and humid locations were the performance of originally used dry-cell batteries was not sufficient.

### 4.2.3 Hallmark 3: Market Adaption

With the announcement of the first solar cell a new hallmark is reached, the market adaption phase. In the first years the product was not really successful in its original application; it was not economically viable to use the device for rural electrification by Bell. The PV device nevertheless showed its potential; in 1955 Bell tested their application in a rural area which showed the cell was reliable but expensive. Instead Bell searched for more profitable applications by selling commercial licences via their subsidiary company Western Electric. One company that bought a licence in 1955 was National Fabricated Products, the next year Hoffman Electronics bought the company and later announces a portable radio making use of the solar cells. In the same year Hoffman Electronics also starts to use the solar cells for space applications.

In 1958 Mandelkorn, working at the US Signal Corps Laboratories, develops silicon solar cells which are more resistant to the radiation damage in space. Later that year the Vanguard I satellite is launched, it has a less than 1W solar array, from Hoffman cells, to power the radios. In the same and following years several satellites are launched which make use of PV arrays; e.g. the Explorer III/VI/VII and the Sputnik 3. These projects proved the potential of PV and started a large demand for solar cells from the space industry.

In the year 1962 the first communications satellite Telstar I is launched, getting its power from 3,600 Bell Solar Battery cells (14W). From now on almost all satellites make use of solar cells for their energy need. During the next year, 1963, Sharp starts mass production of silicon solar cells. They may immediately deliver solar cells for the No. 1 Tsurumi light buoy in Yokohama Port. From the mid-60s to the early 70s on the coast guard would make more and more use of solar cells to power buoys.

In the early 70s Elliot Berman working for oil company Exxon invented a way to dramatically reduce solar cell costs by using lower grade, cheaper, silicon and less expensive packaging materials. This development made it possible to shift from a merely space oriented market towards a more terrestrial use of solar cells. Oil companies were the first to use the new type of cells; they used them to bring down maintenance costs for powering horns and flashlights on oil rigs.

In 1974 Japans Project of Sunshine starts, which has as aim the development of solar energy, geothermal energy, coal gasification and liquefaction, and hydrogen energy. This project is the main driver behind Japans renewable energy developments. The same year they develop a new way of manufacturing, they grew the first EFG ribbon by using a continuous belt process. Also in the same year the US the Southern Railroad Company successfully experiment with solar panels to power signalling and shunt equipment. It is the start for worldwide introduction of solar cells for remote railroad applications.

In 1977 Vespieren starts using solar powered pumps for water in Mali. This is the first of many projects using solar power for off-grid systems in developing countries. Later during the 70s Telecom Australia begins providing Australians living in remote areas with high-quality telecommunication services by making use of PV devices, they develop the first major solar powered telecommunications link between Alice Springs and Tennant Creek in 1979.
Similarly during the 1970s significant improvements are made in the efficiencies of multi crystalline solar cells. Also during this period and the early 1980s new PV technologies are invented and introduced on the market; for example cadmium telluride, amorphous silicon and copper indium gallium selenide. Research and development during this time was heavily stimulated as a result of the oil crises in the 1970s.

With the introduction of PV for off-grid electrification in the early 1980s comes wider market diffusion of PV. This starts with the electrification of households in developing countries, later on-grid connections are introduced in western counties. Today grid connected PV arrays seems to have the highest growth potential in the PV market. From the 80s on other PV technologies have been commercially introduced on the market with variable success rates, still the technologies with the largest market shares are the 1G technologies mono- and multi crystalline silicon. Also in the 80s there is a peak in patents granted (Andersson & Jacobsson, 2000).

In western countries many policy initiatives to promote PV systems have been initiated during the fourth phase, an overview of the policies is shown in Appendix VIII. Similarly market shares are shown in Figure 14 and Appendix IV.

**4.3 Technological generations**

The several types of PV cells can be categorized; authors have proposed different ways to categorize, see Appendix III. This report makes a distinction between generations as defined by Green (2006) and further described by Bagnall and Boreland (2008) who defines solar cell materials on the moment of their initial development and current commercial status (efficiency versus cost ratio). In making this categorisation Green does not mention PV technologies developed during the 50s and 60s which are currently not developed anymore. For this study it is important to show all technologies, since this provides insight in the emergence of dominant designs besides designs which did not develop any further. Nevertheless the focus in this research is only on solar technologies which can be used for producing PV modules, this includes; PV systems used for grid connected electricity production as well as off-grid energy production for example in rural areas. On the other hand; it does not include PV cells used in products such as watches, calculators, toys, etc. An overview of all market shares can be found in Figure 14 and more detailed in Appendix IV.

In Figure 13 can be seen that in the early years there are basically two development phases with the increasing oil prices in the early 1970s marked in this research as the emergence of second generation technologies (Gevorkian, 2007; Razykov et al., 2011; Zeman, 2011).
4.3.1 First Generation Materials
The first generation (1G) starts with the development of the modern PV cell in 1954 (Bell Labs, 2011). In this generation only single junction crystalline silicon solar cells are currently commercially available for the mass market, this technology started with production technologies from the integrated circuit (IC/computer chip) industry. Cadmium sulfide (CdS) and gallium arsenide (GaAs) on the other hand are currently not commercially available. Although CdS is currently used as a part of some second generation cells, it is not available as a standalone PV cell (Rappaport, 1959; Razykov et al., 2011). GaAs are still produced and are able to achieve the highest PV efficiencies today (new multi-layer versions are mentioned under generation 3), they are however very expensive and therefore mainly used for space applications (Razykov et al., 2011).

This generation accounts for roughly 86% of the total annual PV modules sales (Hirshman, 2011; Raugei & Frankl, 2009, p. 393). The following technologies are part of this generation:

- sc-Si (single/mono crystalline silicon)
- mc-Si (multi crystalline silicon)
  - Also includes ribbon based PV modules (these are made in a continuous process on a substrate)
- CdS (cadmium sulfide)
- GaAs (gallium arsenide)
  - Single, double and triple junction cells
  - Mainly used in concentrator applications

On the module market some other variations of technologies can be found, they are in this report considered to be a combination of one of the previous mentioned technologies. For example:

- HIT (Hetero junction with Intrinsic Thin layer)
  - Combination of layers a-Si with mono-crystalline silicon

4.3.2 Second Generation Materials
The second generation (2G) consist of PV cells which emerged after rising oil prices in the early 1970s. This generation intended to reduce costs by using new materials and production processes to reduce the material use. Often this generation is associated with the name “thin-film cells”, however this definition is not definite and therefore not used in this research. CI(G)S and CdTe could not use fabrication techniques from the IC industry, making their production capacity improvement slow. CdTe is now however the market leader for four years in this generation with the largest share in 2009 of 50% (Hirshman, 2010). For initial development a-Si and pc-Si on the other hand could rely on fabrication know-how from the flat-panel display sector.

This generation account for roughly the rest of the PV market left by the 1G; i.e. 14% in 2010 (Hirshman, 2011). The following technologies are part of this generation:

- a-Si (amorphous silicon)
  - Also called hydrogenated amorphous silicon (a-Si:H)
  - Covers also a-Si multi junction cells
- CI(G)S (Cu(In, Ga)Se2, copper indium gallium selenide)
  - Variants without gallium are called CIS (CuInSe2)
  - Often cadmium is used in these cells
CdTe (cadmium telluride)
- μc-Si (micro crystalline silicon)
  - Consists of small crystals in an amorphous stage

Similar to the first generation technologies, also in the second generation there are combinations of technologies. For example:

- Micromorphous silicon
  - Multilayer module with microcrystalline and amorphous silicon (a-Si/μc-Si)

In comparison with the first generation these second generation technologies have several benefits (Razykov et al., 2011):

- a-Si greatly reduces the thickness of the silicon layer in comparison with mono and multi crystalline silicon; it uses even a 1µm layer in comparison to the some 1G silicon cells having a silicon layer somewhere between 100 and 200µm (Green, Zhao, Wang, & Wenham, 2001).
- They can be deposited on low cost substrates; making it possible to have flexible panels and reducing the need for heavy glass modules.
- Similarly, they can be made on regular module sized substrates which use internally connected structures; reducing the need for a web of wires on top of the cells.

### 4.3.3 Third Generation Materials

The third generation of PV technologies is still mainly in the research phase, or too expensive for terrestrial use (Berenschot et al., 2011; Razykov et al., 2011), and have no market share noteworthy (see Figure 26 on page 120). In this research, it is recognised to contain the following technologies:

- III-V solar cells (solar cells using elements from group III and V of the periodic table)
  - Materials that are most used: GaAs (gallium arsenide, multi junction) and InP (indium phosphide)
  - Although not yet widely used for commercial terrestrial applications, it is already used for space and concentrator applications
  - There are also several concepts using a combination of 2/3G materials
    - GaInP/GaAs/Ge
    - GaInP/GaAs/GaInNAs
    - GaAs/CIS
- Nanophotovoltaics
  - Using crystalline semiconductor III–V materials, polymeric materials or carbon-based nanostructures
  - QWSC (quantum solar cells, with quantum wells and quantum dots solar cells)
    - The quantum wells are incorporated into the p-i-n junction to extend the absorption of the cell.
  - QD cells (quantum dot solar cells, nanometre sized crystallite semiconductor)
    - The quantum well severs as a semiconductor with a small band gap in between two semiconductor layers with a larger band gap; significantly increasing efficiency (up to 63%).
- Organic PV
  - DSC (dye-sensitized solar cells, (partly) on organic material)
    - Also called DSSC or DYSC
  - DSSC uses organic–inorganic nanocomposites such as gel electrolytes like sol–gel silica
    - A dye-sensitized solar cell is composed of a layer of nanoparticles, covered with a molecular dye that absorbs sunlight (similar to the effect of chlorophyll in green leaves)
    - Same efficiencies as a-Si but at lower costs
    - Can be used in combination with nanocrystals to increase efficiencies
  - Organic solar cells (fully based on organic material)
    - Uses organic electronic materials in combination with metallic layer(s)
    - Efficiencies up to a-Si devices and a cost structure derived from plastic processing; they can be easily manufactured using well known printing techniques in a continuous roll-to-roll process

4.3.4 Selected Technologies

Not all the PV technologies from the above list are used in this research; five have been selected on the basis of their stage in the technological development process. These five technologies are all in the same phase; market adaption. This is essential in order to prevent using incommensurable PV technologies in the analysis; since it has been argued in section 4.2, how the importance of factors differs depending on the phase of market diffusion (Ortt & Schoormans, 2004; Suárez, 2004). To prevent these shifts in importance of factors only technologies that currently can be produced commercially for terrestrial electricity production have been selected; this is the phase of market adaption. In theory all PV technologies can be used for terrestrial large scale electricity production, however in the current stage of development some PV technologies still have problems that prevent them from being used as a reliable and efficient design in these large scale applications.

The five technologies shown in Table 6 are recognized to be currently available for production of commercial PV designs for terrestrial energy production.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Year of invention (Bubenzer &amp; Luther, 2003; Fraas &amp; Partain, 2010; Green, 2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>Mono-crystalline silicon</td>
</tr>
<tr>
<td>mc-Si</td>
<td>Multi-crystalline silicon</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium telluride</td>
</tr>
<tr>
<td>a-Si</td>
<td>Amorphous silicon</td>
</tr>
<tr>
<td>CI(G)S</td>
<td>CuIn(Ga)Se2; copper, indium, (gallium), selenide</td>
</tr>
</tbody>
</table>
From Figure 14 can be seen that not one technology has yet reached a stable state of market dominance, although mc-Si currently has a market share of over 50% its share has been fluctuating over the years.

\[\text{Market shares}\]

Like previously explained, there are some modules available on the market use different technologies, since these technologies use as a basis one or a combination of the above mentioned five technologies. Furthermore there are other technologies that only sometimes get used for terrestrial energy production yet (i.e.: III-V and organic solar cells), however these are only used for question four of this research because their share is only minimal and these technologies have only a very small market share, which is expected to grow but only in the future (around 2020) (IEA, 2010a; NEDO, 2010).

4.4 DISTRIBUTION OF FIRMS IN THE SUPPLY CHAIN

The 1G silicon based PV module manufactures do not often do purification of silicon themselves. Similarly there are also companies solely making cells from purified silicon and do not do the assembly of PV panels. Before raw materials such as silicon get transformed and eventually installed as solar panels there are a couple of production steps to take; generally the production process of 1G silicon technologies looks like shown in Figure 15. For manufacturing 2G technologies there are many different processes, however the basics are shown in Figure 16. The coating of active material on a substrate is the most distinguishing production in comparison with the 1G silicon technologies.
The 1G silicon technology supply chain is characterised by separate production steps that can be done by different manufactures. In the process of manufacturing 1G silicon modules there is already some standardization of production machines, while manufactures of 2G use several different production processes which are not standardized and consequently research and development is not concentrated.
around one production method. In the cost breakdown structure of the PV manufacturing process the first three steps each account for approximately one fifth of the final module price and the last step the remaining two fifths, see also Figure 17 (Cisztek, 2010; Grau, Huo, & Neuhoff, 2011; Hoffmann, 2006). However, because of efficiency improvements down the supply chain is the price of wafer production becoming an increasing part of the cost breakdown structure; up to 50% for the first two steps of the manufacturing process (Sachs, 2010).

At the top of the supply chain, in the refinement of raw materials, the market can be described as an oligopoly, since there are only a few firms and the largest producers have a substantial market share. This part of the market is characterised with entry barriers that are high because of the substantial start-up costs, though the profits are high (Cai, 2011; Grau et al., 2011). Nevertheless it is expected that after the silicon shortages of the last decade the number of firms in this market is increasing. Moving down the value chain the number of manufactures and the competition increases, though profit margins and entry barriers decline. In a report from EPIA and Greenpeace (2011) on the PV market is presented that in the 1G silicon market; there where about 75 firms operating in the first step of the value chain (shown in Figure 15), 208 in the second step, 239 in the third and 988 in the last step. A similar structure is found in other studies (Cai, 2011; Grau et al., 2011). In comparison, the 2G market consisted in 2009 of 4-9 manufactures engaged in CdTe, around 130 in a-Si (or μc-Si) and 30 in CI(G)S (EPIA & Greenpeace, 2011; Jäger-Waldau & Institute for Energy (European Commission), 2010). The market of module manufactures consist classically of a few large firms having a large market share; for example the ten largest manufactures had a market share of over 76% in 2006 (EPIA & Greenpeace, 2007). However recently this large market share is rapidly declining; in 2010 the largest ten (only) manufactured about 40% of all modules (EPIA & Greenpeace, 2008, 2011; Hirshman, 2011).

The 2G generation manufactures have often a fully integrated value chain, since the production process does not contain the several distinct steps from the 1G silicon production process (EPIA & Greenpeace, 2011; Knulst, 2011). Though a-Si uses the same raw materials like sc-Si and mc-Si and hence can partly use the same value chain. At the largest producer of 2G modules, First Solar with their CdTe technology, we see an example of vertical integration since they even integrated a recycling program and they seem to own their own tellurium mine (First Solar, 2011a; Sinke, 2011; Eric Wesoff, 2011a). However recently there is also a trend among 1G silicon PV companies to vertically integrate their value chain or make agreements with other firms to work together in producing, parts of, PV modules (EPIA & Greenpeace, 2011; Google News, 2011; Photon International, 2011; Sinke, 2011; van Roosmalen, 2011; Weeber, 2011). The main reason for this is the ability to benefit from economies of scale which helps to bring down prices; not for every separate step in the production process a certain profit margin needs to be retained and a perfect fit between demand and supply can be made (Olivierse, 2011; Sinke, 2011; Weeber, 2011). On the other hand companies separating the production steps can focus completely on their core activity, though they are more dependent on standardisation and suppliers (EPIA & Greenpeace, 2011).
4.5 PV SYSTEMS

Since this research focuses on PV devices which are used for energy production, either grid connected or directly connected to the load; a balance of system (BOS) is needed for completion of the PV system (see Figure 17 and Figure 18). The BOS consists of all components needed to let the system properly function between the DC electricity generated by the PV devices and the load; electrical interface components (e.g. DC/AC converter), mounting structures and storage devices (e.g. batteries). In 2009 this market consisted of over 300 companies manufacturing inverters, though the largest ten firms produce 80% of the market (EPIA & Greenpeace, 2011). See Figure 18 for an example of a grid connected PV system. The price users need to pay for their PV systems is also related to the BOS; this can count up to 50% of the total cost of the system (see Figure 17) (Hoffmann, 2006; Raugei & Frankl, 2009; Smets, 2011).
5 Factors influencing the PV market

In this chapter the factors influencing the photovoltaic (PV) technology dominance process have been listed. The process in the battle for a dominant designs is uncertain, nevertheless researchers in the fields of; industrial economics, institutional economics, technology management, standardization and social networks found different factors contributing to the outcome of battles for dominance (Van de Kaa, 2009). Others have researched characteristics of markets in which not one though multiple designs may coexist (e.g.: de Vries et al., 2011). This chapter gives answer to research question two: Which factors influence the chances that a photovoltaic cell technology achieves industry dominance?

After a short introduction this chapter will first describe which existing frameworks have been used in the analysis. Next, an overview is given of both factors that have been found to influence the dominance process and the coexistence of multiple designs, and on the other hand factors from previous framework that have been found to have no effect on the market. The following sections in this chapter gives an in depth analysis of each factor using the notion of levels (see section 2.2); starting with an overview of all frameworks, next factors influencing PV dominance are described, followed by factors in favour of multiple designs and lastly factors not applicable to the PV market.

The factors have been researched and checked on their applicability in the PV market using scientific literature, expert interviews and industry data (see also section 3.1.2). For each factor examples of its existence in the PV market have been tried to find; this procedure was used to select which factors are applicable in this market. Historical industry data consisted of literature that reports on the PV industry, market (share), technologies and policies. In total nine industry experts have been interviewed, originating from; research institutes, universities, manufactures and installation companies. Though the industry experts have been asked during interviews to describe which aspects of the PV market are important in the adoption and selection process, as a basis existing frameworks on technology selection were used. Aspects that have not directly been mentioned in dominant designs literature before have been tried to be linked to existing literature, in the case this was not possible and multiple experts confirmed the existence of a factor it was added to the list of factors.

5.1 Existing literature

5.1.1 Existing literature on the technology selection process

For the analyses of which factors influence the technology selection process has been made use of frameworks by Van de Kaa (2009) and Suárez (2004). Moreover insights from Schilling (1998, 2008) and Murmann & Frenken (2006) have been used in the analysis. Van de Kaa (2009) is used as a basis, since this framework provides the most complete overview of factors influencing technology selection from previous literature. Table 7 gives overview of all factors in the framework from Van de Kaa (2009) that has been used as a starting point in the analysis of the PV market.
<table>
<thead>
<tr>
<th>Category</th>
<th>Factor</th>
<th>Description (Schilling, 1998; Suárez, 2004; Van de Kaa, 2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics of the standard</td>
<td>Financial strength</td>
<td>Part of the firm’s resources; it entails the current and (expected) future financial condition of supporters of the design.</td>
</tr>
<tr>
<td></td>
<td>Brand reputation and credibility</td>
<td>The opinion (potential) consumers have about a company, or the credibility based on actions from the past.</td>
</tr>
<tr>
<td></td>
<td>Operational supremacy</td>
<td>How supporters of a design can better make use of resources than competitors.</td>
</tr>
<tr>
<td></td>
<td>Learning orientation</td>
<td>Ability to learn on core-capabilities and the absorptive capacity to capture this learning.</td>
</tr>
<tr>
<td>Characteristics of the standard</td>
<td>Technological superiority</td>
<td>How one design outperforms other technological designs.</td>
</tr>
<tr>
<td></td>
<td>Compatibility</td>
<td>Having multiple entities being able to work together.</td>
</tr>
<tr>
<td></td>
<td>Complementary goods</td>
<td>Complementary goods are other goods or services needed to commercialize a product.</td>
</tr>
<tr>
<td></td>
<td>Flexibility</td>
<td>The incremental cost and time needed to adapt a technological design.</td>
</tr>
<tr>
<td>Standard support strategy</td>
<td>Pricing strategy</td>
<td>The aggressive or below profit margin pricing of designs.</td>
</tr>
<tr>
<td></td>
<td>Appropriability strategy</td>
<td>The actions a firm takes to protect its design from imitators.</td>
</tr>
<tr>
<td></td>
<td>Timing of entry</td>
<td>The window of opportunity in which it is optimal for a company to bring its design on the market.</td>
</tr>
<tr>
<td></td>
<td>Marketing communications</td>
<td>Positively influencing consumer expectations on technological capabilities.</td>
</tr>
<tr>
<td></td>
<td>Pre-emption of scarce assets</td>
<td>Assets that a firm is able to capture in an early stage of the development process and deny them from usage by other firms.</td>
</tr>
<tr>
<td></td>
<td>Distribution strategy</td>
<td>How a firm develops the distribution system of a product of technology.</td>
</tr>
<tr>
<td></td>
<td>Commitment</td>
<td>The support and attention of a firm in supporting the design through low revenue periods.</td>
</tr>
<tr>
<td>Other stakeholders</td>
<td>Current installed base</td>
<td>Actors currently using the design.</td>
</tr>
<tr>
<td></td>
<td>Previous installed base</td>
<td>Users willing to switch from a previous design to the new technological design.</td>
</tr>
<tr>
<td></td>
<td>Big fish</td>
<td>A firm that can substantially support a design.</td>
</tr>
<tr>
<td></td>
<td>Regulator</td>
<td>Actors that prescribes the use of a certain design to be used in the market.</td>
</tr>
<tr>
<td></td>
<td>Judiciary</td>
<td>Antitrust law to prevent certain designs from becoming dominant.</td>
</tr>
<tr>
<td></td>
<td>Suppliers</td>
<td>Producers of complementary goods or services.</td>
</tr>
<tr>
<td></td>
<td>Effectiveness of the standard</td>
<td>The level of bureaucracy and time needed in the official standard setting process.</td>
</tr>
<tr>
<td></td>
<td>development process</td>
<td>Diversity of the network</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The diversity of the set of actors supporting a technological design.</td>
</tr>
</tbody>
</table>
Market characteristics

Bandwagon effect
The effect of users adopting a design on other users for choosing for the same design.

Network externalities
The value of a design is related to the number of consumers.

Switching costs
Costs occurring when an actor switches from one design to another.

Number of options available
The number of available competing technologies influencing dominance of a single design.

Uncertainty in the market
With uncertainty actors are not willing to commit themselves solely to one single design.

Rate of change
The speed of research and development.

5.1.2 Existing literature on multiple designs coexisting in the market

To analyse whether the PV market is characterised by multiple designs coexisting in the market, insights from de Vries, de Ruijter and Argam (2011), Srinivasan et al. (2006) and den Uijl & de Vries (2010) are used. As a basis the framework from de Vries, de Ruijter and Argam (2011) is used, similarly to the framework of Van de Kaa (2009), their research is also based on previous literature. As described in section 2.1.4 the framework of de Vries et al. (2011) makes a distinction between supply and demand side factors. The factors shown in Table 8 have been used in the analysis of the PV market.

Table 8: Factors in favour of multiple designs (de Vries et al., 2011)

<table>
<thead>
<tr>
<th>Categories</th>
<th>Factors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply side</td>
<td>Distinct features</td>
<td>Designs have various (different) advantages for multiple groups of users.</td>
</tr>
<tr>
<td></td>
<td>Appropriability regime</td>
<td>How firms are able to capture the profits from their innovation and protecting it from being imitated.</td>
</tr>
<tr>
<td></td>
<td>Persistency</td>
<td>Supporting a design during the stage it is already clear another design in winning.</td>
</tr>
<tr>
<td></td>
<td>Speed in technological development</td>
<td>Constant rapid development of new technological designs.</td>
</tr>
<tr>
<td>Demand side</td>
<td>Gateway technologies</td>
<td>Technologies enabling compatibility between two non-compatible designs (separate product).</td>
</tr>
<tr>
<td></td>
<td>Multi-channel end system</td>
<td>Systems that are able to accommodate multiple technologies (integrated in the product).</td>
</tr>
<tr>
<td></td>
<td>Application drives the design</td>
<td>When consumers make a choice for the larger system instead of the technological design.</td>
</tr>
<tr>
<td></td>
<td>Price</td>
<td>The price of one design is almost the same as the other designs; users may be indifferent of what technology they choose.</td>
</tr>
</tbody>
</table>

5.2 Factors influencing the technology selection process

Not all factors that have been described in section 5.1.1 are applicable to the PV market. Moreover two factors are found influencing the technology selection process though they have not been mentioned in the previous literature. This section describes which factors from Table 7 have been found to influence the PV market; an overview of factors with a short description is given in Table 9. In the following section for these factors examples have been found how they influence the PV technology selection process and a more detailed description of the factors is given in comparison with
Table 7. Factors from previous frameworks that have not been found to influence the dominance process in the PV market are listed in Table 10, these factors have been explained in section 5.4.1.

With the definitions from section 2.2, a distinction is made on which level the factors influence the PV market.

**Table 9: Factors influencing the technology dominance process in the PV market**

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Financial strength</td>
<td>For PV manufactures it is essential to have access to sufficient capital; to be successful they have to constantly expand production in order to benefit from economies of scale.</td>
</tr>
<tr>
<td></td>
<td>Brand reputation and credibility</td>
<td>Manufactures that delivered high efficiency modules are able to ask higher prices, also recently several manufactures actively promote their brand name; e.g. at the soccer World Cup or with a Formula 1 team.</td>
</tr>
<tr>
<td></td>
<td>Operational supremacy</td>
<td>Regarding the geographical location, Chinese manufactures may benefit from favourable policy incentives. Regarding production capacity, the first generation silicon technologies have an advantage.</td>
</tr>
<tr>
<td></td>
<td>Learning orientation</td>
<td>A significant part of the decline in prices comes from learning effects.</td>
</tr>
<tr>
<td></td>
<td>Technological superiority</td>
<td>Between PV technologies there are differences in the performance; how efficiently they are able to convert radiation to electricity.</td>
</tr>
<tr>
<td></td>
<td>Flexibility</td>
<td>Since for the second generation technologies manufactures have a multitude of production techniques, it is more expensive to adopt these technologies in comparison with first generation technologies which have some level of standardisation.</td>
</tr>
<tr>
<td></td>
<td>Pricing strategy</td>
<td>Prices differ between technological designs and many manufactures use the strategy of aggressive pricing to gain a larger market share.</td>
</tr>
<tr>
<td></td>
<td>Appropriability strategy</td>
<td>Patents are regularly issued in the PV market, there are however only a few lawsuits.</td>
</tr>
<tr>
<td></td>
<td>Timing of entry</td>
<td>During silicon shortages in the last decade some said there was a window of opportunity to start with the production of a-Si.</td>
</tr>
<tr>
<td></td>
<td>Marketing communications</td>
<td>Several pilot projects are used to increase expectations on technological capabilities.</td>
</tr>
<tr>
<td></td>
<td>Pre-emption of scarce assets</td>
<td>During the recent silicon shortages some manufactures could benefit from contracts they had with silicon suppliers.</td>
</tr>
<tr>
<td></td>
<td>Commitment</td>
<td>PV technologies know long development times; commitment of firms (and government) is essential.</td>
</tr>
<tr>
<td>Meso</td>
<td>Compatibility</td>
<td>Some technologies are found to be better suited for integration in large scale grid connected systems.</td>
</tr>
<tr>
<td></td>
<td>Diversity of the network</td>
<td>PV technologies differ on the amount of stakeholders they have been able to use in their development process.</td>
</tr>
<tr>
<td></td>
<td>Bandwagon effect</td>
<td>Examples are found of companies trying to mimic the success of manufactures of a particular design.</td>
</tr>
<tr>
<td></td>
<td>Number of options available</td>
<td>There are multiple technologies available on the PV market.</td>
</tr>
<tr>
<td></td>
<td>Uncertainty in the market</td>
<td>Several companies are found supporting multiple PV designs.</td>
</tr>
<tr>
<td></td>
<td>Rate of change</td>
<td>Price and production need to increase rapidly in the current PV market in order to stay competitive (benefit from economies of scale).</td>
</tr>
<tr>
<td>Macro</td>
<td>Policy</td>
<td>Some policy incentives are found to favour one technology over another.</td>
</tr>
<tr>
<td></td>
<td>Law</td>
<td>In some countries there are regulations restricting the use of certain raw materials used in PV devices.</td>
</tr>
</tbody>
</table>
Table 10: Factors not influencing technology dominance

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Complementary goods</td>
<td>Complementary goods and services exist in the PV market, they are however largely similar for every technology.</td>
</tr>
<tr>
<td></td>
<td>Distribution strategy</td>
<td>Distributors sell multiple technologies simultaneously.</td>
</tr>
<tr>
<td>Meso</td>
<td>Current installed base</td>
<td>This effect was not found to exist in the PV market, mainly because the market is not characterised by network externalities.</td>
</tr>
<tr>
<td></td>
<td>Previous installed base</td>
<td>Because PV designs last for 15-30 years this factor is not regarded to be influential.</td>
</tr>
<tr>
<td></td>
<td>Suppliers</td>
<td>Not influential because the PV market is not characterised by direct network externalities.</td>
</tr>
<tr>
<td></td>
<td>Effectiveness of the standard development progress</td>
<td>No official standard setting organisations have been found in the PV market.</td>
</tr>
<tr>
<td></td>
<td>Big fish</td>
<td>No firms have been found supporting technologies that would otherwise not have been commercially developed.</td>
</tr>
<tr>
<td></td>
<td>Network externalities</td>
<td>It was not found that users experience extra value of their PV design when more devices get sold.</td>
</tr>
<tr>
<td></td>
<td>Switching costs</td>
<td>Because PV designs have similar outputs users can in theory easily switch between competing designs.</td>
</tr>
<tr>
<td>Macro</td>
<td>Regulator</td>
<td>No regulator was found prescribing a technological design to be used in the market.</td>
</tr>
<tr>
<td></td>
<td>Judiciary</td>
<td>No example of the use of antitrust laws was found in the PV market.</td>
</tr>
</tbody>
</table>

5.2.1 Micro-level factors

This level describes factors that can easily be influenced by individual actors and firms.

5.2.1.1 Financial strength

Financial strength is part of the firm’s resources; it entails the current and (expected) future financial condition of supporters of the design. With the market introduction of a design enough financial resources can be used to survive the start-up costs (Ehrhardt, 2004). These periods are for example the result of aggressive pricing strategies (with low earnings) or marketing efforts by the design company (Van de Kaa, 2009).

Some of the PV manufactures are large multinationals, with several business units in different industrial sectors; they can use their proper financial basis from the other business units to invest in their PV unit (see also Table 11 in section 5.2.1.2). For example Sharp, previously Sharp mainly focused on first generation silicon solar cells, recently their efforts changed more towards 2G technologies (Sharp, 2008); especially production capacities for a-Si are increased in comparison to 1G silicon solar cells, though sc-Si and mc-Si still have the largest production shares (Hirshman, 2011). A similar story holds for Q-Cells, one of the largest 1G PV manufactures on the world (Hirshman, 2011), is involved in a wide variety of research in 2G PV technologies via partnerships and subsidiary companies (Q-Cells, 2011a; Sinke, 2011); though they manufacture CI(G)S themselves (Q-Cells, 2011b). These new generation materials are still being improved and need more research in comparison with the older 1G silicon technologies (Razykov et al., 2011), though their retail price per watt is below 1G silicon (Knoll, 2011a). Suntech, another large silicon solar cell producer, focussed merely on mc-Si and in 2010 announced to start a production line with 2G solar cells (Suntech, 2011). Nevertheless other large international companies, like Kyocera Solar, focus on mc-Si and have not yet announced to start production of 2G and 3G PV panels (Kyocera, 2011). In general, each technology
has one or several very large manufactures which are able to spend considerable amounts of money on research (van Roosmalen, 2011), development and scaling up production lines, for example; in the case of CdTe there is First Solar which is the largest 2G producer and the overall third largest producer (see Table 12), and for CI(G)S there is Solibro which is a substitute of Q-Cells the overall fifth largest producer.

In the current PV industry the 1G silicon PV panels are dominant, they have a market share of over 85% (Figure 27). Since these technologies share an overlap in the production processes, see section 4.4, they can also share part of their research and development. Hence in the global PV market 1G silicon has more money to spend on research and development of technology related PV products and production processes. Consequently new market entrants need sufficient financial basis to scale up their production facilities when entering the market with a widely available technology, since economies of scale are an important driver for bringing down solar cell cost (del Cañizo, del Coso, & Sinke, 2009; Nemet, 2006; Pearce, 2008; Sinke, 2011; van Roosmalen, 2011; H. Yu, Zheng, Zhao, & Zheng, 2006). In a study from Nemet (2006) and in one from Schaeffer et al. (2004) was found that about half of the cost reduction will come from efficiency improvements and the rest from scale advantages. Besides start-up companies also existing companies need to do large investments in increasing capacity to stay competitive in the market. To be cost competitive new firms should be able to enjoy economies of scale or to enter the market with a unique product to secure their competitive advantage. These unique products typically would have higher efficiencies or can be used for new applications; like flexible panels or BIPV. There is a difference between the costs of building a 2G or 1G module factory, especially building CI(G)S or a-Si factories is more expensive (van Roosmalen, 2011). One of the main reasons for this is that manufacturing machines for 1G silicon technologies are built and developed for a large market and there incurs some standardization which results in economies of scale, while production machines for CI(G)S and a-Si systems have a high cost of ownership (Sinke, 2011). Also new innovations can more easily be implemented (partly) using existing production processes. Especially in the 1G silicon based industry this strategy can easily be implemented because the value chain consists of several different production steps (see chapter 4.4) and only a small part of the production process needs to be changed when implementing an incremental innovation (Sinke, 2011). Nevertheless First Solar, producer of CdTe modules, uses the strategy of copying the proven manufacturing process over and over again to scale up the production process (First Solar, 2011b; van Roosmalen, 2011), consequently there is for example no need for learning how to use new machinery; by using this strategy they have become the largest 2G manufacturer with the cheapest production prices per watt (Hirshman, 2011; Knoll, 2011b).

Also there are several examples of financial incentives for PV manufactures. Governments and banks stimulate the development and cost reductions by providing easily obtainable loans for new production capacity (Brown & Hendry, 2009; IEA, 2002, 2010a). Private banks regard the PV sector as risky and therefore expect high returns on their investments, resulting in high interest rates, this is in contrast with development banks (e.g. International Finance Corp., the European Investment Bank and the Asian Development Bank) who have loans available with attractive interest rates (Jennings, Margolis, & Bartlett, 2008). Because the 1G silicon technologies had already the time to prove their working principle, the efficiencies and effectiveness, and they already have some standardisation in the production process they are regarded to be a less risky investment (more extensively described in section 5.2.1.3). Also governments have financial incentives available for the development of manufacturing facilities; an often used incentive is loan guarantees (Grau et al., 2011). Moreover there are general financial incentives to start firms in economically weak regions (e.g. in the Netherlands;
5.2 Factors influencing the technology selection process

Friesland and Limburg, and in eastern Germany) aimed to create local jobs (Olivierse, 2011; Sinke, 2011; Vlek, 2011). It is increasingly difficult for western companies to grow at a similar pace as companies in China, in China is much easier to receive sufficient large amount of capital investments (Sinke, 2011). Moreover, the investments in China are focussed on 1G silicon technologies, probably because of the relative easiness of the production process and the lack of intellectual property concerns. In Europe also considerable investments have been done in 1G silicon technologies because these technologies could be easily ramped up to benefit from the generous feed-in-tariffs (FITs). Consequently the more risky 2G technologies received fewer investments from venture capital, private and public equity; opposed to the US which has a larger 2G PV market (Jennings et al., 2008). Overall it seems investors are willing to spend money in this market because of the enormous growth potential (Davies & Joglekar, 2010; Herron, 2009, 2010a), however because of the need to heavily expand production to benefit from scale advantages it is not certain which companies will succeed and survive which creates uncertainty and makes investors hesitates (e.g.; Sinke, 2011).

5.2.1.2 Brand reputation and credibility

Brand reputation is related to the opinion (potential) consumers have about a company, or the credibility based on actions from the past. This factor is considered to be important in the phase before a dominant design has been established, once a dominant design has emerged this factor is of less importance for manufactures of the design (Schilling, 1998; Shapiro & Varian, 1999). Because the 1G PV technologies (sc-Si and mc-Si) already have considerable market shares, this factor is regarded to be of less importance for firms operating with this generation. The 1G manufactures will however be discussed in the analysis of this factor since they may show some attractive principles for 2G companies in the future. For 1G silicon PV technologies was found that the reputation of manufactures differed, examples of companies with a high reputation are;

- SunPower, because of their high-efficiency sc-Si cells (headquarters in the US).
- Sanyo (subsidiary of Panasonic), because of quality and high-efficiency of their HIT cells (headquarters in Japan).

Furthermore is seen that recently companies with sufficient financial resources start marketing effort to increase brand awareness on a large scale. For example, Yingli Solar was an official sponsor of the 2010 World Cup in South Africa, and will be again a sponsor of the 2014 World Cup in Brazil (Yingli Solar, 2010, 2011a) and they sponsor the German football club Bayern München (Yingli Solar, 2011b). These sponsorships will help Yingli with both global and local brand awareness; the local brand awareness is in the largest PV market in the world, Germany. Similarly Trina Solar sponsors the Renault Formula 1 team (Trina Solar, 2011). By increasing brand awareness these companies are expected to increase demand for their solar panels and both do not have to worry about selling all their modules and may be able to ask a premium price for their modules (Elliott, 2010; Herron & Hirshman, 2010). Only a few 2G companies also do sponsoring to increase brand awareness, this is on a much smaller scale; for example First Solar (produces CdTe modules) together with juwi solar (builds production lines) sponsor a US based cycling team (First Solar, 2011c; juwi solar, 2011). It should be noted that some of the 2G manufactures are fairly big international companies, with several business units in different industrial sectors (see Table 11), they can use historical based brand reputation and credibility from the other business units.
Especially manufactures from China had a slightly worse reputation in comparison with manufactures based in Japan, US and the EU (Olivierse, 2011; Sinke, 2011; Vlek, 2011); this was mainly because of the generally lower quality of Chinese PV cells (Siemer, 2009). However, the Chinese manufactures are recently improving the quality of cells and hereby improving their reputation. Nevertheless, this may take some time since on the one hand experts in the PV industry may be able to easily differentiate between the quality offered by different Chinese manufactures, though consumers may not have this knowledge and therefore simply differentiate between manufactures from Germany or the US and those from China. For the newer technological generations (e.g. 2G technologies; Cl(G)S, CdTe) this factor can be of importance. Therefore, large 2G producers of the last five years are used in the analysis, the companies are selected based on their place in the top 10 second generation producers and the top 20 global module and cell producers of Photon International (DeCarlo, 2005, 2006, 2007, 2008, 2009, 2010).

To measure the brand reputation and credibility of newer generation PV technology producers, expert interviews and the reputation assessment of investors, analysts and executives of competitor companies in the form of data from the Forbes Global 2000 list are used. This ranking uses the metrics; sales, profit, assets and market value, from which market value is the most related metric to brand reputation and credibility, since it incorporates future potential growth.

<table>
<thead>
<tr>
<th>#</th>
<th>Company name</th>
<th>Technology</th>
<th>Forbes ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2005 2006 2007 2008 2009 2010</td>
</tr>
<tr>
<td>1.</td>
<td>First Solar</td>
<td>CdTe</td>
<td>- - - 1717 1331 1239</td>
</tr>
<tr>
<td>2.</td>
<td>Mitsubishi Heavy Ind.</td>
<td>a-Si; a-Si/μ-Si</td>
<td>309 608 531 478 316 428</td>
</tr>
<tr>
<td>3.</td>
<td>Sharp</td>
<td>a-Si/μ-Si</td>
<td>332 328 384 361 304 649</td>
</tr>
<tr>
<td>4.</td>
<td>Honda Motor</td>
<td>CIS</td>
<td>55 63 73 68 39 84</td>
</tr>
<tr>
<td>5.</td>
<td>Fuji Electric Systems</td>
<td>a-Si</td>
<td>1348 1359 1497 1575 1503 1632</td>
</tr>
</tbody>
</table>

The findings from the above table are fairly limited, the number of companies is low and most companies are not only involved in PV but in a number of markets. Nevertheless the company First Solar is a good example of a company that boosted its brand reputation of the years with solely making CdTe modules. However, other companies in the table are moving up and down the performance index. As far as stock prices represent reputation and credibility of companies, stocks of PV companies in are moving up and down (Davies & Joglekar, 2010; Société Générale, 2011). This may indicate the volatility and uncertainties in the market, also explained for the factor financial strength (section 5.2.1.1).

Recently, Applied Materials and another large manufacturer of turnkey production lines Roth & Rau stopped their production of (2G) turn-key solutions (Herron, 2011a; Neuenstein, 2011; Sinke, 2011; Weeber, 2011). This may have a potentially negative influence on expectations of manufactures of these technologies in the market, since investors and other manufacturing machine supplier may doubt whether the 2G production industry will become profitable in the future.

Furthermore there is a characteristic that has some overlap with other factors (like marketing communications, section 5.2.1.10); the role of lobbyist groups. First Solar has an excellent reputation for producing high quality modules (Sinke, 2009; van Roosmalen, 2011), however for making its CdTe modules the raw material cadmium is needed. This material is regarded to be highly toxic; this may have an influence in the consumer perception of this producer or the technology. Lobbyist groups
loyal to First Solar emphasize only a tiny amount is used in the modules, the excellent recycling programs from First Solar and point out that this use of cadmium is the least polluting one so far. On the other side, groups are proposing to ban cadmium completely, since using it in modules will only increase risks for humans and the environment in the future (Podewils, 2010; Schmela, 2010).

5.2.1.3 Operational Supremacy

Operational supremacy is related to how supporters of a design can make better use of resources than competitors (Van de Kaa, 2009). Examples are a technological advantage, production capacity, geographic space (e.g., prime physical locations), technology space (e.g., patents), or customer perceptual space (Lieberman & Montgomery, 1998).

Regarding geographical space Asian manufactures have possibly an advantage over firms in western countries. Recently production capacity is shifting towards Asian countries, either new production facilities are built or production is outsourced to Asia. This process is similar to IC producing companies (e.g.: IBM, Apple, HP, Siemens and Sony) who shifted or outsourced their production towards Asia in ’90s and ‘00s (Hering, 2010a). The main reason for this is the favourable PV supporting policies (Olivierse, 2011; Sinke, 2011; Vlek, 2011; Weeber, 2011) in China and there is a minor role for the lower wages in Asian countries (also described under the factor “pricing strategy” and “policy”); for example the Chinese government supports manufactures by providing (Grau et al., 2011):

- Refund or exemption of land fee and tax by local government
- Loan guarantee by government or government held group
- Loan and credit facilities provided by government

Moreover, it seems that companies in China do not have to comply with the same strict rules for waste management in comparison with western countries (Podewils, 2008; Sinke, 2011). One of the strategies for western companies to keep their competitive advantage is to focus on process and product innovations and to license this to Asian manufactures (de la Tour, Glachant, & Ménière, 2011; Jaegersberg & Ure, 2008; Olivierse, 2011; Vlek, 2011), however Asian companies are recently also working extensively on product and process innovations (e.g.: Geerligs, 2010).

In 2010 China even produced 47.8% of all PV devices (Hirshman, 2011), consequently from the largest 20 producers of the world a considerable amount came from China, see Table 12.
In the future, it is expected part of the PV market to shift back or stay in the market in the locations where the most modules get placed; mainly in western countries currently (Sinke, 2011; Vlek, 2011; Weeber, 2011). One of the reasons is that with the expected decline in module prices, increased efficiency of production processes and a possible rise in transportation costs, the share of these costs for the total price of modules will increase; consequently, it is more favourable to ship (raw) materials to the countries that need the modules and do the production or final assembly locally. Another important reason is that countries subsidizing the PV industry want to have part of their money to stay in their own national economy; currently, this process can be seen in the US were technologies get subsidized that can also be produced in the US (Lorenz, 2011; Sinke, 2011; Susman & Glasmeier, 2009; U.S. Department of Energy, 2011). On a much smaller scale, similar policy incentives can be seen in stimulating local industries to increase the number of jobs; some Dutch PV module manufactures specially located their production plants in the provinces Friesland or Limburg because of favourable local policies (Olivierse, 2011; Vlek, 2011). There are also difficulties in bringing back...
5.2 Factors influencing the technology selection process

production to the local market, especially in the US supply chains will need to be established and workforce trained, since there was such a long trend to outsource production to Asian countries (Hering, 2010a; Sinke, 2011).

Related to the characteristic production capacity the 1G silicon technologies have a clear advantage over the other technologies. This can be seen from their shared dominance in the PV market which consequently gives them more production capacity (Hirshman, 2011). One of the reasons that they are able to manufacture on such large scale is that some standardisation in the production processes and form factors occurred; manufactures using similar techniques to manufacture their modules in similar sizes, which resulted in lower technological risks and easier exploitation of economies of scale (Bradford, Grama, Wesoff, & Bhargava, 2007; Nemet, 2006; van Roosmalen, 2011). For 2G technologies this has not happened at all, although First Solar for example is a large manufacturer and uses the Vapor Transport Deposition (VTD) process other CdTe manufactures (like Abound Solar) use a different method, the Close Space Sublimation (CSS) process, in their manufacturing line (Ullal & von Roedern, 2007; Eric Wesoff, 2011b). A similar story holds for Cl(G)S and a-Si producers; each manufacturer seems to use different technologies in their manufacturing process (Knulst, 2011; van Roosmalen, 2011). Additionally, the 1G silicon manufactures did have the time to start standardisation from the 1970s (Costello & Rappaport, 1980; Nemet, 2006), while during that time most 2G technologies were still in their research and development phase (see chapter 4).

There are differences between the technologies related to the factor technological advantage. While efficiency is described in the factor technological superiority, there are also other technology specific manufacturing related (dis)advantages. Between the 1G silicon technologies there does not seem to be a large difference; the refinement of the raw material required is the same. While for sc-Si generally cylindrical ingots are grown with a perfect crystal structure, mc-Si uses the same raw material but uses a different melting and solidification technique which produces not a perfect crystal structure but the production process is faster and easier (Zeman, 2011). For second generation technologies it is in general difficult to produce monolithic modules without any defects (van Roosmalen, 2011). Almost all 2G technologies have some form of degradation issues (Razykov et al., 2011; Rommel Noufi & Ken Zweibel, 2006; Shah, Torres, Tscharner, Wyrsch, & Keppner, 1999):

- a-Si modules lose efficiency when exposed to sunlight (called the Staebler-Wronski effect).
- Both CdTe and Cl(G)S do not have problems with Staebler-Wronski effect but show some stability issues in a warm and humid environment. However scientists claim that this degradation can be overcome by using proper encapsulation.

Given the technological advantages and the production capacity characteristics there is a difference between building a 2G or 1G module factory; especially building Cl(G)S or a-Si factories is more expensive (van Roosmalen, 2011).

5.2.1.4 Learning orientation

This factor is related to learning on core-capabilities and the absorptive capacity to capture this learning (Schilling, 1998). Learning is considered to be crucial for companies in the innovation system, especially learning from experience is very effective (Kamp et al., 2004). Core capabilities relate to the ability to generate technological breakthroughs (Van de Kaa, 2009), absorptive capacity relates to the ability of firms to “recognize, assimilate and utilize new knowledge” (Schilling, 2008, p. 67); the ability to generate technical breakthroughs (technical knowledge) and how to commercialize these breakthroughs.
As explained in section 2.1.2 learning effects do play an important role in the PV industry. Just looking at the price versus shipments curve (see Appendix V) an impressive learning rate is seen similar to improvements in the IC industry; research proved that a significant part of the decline in prices came from learning effects (C. F. Yu et al., 2011). In recent years learning effects are found to be the largest cost reduction factor for PV technology (McDonald & Schrattenholzer, 2002). In addition to the price of PV modules consumers generally face the cost of a complete PV system, which include for example; building materials, installation costs, DC/AC converters (the total of these costs are called the BOS costs). Therefore the decline in module costs has not been the same for total system costs (Shum & Watanabe, 2008).

To further specify which learning processes are important for supporters of technologies in gaining dominance a paper from Kamp, Smits and Andriesse (2004) on learning in another sustainable energy sector, the wind turbine industry, can be considered. They recognize four kinds of learning that are important in the innovation process: interactive learning, learning by searching, learning by doing and learning by using.

Interactive learning is the knowledge gained from interaction between supporters of the designs. Technologies that have been longer in the market and are better represented in pilot plants and demonstration projects should be able to benefit from the interactions between actors. As explained in chapter 4 mc-Si has been the longest on the market, moreover this technology could benefit from knowledge on production processes from the IC industry. Though this was even more the case for sc-Si cells since their production process is more closely related to producing IC’s (van Roosmalen, 2011). Similarly, a-Si and pc-Si could rely on fabrication know-how from the flat-panel display sector (Bubenzer & Luther, 2003; Razykov et al., 2011), although in comparison with 1G silicon based technologies the similarities in production processes are not that much. Regarding the other facilitator of interactive learning, pilot plants and demonstration projects, the 1G technologies have been generally better represented in pilot projects (Callaghan & McDonald, 1986; Colatat, Vidican, & Lester, 2009). Although, 2G technologies also were involved in several pilot manufacturing plants and other demonstration projects.

Learning by searching is also called R&D and is for example related to the process of searching for optimal design- or technological characteristics. Actors in this process are generally universities, public research institutes and research departments of firms. Dutch universities are generally focussed on 2G or 3G technologies and only minor attention is given to the 1G silicon technologies (RUG, 2011; TU Delft, 2011; TU Eindhoven, 2011; Universiteit Leiden, 2011). On the other hand ECN, the largest PV research institute in the Netherlands, focuses on research on the 1G as well (Geerligs, 2010). On the larger scale of the European Union there is more focus on silicon based 1G technologies as well (Sinke, 2011; Weeber, 2011), for example in 2008 Germany did spend over 50% of its research budget on 1G silicon technologies (Grau et al., 2011). In the US the focus is towards 2G and 3G technologies (US Department of Energy, 2011; Weeber, 2011), while in Japan there seems to be more attention for both 1G and 2G silicon technologies (NEDO, 2010). On a global scale the 1G silicon (sc-Si and mc-Si) technology manufactures have the largest installed base and several large companies are involved in the manufacturing and research process (Hirshman, 2011), which is therefore expected to be higher in comparison with other technologies. Differentiating these two technologies; there are more R&D expenditures on sc-Si since this technology needs to improve efficiency in order to compete with CdTe modules (van Roosmalen, 2011). Overall it seems research
and development at universities and research institutes is quite equally distributed for all the PV technologies (Sinke, 2011; van Roosmalen, 2011; Weeber, 2011).

From learning by doing know-how and practical knowledge of production processes is gained. Since 1G silicon technologies have currently the largest production shares, they should be able to have the opportunity to capture the most knowledge from learning by doing. Furthermore, these 1G silicon and 2G a-Si and pc-Si could benefit from knowledge on production processes of existing industries (the IC and flat panel industry); therefore they have an advantage regarding know-how over competing technologies (e.g.: CI(G)S and CdTe). However, First Solar, producer of CdTe modules, uses the strategy of copying the proven manufacturing process over and over again to scale up the production process without high risks (First Solar, 2011b; van Roosmalen, 2011); consequently, there is for example no need for learning how to use new machinery; by using this strategy they have become the largest 2G manufacturer with the cheapest production prices per watt (Hirshman, 2011; Knoll, 2011b). Currently, some PV manufactures focus on economies of scale by increasing production efficiency and production plant size (C. F. Yu et al., 2011); in this process learning by doing is an important source of knowledge. Similarly, in the future economies of scale are expected to become increasingly important; in a studies from Nemet (2006) and Schaeffer et al. (2004) was found that about half of the cost reduction will come from efficiency improvements and the rest from scale advantages. Before large scale sales took off technologies could also have benefitted from pilot plants in the past ten years (see Figure 26); probably because of their attractive cost/efficiency ratio (similar to what has been previously explained on the success of 1G technologies).

Learning by using is related to knowledge from utilising the technology. This is can both be gained by the current installed base and from ‘historical’ experience from pilot plants and demonstration projects. These elements have been explained above, however besides knowledge on PV modules, it may also be important for manufactures to learn from installing complete PV systems in order to grasp consumer preferences.

Besides the four kinds of learning, Klepper and Kenneth (2000) indicate that for the television industry companies also producing radios where able to survive longer and had higher market shares because of their experience in other, but partly similar, industries. This may be similar to PV manufactures also working in the IC and flat-panel display industries. Companies like Sharp (for a long time PV market leader) who produce a-Si and 1G silicon PV modules, are for a long time active in both the IC and flat panel industry. Nevertheless, looking at the top 20 PV producing companies (see Table 12), almost none was previously engaged in either the IC of flat-panel industry.

5.2.1.5 Technological superiority

This factor is related to how one design outperforms other designs (Schumpeter, 1934; Van de Kaa, 2009). It does not necessarily need to be the that case the best performing design becomes dominant; a well-known example is the fight for the dominant keyboard layout, while the Qwerty layout was not the most efficient it did become the dominant design (David, 1985).

From interviews and industry magazines it has been found that a large share of the PV producers try to get competitive advantage by including differentiating technological characteristics, while others focus on novel production techniques or process optimization for mass production (Olivierse, 2011; Vlek, 2011; Weeber, 2011). An example of changing technological characteristics can be seen from the Dutch company Solland Solar, who designed mc-Si PV panels with electrical contacts on the rear side of the panel which increased overall efficiency. Similar, another Dutch manufacturer, Solar Modules
NL, tries to differentiate by innovative encapsulation techniques which increase efficiency. These two companies are not the only ones differentiating their product in order to achieve higher efficiencies; for example, SunPower manufactures regular modules with high-efficiency sc-Si cells, Sanyo makes the same modules with high-efficiency HIT cells and Würth Solar has high-efficiency CIS cells in mass production (Sanyo, 2011; SunPower, 2011; Würth Solar, 2011). Concluding, efficiencies are important in this industry (Andersson & Jacobsson, 2000) and thus this factor can be best measured from the efficiency by which a PV cell can convert radiation into electricity.

In the PV industry, there is a widely used measure to determine the efficiency of modules; the efficiency under AM1.5 irradiance. This standard was defined to enable worldwide comparisons of PV modules. AM1.5 defines the spectrum of light that reaches the earth’s surface under a certain angle and consequently the energy in the light. PV technologies respond differently to this spectrum, see Figure 19 where the results of an old study of NREL are shown.

Data on efficiency can easily be found in industry magazines or scientific papers, it should be noted however that there is a significant difference between laboratory and commercial efficiency. In this research the commercial production line efficiencies were used, since the technologies in this research have been selected on the basis of their commercial availability (see section 4.3.4). The commercial efficiency is defined as the best efficiency from a PV module produced by a commercial production line, see Table 13. Average efficiencies of the technologies can be found in Table 14.

With the selection of a technology, manufactures will, apart from looking at the current maximum efficiency, also see what the efficiency will be in the future. From Table 14 can be seen that a-Si and CI(G)S modules have the highest growth potential. Especially CI(G)S got considerable attention in scientific journals and from companies the last decades; companies like Boeing, Solar Frontier (subsidiary of Shell) and Siemens have been involved in its research and development (Razykov et al., 2011). According to most of the experts interviewed amorphous silicon is not considered to be very

<table>
<thead>
<tr>
<th>Classification</th>
<th>Efficiency (%)</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si (mono-)</td>
<td>22.9</td>
<td>UNSW/Gochermann</td>
</tr>
<tr>
<td>mc-Si (multi-)</td>
<td>17.8</td>
<td>Schott Solar</td>
</tr>
<tr>
<td>μc-Si</td>
<td>8.2</td>
<td>Pacific Solar</td>
</tr>
<tr>
<td>CIGS</td>
<td>15.7</td>
<td>Miasole</td>
</tr>
<tr>
<td>CdTe</td>
<td>12.8</td>
<td>Prime Star monolithic</td>
</tr>
<tr>
<td>a-Si/a-SiGe/a-SiGe*</td>
<td>10.4</td>
<td>USCC</td>
</tr>
</tbody>
</table>

*A-Si = AMORPHOUS SILICON/HYDROGEN ALLOY; A-SiGe = AMORPHOUS SILICON/GERMANIUM/HYDROGEN ALLOY
promising for mass production on its own (Knulst, 2011; Olivierse, 2011; Sinke, 2011; van Roosmalen, 2011; Vlek, 2011; Weeber, 2011); efficiencies are well below other 2G technologies and the production is expensive since it is difficult to make fully working panels. Nevertheless, the material can have a promising future as being part of multi-layer modules, for example to enable better absorption of energy from light via multiple bandgaps in the PV device. Or like Sanyo’s HIT cells, a first generation technology, which uses a basis of sc-Si with on both sides an a-Si layer to increase efficiency under high temperatures (Sanyo, 2011).

Closely related to the efficiency of modules, the lifetime of modules may also be important for the selection of a PV technology (Weeber, 2011). Despite lifetime being often mentioned in literature and in interviews, there seems to be no consensus on what is defined as the end of the lifetime (Osterwald & McMahon, 2009; Schlumberger, 2006); generally 80% of the original efficiency is used by manufacturers to indicate the end of a solar module. Though for consumers, it may be more cost efficient to keep the solar cells for a longer time since the cost of replacing the modules is a considerable amount in relation to module prices (see also the factor pricing strategy, section 5.2.1.7). In general, 1G silicon modules have lifetimes from around 25 to 30 years; this is not only claimed by the manufactures but results are also proven in numerous field trials over the years (IEA, 2010a). 2G technologies still have to prove themselves in field trials, although the first test results show lifetimes of CdTe modules are similar to the 1G silicon technologies (Raugei & Frankl, 2009). Other 2G technologies however have to be improved to reach these results, especially a-Si suffers from degradation issues with expected lifetimes of around 10 years (Dhere, 2005; IEA, 2010a). However, the 2G technologies do have an advantage in high temperature climates; for example in Southern Europe. The 2G technologies, especially a-Si and CI(G)S, can convert about 10% more kWh per kWp in comparison with sc-Si and mc-Si in high temperature climates (Knulst, 2011; Razykov et al., 2011; Tiwari, Mishra, & Solanki, 2011; van Roosmalen, 2011).

### TABLE 14: CURRENT AND EXPECTED FUTURE AVERAGE COMMERCIAL PRODUCTION LINE EFFICIENCIES.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Average efficiency (EPIA &amp; Greenpeace, 2011; IEA, 2010a)</th>
<th>Expected efficiency for commercial modules in ±2025 (Berenschot et al., 2011; Hering, 2011a; IEA, 2010a; Sinke, 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>14-20%</td>
<td>25%</td>
</tr>
<tr>
<td>mc-Si</td>
<td>13-15%</td>
<td>21%</td>
</tr>
<tr>
<td>a-Si</td>
<td>6-9%</td>
<td>15%</td>
</tr>
<tr>
<td>CdTe</td>
<td>9-11%</td>
<td>15%</td>
</tr>
<tr>
<td>CI(G)S</td>
<td>10-12%</td>
<td>18%</td>
</tr>
</tbody>
</table>

5.2.1.6 Flexibility

Flexibility is related to the incremental cost and time needed to adapt a technological design, because of for example technological improvements (Van de Kaa, 2009). This factor is of importance since in general adopting newer 2G technologies comes with higher costs for research and development in comparison with the more established 1G technologies. The latter manufactures can rely on existing production knowledge, while for 2G technologies much can be gained (Bubenzer & Luther, 2003).

Both manufacturing lines for 1G and 2G PV technologies can be bought on a turnkey basis (Bellini & Beneking, 2011; Hering, 2010b; Neuenstein, 2011; Rutschmann, 2011); these turnkey lines are generally operational in one year (Photon International, 2011). It is therefore expected that it is not the major concern of manufactures to obtain production knowledge, since for all PV technologies this can
be easily bought. Buying turnkey production solutions ensures that module manufactures can focus on assembling modules and the sales, while they do not have to specialize in improving PV efficiency and production processes. Once a production line is bought, business strategy shifts towards incremental improvements using new configurations or manufacturing equipment. This process is also important for manufactures to keep their competitive advantage, since every company with enough money can buy a turnkey system and consequently have similar efficiencies (Olivierse, 2011; Sinke, 2011; van Roosmalen, 2011; Vlek, 2011).

There is a difference between the costs of building a 2G or 1G module factory, especially building CI(G)S or a-Si factories is more expensive (van Roosmalen, 2011). One of the main reasons for this is that manufacturing machines for 1G silicon technologies are built and developed for a large market and there incurs some standardization which results in economies of scale, while production machines for CI(G)S and a-Si systems have a high cost of ownership (Sinke, 2011). Similar, new innovation can more easily be implemented (partly) using existing production processes. Especially in the 1G silicon based industry this strategy can easily be implemented because the value chain consists of several different production steps (see chapter 4.4) and only a small part of the production process needs to be changed when implementing an incremental innovation (Sinke, 2011). One example of a fast implementation of an innovation came from the collaboration of the Dutch research centre ECN, production line manufacturer Amtech and the Chinese panel manufacturer Yingli who developed a high efficient sc-Si wafer which could be commercially produced in about 1-1.5 years (Geerligs, 2010; Weeber, 2011). However, for radical innovations the time to market can be around 15 years (Sinke, 2011). There is also a important difference between producing sc-Si and mc-Si, as explained in section 4.4 both technologies are wafer based, meaning a square of silicon needs to be sawed from an mono or multi crystalline ingot. The creation of mono crystalline ingots is more costly since the process of growing perfect crystal structures is time consuming and technological more complex (Fraas & Partain, 2010).

For the different generations there is a difference in how the technologies are manufactured. While both 1G technology (i.e.: ribbon mc-Si) and 2G CI(G)S and a-Si can be produced on flexible materials, mainly the 2G materials have the potential to be fabricated in a continuous roll-to-roll production process; this can significantly improve production speeds (S. Hegedus, 2006). The roll-to-roll market is still very risky, seen from a well-known Dutch company Helianthos working on this process who have recently stopped their activities (NUON, 2011). Also for the 1G technologies there are some pilot production lines from companies manufacturing regular mc-Si materials using (partially) a continuous process (e.g.: the production process of RGS Development (2011)). These improved production processes are expected to become increasingly important for the future success of these technologies, since markets will keep growing and prices dropping it important to make use of economies of scale.

5.2.1.7 Pricing Strategy

Pricing strategy is generally used to indicate the aggressive or below profit margin pricing of designs, which is likely to increase installed base (Schilling, 1998; Suárez, 2004; Van de Kaa, 2009); thus releasing products below prices of competing designs.

Aggressive pricing is regularly seen in the industry (Herron, 2010b, 2011b), nevertheless, because there are many manufactures for each technology one manufacturer with aggressive prices is not enough to drive out competing designs. In the CdTe market on the other hand one can see one major
manufacturer (First Solar) who maintains prices well below other PV designs (Herron, 2011c). For IG technologies is found that Asian manufactures (e.g. from China) sell PV devices at a price that is equal to the cost price of products of other manufactures (e.g. in western countries). Looking at the largest PV producing country, China (47.8% in 2010), and the country with the biggest installed base of PV capacity, Germany; we can relate this price difference to the difference in subsidizing the industry (Hirshman, 2011). Given the main policy instruments; deployment support programs, investment support for manufacturing plants or R&D support measures (Grau et al., 2011). Germany is famous for its feed-in tariffs, which is a form of a “deployment support program”, while the “investment support for manufacturing plants” incentive is primarily applied in China. Consequently, PV systems can be relatively cheaply installed in Germany, while the devices can be cheaply produced in China (Smets, 2011; van Swaaij, 2011).

The price users need to pay for their PV systems is also related to the balance of system (BOS); this can sometimes count up to 50% of the total cost of the system (see Figure 17) (Hoffmann, 2006; Raugei & Frankl, 2009; Smets, 2011). Since this research focuses on PV devices, which are used for energy production, either grid connected or directly connected to the load; a BOS is needed for completion of the PV system. The BOS consists of all components needed to let the system properly function between the DC electricity generated by the PV devices and the load; electrical interface components (e.g. DC/AC converter), mounting structures, wires and storage devices (e.g. batteries). See Figure 18 for an example of a grid connected PV system. Therefore, the costs of the entire system are only partly related to the costs of the PV material itself, thus even though some manufactures use an aggressive pricing strategy still the costs of the entire system, which users need to buy, are only partially effected. Several module manufactures focus therefore on not only cutting material costs through placements costs as well (Olivierse, 2011); for example innovative BIPV systems are developed to easily and efficiently place PV arrays.

The main aim of current manufactures is to deliver PV devices at grid parity prices. When grid parity is reached, it is expected that sales will increase significantly (Bubenzer & Luther, 2003), this moment of grid parity is achieved when the current price of electricity is equal to the price of electricity from PV devices without the use of subsidies. Because of its easiness in making comparisons this definition is useful, though it does not offer a definite classification since electricity prices vary during the time of the day and according to their location (Sinke, 2009). Several manufactures and researchers have stated that grid parity is reached when the price of electricity drops below $1/W (Bhandari & Stadler, 2009; Bubenzer & Luther, 2003; Perlin, 2002). Regarding manufacturing costs some manufactures already claimed they reached this barrier ($0.98/W; First Solar, 2009), though spot market prices are still somewhat higher. Table 15 shows the current average spot market prices and the expected future prices of several PV technologies. Future prices are expected to be lower because of scale advantages, higher efficiencies and improved production processes; in a study from Nemet (2006) and in one from Schaeffer et al. (2004) was found that about half of the cost reduction will come from efficiency improvements and the rest from scale advantages. For example, the sawing (see section 4.4) of mc-Si of mc-Si wafers can be made much more efficient; currently 50% material is lost (though it can be moulded again for reuse) (van Roosmalen, 2011). Or through different ways of manufacturing, like high efficiency ribbon growth mc-Si modules, in a continuous production process (see for example RSG Development (2011)).
The margin between the manufacturing price and the market price of for example CdTe can be explained by; added research and development costs, depreciation of company assets, design, permitting and the profit margin. Though it seems also to be the case manufactures change prices to compete with total PV systems prices (i.e. BOS costs) (Knulst, 2011; Sinke, 2011; Weeber, 2011). For example CdTe and CI(G)S may be priced well below or at manufacturing costs, manufactures try to gain market share and the necessary volume of sales (economies of scale) in order to be competitive in the future (Knulst, 2011; van Roosmalen, 2011). The same strategy of below profit margin pricing has been seen in this industry during the years 1975 till ’79 (Nemet, 2006). This suggests that end user prices, see Table 15, may not be that best way of comparing different PV designs, since they do not entirely represent the manufacturing costs. Nevertheless, these prices represent what end users need to pay and these users eventually make a technology dominant.

Moreover in competition with other technologies consumers look at the total systems costs and the total revenues, only a part of this is related to the costs of the modules. Technologies with lower efficiencies can only compete with for example sc-Si and mc-Si by having a lower price per Watt. It seems conflicting that sc-Si and mc-Si have similar prices, while sc-Si is generally more efficient than mc-Si (14-20% to 13-15%) (EPIA & Greenpeace, 2011; IEA, 2010a): Knoll (Knoll, 2011c) explains this to be part of the large number of sc-Si modules offered on the market by mainly Asian firms which reduces prices. Also because sc-Si wafers are generally sawed from silicon rods (explained in section 4.4) they miss a small triangle at each corner of the wafer, mc-Si wafers do not have this problem since they have a different production process; consequently the overall square meter efficiency of sc-Si modules similar to mc-Si (Laan, 2011).

Also there sometimes is a difference in the price of panels based on their manufacturing location (Knoll, 2011a; Sinke, 2011), although the difference is decreasing recently. Mainly Chinese and other Asian manufactures could not ask similar prices for their modules than for example German manufactures, while sometimes efficiencies where similar. The difference in price was mainly because the reliability of the Asian modules was not as much as German, Japanese and American manufactures. Also mainly Chinese manufactures can provide low priced PV modules because they are able to exploit economies of scale and make use of favourable regulations. A common misunderstanding is that Chinese manufactures can have low prices because they can make use of cheap labour; the manufacturing process of PV panels is highly automated and only a very small fraction of the price is related to costs of labour (Hering, 2011b; Sinke, 2011; C. F. Yu et al., 2011).

However, some companies manufacturing modules with unique features are able to ask significantly higher prices in comparison with conventional mass produced PV modules mainly from Asia (Knoll, 2010a, 2010b, 2011a, 2011a, 2011b, 2011c, 2011d; Siemer, 2011a, 2011b; Sinke, 2011; Vlek, 2011).

### Table 15: Average panel prices per Watt for the German market

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>€1.37 ($1.94)</td>
<td>€0.43</td>
</tr>
<tr>
<td>mc-Si</td>
<td>€1.37</td>
<td>€0.43</td>
</tr>
<tr>
<td>a-Si</td>
<td>€1.12 ($1.59)</td>
<td>€0.34</td>
</tr>
<tr>
<td>CdTe</td>
<td>€1.16 ($1.64)</td>
<td>-</td>
</tr>
<tr>
<td>CI(G)S</td>
<td>€1.14 ($1.61)</td>
<td>€0.34</td>
</tr>
</tbody>
</table>
It should be noted however that some of these manufacturing companies do originate from Asia or China. The unique features are generally related to efficiency, for example:

- Sanyo developed and mass-produces the HIT modules, a combination of a-Si and a mono-crystalline silicon layer, which have a higher overall efficiency than conventional sc-Si modules (Sanyo, 2011).
- Schott Solar manufactures regular mono and multi crystalline solar cells though they use high quality glass for their modules which promises a lower rate of efficiency degradation; resulting in a 25 year performance guarantee (SCHOTT Solar AG, 2011).
- SolarWorld and Scheuten Solar use similar approaches; with high quality encapsulation materials they ensure a long performance of their modules (Scheuten Solar, 2011; SolarWorld, 2011).
- Solland Solar uses an innovative approach making electrical contacts on mono- and multi crystalline PV cells which leads to higher module efficiencies (Solland Solar, 2011).
- Sunpower: While PV designs in general have contacts at both the front and back of a cell, Sunpower uses a patented design with only back contacts; increasing efficiencies (Mulligan et al., 2004)

Highly efficient PV technologies like GaAs or novel multi junction cells are mainly used for space applications and are regarded to be too expensive for terrestrial use (Yamaguchi et al., 2008; Yamaguchi, Takamoto, Araki, & Ekins-Daukes, 2005). Nevertheless, in combination with concentrators they also may be used for terrestrial use; concentrators are lenses or mirrors bundling solar irradiance of a larger area on a small solar cell. Commonly they are described using several hundred time the equivalent of one sun, consequently the efficiency of these devices is much higher than competing PV designs or the same cell without these concentrators (Razykov et al., 2011). Also because only a small piece of expensive high efficient solar cells is needed the costs of the PV material become less important. However, a disadvantage is the needed cooling of the PV cell to maintain the high efficiencies, as well as the active tracking of the position of the sun. There are examples of companies using low-cost 2G materials in combination with concentrators; e.g. the Dutch company LineSolar tries to effectively combine concentrators with CI(G)S solar cells (Knulst, 2011). As with all solar cells, one of the advantages is that a smaller area of a PV cell offers higher efficiencies in comparison with complete modules (Green et al., 2011).

5.2.1.8 Appropriability Strategy

This factor is related to the actions a firm takes to protect its design from imitators (Srinivasan et al., 2006; Suárez, 2004; Van de Kaa, 2009); e.g. via patents, secrecy, learning curve, service efforts. In case the design is actively protected this has negative influence for reaching dominance, however the firm is able to easily receive revenues from its invention.

Despite patents being regularly issued in the PV industry, there are only few lawsuits over patents (de la Tour et al., 2011; Richard, 2011). This may be because manufactures can easily buy turnkey production lines in which all the needed patents are included (see also the factor flexibility, section 5.2.1.6); thus even if the technologies are heavily patented every manufacturer can still buy the turnkey line and use the patents (van Roosmalen, 2011). Similarly, in a study of the International Centre for Trade and Sustainable Development Barton (2007) found that start-ups in the PV sector are not concerned about acquiring the technology patents. It is mentioned that even if there are issues in becoming solar cell manufactures there are so many firms in the market that it will be no issue to
obtain the needed rights at reasonable terms. Subsequently, licencing is an often used strategy in the PV market, examples include (Olivierse, 2011; van Roosmalen, 2011; Vlek, 2011):

- Research institutes like ECN and INES licence technologies or production techniques. For example ECN with their innovative way to produce contacts on 1G silicon to increase efficiencies, which is licenced to the Dutch company Solland Solar (ECN, 2010).
- Day4 energy; licenced a technology to produce 1G silicon modules which have higher efficiencies and have a higher performance under different forms of shade (Day4 energy, 2011). One of the companies they licenced their technology to is Solar Modules NL.
- Innovalight licences its technology which produces more efficient sc-Si modules using nanoparticles (Innovalight, 2011).

Since most patents only describe a minor part of a technology or the production process it is easy for companies to make a variation on the patented technology and thus to work around the original patent. However, there are some success stories of using patents in this industry, for example one of the largest manufactures Sanyo with its HIT technology or Sunpower with its highly efficient sc-Si. Sanyo stated mass production of this patented technology in 1997; until recently they have been very successful in preventing competitors to enter the market with similar products (Chunduri, 2010; Sinke, 2011). Last year 2010, the patents around this technology expired and immediately the technology gets used by newcomers. Also in the case of the CdTe technology there is only one major manufacturer and a few smaller ones; it may be because this manufacturer (First Solar) has an effective appropriability strategy (Hirshman, 2011). In general, 2G technologies are more protected than 1G silicon technologies (van Roosmalen, 2011), this seems to be related to the standardisation of the production processes (see the factor operational supremacy).

Furthermore, the largest PV producing country in the world, China, does not have a good reputation regarding the protection of intellectual property rights (S. B. Choi, Lee, & Williams, 2011; Hu & Jefferson, 2009; Xuefeng & Minguang, 2011). Nevertheless, China seems more concerned about intellectual property rights recently, mainly because of pressure from western countries. Patents are used in this industry although the most important technological developments do not get patented, but instead kept secret; this is regarded to be the most popular strategy in the PV market (de la Tour et al., 2011; Olivierse, 2011; Smets, 2011). Similarly, non-Chinese manufactures are sceptical to implement new innovative production lines in China (Smets, 2011; van Swaaij, 2011). This is expected to be of influence for the technology dominance rate; 1G silicon based technologies, which are largely produced in China, have a significantly larger market share over 2G technologies (Hirshman, 2011).

5.2.1.9 TIMING OF ENTRY

The timing of entry is related to the window of opportunity in which it is optimal for a company to bring its design on the market in order for the technology to achieve dominance (Schilling, 2008). Entering before or after this period may not be optimal and have a negative influence on the dominance process (Van de Kaa, 2009).

Because 2G PV technologies have been developed since the 1970s and still have no dominance in the market (see Appendix IV), this factor does not seem to be very influential for this technological generation or there has been no window of opportunity yet. For the 1G however, it may be of importance, because the comparable multi- and mono- crystalline silicon designs have been dominant since their market introduction (Bubenzer & Luther, 2003).
During 2003-2004 and 2006-2007 there was a silicon shortage due to lack of capacity for the explosively growing demands (Bernstein, 2006; Berwind, 2009; Hirshman, 2011; Hirshman & Schmela, 2006; Hirshman, Hering, & Schmela, 2007; Photon International editors, 2008). This period was seen by some to be the window of opportunity for especially 2G technologies to enter the market, since these technologies need less or no silicon and could compete on price even though there technological superiority was less than 1G technologies (Smets, 2011; Zweibel, Roedern, & Ullal, 2004). One example comes from the firm First Solar, who is engaged in manufacturing CdTe PV modules (Sinke, 2011), a 2G technology, and has grown during these periods towards being the largest 2G manufacturer in the world. Similarly, some firms switched towards 2G PV technologies during this period, for example Sharp enters the a-Si production market in 2005 (Sharp, 2007) and several other Taiwanese manufactures also start to produce a-Si during the period of shortages (Hirshman, 2008).

More recently, with the availability of feed-in tariffs it is more beneficial to have highly efficient modules (see also the factor distinct features, section 5.3.1.1). Despite this window of opportunity, no rise is seen for the overall share of the 2G technologies in comparison with the 1G; there is even a slight decline (see Figure 27). Correspondingly some experts say there was no window of opportunity at all, since the new 2G technologies lack the technological superiority over existing 1G technologies and the ability to compete on price (Olivierse, 2011; van Roosmalen, 2011; Vlek, 2011). Another characteristic related to price and similar to what has been described under the factor financial strength of the agent is that, in order to compete on price manufactures need to start large production lines to benefit from scale advantages (Sinke, 2011).

5.2.1.10 Marketing Communications

Marketing communication are about positively influencing consumer expectations on PV technology capabilities (Shapiro & Varian, 1999). Several aspects are recognized to play a role in consumer expectations, important ones are; pre-announcements, marketing communications and pilot projects (Brown & Hendry, 2009; Van de Kaa, 2009). With good marketing communications firms can create a self-fulfilling prophesy; a design that has the expectations to become dominant will become dominant.

Pilot projects are an important part of recognizing technological capabilities (Brown & Hendry, 2009). The 1G technologies have generally been used for pilot projects because they have on the market of a long time with an attractive cost/performance ratio and now these technologies have the largest market shares; about 85% of mono- and multi- crystalline silicon (see Figure 27) (Callaghan & McDonald, 1986; Colatat et al., 2009). On the contrary, 1G and 2G PV technologies have been developed since the 1950s and 1970s and still not a single technological design has achieved market dominance. From these pilot projects and other regular placements of modules 1G silicon modules could prove they have lifetimes of around 25 to 30 years in real life (IEA, 2010a), see also the factor technological superiority in section 5.2.1.5. On the other hand, 2G technologies still have to prove themselves in field trials, although the first test results show lifetimes of CdTe modules are similar to the 1G silicon technologies (Raugei & Frankl, 2009). Other 2G technologies have to be improved however to reach these results; especially a-Si suffers from degradation issues with expected lifetimes of around 10 years (Dhere, 2005; IEA, 2010a).

Partly affecting the consumer expectation about the technologies is the current and expected future efficiency and lifetime of the PV modules. As explained for the factor technological superiority (section 5.2.1.5), sc-Si has currently and will have in the future on average the highest efficiencies and lifetimes among 1G and 2G modules. Similarly, the 2G technologies may suffer from a loss of
performance because of degradation issues (see also operational supremacy, section 5.2.1.3); this seems particularly the case for a-Si modules (van Roosmalen, 2011). CdTe is an exception, because it has similar lifetimes as IG silicon modules.

Recently, larger PV companies started to advertise globally instead of the normal regional advertisements (Herron & Hirshman, 2010), see also the factor brand reputation and credibility (section 5.2.1.2). These advertisements are mainly for increasing brand awareness, because PV manufactures expect that the modules will eventually become a commodity good. Usually, technologies are not mentioned in advertisements, since the general public does not have knowledge of the technologies and rather gives attention to the ratio price versus efficiency (Weeber, 2011). Although, there are some examples of companies that specifically promote (characteristics of) their technology beside their brand name (Sinke, 2011):

- First Solar; during the silicon shortages (see factor timing of entry, section 5.2.1.9) they stated their technology is CdTe and this technological design is not influenced by the (at that time) high silicon prices.
- SunPower for using sc-Si; they advertised mainly using silicon, which is considered to be a sustainable raw material and it has the highest efficiencies for commercial solar panels (SunPower, 2008).
- Sanyo; they advertise their HIT technology as being more efficient than conventional sc-Si (Sanyo, 2007).

The European Union could also have influenced consumer expectation specifically about CdTe modules; because cadmium is toxic, the EU regulates the amounts that may be used in products. CI(G)S and CdTe panels are permitted, because the European Union made an exception for the use of cadmium for renewable energies (European Union, 2010; Harrison & Merrifield, 2011). However, the RoHS get revised every few years and given the opposing lobbyist groups, expert opinions and the tendency to only further restrict the usage of toxic materials, it is far from certain that cadmium usage in solar devices remains legal in the future (Olivierse, 2011; Podewils, 2010; Smets, 2011; Weeber, 2011). Consumers may be ignorant to the possible dangers, though it may also be that they are less tending to buy cadmium based solar modules (van Roosmalen, 2011).

5.2.1.11 Pre-emption of scarce assets

This factor relates to assets (e.g. capabilities, organizational processes, firm attributes, information, knowledge, expertise, physical capital, human capital and rare resources) that a firm is able to capture in an early stage and deny them from usage by other firms (Barney, 1991; Van de Kaa, 2009).

Both in industry magazines and press releases is stated that several manufactures have contracts with

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**Figure 20:** Comparison of spot market and contract based prices of silicon during the shortage of 2007/2008 (Boas et al., 2010)
raw materials suppliers or have integrated the supply in their own value chain (Berwind, 2009; Hirshman, 2011; Sinke, 2011; Weeber, 2011). Recently, there were several periods of silicon shortages, notably between 2003-2004 and 2006-2007 (Bernstein, 2006). During these periods companies having contracts with silicon suppliers could keep production and prices on a normal level, though it was probably costly to aggressively increase production. Manufactures without such contracts needed to pay a higher price. See Figure 20 for a comparison of the average spot market price and the contract based prices of silicon. Though 2G and 3G technology manufactures could presumably benefit even more from these silicon shortages (see the factor timing of entry). It should be noted that silicon shortages are not the result of the lack of material in the earth’s crust; silicon is after oxygen the most abundant material on earth. Shortages can therefore always be addressed in the long run by building extra refineries.

One clear example; a manufacturer that needs to invest in securing favourable contracts for their raw material supply is First Solar, the number one manufacturer of CdTe based modules. Tellurium is an extremely rare element and there are doubts whether increased production can be sustained over the years. Nevertheless, whereas some researchers indicate problems for the availability of tellurium others point out there are no problems in the near future at all and for the long term recycling programs can be used as a source of tellurium (Candelise, Spiers, & Gross, 2011; Gellings, Schmittdferick, Schlumberger, & Siemer, 2006). Despite a debate on the availability of raw materials by scientists, the prices are fluctuating over the years. This may be one of the reasons First Solar seems to own its own tellurium mine (Sinke, 2011; Eric Wesoff, 2011a); it is essential for First Solar to compete on the price/efficiency ratio with sc-Si and mc-Si since these technologies offer higher efficiencies and overall it may be cheaper to buy modules with these 1G technologies.

Similarly to tellurium, do investors in CI(G)S worry about the availability of indium. Since CI(G)S are not manufactured like CdTe by one very large company which has the funds to buy mines, it may be even harder for CI(G)S manufactures to find a cheap reliable source of indium. In recent years prices have gone up for this element, although this can also be related to an increased need for this material from the LCD panel industry (Candelise et al., 2011; Fthenakis, 2009; Gellings et al., 2006; Sinke, 2011). A comparable problem arises for the availability of tellurium; there is a debate on the availability in the long term. It is expected that if there is a reduction in the availability of tellurium or indium, prices of the CdTe and CI(G)S modules will increase; consequently, it may not be possible anymore to compete with silicon based 1G technologies.

For operating production facilities, different employees are needed in comparison to the research and development of PV technologies; production facilities need mainly production line workers and managers; these employees do not need to have education in a specific technology (Olivierse, 2011). On the other hand in research positions employees do need to be educated in a specific technology (Olivierse, 2011; Smets, 2011; Swaaij, 2011). This indicates universities have some influence on the technologies that are being researched by the market, since they are the main source of employees in research companies.

Related to capturing information is how PV technologies can use knowledge from similar industries, as explained some PV technologies can make use of knowledge from the IC or flat panel display industry. However, countries in which one of these industries was strong do not always lead in the PV industry; for example the US had a very mature IC industry, although is not the leader in the silicon based 1G industry (Brown & Hendry, 2009).
Related to capturing knowledge and information for this factor was found that, since the silicon based 1G technologies have the largest market share; consequently they are able to spend more on research and development. This eventually benefits an entire industry (Jensen, Johnson, Lorenz, & Lundvall, 2007), see also the factor learning orientation (section 5.2.1.4).

5.2.1.12 Commitment

The factor ‘commitment’ relates to the support and attention of a firm in supporting the design through the low revenues of the early stages (Van de Kaa, 2009). In the stages of development before market introduction or just after the market introduction the returns on investments are low or negative.

There are the long development times of the PV technologies; 1G sc-Si was introduced in 1951, mc-Si in 1954 (Bell Labs, 2011; Green, 2000; Luque & Hegedus, 2011; Perlin, 2002) and production of 2G started in the 1970s (Bubenzer & Luther, 2003). In these periods followed almost immediately mass production at a couple of firms. Although much progress is made from the first market introduction to bring down prices per watt, still PV needs improvement in order to reach prices at grid parity (Bubenzer & Luther, 2003; Hirshman, 2011; Knoll, 2011a). It is expected that when grid parity is reached sales will increase significantly (Bubenzer & Luther, 2003). Consequently, firms can be said to be ‘committed’ to reaching dominance with their design in the PV market.

Pursuing multiple designs is a characteristic of a market with high uncertainties, also it suggests firms are not fully committed to one design (Van de Kaa, 2009). Although in general, PV manufactures only produce one technology there are examples of large international companies pursuing or have pursued several competing technological designs (Hirshman, 2009, 2010, 2011; Hirshman et al., 2007; Hirshman, Hering, & Schmela, 2008; van Roosmalen, 2011):

- Q-Cells, one of the largest 1G PV manufactures on the world (Hirshman, 2011), is involved in a wide variety of research in 2G PV technologies by own research or via partnerships and subsidiary companies (Q-Cells, 2011a, 2011b; Sinke, 2011), though they stopped some research activities into new PV technologies over the years (Hirshman, 2011; Hirshman et al., 2008).
- Also Suntech, another large silicon solar cell producer, focussed merely on mc-Si and in 2010 announced to start a production line with 2G solar cells (Suntech, 2011).
- Previously Sharp mainly focused on first generation silicon solar cells, recently their efforts changed more towards 2G technologies (Sharp, 2008); especially production capacities for a-Si are increased in comparison to 1G silicon solar cells, though sc-Si and mc-Si still have the largest production shares (Hirshman, 2011).
- As a precaution regulations or availability of raw materials becomes a problem for the CdTe modules of First Solar they also research other technologies (Sinke, 2011).

Supporting multiple designs seems to be part of the manufactures strategy that at least one of the technologies has the potential to be successful in the future. This can be seen from Sharp; they first were involved in silicon 1G PV modules, then switched their attention to a-Si and now because prices are not declining fast enough switch their focus back to silicon 1G technologies. Another strategy from manufacturers is by working together with research institutes and universities (van Roosmalen, 2011); mainly to work on the newer 3G technologies, to be able to participate on technological designs that may be successful in the future.
Similarly several manufactures working with 1G technologies produce both sc-Si and mc-Si, e.g.; Suntech Power, JA Solar, Trina Solar and Gintech (Hirshman, 2010). This is generally related to the similarities in the production processes, (to some extend) raw materials and material properties. Consequently, it is easy for manufacturer to have diversification of their products.

5.2.2 Meso-level factors
Environmental/industry specific factors; these factors are related to technological sector of PV. Not all factors can be easily influenced by individual firms.

5.2.2.1 Compatibility
Compatibility relates to having multiple entities being able to work together (Van de Kaa, 2009). Having a design that is compatible with other systems, or which is backwards compatible with previous generations has positive influence on the dominance process. In the PV market compatibility would relate to having PV modules integrated in the grid for energy production.

It is described in chapter 4 that the different PV technologies all have the same output characteristics; DC power. Therefore one could say this factor is not of influence in this research, however there may be some differences between technologies related to large scale implementation of PV technologies. Currently the electricity market is characterised by large scale electricity production, for example; power plants using gas, oil and nuclear fuel. Though almost all renewable technologies including solar provide distributed electricity (Pepermans, Driesen, Haeseldonckx, Belmans, D'haeseleer, 2005). There are several issues with PV in order to be fully compatible with these large ‘conventional’ power plants:

- **Costs**: One of the reasons for the low price of conventional power plants is their large production capacity on a relatively small area. It is not very difficult to build large scale PV systems however, they need a much larger area; this is one of the reasons they are expensive in countries with a lack of available space (like some western countries). In such situations highly efficient PV modules will be favoured over slightly cheaper less efficient modules; sc-Si is generally found to be the best technology able to deliver these high efficient modules for an attractive price to compete with the small area of conventional power plants (see section 5.2.1.5 and 5.2.1.7 as well).

- **Quality and availability**: Conventional power plants provide a stable source of electricity; they can produce day and night, under bad and good weather conditions and in hot and cold climates. PV systems on the other hand cannot work during the night and have lower efficiencies on cloudy days and in warm climates. Stability is essential since modern economies need a constant quality and availability of electricity to keep their businesses working. Although it is impossible to overcome the issue of electricity generation during the night, there are some technologies offering better efficiencies in warm climates; the 2G technologies. Especially a-Si and CI(G)S can convert about 10% more kWh per kWp in comparison with sc-Si and mc-Si in high temperature climates (Knulst, 2011; Razykov et al., 2011; Tiwari et al., 2011; van Roosmalen, 2011).

Nevertheless PV systems together with intelligent technologies are able to deliver stable voltages and frequencies similar to conventional power sources. Also with regard to the availability it is expected that an internationally connected system of PV installations (for example throughout the European Union) is able to deliver a very stable output of electricity during the day, since electricity can be exchanged between places with bright sun and other with cloudy weather.
5.2.2.2 Diversity of the network

A more diverse set of actors will positively influence the dominance process since the stakeholders complement each other’s capabilities and each can represent the design in an (possibly) important industry (Keil, 2002; Van de Kaa, 2009). Hence making it easier to develop and market the technological design.

The manufacturing of 1G silicon solar cells used insights from the IC industry, similarly a-Si and pc-Si could rely on fabrication know-how from the flat-panel display sector (Bubenzer & Luther, 2003; Razykov et al., 2011). Also these 1G and 2G technologies could benefit from glass manufactures for the coating and heat treatment of glass, this was especially useful for CIGS; for example the cooperation of glass manufacturer Saint-Gobain and AVANCIS (AVANCIS, 2011; van Roosmalen, 2011). Though the knowledge spillovers only occurred after new manufacturing processes had been developed in the other industries, they are regarded to be very important in the development process. Especially for speeding up the production processes these spillovers have been very important (Smets, 2011; van Swaaij, 2011). Consequently companies from the IC or flat panel industry enter the PV production market, either with their own production lines, as spin-offs or teaming up with existing PV producers. Some of the larger companies originating from the IC industry are for example Sharp, LG, Texas Instruments, Samsung, Intel and Panasonic (G24, 2011; Hirshman, 2011; Intel, 2008; LG, 2009; Mahon, 2008; Samsung, 2009; Sharp, 2011).

Given the similarities in the production processes between crystalline silicon PV and the IC industry, and a-Si/pc-Si PV and the flat panel industry it is expected that countries with these kinds of industries can benefit from the already present manufacturers and suppliers; consequently they are expected to have a competitive advantage in the emerging PV industry. This is indeed the case for Japan and Germany, which are leading industries in the worldwide PV market however, the PV industry in the US (a strong player in the IC industry) falls behind (Brown & Hendry, 2009). The influence of existing industries is therefore not completely clear.

In a report made by the European Union is analysed from which research, industries and other areas the PV sector may benefit in the future (European Communities, 2009). This resulted in a list of 30 overlaps and learning opportunities; from the areas of law and finance for certificates and credit sources, to the polymer industry for finding alternatives for the glass plates and aluminium frames. This is on a meso scale and no single PV technology is expected to benefit more in comparison to another PV technology from the overlaps with other industries; generally benefits are evenly spread.

There is recently a trend of 1G manufactures to vertically integrate their value chain or make agreements with other firms to work together in producing, parts of, PV modules (EPIA & Greenpeace, 2011; Google News, 2011; Photon International, 2011; Sinke, 2011; van Roosmalen, 2011; Weeber, 2011). Historically 2G generation manufactures are already vertically integrated, since the production process does not contain the several distinct steps from the 1G silicon production process (EPIA & Greenpeace, 2011; Knulst, 2011). A notable example is First Solar, the largest producer of CdTe modules which even has integrated the recycling of modules (First Solar, 2011a). The main reason for vertical integration is the ability to benefit from economies of scale which helps to bring down prices; not for every separate step in the production process a certain profit margin needs to be retained and a perfect fit between demand and supply of subsequent production steps can be made (Olivierse, 2011; Sinke, 2011; Weeber, 2011). On the other hand companies separating the
production steps can focus completely on their core activity, though they are more dependent on standardisation and suppliers (EPIA & Greenpeace, 2011).

For the largest 2G technology, CdTe, it seems it did not make that much use of a diverse network of stakeholders for attaining market share. The CdTe technology can clearly show this since one company is currently by far the largest manufacturer of these cells; during the first year after they were founded in 1999, First Solar did not release any press release indicating that they are working together with other companies to develop their technology (First Solar, 2011d). Solar Energy Development on the other hand, is an example of a company which did make use of vertical integration (Olivierse, 2011). This company assembles silicon panels by buying the PV cells from other companies. And it works on innovative products by working together with research institutes, i.e. the Dutch ECN and the French INES.

5.2.2.3 Bandwagon effect

This factor is related to the effect of users adopting a design on other users for choosing for the same design; in general because of availability of information (de Vries, 1999).

Although the PV market is not characterised by network externalities (see section 2.1.2), the bandwagon effect is found to exist in the PV industry. One example comes with several companies trying to mimic the success of First Solar by starting up research programs and planning pilot plants using the CdTe technology (Hirshman et al., 2007, 2008). First Solar has been one of the fastest growing companies in the PV market, in the 2G technology market they are already for some years the largest company. Moreover they say that they are making considerable profits with their technology (First Solar, 2011e). A second example comes from companies operating in Taiwan; Simon Tsuo (CEO of Motech) indicates that there is a bandwagon effect occurring in the Taiwanese PV market, since in this country many manufactures started to focus (at least partly) on the a-Si technology within a few years’ time (Hirshman, 2006, 2008).

For the 1G technologies can be found similar that similar and standardized manufacturing techniques are used, see also section 5.2.1.6. Combined with the interests in this technology, from for example manufactures in China; this can also be an indication of firms choosing the same designs because of information being widely available.

5.2.2.4 Number of options available

The number of available competing technologies can negatively influence the change one single technological design achieves dominance; Tripsas (1997) found that the market share decreased significantly with each new design in the market.

As explained in section 4.3.4 there are currently five technologies that can be produced on a commercial basis for terrestrial energy production:

- sc-Si: Mono-crystalline silicon
- mc-Si: Multi-crystalline silicon
- CdTe: Cadmium telluride
- a-Si: Amorphous silicon/hydrogen alloy (a-Si:H)
- CI(G)S: CuIn(Ga)Se2, copper indium (gallium) selenide
Furthermore there are multiple designs in development that have the potential to become commercially available in the future, see section 4.3. Concluding the number of options available is regarded to negatively influence the dominance process of a single technology.

5.2.2.5 Uncertainty in the Market

Uncertainty in the market is mainly related to the number of competing designs, this causes uncertainty and negatively influences the technological adoption process because actors tend to postpone their decision for adopting a single design (Leiponen, 2006; Van de Kaa, 2009).

Similar to what has been previously explained for the factor commitment (section 5.2.1.12) is found that PV manufactures in general support only one technological design however, especially larger firms tend to support multiple technologies (Hirshman, 2009, 2010, 2011; Hirshman et al., 2007, 2008; van Roosmalen, 2011). Well known examples of companies involved in multiple generations are: Q-Cells (manufactures 1G silicon and via subsidiaries involved in 2G technologies), Suntech (mc-Si and 2G technologies), Sharp (sc-Si, mc-Si and a-Si) and First Solar (CdTe and research after other 2G or 3G technologies) (Hirshman et al., 2008; Q-Cells, 2011a, 2011b; Sharp, 2008; Sinke, 2011; Suntech, 2011). Similarly, several manufactures working with 1G technologies produce both sc-Si and mc-Si, e.g.; Suntech Power, JA Solar, Trina Solar and Gintech (Hirshman, 2010). Another strategy from manufacturers is by working together with research institutes and universities (van Roosmalen, 2011), mainly to work on the newer 3G technologies, to be able to participate in the technology with the highest potential in the future.

The production of mc-Si and sc-Si has similarities in the production process and material properties, and therefore the easiness for the manufacturer to have diversification of their products. However the other companies supporting multiple technological designs may do this because of the uncertainty of being locked out of the future dominant design.

5.2.2.6 Rate of Change

The speed of research and development in the PV industry may negatively influence the emergence of one dominant design; the development of new PV generations may cause manufactures not to be committed to one technological design, instead they distribute their capacity to multiple designs (extensively explained for the above factor) (Schilling, 1998; Van de Kaa, 2009). When a firm does not invest in newer technologies it has the chance failing to see and anticipate on technological changes (Schilling, 1998).

There are examples of innovations that have been available within a year for commercial production; e.g. high efficient sc-Si wafers by ECN (Geerligs, 2010; Weeber, 2011). However for radical innovations the time to market can be up to 15 years (Sinke, 2011). Nevertheless, similar to what has been discussed for the factor flexibility (section 5.2.1.6), both for 1G and 2G technologies turn-key production lines can be bought (Bellini & Beneking, 2011; Hering, 2010b; Neuenstein, 2011; Rutschmann, 2011); these turnkey lines can be operational in one year (Photon International, 2011). By using a turn-key solution firms can accumulate the for manufactures generally available knowledge and produce modules of an average price and quality.

Also related to fast changing market is the trend in price; First Solar introduced their CdTe modules at very low prices to increase their sales and benefit from scale advantages. With this low price sc-Si and mc-Si manufactures needed to rapidly bring down prices in order to have a competitive price versus performance ratio. Moreover with the overproduction of sc-Si modules mainly from China, prices
could drop to similar rates as the less efficient mc-Si devices (see Table 15) (Siemer, 2010; Sinke, 2011; van Roosmalen, 2011; Weeber, 2011).

Concluding the characteristics of this factor rate of change are found in the PV market, though its influence seems not to be the same in all situations.

### 5.2.3 MACRO-LEVEL FACTORS
This level describes factors that can hardly be influenced by individual firms. The factors are similar for all firms in the PV industry and also some other (energy production) markets. There are many aspects on a macro level that affect the PV market, in this research only factors are listed that influence the selection of a PV technology.

#### 5.2.3.1 POLICY
This factor covers policy measures facilitating the transition of a specific PV technology over the other. Over the world there are several policy incentives to stimulate PV adoption (Brown & Hendry, 2009; EPIA, 2009; EPIA & Greenpeace, 2011; Hirshman, 2010). Some examples of policy incentives help to stimulate the adoption of renewable energies worldwide or PV specifically are; feed-in-tariffs (FITs), tradable green certificates (TGCs), portfolio standard (RPS), pricing laws, production incentives, capital subsidies, pilot projects, tax credit and net metering (Dusonchet & Telaretti, 2010; Solangi, Islam, Saidur, Rahim, & Fayaz, 2011). In combination with manufacturing support these incentives can be defined into three categories: deployment support programs, investment support for manufacturing plants and R&D support measures (Grau et al., 2011).

Germany is famous for its FITs, which is a form of a “deployment support program”, while the “investment support for manufacturing plants” incentive is primarily applied in China (Grau et al., 2011). The deployment support programs are characterised by supporting PV deployment in general; increasing the market share of PV in the total electricity production. This form of policy does not directly differentiate between renewable energy technologies or specific a PV technology directly. Indirectly however, it may favour in the PV market high efficient solar cells over lower efficiencies; consumers can better buy higher priced and more efficient PV modules if they have insufficient space available, since consumers are able to benefit better from the price they receive from delivering to the grid (see also the factor distinct features, section 5.3.1.1). This would consequently lead to favour the 1G silicon technologies, since they offer relatively high efficiencies with an attractive pricing. This effect is seen in countries with high (consumer) electricity prices as well. Also pilot projects have been used to show the potential of PV technologies and to increase the learning curve, see the factor learning orientation (section 5.2.1.4). Since 1G silicon technologies have been on the market for a longer time, these technologies have in general more often been used for pilot plants and demonstration projects (Callaghan & McDonald, 1986; Colatat et al., 2009).

Some researchers however, say these favourable policy incentives may also have a negative effect on market prices of PV modules; “The generous financial support for solar PV stipulated in Germany’s Renewable Energy Sources Act (EEG) currently provides for the largest demand for PV modules in the world, thereby leading to high prices for solar cells and shortages in high-quality silicon used for their production” (Frondel, Ritter, & Schmidt, 2008, p. 15). Also was found that although production prices for components of PV systems are almost equal, the total price paid for the system differs significantly from country to country: it was found that in countries with the most generous policy incentives the highest prices need to be paid (indifferent of the size of the installed system (Krause, 2011). Nevertheless, most researchers found policy incentives are especially useful for the further
diffusion of PV modules (Dusonchet & Telaretti, 2010; Luque & Hegedus, 2011; Solangi et al., 2011; Zhang, Song, & Hamori, 2011), though it not always stimulates one technology in particular. It should be noted however that with current declines in feed-in tariffs manufactures are still able to further bring down their prices.

With the ‘investment support for manufacturing plants’-policy there can be some level of differentiation between PV technologies; governments are able to favour one technology over the other. Mainly China offers support for building manufacturing plants (Grau et al., 2011), they have a large hare in the global PV production market; even 47.8% of all PV devices in 2010 (Hirshman, 2011a). On first sight it seems the 1G technologies are favoured by the Chinese government; since the wafer based silicon technologies have the largest market share (Hirshman, 2011; Marigo, 2007). This market domination is however more likely to come from the relative easiness of starting 1G silicon factories (see the factor flexibility, section 5.2.1.6). Also in examining the policy incentives in China there is no indication found one technology is favoured over another (Byrne et al., 2010; Grau et al., 2011).

5.2.3.2 Law

Law is how institutions can prevent a certain technology from being adopted by the use of rules and guidelines. This factor does not originate from the researched standards literature (e.g.: Schilling, 1998; Suárez, 2004; van de Kaa, 2009). Existing literature describes the slightly similar factors; judiciary and regulator. However judiciary relates to how courts can use antitrust law to prevent certain designs from becoming dominant, and regulator relates to an institute prescribing a certain technology or design to be used in the market; therefore the factor “law” is not fully been captured in existing concepts.

Law can prevent a technology from being adopted in certain countries, for example; because of restrictions on the use of certain materials. This was the case for PV technologies which made use of cadmium (Cd) in their cells (i.e. (forms of) CdTe, Cl(G)S and QWSC). Cadmium is a by-product from zinc mining and its exposure can lead to lung, kidney and bone damage (Godt et al., 2006; Nordberg, 2009); therefore the European Union regulates the amount of cadmium to be used in products. Cl(G)S and CdTe panels are permitted because the European Union made an exception for the use of cadmium for renewable energies (European Union, 2010), in 2011 a revision of the Restriction of Hazardous Substances (RoHS) law was passed which legalized the use of cadmium for solar devices (Harrison & Merrifield, 2011). However, there is not much research after the CdTe technology in Europe, which needs much more cadmium in comparison to Cl(G)S (Weeber, 2011). Also the RoHS get revised every few years and given the opposing lobbyist groups, expert opinions and the tendency to only further restrict the usage of toxic materials; it is far from certain cadmium usage in solar devices remains legal in the future (Olivierse, 2011; Podewils, 2010; Smets, 2011; van Roosmalen, 2011; Weeber, 2011). For the other PV technologies these restrictions are not important since they are generally made from materials that are non-toxic or use non-toxic amounts.

Some counties have also less strict regulations for environmental protection or the need to comply with regulations is lower. Companies in China have been accused of waste disposal in the purification process of the raw material silicon (Eunjung Cha, 2008; Podewils, 2008). Mainly manufactures producing silicon based PV technologies are based in China (Hirshman, 2011), this could make the raw material silicon more cheaply available than it would actually cost to produce and therefore provides the 1G silicon companies with a slight cost advantage.
5.3 FACTORS IN FAVOUR OF MULTIPLE DESIGNS

Similar to the previous section; not all factors that have been described in section 5.1.2 are applicable to the PV market. This section describes which factors from Table 8 have been found to influence the PV market; an overview with short description is given in Table 16. In the following section for each of these factors examples have been found how they influence the chance multiple PV designs are able to coexist in the market, also a more detailed description of the factors is given in comparison with Table 8. Similarly factors from previous frameworks that have not been found to influence the coexistence of multiple designs are listed in Table 17; these factors are explained in section 5.4.2.

Again, with the definitions from section 2.2 a distinction is made on which level the factors influence the PV market.

TABLE 16: FACTORS IN FAVOUR OF MULTIPLE DESIGNS COEXISTING IN THE MARKET

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Distinct features</td>
<td>PV technologies are characterised by different physical characteristics, which make them better suited for certain situations.</td>
</tr>
<tr>
<td></td>
<td>Appropriability regime</td>
<td>Many PV manufactures make use of patents to protect their design; especially second generation manufactures make use of this strategy.</td>
</tr>
<tr>
<td></td>
<td>Price</td>
<td>Although the technologies know different prices, the differences become smaller.</td>
</tr>
<tr>
<td>Meso</td>
<td>Application drives the design</td>
<td>Consumers generally buy complete PV systems; the technological design is only part of this system.</td>
</tr>
</tbody>
</table>

TABLE 17: FACTORS NOT INFLUENCING THE COEXISTENCE OF MULTIPLE DESIGNS

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Persistency</td>
<td>Though some manufactures develop less profitable designs, they also support multiple designs.</td>
</tr>
<tr>
<td>Meso</td>
<td>Speed of technological development</td>
<td>PV technologies know long development times; first generation technologies originate from the 1950s and the second generation form the 1970s.</td>
</tr>
<tr>
<td></td>
<td>Gateway technologies</td>
<td>PV devices know no need to be compatible with other designs. Similar to gateway technologies; PV devices know no need for a system that accommodates multiple PV designs.</td>
</tr>
<tr>
<td></td>
<td>Multi-channel end system</td>
<td></td>
</tr>
</tbody>
</table>

5.3.1 MICRO-LEVEL FACTORS

5.3.1.1 DISTINCT FEATURES

Designs have distinct features when they have various advantages for different groups of users, therefore they may develop an installed base in their own niche with enough critical mass (de Vries et al., 2011). In this scenario users value the features of the design more than network size of other designs, and thus provide the manufacturer with a competitive advantage (Frenken et al., 1999). As a consequence, these designs give incentive to the emergence of product niches and consumer communities.

This factor is partly applicable to the PV industry. However most technologies discussed in this research have similar external characteristics (like mountable solar panels), only some have different physical characteristics; they can be made on a flexible material (e.g.: a-Si, CI(G)S and organic PV) (Pagliaro, Palmisano, & Ciriminna, 2008). Nevertheless, more importantly and within the scope of this research; also pricing and efficiency are important distinguishable characteristics, these characteristics
are often discussed when comparing different technologies (Bubenzer & Luther, 2003; Curtright, Morgan, & Keith, 2008; Photon International, 2011).

Similarly the choice for the most suitable technology in a PV system can also be based on geographical location. For example in a country like the Netherlands with expensive land and high consumer electricity prices it may be more beneficial to use PV panels which are somewhat more expensive but provide higher efficiency. In Table 19 a calculation is made for two modules with different efficiencies, the complete specifications can be found in Table 18. This calculation is made for a fictional house in the Netherlands which only has place for 10 m² of solar modules and the question is which set of modules will deliver the highest revenue in 20 years. The 10 m² is an important constraint since the house has an annual electricity need of 4000 kWh and five modules of type A, with the highest watt-peak (Wp) per m², can still only generate 1800 kWh per year. The total revenues displayed in Table 19 seem to be rather low, especially because this calculation did not account for BOS costs, however, this calculation did not take into account an expected rise in energy prices (OECD & IEA, 2009; Vlek, 2011); which could result in higher overall revenues. Concluding from the outcome of the calculations it is beneficial to buy higher priced and more efficient PV modules if you have insufficient available space. On the other hand if the availability of space in not an issue it is more beneficial to use the cheapest available modules which can provide the needed energy. Moreover this calculation shows that price and efficiency of the module is an important characteristic when choosing the most suitable technology for the application.

<table>
<thead>
<tr>
<th>Table 18: PV system information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General information:</strong></td>
</tr>
<tr>
<td>Roof (available area): 10 m²</td>
</tr>
<tr>
<td>Electricity use: 4000 kWh</td>
</tr>
<tr>
<td>Consumer electricity price: 0.23 Euro</td>
</tr>
<tr>
<td>Annual power from sun: 1000 W/m² (AM1.5)</td>
</tr>
<tr>
<td>Average sun hours/day (of AM1.5): 2.8 hour</td>
</tr>
<tr>
<td><strong>Module A:</strong></td>
</tr>
<tr>
<td>Technology: sc-Si</td>
</tr>
<tr>
<td>Efficiency: 18 %</td>
</tr>
<tr>
<td>Peak power: 350 Wp</td>
</tr>
<tr>
<td>Size: 2 m²</td>
</tr>
<tr>
<td>Cost: 525 Euro</td>
</tr>
<tr>
<td>Yearly energy from module: 350Wp * 2.8h * 365days = ~360 kWh</td>
</tr>
<tr>
<td><strong>Module B:</strong></td>
</tr>
<tr>
<td>Technology: CdTe</td>
</tr>
<tr>
<td>Efficiency: 10 %</td>
</tr>
<tr>
<td>Peak power: 195 Wp</td>
</tr>
<tr>
<td>Size: 2 m²</td>
</tr>
<tr>
<td>Cost: 325 Euro</td>
</tr>
<tr>
<td>Yearly energy from module: 195Wp * 2.8h * 365days = ~200 kWh</td>
</tr>
</tbody>
</table>

**Table 19: Total revenue of PV modules in 20 years (keeping the same electricity price and interest rate at 4%)**

\[
\text{Total revenue in 20 years} = -\left(\text{# of modules} \ast \text{module cost}\right) + \left(\text{# of modules} \ast \text{yearly revenue} \ast \text{elec. price}\right) \left\{ \frac{1 - (1 + \text{interest rate})^{-\text{years}}}{\text{interest rate}} \right\}
\]

| Module A | -(5*525)+5*350*0.23*(13.6) = 2850 Euro |
| Module B | -(5*325)+5*200*0.23*(13.6) = 1500 Euro |

Difference = ~90%
In the future it is expected that a significant difference between efficiencies of PV technologies remains, see also the factor technological superiority (section 5.2.1.5). Consequently in countries with expensive ground or with lower temperatures, highly efficient 1G silicon technologies may be preferable, because they offer relative cheap high efficient solar panels. However 1G silicon technologies lose some of their efficiency when exposed to high temperatures, therefore it may be more effective to use 2G technologies in warmer countries (like southern Europe). The 2G technologies, especially a-Si and Cl(G)S, can convert about 10% more kWh per kWp in comparison with sc-Si and mc-Si in high temperature climates (Knulst, 2011; Razykov et al., 2011; Tiwari et al., 2011; van Roosmalen, 2011).

In densely populated countries building integrated PV (BIPV) is expected to become increasingly popular (Kaan & Reijenga, 2004; Olivierse, 2011; Vlek, 2011; Weeber, 2011), although there will also be room for high efficient building applied PV (BAPV) as explained above. Flexible 2G PV materials can be integrated in buildings or installed like conventional PV modules; advantages are the new way of combining PV with buildings and savings on installation costs. Maybe even more important is the possibility to have a continuous roll-to-roll production process, this enables increased production speeds resulting in scaling possibilities and reduced costs (Bubener & Luther, 2003; Pagliaro et al., 2008). Given the aesthetics, ease of modification and relative high efficiencies of Cl(G)S modules this technology is promising to be used for BIPV (van Roosmalen, 2011). Also static modules become more popular for BIPV applications, although they cannot be used for curved objects. Especially for static modules BIPV is used to bring down building costs; sc-Si and mc-Si modules last for about 20-30 years, while buildings usually last for around 60 years (Olivierse, 2011). This means modules have to be installed twice during the lifetime of a building while the BOS costs can count up to 50% of the total PV system (see section 5.2.1). Given the analysis made for the factor technological superiority (section 5.2.1.5), can be seen that there exist significant differences in lifetimes of modules; this makes different materials better or worse for being used in BAPV or BIPV.

Also the use of toxic or rare materials in modules may influence on the choice by environmentally aware consumers; critical environmentally conscious consumers and manufactures may prefer PV designs that use abundant, non-toxic raw materials over designs that use rare and possible toxic materials. Both CdTe and Cl(G)S use these toxic (e.g.: cadmium) and rare materials (e.g.: cadmium and indium); although Cl(G)S is regarded to be slightly better since it uses relative small amounts (Knulst, 2011). The 1G silicon technologies and a-Si have a clear advantage since they use silicon, which is the second most abundant element on Earth.

Lastly Laan (2011) describes how consumers seem to be ignorant of the technology used in the PV system. Nevertheless some prefer the highest efficiencies per square meter in combination with a not too expensive price (thus no modules based on GaAs), consequently there is a tendency for installation companies to deliver efficient sc-Si and mc-Si modules.

5.3.1.2 Appropriability regime

Appropriability is how firms are able to capture the profits from their innovation and protecting it from being imitated (de Vries et al., 2011; Van de Kaa, 2009); e.g. via patents, secrecy, learning curve, service efforts. Similarly to the negative effect described by previous literature (Srinivasan et al., 2006; Suárez, 2004; Van de Kaa, 2009), de Vries et al. found that appropriability increases the chance multiple designs survive in the market. One reason is that if a firm achieves market dominance with its
product it can be forced by antitrust authorities to provide the opportunity for competitors to enter the market. Moreover appropriability reduces selection pressure and may result in product niches.

As described for the factor appropriability regime in favour of a single dominant design (section 5.2.1.8); there are regularly patents issued in the PV industry, nevertheless there are only few lawsuits over intellectual property rights (de la Tour et al., 2011; Richard, 2011). This may be because manufactures can easily buy turnkey production lines in which all the needed patents are included (see also the factor flexibility, section 5.2.1.6); thus even if the technologies are heavily patented every manufacturer can still buy the turnkey line and use the patents (van Roosmalen, 2011). Also licencing is often used in the PV industry (Olivierse, 2011; van Roosmalen, 2011; Vlek, 2011). Moreover no example was found of antitrust authorities intervening in the PV market (Google News, 2011; Photon International, 2011). Combining these findings it seems characteristics of the factor appropriability regime causing multiple designs to coexist in the market are present, nevertheless they seem not to be very influential.

Although especially for the 2G technologies CdTe and Cl(G)S, patents and secrecy seem to play an important role. In the CdTe market this is seen from the single firm that is by far the largest in this market niche; it is likely that this manufacturer (First Solar) has an effective appropriability strategy (Hirshman, 2011). In general 2G technologies are more protected than 1G silicon technologies (van Roosmalen, 2011), this seems to be related to the standardisation of the production processes (see the factor operational supremacy).

5.3.1.3 PRICE

Designs or technologies can also compete with each other in terms of pricing, however if the price of one design is almost the same as the other designs; users may be indifferent of what technology they choose (de Vries et al., 2011). This is because the technologies all deliver (almost) the same functions for approximately the same price. This definition of pricing is slightly different from the definition generally used to indicate the factor positively influencing dominant designs (Schilling, 1998; Suárez, 2004; Van de Kaa, 2009); here aggressive or below profit margin pricing is used to increase installed base.

On first sight this factor seems not to be applicable to the PV market since prices of different designs differ significantly in price, see Table 15 and Figure 21. However there is high pressure on manufactures to constantly bring down prices, this can be seen in Figure 21; in less than a year differences in prices between technologies became considerable smaller. Therefore this factor currently only slightly influences the PV market, though its effect is expected to become stronger in the future.

Laan (2011) confirms indifference of the consumer for the used technology, explained for the factor distinct features (section 5.3.1.1).
5.3.2 MESO-LEVEL FACTORS

5.3.2.1 APPLICATION DRIVES THE DESIGN

Some designs are complementary goods for larger systems, in which consumers make a choice for the larger system instead of the complementary good (de Vries et al., 2011); hereby supporting indifferently multiple designs.

This factor is partly the case for PV devices, since end user generally buy them together with a complete system; including batteries, wiring, convertors, meters, etc. Therefore the choice for a PV technology is generally not made by the end user but by the firm who installs the system (Vlek, 2011). Nevertheless critical environmentally conscious consumers and manufactures may prefer PV designs that use abundant, non-toxic raw materials over designs that use rare and possible toxic materials. Both CdTe and Cl(G)S use these toxic (e.g.: cadmium) and rare materials (e.g.: cadmium and indium), as described for the factor distinct features (section 5.3.1.1). The 1G silicon technologies and a-Si have a clear advantage since they use silicon, which is the second most abundant element on Earth.

From a short analysis of the Dutch market only a small percentage of the consumers that buy a PV system is aware of the technology that has been used. Consumers have more interest in the electricity generation per square meter, payback time of a system, risks during its lifetime, initial costs and expected maintenance costs (Laan, 2011). However like also explained in the factor distinct features (section 5.3.1.1) does the demand for the highest generation per m² gives tendency to choose technologies with high efficiencies, like sc-Si and mc-Si.

5.4 EXISTING FACTORS NOT APPLICABLE TO THE PV MARKET

Described earlier in this chapter, section 5.1, is that some factors from previous frameworks do not apply to the PV market. This section describes subsequently why certain factors are found not to affect the technology selection process and why not are in favour of multiple designs in the PV market.
5.4.1 Factors related to technology selection

An overview of factors described in this section is given in Table 20, using the levels as categories.

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Complementary goods</td>
</tr>
<tr>
<td></td>
<td>Distribution strategy</td>
</tr>
<tr>
<td>Meso</td>
<td>Current installed base</td>
</tr>
<tr>
<td></td>
<td>Previous installed base</td>
</tr>
<tr>
<td></td>
<td>Suppliers</td>
</tr>
<tr>
<td></td>
<td>Effectiveness of the standard development progress</td>
</tr>
<tr>
<td></td>
<td>Big fish</td>
</tr>
<tr>
<td></td>
<td>Network externalities</td>
</tr>
<tr>
<td></td>
<td>Switching costs</td>
</tr>
<tr>
<td>Macro</td>
<td>Regulator</td>
</tr>
<tr>
<td></td>
<td>Judiciary</td>
</tr>
</tbody>
</table>

5.4.1.1 Complementary goods

Complementary goods are other goods or services needed to commercialize a product (Teece, 1986), they consist for example of: “specialized training, after-sales support, compatible software, etc.” (Suárez, 2004, p. 278). Moreover complementary goods are often seen with products experiencing network externalities (Schilling, 2008; Van de Kaa, 2009).

All the PV technologies can share compatible goods and (in general) after sales support since the external characteristics of PV devices are the same (DC power). Similarly training on how to install and use PV systems is for every technology the same; the BOS components are similar.

Regarding the after sales support there is one manufacturer especially engaged in promoting their recycling program; this is First Solar, market leader in CdTe modules (First Solar, 2011a). It is expected this emphasis on their recycling program is related to concerns in the largest PV market, Europe, on the use of cadmium in electronic devices (European Union, 2010; Harrison & Merrifield, 2011; Hirshman, 2011). Therefore it seems the recycling program is not (only) to attract more consumers to buy their product; though largely focused on influencing policymakers for making favourable regulations. Moreover, many other manufactures of different technologies are also engaged in recycling programs (J.-K. Choi & Fthenakis, 2010), for example; the European program for “take back and recovering” of PV devices called PV Cycle (PV Cycle, 2010).

The costs of mounting materials in PV systems (incorporated in the BOS costs) may vary based on the used technological design; since PV modules vary in weight lighter mounting materials may be used (Bubenzer & Luther, 2003; Pagliaro et al., 2008; U. Wang, 2010). Generally, 2G technologies which do not use glass are considerable lighter; consequently the mounting material can also be lighter. However, there is still the problem of wind, which requires mounting systems to be rigid enough to keep supporting solar panels safely with strong winds. From Photon international and interviews with companies selling complete PV systems was found that no specific mounting systems exist (yet) for different PV technologies (Cals, 2011; Landman, 2011; Photon International, 2011; Vervoort, 2011). For BIPV systems the mounting system is different, nevertheless, this is considered to be a relative small market and therefore does not have a major influence on the PV manufactures in general.
Concluding the factor complementary goods seems not to influence the selection and adoption of PV technologies. There are some examples of existing complementary goods or services, recycling programs and mounting materials, still these products are similar for each PV technology.

5.4.1.2 Distribution strategy

The factor distribution strategy is related to how a firm develops the distribution system for a product or technology. Utterback and Suárez (1993) describe that this process can both positively and negatively influence the dominance process; for example a well-developed distribution network serves as a powerful market barrier. Nevertheless, existing firms may also fail to recognize the thread from newcomers; new firms make use of the present distribution systems.

The distribution strategy is not expected to be very important. Since firms in the PV market share distribution channels, consequently multiple technologies are distributed by the same firm (Laan, 2011).

5.4.1.3 Current installed base

The current installed base consists of actors currently using the design; these users consist of manufactures and consumers (Suárez, 2004; Van de Kaa, 2009). Current base of users may positively influence design dominance in the market; there is a tendency to choose the technology with the largest installed base in markets with network effects, since the number of users is related to the value of the technology (Schilling, 1998).

Because this factor is based on network effects and the PV market is not characterized by these effects, see section 2.1.2, this factor is not regarded to be important in this industry.

5.4.1.4 Previous installed base

This factor is related to users willing to switch from a previous design to the new technological design (Van de Kaa, 2009). This factor is not regarded to be important because PV solar cells can last for a relatively long period of 15-30 years, so there is no need to switch. Moreover, 15 years ago in 1995 the total installed PV capacity was 89 megawatt peak (MWp) (Figure 30), while in 2010 even 27200 MWp was shipped (Hirshman, 2011); thus even if all installed capacity from 1995 would be substituted by newer technologies this has only a minor influence on the market.

5.4.1.5 Suppliers

The supplier factor is related to producers of complementary goods or services (Van de Kaa, 2009). Complementary goods or services get offered mainly with products characterized by network externalities. The design may benefit from more complementary goods because consumers get locked into a single design.

As explained in section 2.1.2 PV technologies are not affected by strong network effects and therefore this factor is not regarded to be important. Secondly, although there exist complementary goods that are needed for PV systems to function, these goods do not differentiate between PV technologies; therefore not one single technology is able to benefit more in comparison to its competitors.

5.4.1.6 Effectiveness of the standard development process

This factor is related to how bureaucratic or time consuming the official standard setting process is (Lehr, 1992). Since the PV industry does not know official standardization of technological designs, only standardized testing methods, this factor does not influence the dominance process.
5.4.1.7 **BIG FISH**

The factor big fish is used to describe a single firm which is able to substantially support a design; by promotion, financial support or by buying significant quantities (Van de Kaa, 2009).

Currently there are no important players in the PV market supporting one technology which otherwise would not have been commercially developed, therefore this factor seems not to be very important. An example can be seen from BP and Shell, who during the last 10 years largely withdrew themselves from the PV market; both companies which can be regarded as “big fishes”. However, during the time Shell was active on the PV market it did considerably support research and development of CIGS solar cells. Similarly, during the first development of the crystalline silicon solar cell there was one large company adopting a substantial share of solar cells, this was NASA who needed solar cells for space applications. It has been recognized in previous literature NASA played an important role in supporting the development of crystalline silicon solar cells (Bubenzer & Luther, 2003).

5.4.1.8 **NETWORK EXTERNALITIES**

Network externalities generally describe how a consumer receives higher value from the design when there are more users (Schilling, 1998; Van de Kaa, 2009). Network externalities can be both direct and indirect; with direct network externalities the value of a product depends on the numbers of users (e.g. telephone networks), indirect network externalities are generated when a user needs to purchase two or more components before it can benefit from the technology.

For PV technology both these externalities do not play a role; PV adopters do not experience increased value of their technology when the next individual adopts PV. Although consumers need an entire PV system to benefit from their solar modules, PV systems do not differentiate between technological designs. This factor is also described in section 2.1.2.

5.4.1.9 **SWITCHING COSTS**

Switching costs occur when an actor switches from one design to another (Suárez, 2004). From the five sources of switching costs (i.e. contracts, training and learning, data conversion, search cost and loyalty cost); only search cost are applicable to the adopters of PV technologies (Shy, 2001). Because PV adopters do not have to replace their entire PV system since all outputs (electrical properties) are similar for each PV technology and normally only the solar panels need to be replaced. Nevertheless, search costs are experienced every time consumers buy something; therefore, switching costs are not considered to be very influential in the adoption process.

5.4.1.10 **REGULATOR**

This factor relates to a regulator prescribing a certain technology or design to be used in the market (Van de Kaa, 2009). This makes the outcome of the dominance process not purely a market outcome.

Although mainly the European Union seems to have doubt with the use of CdTe based modules (see also section 5.2.3.2); there is in the PV industry no regulator that prescribed a certain technology to be used for terrestrial electricity generation.

5.4.1.11 **JUDICIARY**

Judiciary relates to how courts can use antitrust law to prevent certain designs from becoming dominant; examples are the use of Microsoft’s Windows and Windows Media Player in the European Union and instant photography from Kodak in the US (Van de Kaa, 2009).
No examples of the use of antitrust laws have been found in the PV industry (Google News, 2011; Photon International, 2011).

5.4.2 FACTORS RELATED TO MULTIPLE DESIGNS
An overview of factors described in this section is given in Table 21, using the levels as categories.

<table>
<thead>
<tr>
<th>Table 21: Factors not influencing the coexistence of multiple designs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level</strong></td>
</tr>
<tr>
<td>Micro</td>
</tr>
<tr>
<td>Meso</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

5.4.2.1 PERSISTENCY
Especially larger firms (multinationals) can persistently support their own product design, even when it is already clear another design is winning the battle (de Vries et al., 2011); resulting in a market with multiple designs. This is related to the factor ‘big fish’ in section 5.4.1.7.

There are some examples of (multinational) companies supporting a technology during a period this technology was not the best commercial choice (Photon International, 2011), because sc-Si, mc-Si and CdTe or variants on these technological designs offered better price versus efficiency ratios:

- Sharp with a-Si PV cells
- Shell Solar (does not exist anymore) with CIGS PV cells

Nevertheless, this factor is not regarded to be very influential in the PV industry; since most multinationals develop multiple technological designs at the same time (see also the section 5.2.1.12). Moreover as explained in section 2.1.2, there is not yet a clear winning design in the PV market.

Furthermore the PV market is characterised with a large number of smaller companies solely operating the PV market and which do not have the financial resources to support long periods of losses or low revenues. Even larger companies producing operating in multiple market and producing new technologies seem to have problems sustaining their business; see the recent example of Nuon stopping the production of a-Si technologies at their subsidiary Helianthos (NUON, 2011).

5.4.2.2 SPEED IN TECHNOLOGICAL DEVELOPMENT
With the constant development of new technological designs, there is no time for the one dominant design to emerge in the market (de Vries et al., 2011). This was for example seen in the flash memory market in which multiple designs coexist and new variant get introduced before a dominant design has emerged.

The PV technologies are under constant development and new more efficient variants enter the market every year. Therefore can be said the PV market suffers from speed in technological development for the emergence of one dominant design. However, searching through industry news (Google News, 2011; Photon International, 2011) this seems not to be an aspect ever mentioned. Also the improvements are merely incremental innovation; fundamentally new PV designs get only introduced rarely.
Besides the speed of incremental improvements, there is the speed of development of new technological designs; this is certainly not characterised by fast introductions. As explained in section 4.2 first generation designs originate from the 1950s and second generation technologies have been developed since the 1970s.

5.4.2.3 Gateway Technologies

Gateway technologies enable compatibility between two non-compatible designs. Generally are these gateway technologies the result of markets with multiple designs in which users want some form of “communication or compatibility” between them (de Vries et al., 2011). For a gateway technology to be successful it should be cheaper than switching to the other design. This will result in a situation where it is not necessary for users to switch and consequently helps the survival of multiple designs.

PV designs do need “communication or compatibility” with other systems, though this is electricity which can be converted to every desirable characteristic; therefore this factor is not regarded to be important.

5.4.2.4 Multi-channel End System

Different from gateway technologies, which are considered to be a separate product, multi-channel end systems are able to accommodate multiple technologies (de Vries et al., 2011). Again this “ex-post compatibility” product enables the stable coexistence of multiple designs; for example cameras supporting multiple types of flash memory cards.

Similar to gateway technologies; PV designs do need “ex-post compatibility” with other systems, but this is electricity and therefore this factor is not regarded to be important.
6 IMPORTANCE OF FACTORS FOR INDIVIDUAL FIRMS

This chapter analyses the relative importance, from the viewpoint of manufactures, and status of factors as described section 5.2. This answers research question three: What is the relative importance of factors in the decision making process of individual firms for a specific cell technology? The importance of factors is researched by doing (semi) structured interviews with three industry experts, using a questionnaire structured with the analytic hierarchy process (AHP). The current status of technologies regarding each factor is also analysed using an AHP questionnaire filled in by three industry experts. Some of these factors however, could be evaluated based on quantifiable metrics. The data from the questionnaire has been analysed by both the crisp AHP method introduced by Saaty (1977, 1980), and the logarithmic fuzzy preference programming (LFPP) method from Wang and Chin (2011). This chapter will first start by describing how the AHP questionnaire has been designed, followed by an analysis of the results of both the crisp AHP and LFPP method, and lastly the three most influential factors are described in more detail.

6.1 ANALYTIC HIERARCHY PROCESS QUESTIONNAIRE

The questionnaire uses the AHP method as developed by Saaty (1977) to assess the importance and current status of factors. This questionnaire has been answered by experts from the PV industry during an interview. The analysis of the factors is divided in three parts according to Figure 22; first the importance of the categories is measured in relation to the overlapping goal, secondly the importance of the factors is researched and third the current status of the selected technologies is assessed. The experts have been interviewed in person, which is necessary because of the vagueness of the theoretical concepts; industry experts are not familiar with the terminology used in existing frameworks. Speaking face to face with a person ensures better mutual understanding of the used concepts (see also section 3.2).

Not all factors described in chapter 5 are included in the AHP questionnaire, because only factors are included that can be influenced by individual firms. These factors are mainly on the micro level, since factors on other levels are regarded to be of equal importance for each manufacturer and technological design in the PV market.

The experts in the interview come from both research institutes and companies. For the analysis of categories and factors (see Figure 22) experts from companies are interviewed, because business insights and knowledge of the market are required; both experts from universities and research institutes could not rate all factors on their importance. Nevertheless, to assess possible differences in ranking the experts from research institutes were also asked to explain what they fought where the most important factors.

In the analysis of the current status of technological design alternatives experts from research institutes have been interviewed. From own experience was found that experts from companies tend to be over optimistic about the capabilities and characteristics of the technology they manufacture. On the other hand, experts from research institutes were found to evaluate the technological designs more objectively, also in comparison to experts form universities they had more knowledge of the PV market.
As explained in section 3.3, the consistency of answers in the AHP questionnaire can be checked using the consistency index (CI) as proposed by Saaty (1977, 1980) and by calculating the values for $\lambda^*$ and $\delta^*$ as proposed by Wang and Chin (2011). When answers from the questionnaire have been found to be inconsistent using the CI from Saaty, respondents were called and asked to explain their ranking of the factor again in order to reach consistent answers. The CI has been used for this purpose since Saaty has defined clear threshold levels at which answers are inconsistent.

![AHP Decision Hierarchy](image_url)
6.1.1 Part I

The first part of the AHP questionnaire is used to assess the importance of the factors on a ratio scale. First experts from PV companies were consulted to rank the categories on their importance for the success and dominance of a PV technology on a nine point scale (see Table 5). Two of the three company experts came from companies which had not publically announced which technological design they supported. The question that was asked:

*How much more does category A in relation to category B influences the changes a PV technology receives dominance?*

The expert could use the following table for answering this question:

<table>
<thead>
<tr>
<th>Category A</th>
<th>9</th>
<th>7</th>
<th>5</th>
<th>3</th>
<th>1</th>
<th>-3</th>
<th>-5</th>
<th>-7</th>
<th>-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant agent</td>
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<tr>
<td>Dominant agent</td>
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<tr>
<td>Dominant agent</td>
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<tr>
<td>Superior design</td>
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<tr>
<td>Superior design</td>
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<td>Strategy</td>
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<tr>
<td>Dominant agent</td>
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<tr>
<td>Superior design</td>
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</tbody>
</table>

Secondly the same experts were asked to give their judgement on the importance of factors the several categories. The following question was asked:

*How much more does factor A in relation to factor B influences the changes a PV technology receives dominance?*

A similar table could be used to answer this question, for example for the category dominant agent:

<table>
<thead>
<tr>
<th>Factor A</th>
<th>9</th>
<th>7</th>
<th>5</th>
<th>3</th>
<th>1</th>
<th>-3</th>
<th>-5</th>
<th>-7</th>
<th>-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial strength of the agent</td>
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<tr>
<td>Financial strength of the agent</td>
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<tr>
<td>Financial strength of the agent</td>
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<tr>
<td>Brand reputation and credibility</td>
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<td></td>
<td></td>
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<tr>
<td>Brand reputation and credibility</td>
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<tr>
<td>Operational supremacy</td>
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<tr>
<td>Learning orientation of the agent</td>
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</tr>
</tbody>
</table>
6.1.2 Part II

In the second part of the questionnaire three experts from research institutes have been asked to rate how the technological designs score on each factor using the same nine point scale (see Table 5); resulting in a measurement of the current status of the selected PV designs. Not all PV technologies are used in the questionnaire; five have been selected from the list in section 4.3. These five technologies are recognized to be currently available for production of commercial PV devices for terrestrial applications:

- **sc-Si**  Mono-crystalline silicon
- **mc-Si**  Multi-crystalline silicon
- **CdTe**  Cadmium telluride
- **a-Si**  Amorphous silicon/hydrogen alloy (a-Si:H), multi junction and in combination with micro crystalline silicon (μc-Si)*
- **CI(G)S**  CuIn(Ga)Se2, copper indium (gallium) selenide

*Some authors note a-Si and μc-Si are different technologies since a-Si is completely unstructured (amorphous) and μc-Si contains some crystals in an amorphous layer (Zeman, 2011). However, because commercially produced μc-Si cells often make use of an a-Si layer they are regarded as the same technology in this report.

In this part of the questionnaire for each of the 11 factors a different question has been asked. For example for the factor timing of entry:

*How much better is it for technology A in comparison with technology B to currently enter the market?*

Experts used the following table for answering this question:

<table>
<thead>
<tr>
<th>Technology A</th>
<th>Technology B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>sc-Si</strong></td>
<td>mc-Si</td>
</tr>
<tr>
<td><strong>sc-Si</strong></td>
<td>CI(G)S</td>
</tr>
<tr>
<td><strong>sc-Si</strong></td>
<td>CdTe</td>
</tr>
<tr>
<td><strong>sc-Si</strong></td>
<td>a-Si</td>
</tr>
<tr>
<td><strong>mc-Si</strong></td>
<td>CI(G)S</td>
</tr>
<tr>
<td><strong>mc-Si</strong></td>
<td>CdTe</td>
</tr>
<tr>
<td><strong>mc-Si</strong></td>
<td>a-Si</td>
</tr>
<tr>
<td><strong>CI(G)S</strong></td>
<td>CdTe</td>
</tr>
<tr>
<td><strong>CI(G)S</strong></td>
<td>a-Si</td>
</tr>
<tr>
<td><strong>CdTe</strong></td>
<td>a-Si</td>
</tr>
</tbody>
</table>
6.1.3 **QUANTIFIABLE FACTORS**

The factors technological superiority and pricing strategy can be quantified, consequently, there is no need to ask experts on the current status of these technologies; this also ensures complete objective ranking of the technologies.

For the factor technological superiority the current average efficiencies of commercial modules is used, as explained in section 5.2.1.5 efficiency is the best approach to assess the performance of the technologies. Results are shown in Table 22.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Average efficiency (EPIA &amp; Greenpeace, 2011; IEA, 2010a)</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>14-20%</td>
<td>0,29</td>
</tr>
<tr>
<td>mc-Si</td>
<td>13-15%</td>
<td>0,24</td>
</tr>
<tr>
<td>a-Si</td>
<td>6-9%</td>
<td>0,13</td>
</tr>
<tr>
<td>CdTe</td>
<td>9-11%</td>
<td>0,17</td>
</tr>
<tr>
<td>Cl(G)S</td>
<td>10-12%</td>
<td>0,18</td>
</tr>
</tbody>
</table>

Similarly, the current average module market prices is used to rank technologies for the factor pricing strategy. The results shown in Table 23 have less variation in comparison with the above factor, note that a lower priced technology ranks higher. Using market prices may not necessarily represent the real cost advantages of one technology over the other, since almost all manufactures adapt prices to compete with the best efficiencies/price ratio in the market. Consequently the market prices of PV modules may be priced well below or at manufacturing costs, since manufactures try to gain market share and the necessary volume of sales (economies of scale) in order to be competitive in the future (Knulst, 2011; van Roosmalen, 2011). However, in this research it was not possible to find the real manufacturing costs of the technologies, since; companies use different definitions, others kept it a secret and the interviewed experts did not know this information.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Price (Hering, 2011a; Knoll, 2011b; Mehta, 2010)</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>€1.37 ($1.94)</td>
<td>0,18</td>
</tr>
<tr>
<td>mc-Si</td>
<td>€1.37</td>
<td>0,18</td>
</tr>
<tr>
<td>a-Si</td>
<td>€1.12 ($1.59)</td>
<td>0,22</td>
</tr>
<tr>
<td>CdTe</td>
<td>€1.16 ($1.64)</td>
<td>0,21</td>
</tr>
<tr>
<td>Cl(G)S</td>
<td>€1.14 ($1.61)</td>
<td>0,21</td>
</tr>
</tbody>
</table>

6.2 **RESULTS**

6.2.1 **RESULTS OF THE CRISP AHP ANALYSIS**

The results of the AHP questionnaire show ‘strategy of supporters of the design’ is regarded to be the most important category. Furthermore there are clearly three factors that are found to be the most important ones for technology dominance, in the following order; technological superiority, pricing strategy and timing of entry. The results of the data analysis using the crisp AHP method of part I are shown in Table 24, the results of part II in Table 25.
### Table 24: Results CRISP AHP part I; influence of factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>Effect</th>
<th>Local weight</th>
<th>Global weight</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant agent</td>
<td></td>
<td></td>
<td>0.19</td>
<td>3</td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>+</td>
<td>0.16</td>
<td>0.03</td>
<td>12</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>+</td>
<td>0.41</td>
<td>0.08</td>
<td>4</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>+</td>
<td>0.22</td>
<td>0.04</td>
<td>8</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>+</td>
<td>0.22</td>
<td>0.04</td>
<td>9</td>
</tr>
<tr>
<td>Superior Technology</td>
<td></td>
<td></td>
<td>0.29</td>
<td>2</td>
</tr>
<tr>
<td>Technological superiority</td>
<td>+</td>
<td>0.75</td>
<td>0.22</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>+</td>
<td>0.25</td>
<td>0.07</td>
<td>5</td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td></td>
<td>0.46</td>
<td>1</td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>-</td>
<td>0.41</td>
<td>0.19</td>
<td>2</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>-</td>
<td>0.05</td>
<td>0.02</td>
<td>13</td>
</tr>
<tr>
<td>Timing of entry</td>
<td>∩</td>
<td>0.24</td>
<td>0.11</td>
<td>3</td>
</tr>
<tr>
<td>Marketing communications</td>
<td>+</td>
<td>0.13</td>
<td>0.06</td>
<td>6</td>
</tr>
<tr>
<td>Pre-emption of scarce assets</td>
<td>+</td>
<td>0.08</td>
<td>0.04</td>
<td>10</td>
</tr>
<tr>
<td>Commitment</td>
<td>+</td>
<td>0.09</td>
<td>0.04</td>
<td>11</td>
</tr>
<tr>
<td>Stakeholders</td>
<td></td>
<td></td>
<td>0.06</td>
<td>4</td>
</tr>
<tr>
<td>Diversity of the network</td>
<td>+</td>
<td>1</td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

*Explanation of the symbols; + is positive influence on the dominance process, - is negative and ∩ means not a clear direction can be given.

### Table 25: Results CRISP AHP part II; status of technologies in relation to the factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>Technological design</th>
<th>sc-Si</th>
<th>mc-Si</th>
<th>CI(G)S</th>
<th>CdTe</th>
<th>a-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant agent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>0.44</td>
<td>0.35</td>
<td>0.06</td>
<td>0.08</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>0.39</td>
<td>0.33</td>
<td>0.11</td>
<td>0.12</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>0.36</td>
<td>0.35</td>
<td>0.05</td>
<td>0.17</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>0.42</td>
<td>0.30</td>
<td>0.08</td>
<td>0.09</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Superior Technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological superiority</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.32</td>
<td>0.37</td>
<td>0.09</td>
<td>0.12</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>0.32</td>
<td>0.44</td>
<td>0.07</td>
<td>0.08</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Timing of entry</td>
<td>0.35</td>
<td>0.27</td>
<td>0.15</td>
<td>0.18</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Marketing communications</td>
<td>0.31</td>
<td>0.28</td>
<td>0.16</td>
<td>0.15</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Pre-emption of scarce assets</td>
<td>0.28</td>
<td>0.30</td>
<td>0.08</td>
<td>0.06</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Commitment</td>
<td>0.31</td>
<td>0.26</td>
<td>0.15</td>
<td>0.15</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>
In Table 26 part I and II of the crisp AHP analysis are combined; the weights of the factors are multiplied by the current status of the technological designs. The totals show both sc-Si and mc-Si are clearly favoured over the 2G technologies, while from the 2G technologies a-Si is lagging behind. It was expected that sc-Si is favoured over mc-Si, given the importance of the factor technological superiority and the better efficiencies offered by sc-Si. With the 2G technologies can be seen that a-Si clearly loses on the factor timing of entry; experts regard it currently to be the worst moment to adopt a-Si.

Table 26: Results CRISP AHP; Part I and II Combined

<table>
<thead>
<tr>
<th>Factors</th>
<th>Technological design</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant agent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>0.013 0.010 0.002 0.002 0.002</td>
<td>12</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>0.030 0.025 0.008 0.009 0.004</td>
<td>4</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>0.015 0.014 0.002 0.007 0.003</td>
<td>8</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>0.017 0.012 0.003 0.004 0.005</td>
<td>9</td>
</tr>
<tr>
<td>Superior Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological superiority</td>
<td>0.063 0.052 0.041 0.037 0.028</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.023 0.027 0.006 0.008 0.008</td>
<td>5</td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>0.034 0.034 0.041 0.040 0.042</td>
<td>2</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>0.008 0.011 0.002 0.002 0.002</td>
<td>13</td>
</tr>
<tr>
<td>Timing of entry</td>
<td>0.038 0.029 0.016 0.020 0.005</td>
<td>3</td>
</tr>
<tr>
<td>Marketing communications</td>
<td>0.019 0.017 0.010 0.009 0.006</td>
<td>6</td>
</tr>
<tr>
<td>Pre-emption of scarce assets</td>
<td>0.010 0.011 0.003 0.002 0.010</td>
<td>10</td>
</tr>
<tr>
<td>Commitment</td>
<td>0.013 0.011 0.006 0.006 0.005</td>
<td>11</td>
</tr>
<tr>
<td>Stakeholders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diversity of the network</td>
<td>0.022 0.018 0.005 0.003 0.011</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>0.30 0.27 0.15 0.15 0.13</td>
<td></td>
</tr>
</tbody>
</table>
Moreover, from part I and II is seen that three factors are clearly more important in comparison with the others; technological superiority, pricing strategy and timing of entry. Table 27 shows a comparison of only the three most important factors. This shows less variation in the results than the total from Table 26; although a-Si now clearly has the lowest ranking.

The consistency of the results is checked by calculating the consistency ratio (CR) as described in section 3.3.1. For the part I an average CR of 0.070 is found, well below the threshold level of 0.10 as described by Saaty (1977, 1980). For part II the average CR is 0.062.

### 6.2.2 Results of the Fuzzy AHP Analysis

Several researchers indicated shortcomings in using the crisp AHP analysis as described by Saaty (1977, 1980). To overcome these shortcomings is made use of the logarithmic fuzzy preference programming (LPFF) method from Wang and Chin (2011); this method uses triangular fuzzy numbers in the pairwise comparison (see also section 3.3.3). The results of the data analysis using the LFPP method of part I are shown in Table 28, the results of part II in Table 29.

**Table 27: Results crisp AHP; technological superiority + pricing strategy + timing of entry**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>0.26</td>
</tr>
<tr>
<td>mc-Si</td>
<td>0.22</td>
</tr>
<tr>
<td>a-Si</td>
<td>0.14</td>
</tr>
<tr>
<td>CdTe</td>
<td>0.19</td>
</tr>
<tr>
<td>Cl(G)S</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Table 28: Results LFPP part I; influence of factors**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Effect*</th>
<th>Local weight</th>
<th>Global weight</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant agent</td>
<td></td>
<td>0.18</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>+</td>
<td>0.15</td>
<td>0.03</td>
<td>13</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>+</td>
<td>0.40</td>
<td>0.07</td>
<td>4</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>+</td>
<td>0.23</td>
<td>0.04</td>
<td>11</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>+</td>
<td>0.23</td>
<td>0.04</td>
<td>10</td>
</tr>
<tr>
<td>Superior Technology</td>
<td>0.28</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Technological superiority</td>
<td>+</td>
<td>0.75</td>
<td>0.21</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>+</td>
<td>0.25</td>
<td>0.07</td>
<td>5</td>
</tr>
<tr>
<td>Strategy</td>
<td>0.48</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>-</td>
<td>0.40</td>
<td>0.19</td>
<td>2</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>-</td>
<td>0.06</td>
<td>0.03</td>
<td>12</td>
</tr>
<tr>
<td>Timing of entry</td>
<td>∩</td>
<td>0.21</td>
<td>0.10</td>
<td>3</td>
</tr>
<tr>
<td>Marketing communications</td>
<td>+</td>
<td>0.09</td>
<td>0.04</td>
<td>9</td>
</tr>
<tr>
<td>Pre-emption of scarce assets</td>
<td>+</td>
<td>0.11</td>
<td>0.05</td>
<td>8</td>
</tr>
<tr>
<td>Commitment</td>
<td>+</td>
<td>0.13</td>
<td>0.06</td>
<td>6</td>
</tr>
<tr>
<td>Stakeholders</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diversity of the network</td>
<td>+</td>
<td>1</td>
<td>0.06</td>
<td>7</td>
</tr>
</tbody>
</table>

*EXPLANATION OF THE SYMBOLS; + IS POSITIVE INFLUENCE ON THE DOMINANCE PROCESS, - IS NEGATIVE AND ∩ MEANS NOT A CLEAR DIRECTION CAN BE GIVEN.
Table 29: Results LFPP part II; status of technologies in relation to the factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>Technological design</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sc-Si</td>
<td>mc-Si</td>
</tr>
<tr>
<td>Dominant agent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>0,44</td>
<td>0,36</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>0,39</td>
<td>0,33</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>0,36</td>
<td>0,35</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>0,41</td>
<td>0,32</td>
</tr>
<tr>
<td>Superior Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological superiority</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0,32</td>
<td>0,35</td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>0,30</td>
<td>0,48</td>
</tr>
<tr>
<td>Timing of entry</td>
<td>0,29</td>
<td>0,26</td>
</tr>
<tr>
<td>Marketing communications</td>
<td>0,31</td>
<td>0,27</td>
</tr>
<tr>
<td>Pre-emption of scarce assets</td>
<td>0,29</td>
<td>0,31</td>
</tr>
<tr>
<td>Commitment</td>
<td>0,32</td>
<td>0,24</td>
</tr>
<tr>
<td>Stakeholders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diversity of the network</td>
<td>0,37</td>
<td>0,32</td>
</tr>
</tbody>
</table>

The results of part I and II show similar results as the crisp AHP analysis; strategy is regarded the most important category with technological superiority and pricing strategy being the most influential factors, also sc-Si receives on average the highest ratings. Part I and II are combined by multiplying the status of factors with the relative importance of factors, shown in Table 30.

Table 30: Results LFPP; part I and II combined

<table>
<thead>
<tr>
<th>Factors</th>
<th>Technological design</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sc-Si</td>
<td>mc-Si</td>
</tr>
<tr>
<td>Dominant agent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>0,012</td>
<td>0,009</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>0,027</td>
<td>0,023</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>0,014</td>
<td>0,014</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>0,016</td>
<td>0,013</td>
</tr>
<tr>
<td>Superior Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological superiority</td>
<td>0,061</td>
<td>0,050</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0,022</td>
<td>0,024</td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>0,034</td>
<td>0,034</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>0,008</td>
<td>0,013</td>
</tr>
<tr>
<td>Timing of entry</td>
<td>0,029</td>
<td>0,026</td>
</tr>
</tbody>
</table>
Chapter 6. Importance of factors for individual firms

The result of the combined analysis again shows little variation in the end results; sc-Si closely followed by mc-Si are seen as the most promising technologies.

The consistency of the answers is found from the calculation of $\lambda^*$ and $\delta^*$, as explained in section 3.3.3. In part I not a single comparison matrix had a $\lambda^*$ value equal to zero, consequently the answers can be considered to be consistent. For part II however several matrices where found with $\lambda^*$ equal to zero; 12 out of the 33 matrices. For these matrices the value of $\delta^*$ has been calculated; none of the matrices had an value of $\delta^* = 0$, meaning that in over a third of the matrices there exists some form of inconsistency. The average value of $\delta^* = 0.55$ was found in the range between 0.05 and 0.93. According to Wang and Chin (2011) this means that the majority of the inconsistent matrices can be considered as “strongly inconsistent” (since $\delta^* > 0.23$).

6.2.3 Comparison of the Crisp AHP and LFPP data analysis

By using two methods of data analysis can be compared whether there are any significant differences in priorities occur because of rank reversal. Firstly the results of part I are compared in Table 31, this shows that the five most influential factors are similar regardless the method. Similarly there is no significant shift in the importance of categories. The factors commitment and marketing communications show the largest shift in importance, however since these factors are not that important in the technology selection process there is not much change in the overall rankings.

### Table 31: Comparison of the Crisp AHP and LFPP method with the results of part I of the questionnaire

<table>
<thead>
<tr>
<th>Factors</th>
<th>Crisp AHP Local weight</th>
<th>Crisp AHP Global weight</th>
<th>Crisp AHP #</th>
<th>LFPP Local weight</th>
<th>LFPP Global weight</th>
<th>LFPP #</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dominant agent</strong></td>
<td>0.19</td>
<td>3</td>
<td>0.18</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>0.16</td>
<td>0.03</td>
<td>12</td>
<td>0.15</td>
<td>0.03</td>
<td>13</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>0.41</td>
<td>0.08</td>
<td>4</td>
<td>0.40</td>
<td>0.07</td>
<td>4</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>0.22</td>
<td>0.04</td>
<td>8</td>
<td>0.23</td>
<td>0.04</td>
<td>11</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>0.22</td>
<td>0.04</td>
<td>9</td>
<td>0.23</td>
<td>0.04</td>
<td>10</td>
</tr>
<tr>
<td><strong>Superior Technology</strong></td>
<td></td>
<td></td>
<td>0.29</td>
<td>2</td>
<td>0.28</td>
<td>2</td>
</tr>
<tr>
<td>Technological superiority</td>
<td>0.75</td>
<td>0.22</td>
<td>1</td>
<td>0.75</td>
<td>0.21</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.25</td>
<td>0.07</td>
<td>5</td>
<td>0.25</td>
<td>0.07</td>
<td>5</td>
</tr>
<tr>
<td><strong>Strategy</strong></td>
<td></td>
<td></td>
<td>0.46</td>
<td>1</td>
<td>0.48</td>
<td>1</td>
</tr>
<tr>
<td>Pricing strategy</td>
<td>0.41</td>
<td>0.19</td>
<td>2</td>
<td>0.40</td>
<td>0.19</td>
<td>2</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td>0.05</td>
<td>0.02</td>
<td>13</td>
<td>0.06</td>
<td>0.03</td>
<td>12</td>
</tr>
</tbody>
</table>
From the comparison of the values of part II of the analysis in Table 25 and Table 29 is seen that they are almost identical, sc-Si gets slightly lower valued mainly from the factors appropriability strategy and timing of entry. Since there are only very small differences in weights the combinations of part I and II (shown in Table 26 and Table 30) are also very similar. The totals are almost equal (see Table 32), the only difference shown comes from a-Si which changed from 0.131 to 0.137 in the LFPP method.

Significant differences are seen in the analyses of the consistencies of answers. The crisp AHP analyses was, as explained in section 3.3.1 and 6.1, checked on consistency using the CI and respondents have been contacted in the case of inconsistent answers; this resulted in consistent data from which the consistency ratio of each comparison matrix was below the threshold of 0.10. However as explained in section 6.2.2, just over one third of the matrices in part II of the LFPP analyses are considered to have inconsistent answers, from which an average inconsistency δ* of 0.55 was found.

<table>
<thead>
<tr>
<th>Method</th>
<th>Technological design</th>
<th>sc-Si</th>
<th>mc-Si</th>
<th>CI(G)S</th>
<th>CdTe</th>
<th>a-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crisp AHP</td>
<td></td>
<td>0.30</td>
<td>0.27</td>
<td>0.15</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>LFPP</td>
<td></td>
<td>0.30</td>
<td>0.27</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
</tr>
</tbody>
</table>

6.3 INTERESTING RESULTS – NOTIONS FROM RESPONDENTS

This section describes why the three most important factors from the AHP analysis receive such a high ranking, with explanations from respondents and existing literature. This explanation is in addition to the earlier analysis of these factors in chapter 5. Moreover is tried to explain why the factor

6.3.1 TECHNOLOGICAL SUPERIORITY

The most influential factor in the dominance process is technological superiority. Like shown in Table 22, the efficiency of converting solar radiation into electricity has been used for the ranking of this factor. The ranking shows more variety than pricing; the older 1G silicon technologies score higher in comparison with their younger 2G substitutes. Interesting to see for the 2G technologies is that although CI(G)S offers on average higher efficiencies, its sales are still well below CdTe or a-Si modules (see Figure 29). Although it seems the same story holds in the case of the 1G silicon technologies, since sc-Si offers higher efficiencies while it has lower market shares, the difference between the market shares is not that much.
The a-Si modules from Table 22 clearly have the lowest efficiencies of all measured technologies, however in warm climates efficiencies of a-Si improve with 10%. Even though a-Si does not seem to have a bright future, it may be effectively used with other PV technologies. One often mentioned example comes from Sanyo’s sc-Si cells; which make use of an a-Si layer to increase efficiencies.

Several respondents have indicated that besides the importance of the efficiency of the PV technologies, also the lifetime of modules plays a role in the determining the technological superiority. 1G technologies had for a longer time the opportunity to prove their lifetimes of about 25 to 30 years, since have been for a longer period on the market. 2G technologies are improved to reach similar results, especially for a-Si this is an issue since it suffers from degradation; reaching an average lifetime of 10 years.

Moreover, future expected efficiencies may have a role in the selection process. For all technologies expected efficiencies for 2025 have been found (see Table 14), if it indeed is the case commercial modules reach these efficiencies the above ranking will not differ for the top three technological designs; see Table 33.

### 6.3.2 Pricing Strategy

Pricing of the PV devices is regarded to be the second most important for the dominance process. From Table 23 can be seen that there are only minor differences in the ranking of this factor; sc-Si and mc-Si are most expensive and have consequently the lowest rankings, the higher ranked 2G technologies are close together with a-Si having a slightly better price.

As explained in section 5.2.1, pricing is one of the main areas of concern for manufactures, though they cannot control all the costs of the PV systems. Especially BOS and installation costs are an important part of the PV system, some researchers and experts even say this can count up to 50% of the total price (Hoffmann, 2006; Raugei & Frankl, 2009; Smets, 2011). By lowering manufacturing costs of PV devices this ratio will keep rising and therefore also in other sectors (BOS manufactures and PV installers) developments are needed to bring down total pricing and to eventually reach the ‘ultimate’ goal; grid parity.

Manufactures will of course also look at the potential technologies have to bring down prices, thus the expected future price. Not for all technological designs it was possible to find possible future prices (see the factor pricing strategy in section 5.2.1). If in 2025 the technologies can be bought at the prices mentioned in Table 15, there will not change much in the ranking of the technologies; only the differences between 1G and 2G technologies becomes larger.

### 6.3.3 Timing of Entry

Timing of entry is regarded as the third most influential factor, though the difference with the next factor is not as much as the difference with pricing strategy and timing of entry (see Table 24 and Table 28). From the results shown in Table 25 and Table 29 can be seen that it is now regarded to be the worst moment to adopt a-Si modules. Experts explained the reason for this low score was that still a lot of research and development efforts need to be made to improve the production processes and to increase efficiencies (Knulst, 2011; Olivierre, 2011; Sinke, 2011; van Roosmalen, 2011; Vlek, 2011; Weeber, 2011). However, they also mentioned that it is even not certain these improvements can be made in the short term; given the research and development efforts in the last decades (i.e. from:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Ranking 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>0,27</td>
</tr>
<tr>
<td>mc-Si</td>
<td>0,22</td>
</tr>
<tr>
<td>a-Si</td>
<td>0,16</td>
</tr>
<tr>
<td>CdTe</td>
<td>0,16</td>
</tr>
<tr>
<td>CI(G)S</td>
<td>0,19</td>
</tr>
</tbody>
</table>
companies, research institutes and universities). The high rating of the CI(G)S technology is interesting since this technology has even a lower market share than a-Si (see Figure 29). Some experts indicated that especially CI(G)S may have the potential to become an important technology in the future and when at this moment a manufacturer will enter the market it may be able to scale up production and compete in the future with 1G silicon technologies. Modules based on CI(G)S have a high potential mainly because this they (similar to the above mentioned factors) can be produced at relative low cost with high efficiencies; in comparison with mc-Si they should be able to be produced at significantly lower cost while only having a slightly worse efficiency. Until now, the CI(G)S technology seems to have some problems with the complexity of the production process and not having standardized manufacturing machines available (Knulst, 2011; van Roosmalen, 2011).

For sc-Si it is now regarded to best moment to enter then market, this can be related to the other important factors; pricing and technological superiority. This technology has the highest efficiencies combined with a price that does not differ much from the other technological designs. Also sc-Si has access to standardised manufacturing lines (also available on turnkey basis), a raw material that is the second most abundant material on Earth and has promising future efficiencies. Slightly lower rated than sc-Si is mc-Si, which is almost equally priced to sc-Si though it offers somewhat lower efficiencies, the production process however is easier and standardised manufacturing machines are available.

On the third place comes CdTe, this technology uses toxic materials though it can be offered at low prices on which it is able to compete with 1G silicon technologies. The production process is relatively simple in comparison with other 2G technologies and the design has proven its efficiencies and lifetime (van Roosmalen, 2011). Therefore, it is currently regarded as the best 2G technology to start with.
The various technology roadmaps on photovoltaics (PV) show the potential this technology has to deliver a significant share in the world’s energy needs, by 2050 about 10% of the global needed electricity should come from PV (IEA, 2010a; NEDO, 2010). The European PV organisation EPIA even indicates that by 2020 over 10% of the European electricity should come from PV (EPIA, 2009). Therefore, it is very important for future technological designs that they can be produced on a large scale. In section 5.2 is derived at a list of 20 factors influencing technology selection in the PV market, given these insights a prediction is made of factors influencing the dominance process in future generations.

This chapter will answer the fourth research question: Which factors influence the chances that a photovoltaic cell technology of the third generation achieves dominance? First an overview of the third generation technologies is given, followed by an analysis of the factors from chapter 5, and this chapter ends with a short conclusion on the results.

7.1 Third generation technologies

Third generation PV technologies (3G) is still mainly in the research phase, or too expensive for terrestrial use (Berenschot et al., 2011; Razykov et al., 2011), and have no market share noteworthy (see Figure 14 and Appendix IV). The following technologies are considered to be part of the third generation (as derived in section 4.3.3) and are expected to become available in the future for terrestrial energy production:

- III-V solar cells (solar cells using elements from group III and V of the periodic table)
  - Materials that are most used: GaAs (gallium arsenide, multi junction) and InP (indium phosphide)
- Nanophotovoltaics
  - QWSC (quantum solar cells, with quantum wells and quantum dots solar cells)
  - QD cells (quantum dot solar cells, nanometre sized crystallite semiconductor)
- Organic PV
  - DSC (dye-sensitized solar cells)
  - Organic solar cells (based on organic material)

These technologies are not yet commercially available, though they are produced in laboratories. III-V solar cells are not commercially available because they are too expensive to be used in large scale energy production for terrestrial use, and nanophotovoltaics and organic PV do not provide the required efficiencies or have only a short lifetime. Nevertheless current laboratory efficiencies and expected production line efficiencies show their potential in the future; Table 34 shows the current and expected efficiencies and prices of some of the technologies.
7.2 Factors Influencing Dominance

This chapter contains an explorative study after possible future dominant PV technologies, as a basis results from the earlier analysis in section 5.2 are used. This earlier analysis was largely based on frameworks on dominant designs, it is expected the analysis on the third generation technologies will deliver useful results, since the two main frameworks that have been used in the earlier analysis describe the ex-ante process of standard formation and selection of technologies (Suárez, 2004; Van de Kaa, 2009).

The framework of Van de Kaa (2009) on standards dominance defines five categories based on their theoretical background; characteristics of the standard supporter, characteristics of the standard, standard support strategy, other stakeholders and market characteristics. With analysing the 3G technologies it is not possible to use the category ‘market characteristics’, since predictions about the future market are concerned with uncertainties. Also analysis of the category ‘characteristics of the standard supporter’ is not considered to deliver useful results, since from a first explorative analysis was found that the majority of research and development comes from universities and public research institutes (Bubenzer & Luther, 2003; Fraas & Partain, 2010). On the other hand, the category ‘other stakeholders’ may provide useful insights since it contains the factor diversity of the network; which is expected to be very beneficial in the early stages of the technology development process.

This research question is explorative, meaning that the underlying analysis should be systematic (Stebbins, 2001). Therefore as a starting point, the analysis of the third generation technologies starts with the list of factors from the prior analysis in chapter 5, minus the categories market characteristics and characteristics of the standard supporter from the framework from Van de Kaa (2009); the resulting list of 12 factors is shown in Table 35. The choice not to start with the complete framework of Van de Kaa was made because of uncertainty in making predictions about future technological characteristics, and it would limit the comparison ability between the generations (factors from chapter 5 certainly do influence the PV market). Furthermore, a timeframe of 15 years have been used since this should leave the third generation technologies with enough time to develop and become commercially available; according to Sinke (2011) the time to market for fundamentally new technologies is about 15 years.

### Table 34: Expected future price and efficiency of third generation technologies

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>III-V solar cells</td>
<td>28.1%</td>
<td>40% (Yamaguchi et al., 2008, 2005)</td>
<td>€0.43</td>
</tr>
<tr>
<td>DSC</td>
<td>10.9%</td>
<td>15%</td>
<td>&lt;€0.34</td>
</tr>
<tr>
<td>Organic solar cells</td>
<td>8.3%</td>
<td>15%</td>
<td>&lt;€0.34</td>
</tr>
</tbody>
</table>
7.2 Factors influencing dominance

Table 35: Factors influencing the technology dominance process in the PV market for first and second generation technologies

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description (Schilling, 1998; Suárez, 2004; Van de Kaa, 2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Technological superiority</td>
<td>How one design outperforms other technological designs.</td>
</tr>
<tr>
<td></td>
<td>Flexibility</td>
<td>The incremental cost and time needed to adapt a technological</td>
</tr>
<tr>
<td></td>
<td>Pricing strategy</td>
<td>The aggressive or below profit margin pricing of designs.</td>
</tr>
<tr>
<td></td>
<td>Appropriability strategy</td>
<td>The actions a firm takes to protect its design from imitators.</td>
</tr>
<tr>
<td></td>
<td>Timing of entry</td>
<td>The window of opportunity in which it is optimal for a company to</td>
</tr>
<tr>
<td></td>
<td>Marketing</td>
<td>Positively influencing consumer expectations on technological</td>
</tr>
<tr>
<td></td>
<td>Pre-emption of scarce assets</td>
<td>Assets that a firm is able to capture in an early stage of the</td>
</tr>
<tr>
<td></td>
<td>Commitment</td>
<td>The support and attention of a firm in supporting the design</td>
</tr>
<tr>
<td></td>
<td>Diversity of the network</td>
<td>The diversity of the set of actors supporting a technological</td>
</tr>
<tr>
<td></td>
<td>Compatibility</td>
<td>Having multiple entities being able to work together.</td>
</tr>
<tr>
<td>Meso</td>
<td>Diversity of the network</td>
<td>The diversity of the set of actors supporting a technological</td>
</tr>
<tr>
<td></td>
<td>Commitment</td>
<td>The support and attention of a firm in supporting the design</td>
</tr>
</tbody>
</table>

Factors not from previous frameworks:
- Macro: Policy (government) Policy incentives, for example stimulation renewable energy sources.
- Law: Regulations; for example in the use of raw materials.

7.2.1 Micro level

7.2.1.1 Technological superiority

Whereas for the 1G and 2G technologies differences in the lifetime of modules can almost be neglected, for the 3G technologies this is expected to become increasingly important. The organic solar cells have the worst lifetimes, degradation effects are high; using organics in combination with inorganic substitutes provides a slightly better lifetime (Weeber, 2011).

Not for all technologies the expected future efficiencies of 3G technologies could be found from reliable sources, the remaining efficiencies are shown in Table 34. From this table can be seen that II-V type of solar cells have the highest projected efficiencies. Earlier versions of these technologies are currently already used for space applications because of their high efficiencies (Bubenzer & Luther, 2003). A major problem however is the high price of these technologies, therefore it is expected they are used together with complementary technologies (Fraas & Partain, 2010); like concentrators. Concentrators increase the level of sunlight that reaches the cell, increasing efficiencies; consequently they bring down the needed PV material for the same electricity output (Knulst, 2011).

For the organic PV technologies still a lot of fundamental research is needed to increase efficiencies and it is not certain the expected rates will be reached. Also nanophotovoltaics still needs fundamental research, however this technology may be easily used in combination with other PV technologies. Increasing efficiencies is regarded to be the main concern for these two categories of 3G technological designs (Sinke, 2011; van Roosmalen, 2011; Weeber, 2011).
7.2.1.2 Flexibility

Technologies that are able to make use of existing production processes or research in other sectors are also expected to benefit. For this factor the nanophotovoltaics PV technologies clearly have a disadvantage, since research after nano materials in general has only quite recently started and although it receives considerable attention in scientific literature, there is only a relatively few number of commercially available products. Organic solar cells can on the other hand make use of knowledge and insights from the IC industry and also from considerable attention in scientific literature (Weeber, 2011).

7.2.1.3 Pricing strategy

For only a few technologies reliable sources could be found that showed expected future efficiencies and production costs, the results are shown in Table 34. From this table can be seen that the III-V PV technologies in theory have the most attractive price versus efficiency ratio, although it depends on how low the price for organic based PV technologies is able to get.

In general organic PV designs have the lowest price per watt; for these technologies pricing is not regarded as an issue in research and development. For nanophotovoltaics and III-V solar designs pricing is regarded to be one of the most important issues in research and development. As explained for the factor technological superiority (section 7.2.1.1), it is very likely these technologies will be used in combination with complementary technologies like concentrators; reducing the amount of PV material needed and consequently reducing prices (Fraas & Partain, 2010). A disadvantage however of using concentrators is the need for a tracking system, since these cells only work efficiently under a certain angle with the sun (Luque & Hegedus, 2011).

Related to pricing is the share of module prices in relation to the entire PV system; whereas for 1G and 2G technologies the module consists at least for 50% of the total systems price this will drop for 3G and other future technologies. Consequently more effort may be put in bringing down system component prices than in bringing down PV technology prices; although this is not favourable for one technology over the other.

7.2.1.4 Appropriability strategy

The market is currently still focused on research and development in universities and research institutes, therefore not many patents have been issued. However it is expected because of the growth potential that companies engaged in this market will actively protect their technological designs and production processes. This may be an issue for the emergence of a dominant design (Schilling, 1998; Utterback & Suárez, 1993).

7.2.1.5 Timing of entry

Mentioned as third most important factor on the list of chapter 6 is timing of entry; given the significantly lower results of 2G technologies on this factor (see Table 26 and Table 30), the 3G must first make significant improvements. It was recognised the 1G silicon technologies can benefit from mature production processes and well known materials (see also 5.2.1.9). Similar to the 2G technologies also 3G technologies need to invest in developing their supply chain and technological viability. Especially a well-functioning supply chain with standardisation of production processes will help to increase production scale and benefit from economies of scale.
7.2.1.6 Marketing Communications

Regarding this factor the III-V PV designs have a clear advantage, since they are currently used in space applications. The efficiency of these technologies is proven and variants currently provide the best efficiencies (Green et al., 2011). Organic PV designs are widely known; however their low efficiencies and short lifetime as well. Like discussed for the factor flexibility (section 7.2.1.2) nanophotovoltaics is a new field of study and they are there not yet widely known.

However expectations about technologies are currently only shared among researchers; consumers are not yet aware of the 3G technologies. Therefore this factor is not yet regarded to be applicable to the PV market.

7.2.1.7 Pre-emption of Scarce Assets

This factor is expected to become more important. Since the expected growth of the market new technologies need to have sufficiently access to cheap raw materials. Availability of raw materials can be a problem in the future, not for silicon based or organic PV technologies; they make mainly use of carbon and silicon. Nevertheless the other 2G and some 3G technologies may experience constraints in their growth from the availability of materials (Bubenzer & Luther, 2003; Zeman, 2011). For example III-V designs; these designs make use of rare materials and manufactures may need to secure considerable amounts to be able to deliver the needed quantities when sales take off. Nevertheless, from more recent literature there seems to be no definite answer on the availability of materials since reserves differ from one study to another (Candelise et al., 2011). Until today there are no constraints on the availability of scarce raw materials while some researchers calculated in 1998 that by now (in 2011) there should be a shortage of for example indium (used in CIGS PV cells) (Bubenzer & Luther, 2003) (see also section 5.2.1.11).

7.2.1.8 Commitment

This factor is not yet regarded to be applicable to the PV market, because generally firms are not engaged in 3G research and development.

7.2.2 Meso Level

7.2.2.1 Compatibility

Similar to the analyses for the 1G and 2G technologies there may be differences in usage of the technology to supplement conventional power plants. To ensure a long term stable supply of electricity III-V and nanophotovoltaics are regarded to be the most suitable technologies. Organic PV designs however have a serious problem with the stability, and consequently the lifetime, of the cells (Fraas & Partain, 2010).

7.2.2.2 Diversity of the Network

All the three types of technologies are able to benefit from other industries; III-V from the space industry, nanophotovoltaics from the increasing nano-technology sector and organic PV from the plastics industry (Fraas & Partain, 2010; Razykov et al., 2011). Therefore no significant differences are expected between the technological designs.
7.2.3 MACRO LEVEL

7.2.3.1 POLICY
Since research and development after 3G technological designs is quite evenly distributed and the cells are not yet on the market to benefit from other policy incentives, this factor is regarded to be largely similar for all designs.

7.2.3.2 LAW
Regarding this factor organic PV has the least to worry about regulations that may restrict its raw material usage, since it makes use of materials that are currently already in large amounts on the market. III-V designs make use of rare materials that can be toxic (like indium). Given that regulations normally only get stricter it may be the case these raw materials get completely banned in the future, at least in part of the world. For nanophotovoltaics there still exists a lot of uncertainty, this industry is very new and effects on humans are still not completely clear. On the other hand nanophotovoltaics are only used in stable forms, like CdTe, resulting in no restriction at all.

7.3 ANALYSIS OF THE RESULTS
From the current third generation technologies, organic solar cells seem to have the best characteristics to be a future dominant technology; it is expected organic solar cells can be cheaply produced and they make use of a widely available material. However, because there are some problems with the stability of the modules, it may be necessary to introduce some other (rare) materials to mitigate this problem (Jørgensen, Normman, & Krebs, 2008). Additionally, organic solar cells are expected to be capable of reaching efficiencies similar to the current most successful 2G technology CdTe within 14 years (see Table 14 and Table 34).

On the other hand, organic solar cells as well as other 3G technologies do not have a well-developed value chain, and since 1G and 2G technologies keep being improved by a large number of manufactures and other actors in the value chain, these technologies are as likely to remain dominant in the following decade(s). This can be seen from the research efforts for the 1G silicon based materials; improved forms or combinations of materials, like the HIT technology from Sanyo, bring lower prices for highly efficient modules. While at the same time there are 2G technologies which, in theory, can be produced for even better prices and efficiencies. The expectations of 3G technologies are also shown in the results from chapter 6; it is still considered a good time to start with manufacturing both sc-Si and mc-Si (see Table 25 or Table 29).

In chapter 5 a list of factors influencing the technology selection process of 1G and 2G technologies is defined. For the selection process of 3G technologies it is expected this list of factors will largely remain similar, though the importance of factors in this process may change for 3G technologies. The results of chapter 6 show that the two most influential factors in the dominance process are pricing and technological superiority. As mentioned before, the ratio between these two factors is regarded to be very important in the technology selection process, because the basics of the market are not expected to change (remains similar to for example commodity goods); the same factors are likely to remain important for future technologies. In should be noted however, that the analysis in this chapter is purely explorative; based on an existing list of factors and current expectations of technological capabilities, therefore the outcome of the analysis may be different from what takes place in the future.
8 Conclusion and Discussion

8.1 Conclusion
The purpose of this study is to provide insight in the factors and their importance in the selection process towards dominance of a specific photovoltaic (PV) design within the PV market. First, it was studied how technological lock-ins may block the introduction of renewable energies in general, several theories have been developed describing how lock-ins emerge; from transitions in socio-technological regimes to factors influencing the selection process of technologies. An inventory of existing work on dominant designs showed that already a large body of literature was written on this topic, though not on factors influencing the dominance process of specifically the PV market. Determining which factors influence the PV technology selection process was first of all based on existing frameworks on technology adoption. Both frameworks on dominant designs as well as the coexistence of multiple designs have been used. These frameworks are combined with the notion of levels originating from policy literature to structure the analysis. Levels have only been partly used in existing literature, while it was found that there are factors on all levels (micro, meso and macro) that affect the technology selection process in the PV market.

To address the issue of having a lack of literature in this specific industry using the notion of lock-ins and dominant designs, also; technology specific articles, industry magazines and interviews with industry experts were used as data sources. Combining these data sources resulted in a list of five commercially available technologies that were used for further research on which factors influence technology selection. Next their influence from the viewpoint of the individual firm was researched, and an analysis of the current status of technologies was carried out; using a questionnaire based on the Analytic Hierarchy Process (AHP). The results have been analysed using the crisp AHP method as well as a method using triangular fuzzy numbers, the logarithmic fuzzy preference programming (LFPP) method. By using the outcomes of the first research questions, an analysis of factors influencing dominance in the emerging third generation of PV technologies was made.

The investigation of the first research question on what the specifics are of the PV technologies in the market revealed that there are currently five technologies that can be manufactured on a commercial basis, while three technology generations can be distinguished. The technological development is characterised by an increase in government interest during the oil crises of the 1970s; this triggered research spending which resulted in the development of second generation technologies. The third generation consists of technologies that have been developed only recently and are not yet commercially available. Interestingly, it was found that the supply chain of first generation technologies (currently with a market share of about 85%) is characterised by several subsequent production steps, while producers of second generation technologies generally have an integrated supply chain. For first generation silicon producers these subsequent steps result, in combination with partly standardized production steps, in the ability to implement incremental improvements fast and cost efficient.

The analysis of the PV market to answer the second research question on which factors influence the chances that a PV cell technology achieves industry dominance made use of existing frameworks from Van de Kaa (2009) and Suárez (2004) on dominant designs. This analysis resulted in a list of 18 factors influencing the technology dominance process, furthermore two other relevant factors, not
from previous frameworks, were also identified. The resulting 20 factors are categorised using the notion of levels and are shown in Table 36 including a short description. The possibility of multiple designs coexisting in the market was also analysed by making use of existing frameworks; this resulted in a list of four factors, shown in Table 37.

**Table 36: Factors Influencing the Technology Dominance Process in the PV Market**

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Financial strength</td>
<td>For PV manufactures it is essential to have access to sufficient capital; to be successful they have to constantly expand production in order to benefit from economies of scale.</td>
</tr>
<tr>
<td></td>
<td>Brand reputation and credibility</td>
<td>Manufactures that delivered high efficiency modules are able to ask higher prices, also recently several manufactures actively promote their brand name; e.g. at the soccer World Cup or with a Formula 1 team.</td>
</tr>
<tr>
<td></td>
<td>Operational supremacy</td>
<td>Regarding the geographical location, Chinese manufactures may benefit from favourable policy incentives. Regarding production capacity, the first generation silicon technologies have an advantage.</td>
</tr>
<tr>
<td></td>
<td>Learning orientation</td>
<td>A significant part of the decline in prices comes from learning effects.</td>
</tr>
<tr>
<td></td>
<td>Technological superiority</td>
<td>Between PV technologies there are differences in the performance; how efficiently they are able to convert radiation to electricity.</td>
</tr>
<tr>
<td></td>
<td>Flexibility</td>
<td>Since for the second generation technologies manufactures have a multitude of production techniques, it is more expensive to adopt these technologies in comparison with first generation technologies which have some level of standardisation.</td>
</tr>
<tr>
<td></td>
<td>Pricing strategy</td>
<td>Prices differ between technological designs and many manufactures use the strategy of aggressive pricing to gain a larger market share.</td>
</tr>
<tr>
<td></td>
<td>Appropriability strategy</td>
<td>Patents are regularly issued in the PV market, there are however only a few lawsuits.</td>
</tr>
<tr>
<td></td>
<td>Timing of entry</td>
<td>During silicon shortages in the last decade some said there was a window of opportunity to start with the production of a-Si.</td>
</tr>
<tr>
<td></td>
<td>Marketing communications</td>
<td>Several pilot projects are used to increase expectations on technological capabilities.</td>
</tr>
<tr>
<td></td>
<td>Pre-emption of scarce assets</td>
<td>During the recent silicon shortages some manufactures could benefit from contracts they had with silicon suppliers.</td>
</tr>
<tr>
<td></td>
<td>Commitment</td>
<td>PV technologies know long development times; commitment of firms (and government) is essential.</td>
</tr>
<tr>
<td>Meso</td>
<td>Compatibility</td>
<td>Some technologies are found to be better suited for integration in large scale grid connected systems.</td>
</tr>
<tr>
<td></td>
<td>Diversity of the network</td>
<td>PV technologies differ on the amount of stakeholders they have been able to use in their development process.</td>
</tr>
<tr>
<td></td>
<td>Bandwagon effect</td>
<td>Examples are found of companies trying to mimic the success of manufactures of a particular design.</td>
</tr>
<tr>
<td></td>
<td>Number of options available</td>
<td>There are multiple technologies available on the PV market.</td>
</tr>
<tr>
<td></td>
<td>Uncertainty in the market</td>
<td>Several companies are found supporting multiple PV designs.</td>
</tr>
<tr>
<td></td>
<td>Rate of change</td>
<td>Price and production need to increase rapidly in the current PV market in order to stay competitive (benefit from economies of scale).</td>
</tr>
</tbody>
</table>

**Not from previous frameworks:**

| Macro    | Policy                        | Some policy incentives are found to favour one technology over another. |
|          | Law                           | In some countries there are regulations restricting the use of certain raw materials used in PV devices. |
The third research question was: *what is the relative importance of factors in the decision making process of individual firms for a specific cell technology?* To answer this question factors listed in Table 36 affecting the firm have been analysed on the basis of the AHP method developed by Saaty (1977, 1980). This analysis resulted in a questionnaire comparing 13 factors and 5 technological designs. The data form this questionnaire has been analysed using the crisp AHP method developed by Saaty and the LFPP method from Wang and Chin (2011). The results show that the most influential factors are; ‘technological superiority’ and ‘pricing strategy’, followed at some distance by ‘timing of entry’, ‘brand reputation and credibility’ and ‘flexibility’ (see Table 38). After these first five factors the ranking from the crisp AHP and LFPP method begin to differ. It should be noted that all comparison matrices from the questionnaire are found to be consistent using Saaty’s consistency ratio calculation, nevertheless when checked by calculating $\lambda^*$ and $\delta^*$ as proposed by Wang and Chin multiple comparison matrices are found to be inconsistent. This is a possible indication of the rank reversal problem with the AHP method, however it is as likely that it was introduced with the use of triangular fuzzy numbers in the LFPP method (Çakır, 2008).

### Table 37: Factors in favour of multiple designs coexisting in the market

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Distinct features</td>
<td>PV technologies are characterised by different physical characteristics, which make them better suited for certain situations.</td>
</tr>
<tr>
<td></td>
<td>Appropriability regime</td>
<td>Many PV manufactures make use of patents to protect their design; especially second generation manufactures make use of this strategy.</td>
</tr>
<tr>
<td></td>
<td>Price</td>
<td>Although the technologies know different prices, the differences become smaller.</td>
</tr>
<tr>
<td>Meso</td>
<td>Application drives the design</td>
<td>Consumers generally buy complete PV systems; the technological design is only part of this system.</td>
</tr>
</tbody>
</table>
Combining the influence of factors with the analysis of the current status of technological designs, shows that the first generation technologies sc-Si and mc-Si are considered to be currently the best options; having an averaged combined score of 0.30 and 0.27 respectively (see Table 39).

**Table 38: Comparison of the CRISP AHP and LFPP method with the results of Part I of the questionnaire**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Crisp AHP</th>
<th>LFPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant agent</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>Financial strength of the agent</td>
<td>0.16  0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Brand reputation and credibility</td>
<td>0.41  0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Operational supremacy</td>
<td>0.22  0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Learning orientation of the agent</td>
<td>0.22  0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Superior Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.75  0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Technological superiority</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.22  0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.25  0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.46  0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Pricing strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.41  0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Appropriability strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.05  0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Timing of entry</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.24  0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Marketing communications</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.13  0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Pre-emption of scarce assets</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.08  0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Commitment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.09  0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Stakeholders</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Diversity of the network</td>
<td>1  0.06</td>
<td>7  0.06</td>
</tr>
</tbody>
</table>

**Table 39: Comparison of the total averaged values of the LFPP and CRISP AHP method**

<table>
<thead>
<tr>
<th>Method</th>
<th>sc-Si</th>
<th>mc-Si</th>
<th>CI(G)S</th>
<th>CdTe</th>
<th>a-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crisp AHP</td>
<td>0.30</td>
<td>0.27</td>
<td>0.15</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>LFPP</td>
<td>0.30</td>
<td>0.27</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
</tr>
</tbody>
</table>

With the analysis of research question four on which factors influence the chances that a PV cell technology of the third generation achieves dominance, there is still a lot of uncertainty. Generally, it can be said that ’pricing strategy’ and ’technological superiority’ remain the most influential factors; since new designs need to compete with the existing 1G and 2G designs in the market. For some technologies the factor pre-emption of scarce assets may become very important; they currently already make use of scarce materials and scarcity will only increase in the future. On the other hand there are the 3G organic PV designs that are specifically aimed to take the hurdle of scarce assets.

The results of the main research question on which factors influence the selection of designs in the PV cell technology market are given in Table 36. The frameworks used as a basis in the analysis could not fully describe the selection process in the PV market, since two new factors needed to be introduced;
policy and law. These twenty factors influencing PV design selection differ in their importance for firms in the value chain as shown in Table 38. This shows that ‘technological superiority’ and the ‘pricing strategy’ are by far the most influential factors. The interviewed industry experts all recognise the ratio between price and performance is important for the success of a technological design. Interesting to see is that although continuous investments are needed to increase efficiencies and lower prices, the respondents do not regard the factor ‘financial strength of the agent’ to be very important. However, as expected the technologies sc-Si and mc-Si score significantly higher on this factor (see Table 26 and Table 30); since their value chain consists of several different production steps, which make incremental improvements less expensive. Similarly, the factor ‘pre-emption of scarce assets’ was expected to be more important, since with most second generation technologies there is uncertainty over the availability of raw materials.

Previous literature found that the larger the number of firms concentrated around one technological design, the sooner a dominant design will emerge (Srinivasan et al., 2006); however in the PV market no such effect is found. Based on the analysis of currently commercially available technologies it can be seen that sc-Si currently has the best chances to be a future dominant design (see Table 39); however, at this moment mc-Si is the most used design in the market (see Figure 14). The reason behind the current success of mc-Si likely originates from the factor flexibility (see Table 26 and Table 31); this factor shows how it is easier to set up a production process of mc-Si in comparison with sc-Si. This is mainly because the process of growing multi crystalline ingots for the production of mc-Si is easier and faster in comparison with mono crystalline ingots.

Furthermore, the possibility that multiple designs may coexist in the market remains; the factors found to be present in in the PV market are shown in Table 37. Especially the factors ‘distinct features’ and ‘pricing strategy’ seem to be of influence in the market; the prices between PV technologies show a converging trend, also there may remain niches which support individual designs. Examples of niches for electricity production are designs applied in large scale desert projects or design used for rooftops in western countries. For firms in the PV supply chain it is more cost efficient to have a single dominant design, however the coexistence of multiple designs is found to stimulate the continuous innovation process (de Vries et al., 2011); which is again beneficial for the end user.

8.2 DISCUSSION

This section analyses the use of the theories and frameworks described in chapter 2 on the PV market. It also reflects on the importance of factors from the Analytic Hierarchy Process from chapter 6 and their role in the dominance process.

8.2.1 ANALYSIS OF USING EXISTING FRAMEWORKS IN THE PV MARKET

As a basis this research uses existing frameworks from Van de Kaa (2009) on dominant designs and Suárez (2004) on technological lock-out. The extensive list of factors from the framework of van de Kaa proved to be useful in providing a comprehensive overview of factors influencing technology selection from multiple literature backgrounds; to not overlook other aspects of technology selection besides the obvious design specific characteristics (such as efficiency or price). This aspect is very useful for managers and decision makers in the PV industry. Similarly, with the framework of van de Kaa factors influencing the technological design could systematically be analysed. It is interesting to find that although the PV market is not characterised by strong network effects, there are still some factors from the category ‘other stakeholders’ that influence the dominance process. From the case study the factor diversity in the network is found to be influential for the dominance process,
especially in the earlier stages of development when technologies can benefit from knowledge spillovers of complementary industries. There are however two factors that have not been described in previous literature before, though they affect the technology dominance process in the PV market; law and policy. Regarding the generalizability of these factors for other industries, it seems that law, although it is applicable to other industries, may have very different effects in each industry. Moreover, during normal conditions manufactures will be able to anticipate on this factor in an early stage of the development process, preferably even before the invention of the technology. Regarding the factor policy, it is expected that also in other industries there is a difference between technologies in how they benefit from policy incentives; this seems to be inevitable with providing government funded incentives.

Furthermore, a framework has been used that describes how multiple designs may coexist in the market. The framework from de Vries, de Ruijter and Argam (2011) provides a solid starting point for analysing the possibility of the coexistence of multiple designs; no new factors needed to be introduced in the analyses of the PV market. Its usability shows the framework also works effectively for designs not characterised with strong network effects. The reason for this may be found in previous research of De Vries et al. (2011) used for their framework; they base their theories partly on Frenken, Saviotti and Trommetter (1999), who tested their theories on the microcomputer market (amongst others). The PV market is partly similar to the microcomputer market since they are both characterised by “a very high rate of cost reductions and by strong demand inducements to purchase high-performance models” (Frenken et al., 1999, p. 484).

8.2.2 Analysis of factors influencing dominant designs
In section 5.2 there are 20 factors on three levels described which influence the dominance process in the PV market, furthermore in section 5.3 there are four factors on two levels which are in favour of multiple designs coexisting in the PV market. This section provides an evaluation of these factors; it starts with a reflection of incorporating some new factors that have not been mentioned in the literature before, followed by feedback on incorporating the micro-, meso- and macro level in the analysis. Finally the influence of the factors in favour of multiple designs will be described.

8.2.2.1 Reflection on new factors in the dominance process
When taking the comprehensive overview of factors affecting technology dominance by van de Kaa (2009) as a basis, then two new factors are mentioned in this research; policy and law. These factors are very interesting since they are on the macro level and consequently the factors can only be influenced on an international level and are not only applicable to the PV industry.

Especially in the PV market policy incentives have an influential role, it is recognised they have helped the PV market to grow (e.g.: EPIA & Greenpeace, 2011; IEA, 2010b). Moreover, it was found that these policy incentives discriminate between technological designs, and it is therefore necessary to incorporate the factor policy to fully describe selection processes in the PV market (section 5.2.3.1). Research on policies in the PV market serves as a first analysis of how government incentives may (indirectly) influence technology selection; this has not been described in dominance literature before. Moreover, the analysis of policies in the PV market helps policy makers to increase their understanding of how their incentives affect the market. Because many policy incentives are not only aimed at PV but support renewable energies in general, this factor has been placed on the macro level. For example, one of the most frequently used policy incentives is the feed in tariff system; this system awards a premium price per kWh delivered to the grid. This incentive is not only aimed to support
electricity from PV systems but also from other renewable energies, such as wind and tidal energy (e.g.: Jacobsson & Lauber, 2006).

Previous literature uses factors similar to law (section 5.2.3.2); both judiciary (or antitrust laws) and regulator (e.g.: Schilling, 1998; Suárez, 2004; Van de Kaa, 2009). Judiciary relates to how courts use antitrust law to prevent certain designs from becoming dominant, and regulator relates to an institute prescribing a certain technology or design to be used in the market. The new factor law on the other hand describes how institutions can prevent a certain technology from being adopted by the use of regulations and guidelines; the existing concepts do not fully grasp the definition of the new factor law. Furthermore, this factor has been placed on the macro level since regulations come from national governments, and in the largest PV market (the EU) from an international institution. Secondly, the law may also affect other products, for example in the case of the cadmium regulations also other products using cadmium are prohibited from use; like certain batteries and plastics.

The influence of the above two factors on the dominance process differs with the technological design. The factor policy has a slight positive influence on the dominance of sc-Si, since this technology offers higher efficiencies and is therefore able to better benefit from the price per kWh rebates. The factor law may have a very strong influence on the future growth of CdTe, since it remains uncertain if CdTe modules will remain legal in the largest PV market (the EU).

8.2.2.2 Analysis of using levels in the dominance process

By using the notion of levels in the analysis it is easier to distinguish on each individual level which factors can be influenced by firms, groups of firms or even institutes. In designing the AHP questionnaire for the analysis of research question three the notion of levels is considered crucial to differentiate between factors that are influenced on an international level, and those that can be influenced by individual firms and consequently can be ranked by experts from these firms.

The notion of levels has been used in previous literature on dominant designs, though not as extensively as the definitions from this research. Moreover, the notion of a macro level influencing the dominance process of an individual design has not been found in previous literature on dominant designs (e.g.: Clymer & Asaba, 2008; Suárez, 2004; Van de Kaa, 2009). However, in the case of the PV market it has been found, that the factors law and policy both influence dominance of individual technologies, while they can only be influenced by international institutes on the macro level. See also the above section 8.2.2.1, for an extensive explanation of the factors on this level.

8.2.2.3 Factors in favour of multiple designs

The majority of experts interviewed for this research indicated they expect several technological designs to survive in the market. The main reason for this comes from the factor distinct features; that is in favour of multiple technological designs. It has been described in section 5.3.1.1 that there are several applications that remain important in the future and for which different technologies may be better suited. For example in south Europe 2G technologies may offer better efficiencies in the warm climate, while in west and north Europe sc-Si offers a better price versus performance ratio for the limited available space. Moreover in the north rooftop installation are expected to become dominant while in the south, with high radiations, large scale PV installations may be build using 2G technologies (Brown & Hendry, 2009). Similarly there is a difference between how technologies can be integrated or applied on buildings or curved surfaces; currently mainly Cl(G)S and a-Si PV devices
are available in flexible configurations. Therefore these technologies may remain dominant in the niche of building integrated- and applied systems.

Also the factor ‘application drives the design’ (section 5.3.2.1) is important in the PV industry. Since most end user merely buy an entire PV system, they may be ignorant of the technology of the PV modules in this system. Some consumers however, may prefer technologies that use raw materials that are widely available on earth; thus technologies such as Cl(G)S and CdTe would have a disadvantage since they use several rare materials (see also section 5.3.1.1).

8.2.3 Importance of factors from the AHP Questionnaire

Chapter 5 describes the importance of factors for technological design dominance in the PV sector from the point of view of the firm. From chapter 5 a list of 13 factors was obtained on the micro and meso level that can be influenced by individual firms. These factors have been rated by experts from companies on their influence in the dominance process using the Analytic Hierarchy Process (AHP). Moreover, experts from research institutes also used the AHP method to evaluate the current status of the five selected technological designs in relation to the factors. The AHP methodology proved to be efficient in creating a systematic overview of the decision making situation, even with a multitude of factors and alternatives. Consequently, the overview of factors structured with the AHP method is expected to be useful for managers and decision makers in the PV market.

By using the AHP multiple factors can be rated on a variety of scales, this data has been analysed both by using the crisp AHP method proposed by Saaty (1977, 1980) and the logarithmic fuzzy preference programming (LFPP) method form Wang and Chin (2011). In a comparison of the two methods no large differences in the ratings have been found; the five most important factors are the same for both methods (see Table 31). In the combined analysis of both the rating of factors and the rating of alternatives comparable results were found (see Table 32). This means both the methods are equally well suited to analyse factors in the case of the PV market. Nevertheless, differences are found in analysing the consistency of the answers; even though all the comparison matrices are considered to be consistent according to the consistency ratio from Saaty (1977, 1980), over one third of the matrices in part II of the questionnaire is found to be inconsistent using the LFPP approach. There are several explanations for this difference; it may be because of the rank reversal problem with the crisp AHP method (Y.-M. Wang & Luo, 2009), though it may also be because by using triangular fuzzy numbers in the LFPP method inevitably some form of inconsistency is introduced (Çakır, 2008).

The results from part I of the questionnaire (Table 24 and Table 28) show that ‘strategy of supporters of the design’ is regarded to be the most important category of factors, second is the category ‘superior technology’. Furthermore do all the respondents from part I regard the same three factors to be most important. Although in previous literature on dominant designs showed that technological superior designs do not necessarily become dominant (e.g.: David, 1985; Rosenbloom & Cusumano, 1987), the results of this study show that technological superiority is an important factor for the dominance process in the PV market. The two most important factors, pricing and technological superiority, are almost equally important; this is consistent with what all interviewed experts mentioned to be important elements in the PV market (Knulst, 2011; Olivierse, 2011; Sinke, 2011; Smets, 2011; van Roosmalen, 2011; van Swaaij, 2011; Vlek, 2011; Weeber, 2011). The importance of these factors seems to relate to characteristics that PV modules have in common with commodity goods; consumers are ignorant about the technological design, the merely look at the price versus performance ratio. Similarly Gallagher (2007) described how these two factors are expected to be important in the dominance process, as opposed to interface standards. Since actors in the supply chain of PV modules
choose to support a technological design based on what consumers or end user want, they choose their
design based on its (expected) price versus performance ratio; to compete with other PV designs but
also other renewable energy technologies.

However, there are also indications that consumers may prefer certain technological designs in
particular situations over others, as explained for the factor distinct features (section 5.3.1.1); in
densely populated countries building integrated PV (BIPV) or building applied PV (BAPV) is
expected to become increasingly popular and currently only 2G technologies can be used in curved
applications that require flexible solar modules. However static modules may also be used for BIPV,
since in general roofs are not curved and static modules have longer lifetimes. Similarly critical
environmentally conscious consumers and manufactures may prefer PV designs that use abundant,
non-toxic raw materials over designs that use rare and possible toxic materials. Both CdTe and Cl(G)S
use these toxic (e.g.: cadmium) and rare materials (e.g.: cadmium and indium), although Cl(G)S is
regarded to be slightly better since it uses only relative small amounts (Knulst, 2011). The 1G silicon
technologies and a-Si have a clear advantage since they use silicon, which is the second most abundant
element on Earth.

As previously explained in chapter 6, it is currently the best moment to start with sc-Si. Although sc-Si
was one of the first technologies on the market, it is currently together with mc-Si one of the best
available technologies. This is slightly contradicting from what Schilling found in her research;
“Timing of entry will have a U-shaped relationship with the likelihood of lockout: entering very early
or very late will increase the likelihood of technological lockout” (1998, p. 277). Nevertheless, she
does indicate that in markets with high entry barriers early entry may be more beneficial.

8.2.4 LIMITATIONS OF THIS RESEARCH

There are a few limitations with this study. First of all only six questionnaires have been filled in for
the AHP analysis, three for each part; this limits the possibility of finding significant correlations for
quantitative evidence. Nevertheless, Saaty (1980) argues even one consistent questionnaire from a
respondent is enough to deliver significant quantifiable results. Previous literature using the AHP
analysis also has proven that a small number of respondents is enough to have valid results; for
example five respondents in Peterson, Silsbee and Schmoldt (1994), two in Cheng and Li (2001), or
eight in Lam and Zhao (1998). Secondly, the experts that have been used for the data analysis are all
situated in the Netherlands; this may limit the generalizability of this research. Although most of the
respondents worked on a European level, the results may only reflect the choices of Dutch companies.
Nevertheless, this is only applicable to the first part of the AHP analysis since the rest of this research
made use of other data sources (the industry magazines and scientific literature for example) that
originate from worldwide sources.

Furthermore, there may be problems with retrospective bias with gathering information from
respondents on events that happened in the past; the influence of factors affecting technological choice
may be rated differently afterwards than during the decision making process. This research tried to
address this problem by having respondents from only relatively young companies; the “oldest”
company used for the questionnaire was founded in 2009 (Solar Modules NL). Moreover, two of the
tree respondents came from companies that had not yet publicly announced which PV technology they
would adopt. Also respondents in the second part of the AHP questionnaire (experts from research
institutes) where asked to explain what they found to be the most influential factors in the dominance process.

With the use of categorization of factors within the AHP method the rating of factors may be influenced. Since respondents filling in AHP questionnaires tend to rate categories with many factors higher than those with only a few factors (Ishizaka & Labib, 2011); in this research this could be the case for the category strategy. On the other hand the category superior technology was rated as the second most important category while it only contains two factors.

Lastly with conducting the AHP analysis respondents have been contacted and asked to reassess their answers in the case their answers have been found to be inconsistent. This is a limitation to accuracy of this research, since “raising consistency should never be an objective in itself and judgments should only be revised if it results in a more accurate representation of the respondent’s judgments” (Van de Kaa, 2009, p. 98). Nevertheless, Wang Chin and Luo (2009) describe inconsistencies to be inevitable in applying the AHP method; especially with a large number of pairwise comparisons the direct and indirect judgements can easily be conflicting or inaccurate. Consequently, Chin and Luo see no problems with the revaluation of judgements.

Another limitation is that although two methods of analysis have been used, they are closely related to each other. The validity of this research could be improved with using a fundamentally different method of analysis; for example a quantitative approach with sending out a large number of questionnaires or conducting a large number of interviews. It should be noted that besides the interviews, also sending out questionnaires is time consuming, because as explained for the AHP questionnaire in this research, interviews are needed to assure mutual understanding of the used theories and terminologies. Therefore, the researcher should give considerable attention to formulation in the questionnaire.

There are some difficulties with different stages of technology development; each of the generations contains technologies that have been developed for a variable periods of time. Although the five main technologies are all commercially available, mainly first generation technologies are already produced on very large scale with standardized equipment while the second generation still knows many different production methods. The reason for this may be the appropriability strategy of manufactures in the second generation, though it may also be the case that they are still in an earlier phase of development.

It is also difficult for several reasons to make an accurate analysis of factors affecting dominance in the third generation; there have not been enough reliable sources of information on all technological designs and it is not yet certain what the possibilities and limitations of these technologies are. The latter difficulty originates from the lack of commercial producers currently working on 3G technologies (no experience yet with large scale production) and scientists that work on new technologies tend to make a too optimistic assessment of their own technology.

The frameworks on dominant designs from van de Kaa (2009) and Suárez (2004) provide a comprehensive overview of factors influencing technology development. For the case of the PV market however, these frameworks may be not able to provide enough detail in analysing the most important aspects. For example, the factors technological superiority and pricing strategy know many different facets that contribute to their influence. Integrating different theories that provide more detail on these specific aspects in the research could result in a more useful in depth analysis of the PV market.
Another limitation is the use of efficiency to represent the factor technological superiority. Although, as explained in section 5.2.1.5, this element was found to be the most influential element; there are more aspects that contribute to the technological capabilities.

As described in the theoretical background (chapter 2), there is a disagreement on the definitions of standards and dominant designs. In this research it has been argued that theories resulting from both dominant designs and standards can be used to analyse the PV market. Nevertheless, other scientists may argue these two definitions are fundamentally different and may not be used together (e.g.: Gallagher, 2007).

### 8.2.5 Recommendations for future research

To further validate the results of this research more interviews should be conducted. Especially in for analysis of research question 3, on the importance of factors, using more respondents would lead to more generalizable results. This is beneficial for dominant design literature in which researchers try to build a pattern of the influence factors have in the technology dominance process related to their stage of diffusion (Van de Kaa, 2009); using the phases as described by Suárez (2004) and Ortt & Schoormans (2004). Similarly, using respondents from different continents and from more mature companies (older than 10 years) would result in a more comprehensive overview of the PV market in which new characteristics may be found.

Also, analysing the PV market again in 10 to 20 years’ time will add to the ability to find patterns in the influence of factors, since some of the currently researched technologies may have entered a new stage in the development process and some new technologies (third generation) may have become commercially available. Similarly, the effectiveness of the used models to ex-post determine the success of technologies in the PV market can be tested; if the models are suitable for prediction this would result in having sc-Si as the most successful technological design in the coming period.

The results can be used to provide insights in the linkage between factors that influence dominant designs and the effects this has on the structure of the market; it has been suggested by Clymer and Asaba (2008) there exist such a linkage.

The concept of product niches may be able to provide useful results in the analysis. Brown and Hendry (2009) have used this approach before to analyse the emergence of a dominant design; they did not make the distinction between two technological generations, though between different product niches (like grid connected centralised power and off grid local localized power). Using a technology categorisation may provide insights in the differences in factors between product niches.

The two new factors that have been introduced in this research (law and policy) need to be validated using empirical case studies in order to include them in existing frameworks. Especially the factor policy may be also applicable in other industries. For this factor, further differentiation can be made on how different government incentives affect the dominance of technological designs.
### Appendix I. Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current, normally the grid has AC.</td>
</tr>
</tbody>
</table>
| AM (1.5) | Air Mass. “The most important parameter that determines the solar irradiance under clear sky conditions is the distance that the sunlight has to travel through the atmosphere. This distance is the shortest when the sun is at the zenith, i.e. directly overhead. The ratio of an actual path length of the sunlight to this minimal distance is known as the optical air mass. When the sun is at its zenith the optical air mass is unity and the radiation is described as air mass one (AM1) radiation. When the sun is at an angle $\theta$ to the zenith, the air mass is given by; \( \text{Air mass} = (\cos \theta)^{-1} \) (Zeman, 2011, p. 2.2). Thus AM1.5 is at an angle of 48.2° between the sun and the zenith, this value is generally used to normalize test results from different locations on the earth.
| Band gap | “Is an energy range in a solid where no electron states can exist. In graphs of the electronic band structure of solids, the band gap generally refers to the energy difference (in electron volts) between the top of the valence band and the bottom of the conduction band in insulators and semiconductors.” (Wikipedia, 2011a) |
| BAPV | Building adapted photovoltaic system (built on top of a roof) |
| BIPV | Building integrated photovoltaic system (forms part of a building) |
| BOS | The BOS consists of all components needed to let the system properly function between the DC electricity generated by the PV devices and the load; electrical interface components (e.g. DC/AC converter), mounting structures and storage devices (e.g. batteries). See Figure 18 for an example of a grid connected PV system. |
| BOS | Balance of system |
| Carbon lock-in | Barriers in the energy transition created by technological and institutional lock-in mechanisms from returns to scale of existing technological systems (Unruh, 2000). |
| CdS | Cadmium sulphide |
| CdTe | Cadmium telluride |
| Charge Controllers | Converts DC into AC and protects batteries from excessive discharge and overcharging. |
| CPV | Concentrating photovoltaic |
| DC | Direct Current, for example generated by PV devices. |
| EC | European Commission |
| ECN | Energy research Centre of the Netherlands |
| EEG | German Feed-in Law |
| Energy gap | See band gap |
| EPBT | Energy payback time |
| EPIA | European Photovoltaic Industry Association |
| EU | European Union |
FIT: Feed-in Tariff
GDP: Gross domestic product
Grid: A grid is the electricity network delivering electrical energy from producers to consumers. In general the term is used for the electricity network connecting all users (households, firms) and all producers (nuclear, coal, wind, PV) in a country or continent (e.g. Europe).
Grid parity: Grid parity is the point at which alternative means of generating electricity is at least as cheap as grid power (Wikipedia, 2011b).
GW: Gigawatt (10^9)
Hydropower: Electricity derived from the energy of water moving from higher to lower elevations. Hydropower can be “run-of-river” without a reservoir, or can include reservoir storage capacity. Large hydropower is usually defined as larger than 10 megawatts; the definition can vary by country. Smaller-scale installations are called small-, mini-, micro-, or pico-hydropower, depending on the scale. (REN21, 2010)
IEA: International Energy Agency
INES: (French) National Institute for Solar Energy
IRR: Internal rate of return
JRC: European Joint Research Centre
kW: Kilowatt (10^3)
kWh: Kilowatt hour
kWp: Kilowatt-peak units
Lattice matching: “Matching of lattice structures between two different semiconductor materials allows a region of band gap change to be formed in a material without introducing a change in crystal structure. This allows construction of advanced light-emitting diodes and diode lasers.” (Wikipedia, 2011c)
Load: Application in which the generated electricity is used.
Lock-in: A change from the current situation becomes uneconomic.
Macro level: On a (inter-)national level.
Meso level: The level of technological sectors.
METI: Ministry of Energy, Trade and Industry (Japan)
Micro level: Individual actors and firms.
Module: Larger area of photovoltaic material, normally a rectangle. Can also consist of a package of interconnected photovoltaic cells.
MW: Megawatt (10^6)
NEA: National Energy Authority (China)
NEDO: New Energy and Industrial Technology Development Organisation (Japan)
OPV: Organic photovoltaic
Panel: See module.
p-n junction: Potential difference junction
<table>
<thead>
<tr>
<th>PV</th>
<th>Photovoltaic</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;D</td>
<td>Research and development</td>
</tr>
<tr>
<td>Renewable energies</td>
<td>Energy source other than from fossil fuels, like; wind, solar, water and biofuels.</td>
</tr>
<tr>
<td>RoHS</td>
<td>Restriction of Hazardous Substances</td>
</tr>
<tr>
<td>Solar photovoltaic (PV) panel/module/cell</td>
<td>Converts sunlight into electricity. The PV cell is the basic building block, which is then manufactured into modules and panels for installation. (REN21, 2010)</td>
</tr>
<tr>
<td>Staebler-Wronski effect</td>
<td>“Is an example of the metastable creation of additional defects in the material under illumination. In solar cells these additionally created defects will act as extra trapping and recombination centres. As a result of the trapping a space charge distribution in the intrinsic [...] layer is changed in such a way that the internal electric field is distorted. This leads to lower drift and thus to a lower collection efficiency” (Zeman, 2011, p. 7.21)</td>
</tr>
<tr>
<td>Sustainable systems</td>
<td>Using natural resources without destroying the ecological balance.</td>
</tr>
<tr>
<td>TCO</td>
<td>Transparent conducting layer</td>
</tr>
<tr>
<td>TIS (technological innovation system)</td>
<td>“A network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilise technology”. (Hekkert &amp; Negro, 2009, p. 586)</td>
</tr>
<tr>
<td>TW</td>
<td>Terrawatt ($10^{12}$)</td>
</tr>
<tr>
<td>TWh</td>
<td>Terawatt hour</td>
</tr>
<tr>
<td>Wp</td>
<td>Watt-peak. A measure of the nominal power of a photovoltaic solar energy device</td>
</tr>
</tbody>
</table>
## Appendix II. Standards Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Positive effects</th>
<th>Negative effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatibility/Interface</td>
<td>• Network externalities</td>
<td>• Monopoly</td>
</tr>
<tr>
<td></td>
<td>• Avoiding lock-ins</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Increased variety of systems products</td>
<td></td>
</tr>
<tr>
<td>Minimum quality/safety</td>
<td>• Correction for adverse selection</td>
<td>• Regulatory capture</td>
</tr>
<tr>
<td></td>
<td>• Reduced transaction costs</td>
<td>• 'Raising rival’s costs’</td>
</tr>
<tr>
<td></td>
<td>• Correction for negative externalities</td>
<td></td>
</tr>
<tr>
<td>Variety reduction</td>
<td>• Economies of scale</td>
<td>• Reduced choice</td>
</tr>
<tr>
<td></td>
<td>• Building focus and critical mass</td>
<td>• Market concentration</td>
</tr>
<tr>
<td>Information standards</td>
<td>• Facilitates trade</td>
<td>• Regulatory capture</td>
</tr>
<tr>
<td></td>
<td>• Reduced transaction costs</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 23: The four standard categories and their economic effects (Blind, 2004, p. 22)*
Appendix III.  PHOTOVOLTAIC TECHNOLOGIES

Figure 24: Overview of solar cell types (Zeman, 2011)

Figure 25: Classification according to the type of solar modules (Raugei & Frankl, 2009)
Appendix IV. PHOTOVOLTAIC MARKET SHARES

The market share numbers are mainly based on research from PHOTON International (Hirshman, 2009, 2010, 2011) they are checked and combined with data from EPIA (2011), Raugei et al. (2009) and Razykov et al. (2011).

**Figure 26: Total market shares for 1G, 2G and 3G photovoltaics**

**Figure 27: Market shares of 1G and 2G compared**
**Figure 28: Market shares within the first generation**

**Figure 29: Market shares within the second generation**
**Figure 30:** Total MWp (Megawatt Peak) of installed photovoltaic capacity worldwide for the period 1973-2010.

**Table 40:** Approximate number of companies in the value chain (Cai, 2011; EPIA & Greenpeace, 2011; Grau et al., 2011; Jäger-Waldau & Institute for Energy (European Commission), 2010)

<table>
<thead>
<tr>
<th>Technology</th>
<th>sc-Si/ mc-Si</th>
<th>CdTe</th>
<th>a-Si (and µc-Si)</th>
<th>Cl(G)S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refining of raw materials</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wafer production</td>
<td>210</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell production</td>
<td>240</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module production</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of companies (2009)</td>
<td>4-9</td>
<td>130</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>
Appendix V.  PHOTOVOLTAIC LEARNING RATES

Figure 31: The PV learning curve (C. F. Yu et al., 2011)

Figure 32: Increases in PV plant size in megawatt (MW) (C. F. Yu et al., 2011)
**Figure 33: PV Cost Breakdown (C. F. Yu et al., 2011)**

- **LOG A** = Remaining-factors effect
- **B_1** = B(N + 1) Learning-by-doing index
- **A_1** = A(N + 1) Learning-by-researching index
- **N** = (1 - R)/R Scale index or the elasticity of plant size
- **Δs** = D3 (N + 1) Silicon Price index
- **Δac** = D4 (N + 1) Silver price index
- **Δo** = D5 (N + 1) Other input-prices index
**Figure 2**  Solar PV modules: prices (upper left), cumulative shipments (upper right), learning curve (lower left) and learning rates (lower right)

**Figure 34:** Learning rate of photovoltaic technology (A. McDonald & Schrattenholzer, 2002)
<table>
<thead>
<tr>
<th>Date</th>
<th>Remarks</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1839</td>
<td>Antoine-César Becquerel discovers that voltage can be changed when exposing one of two metal plates in a dilute acid to light.</td>
<td>(Green, 2000; Lenardic, 2011)</td>
</tr>
<tr>
<td>1873</td>
<td>Willoughby Smith discovers the photovoltaic effect in selenium while doing his research in testing underwater telegraph cables with semi-conducting material. He notices a correlation between the illumination of selenium metal and its electrical resistance.</td>
<td>(Khan, 2004)</td>
</tr>
<tr>
<td>1876</td>
<td>William Grylls Adams together with his student R. E. Day discovers that illuminating a junction between selenium and platinum has a photovoltaic effect; a current is produced instead of altered in previous milestones. <em>This effect forms the bases for modern solar cells.</em></td>
<td>(Green, 2000; Lenardic, 2011; Perlin, 2002)</td>
</tr>
<tr>
<td>1883</td>
<td>Charles Fritts builds a solar cell with forming p-n junctions by coating selenium with a gold layer. <em>This is the first build modern solar cell.</em></td>
<td>(Green, 2000; Lenardic, 2011; J. Nelson, 2003)</td>
</tr>
<tr>
<td>1906</td>
<td>Anthracene, the first organic compound with the photovoltaic effect is described by Pochettino.</td>
<td>(Spanggaard &amp; Krebs, 2004)</td>
</tr>
<tr>
<td>1913</td>
<td>Patent describing the casting of multicrystalline silicon is issued.</td>
<td>(Scheel &amp; Fukuda, 2003)</td>
</tr>
<tr>
<td>1916</td>
<td>Jan Czochralski discovers a method for growing monocrystalline silicon when conducting research in the crystallization rate of metals. <em>This forms the basis for the future production of solar cells.</em></td>
<td>(Szymy &amp; Suzuki, 2000)</td>
</tr>
<tr>
<td>1921</td>
<td>Einstein receives the Nobel prize for his explanation of the photoelectric effect in 1904.</td>
<td>(Green, 2000)</td>
</tr>
<tr>
<td>1941</td>
<td>Russell Ohl, working in the Bell labs on radar detectors, discovers that the photovoltaic effect can occur in silicon when there is only a small amount of</td>
<td>(Green, 2000)</td>
</tr>
</tbody>
</table>
impurities. In experimenting with the impurities he discovered together with colleague Jack Scaff the p- and n-type regions made with phosphorus and boron.

*First controlled fabrication of p- and n-type regions with silicon.*

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948</td>
<td>William Shockley while working at Bell does research on an improved transistor structure, resulting in better theoretical understanding of the p-n junction. (discovery of the bipolar transistor)</td>
<td>(Green, 2000; Riordan, Hoddeson, &amp; Herring, 1999)</td>
</tr>
<tr>
<td>1951</td>
<td>Gordon Teal from the Bell labs finds a way to grow large single crystals of germanium, together with Morgan Sparks he is able to fabricate a p-n-p transistor. William Pfann and Henry Theurer of the Bell labs find a way to further refine and to produce ultra-pure semiconductor materials. Invention of multi crystalline silicon solar cells by Ohl</td>
<td>(Bell Labs, 2011; Fraas &amp; Partain, 2010; Green, 2009)</td>
</tr>
<tr>
<td>1952</td>
<td>Calvin Fuller from the Bell labs demonstrates how impurities are introduced into germanium, later he described the process for silicon, by exposing them to high temperature gases containing the dopants.</td>
<td>(Trivich, 1953)</td>
</tr>
<tr>
<td>1953</td>
<td>Dan Trivich, professor at the Wayne State University (US), conducts research after the theoretical solar cell efficiency given different materials.</td>
<td>(Bell Labs, 2011; Green, 2000; Perlin, 2002)</td>
</tr>
<tr>
<td>1954</td>
<td>Bell Labs announces the invention of the first single crystalline silicon solar cell, called the Bell Solar Battery. Introduced by Daryl Chapin, an electrical engineer, Gerald Pearson, a physicist and chemist Calvin Fuller. These cells have about 6% efficiency. <em>First mature silicon solar cell.</em></td>
<td>(Bell Labs, 2011; Green, 2000; Perlin, 2002)</td>
</tr>
<tr>
<td>1955</td>
<td>Western Electric, a subsidiary of Bell, begins selling commercial licenses for silicon photovoltaic technologies. National Fabricated Products is the first to buy a licence. Bell does a first test with the Bell solar battery in Americus, Georgia US. The test consisted of the substitution of the Bell Solar Battery for the usual batteries. The results show that the solar cell is reliable enough but too expensive to completely substitute conventional power sources. In search for new applications for the solar cell Hoffman Electronics finds together with James Coolbaugh space satellites as an attractive platform to make use of the new technology. A big advantage of the space industry was the Cold War, which resulted in promising budgets.</td>
<td>(Bell Labs, 2011; The space...</td>
</tr>
<tr>
<td>Year</td>
<td>Event</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>1956</td>
<td>Hoffman Electronics buys National Fabricated Products and continue their photovoltaics programme. They announce a portable radio with battery which could be charged and powered making use of solar cells, although the battery alone could last for 8 months. The power pack with solar cell from this radio costs 185 dollar, against a conventional battery with capacity for 100 hours for less than a dollar (1956 prices).</td>
<td></td>
</tr>
</tbody>
</table>
| 1958 | The satellite Vanguard I is launched with an less than 1W photovoltaic array, from Hoffman cells, to power the radios. Later the Explorer III, Vanguard II and Sputnik III (from the Russians) are launched with photovoltaic powered systems.  
*From this moment on the space industry had a large demand for solar cells and as a consequence a relative large manufacturing business for companies is created.*  
Development of organic solar cells continues; Kearns et al. develop magnesium phthalocyanines based cells. |
| 1963 | Sharps start mass production of silicon solar cells. They immediately deliver solar cells for the Tsurumi light buoy in Yokohama Port.  
*From the mid-60s to early 70s on the coast guard made more and more use of solar cells to power buoys.* |
| 1965 | First amorphous silicon layer reported. |
| 1970 | Elliot Berman working for Exxon develops a way to dramatically reduce solar cell costs by using lower grade, cheaper, silicon and less expensive packaging materials. |
| 1972 | Cadmium telluride is invented |
| Mid 1970 | Oil companies substituted their maintenance expensive batteries for a cheaper combination with solar cells for powering their horns and flashlights on oil rigs.  
*Also oil and gas companies saw this as a long term investment in search for other energy sources since the 1973 OPEC oil embargo.* |
<p>| 1974 | Start of Japans Project of Sunshine, which has as aim the development of solar |</p>
<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>NASA Lewis Research Center installed 20 off-grid PV systems. <em>First notable PV potential demonstration project.</em> Semiconductor properties are demonstrated for amorphous silicon by Spear and LeComber.</td>
</tr>
<tr>
<td>1976</td>
<td>First a-Si:H solar cell is made by Carlson and Wronski with an conversion efficiency of 2.4%. <em>In the 70s s-Si is mainly used for calculators and watches.</em></td>
</tr>
<tr>
<td>1977</td>
<td>Vespieren starts using solar powered pumps for water in Mali. <em>This is the first of several projects using solar powered water pumps, in mainly underdeveloped countries.</em></td>
</tr>
<tr>
<td>1979</td>
<td>Telecom Australia begins providing Australians living in remote areas with high-quality telecommunication services by making use of solar power supplies. <em>First major solar powered telecommunications link in Australia.</em></td>
</tr>
<tr>
<td>1986</td>
<td>First heterojunction PV is developed by Tang.</td>
</tr>
</tbody>
</table>
Appendix VII. **SCHEMATIC DIAGRAMS OF PV TECHNOLOGIES**

**Figure 35**: The photovoltaic cell; left crystalline silicon (1st generation), right the second generation technology amorphous silicon (Zeman, 2011)

*Black lines on both sides indicate the junction area of the cell. The lines in between the pictures indicate the relative size to each other.*
Fig. 3. Schematic diagrams of thin-film CdTe, CIGS and a-Si thin-film PV devices.

Fig. 4. Key features of the crystalline silicon on glass (CSG) technology (Green et al., 2004).

FIGURE 36: DIAGRAMS 2G PV (BAGNALL & BORELAND, 2008)
Figure 37: Multi-junction or tandem cell; a-Si:H/a-SiGe:H (Zeman, 2011)
Appendix VIII. **Timeline of Worldwide PV Policies**

**Figure 38:** Policy initiatives in relation to the annual incremental growth of installed PV capacity in the US (1993–2007) (Brown & Hendry, 2009)

**Figure 39:** Policy initiatives in relation to the annual incremental growth of installed PV capacity in Japan (1993–2007) (Brown & Hendry, 2009)
Figure 40: Policy initiatives in relation to the annual incremental growth of installed PV capacity in Japan (1993–2007) (Brown & Hendry, 2009)
**Figure 41: Policy support mechanisms in several countries (IEA, 2010b)**

| Policy Support Mechanism                        | AUS | AUT | CAN | CHE | DNK | DEU | ESP | FRA | ISR | ITA | JPN | KOR | MEX | MYS | NLD | NOR | PRT | SWE | TUR | USA |
|------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Enhanced feed-in tariffs                       | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | *(2)* | ✔   | ✔   | ✔   | ✔   |
| Direct capital subsidies                       | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Green electricity schemes                      | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| PV-specific green electricity schemes          | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Renewable portfolio standards (RPS)             | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| PV requirement in RPS                           |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Investment funds for PV                         | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Tax credits                                     | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Net metering                                    | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Net billing                                     | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Commercial bank activities                      | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Electricity utility activities                  | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Sustainable building requirements               | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| Indicative household retail electricity price USD cents (1.) | 10.2–16.6 | 10.4 | 6.1 | 14.7 | 37.5 | 31.5 | 12.5 | 23.6 | 10.1–25.8 | 13.3–19.6 | 13.3–19.6 | 17.3–26.2 | 10.1–14.3 | 10.3–10.2 | 10.3–20.9 | 16.0 | 10.4 |

**Notes:**
1. Typical residential kWh price expressed in USD cents (1 USD/100), including all taxes but not including variations due to time of use, total electricity consumption or any fixed rates.
2. Local, community-based scheme.
3. Demonstration programme.
<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Type of strategy</th>
<th>Programme name</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>US</td>
<td>Net metering</td>
<td>&quot;REN&quot;</td>
<td></td>
</tr>
<tr>
<td>1987-present</td>
<td>DE</td>
<td>Rebate</td>
<td>&quot;1000-Dächer-Programm&quot;</td>
<td></td>
</tr>
<tr>
<td>1991-2000</td>
<td>CH</td>
<td>Voluntary target programme</td>
<td>&quot;200 kW PV-Programm&quot;</td>
<td></td>
</tr>
<tr>
<td>1992-1994</td>
<td>AT</td>
<td>Rebate</td>
<td>&quot;Kostendeckende Vergütung&quot;</td>
<td></td>
</tr>
<tr>
<td>1992-1999</td>
<td>DE, CH, AT</td>
<td>Regulated rates</td>
<td>&quot;Minimum PV promotion programme&quot;</td>
<td></td>
</tr>
<tr>
<td>1993-1997</td>
<td>US</td>
<td>Contracting</td>
<td>&quot;PV pioneer I&quot;</td>
<td></td>
</tr>
<tr>
<td>1994-present</td>
<td>DE</td>
<td>Rebate, contribution</td>
<td>&quot;Sonnen in der Schule&quot;, &quot;SONNEonline&quot;</td>
<td>launched by various utilities and Governmental institutions</td>
</tr>
<tr>
<td>1996-present</td>
<td>DE</td>
<td>Green pricing</td>
<td>&quot;Umwelttarif&quot;</td>
<td></td>
</tr>
<tr>
<td>1996-present</td>
<td>CH</td>
<td>Bidding/Green Pricing</td>
<td>&quot;Solarstrombörse&quot;</td>
<td></td>
</tr>
<tr>
<td>1997-present</td>
<td>NE</td>
<td>Voluntary target programme</td>
<td>&quot;Heading into the Solar age together&quot;</td>
<td></td>
</tr>
<tr>
<td>1997-present</td>
<td>CH</td>
<td>Green Pricing</td>
<td>&quot;Solarstrom vom E-Werk&quot;</td>
<td></td>
</tr>
<tr>
<td>1997-2001</td>
<td>DE</td>
<td>Bidding</td>
<td>&quot;Solarbörse Berlin&quot;</td>
<td></td>
</tr>
<tr>
<td>1998-present</td>
<td>DE</td>
<td>Labelling</td>
<td>Golden and Silver label (EUROSOLAR)</td>
<td></td>
</tr>
<tr>
<td>1999-present</td>
<td>AT</td>
<td>Shareholder</td>
<td>&quot;Sonnenschein&quot;</td>
<td></td>
</tr>
<tr>
<td>1999-present</td>
<td>DE</td>
<td>Soft loans</td>
<td>&quot;100,000 Dachvertrag&quot;</td>
<td></td>
</tr>
<tr>
<td>1999-present</td>
<td>NE</td>
<td>NGO initiative</td>
<td>&quot;SOLARIS&quot;</td>
<td></td>
</tr>
<tr>
<td>1999-present</td>
<td>US (CA)</td>
<td>Rebates</td>
<td>&quot;California's emerging renewables buydown programme&quot;</td>
<td></td>
</tr>
<tr>
<td>1999-present</td>
<td>AU</td>
<td>Rebates</td>
<td>&quot;PV Roof Program&quot;</td>
<td>For grid and off-grid buildings. Revised 2000</td>
</tr>
<tr>
<td>2000-present</td>
<td>DE</td>
<td>Enhanced feed-in tariff</td>
<td>&quot;Neues Einspeisegesetz (EEG)&quot;</td>
<td></td>
</tr>
<tr>
<td>2000-present</td>
<td>DE</td>
<td>Rebate, contribution</td>
<td>&quot;Kirchengemeinden für die Sonnenenergie&quot;</td>
<td></td>
</tr>
</tbody>
</table>

Figure 42: Historical policies (IEA, 2002)
Appendix IX. LIST OF INTERVIEWS

This appendix provides a list in alphabetical order of the people interviewed for this research. Only interviews that added significant insights for this study have been listed.

<table>
<thead>
<tr>
<th>Name</th>
<th>Organisation or company</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knulst, Walter</td>
<td>LineSolar</td>
<td>CSO (Chief Scientific Officer).</td>
</tr>
<tr>
<td>Laan, Jorrit</td>
<td>Infinity NRG</td>
<td>Owner of Infinity NRG.</td>
</tr>
<tr>
<td>Olivierse, Teus</td>
<td>Solar Electricity</td>
<td>CEO (Chief Executive Officer).</td>
</tr>
<tr>
<td>Van Roosmalen,</td>
<td>ECN</td>
<td>Project leader Joint Solar Panel. Senior scientist crystalline silicon &amp;</td>
</tr>
<tr>
<td>John Sinke, Wim</td>
<td>ECN, Utrecht University</td>
<td>device architecture.</td>
</tr>
<tr>
<td>Smets, Arno</td>
<td>TU Delft</td>
<td>Associate professor section ‘photovoltaic materials and devices’, faculty</td>
</tr>
<tr>
<td>René Vlek,</td>
<td>Solar Modules NL</td>
<td>Sales manager.</td>
</tr>
<tr>
<td>Weeber, Arthur</td>
<td>ECN</td>
<td>Project leader ‘Silicon Photovoltaics’, section ‘Device Architecture &amp;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integration’. Guest lecturer at TU Delft.</td>
</tr>
</tbody>
</table>

**Table 41: List of interviews**


Cals, R. (2011, June 1). From Energiebau.


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Laan, J. (2011, September 12). Interview with Infinity NRG.


Sinke, W. C. (2011, July 1). Interview at ECN.


van Roosmalen, J. A. M. (2011, July 6). Interview at ECN.


Weeber, A. (2011, June 28). Interview at ECN.


Thank you for reading my thesis. If you have any questions, comments or if you want to use parts of this thesis, please contact me at: allarddewinter@gmail.com