MSc Program

Renewable Energy in Central and Eastern Europe

Can CdTe PV Modules become the Market Leading PV Technology and Replace Crystalline Modules based on Current Market Dynamics, Aspects of Sustainability and Price Developments?

A Master's Thesis submitted for the degree of
"Master of Science"

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Affidavit

I, SEDAT IRDELP, hereby declare

1. that I am the sole author of the present Master Thesis, "CAN CDTE PV MODULES BECOME THE MARKET LEADING PV TECHNOLOGY AND REPLACE CRYSTALLINE MODULES BASED ON CURRENT MARKET DYNAMICS, ASPECTS OF SUSTAINABILITY AND PRICE DEVELOPMENTS?",
46 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

As a result of recent unprecedented growth and high future expectations of growth this analysis aims to identify, whether promising CdTe thin film modules have the chance of becoming the market leading PV technology. Specifically this work will compare CdTe modules with currently market leading crystalline PV modules and evaluate the prospects of the former overtaking the latter in years to come. Both technologies will be evaluated by means of a SWOT analysis in three important areas: market characteristics focused on supply and demand, sustainability concentrated on the use of raw materials, possible impacts on the environment and energy payback and economic development dedicated on the analysis of the price changes.

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Abbreviations

a-Si	amorphous silicon
CAGR	compound annual growth rate
c-Si	crystalline silicon
CdTe	cadmium telluride
CIGS	Copper Indium Gallium Diselenide
CIS	Copper Indium Diselenide
EPIA	European Photovoltaics Industry Assocaition
EU	European Union
GW	gigawatt
kW	kilowatt
kg	kilograms
kWh	kilowatt hour
LCOE	levelised cost of energy
NiCd	nickel cadmium
lbs	pounds
MW	megawatt
PV	photovoltaic
W	watt

1. Introduction

In a rapidly developing world, in which natural resources are scarce the movement towards a sustainable future, especially in terms of energy production and supply security, is an inevitable necessity to cement and secure wealth, prosperity and the ecological balance of the Earth. Among one of several solutions is the harnessing of the sun to create abundant, clean and sustainable solar energy through the use of photovoltaic modules. Although the concept of photovoltaic technology has been around for many decades, the demand for this technology only started to gain noticeable momentum during the past decade in light of the numerous support schemes initiated by various countries around the world. Despite photovoltaic energy being the production of electricity from photons, there are a number of different kinds of modules made of different materials. Generally speaking photovoltaic modules are categorised into silicon based crystalline or thin-film modules, of which CdTe modules currently have the largest market share. Yet when considering PV energy to be one of the key factors to a sustainable source of electricity, it is important to analyse, which PV modules and technology are the most promising and viable for decades to come.

1.1. Objective of the thesis

The objective of this thesis is to identify whether thin-film CdTe PV modules have the potential and prerequisites of overtaking and replacing current market leading crystalline PV modules in years to come. To reach this objective and establish a sound conclusion this research will make use of a SWOT analysis of a number of important factors and aspects of both the crystalline and CdTe PV technologies. The aspects analysed will include current and future market trends, supply and demand and the production costs and prices of CdTe and crystalline PV modules. Furthermore, the sustainability of both technologies will be evaluated on the basis of the use of raw materials and their sources, the energy payback, module lifetimes and power generating capacities of CdTe and crystalline modules.

The growing importance and greater implementation of PV technology as a renewable source of energy, makes this analysis both current and relevant in today's environment. Moreover the direct comparison between two PV technologies, crystalline technology, which is the pioneering and market leading PV technology commercially available and CdTe technology, the leading and most cost competitive of all currently available commercial thin-film PV technologies, signals the importance of this form of analysis.

2. General characteristics of silicon crystalline and CdTe PV modules

A PV system uses solar radiation to generate electricity through semiconductors that display the photovoltaic effect. The basic building block of a PV system is the PV cell, which consists of the semiconductor material and generates direct current electricity. These cells are interconnected to form a module, which also acts as a protection of the individual cells. The power output of a module varies from manufacturer to manufacturer and depends on the semiconductor material, but typically they are between 50W and 250W. "The PV modules combined with a set of additional application-dependent system components (e.g. inverters, batteries, electrical components, and mounting systems), form a PV system." (IEA, October 2010) Depending on the semiconductor material used in the cell, they are categorised into crystalline silicon or thin film cells. The market for crystalline cells is generally split among multi- and mono-crystalline, although a small fraction of the market also consists of string-ribbon cells. On the other hand thin-film cells can further be split into three groups: i) amorphous and micromorph silicon, ii) Cadmium Telluride and iii) Copper Indium Diselenide and Copper Indium Gallium Diselenide.

The significant difference between crystalline and thin film cells is the thickness and pliability. Crystalline cells consist of crystalline or solar grade silicon, which has a purity of 9.9×10^{10} % and is also sometimes referred to as 9N silicon. (Kaltschmitt et al, 2007) Owing to the energy gap crystalline silicon is not regarded as an ideal semiconductor material for PV cells. (Kaltschmitt et al, 2007). "Furthermore, silicon is a so-called indirect semiconductor material whose absorption coefficient for solar radiation shows relatively low values." (Kaltschmitt et al, 2007) "The typical thickness of multi- and mono-Si PV is 200 and 180 µm, respectively." (Fthenakis et al, August 2011) As a result the cells benefit from a higher contact surface area thus increasing efficiency and output, but are also subject to far higher material costs.

On the contrary the semiconductor materials used in CdTe cells have an energy gap, which is closer to the theoretically achievable optimum efficiency. Thus these cells require significantly less semiconductor material, for which a typical thickness of three microns is required. (Kaltschmitt et al, 2007) However, due to less contact surface area CdTe cells are also less efficient than crystalline cells, but benefit from lower material costs. (Kaltschmitt et al, 2007)

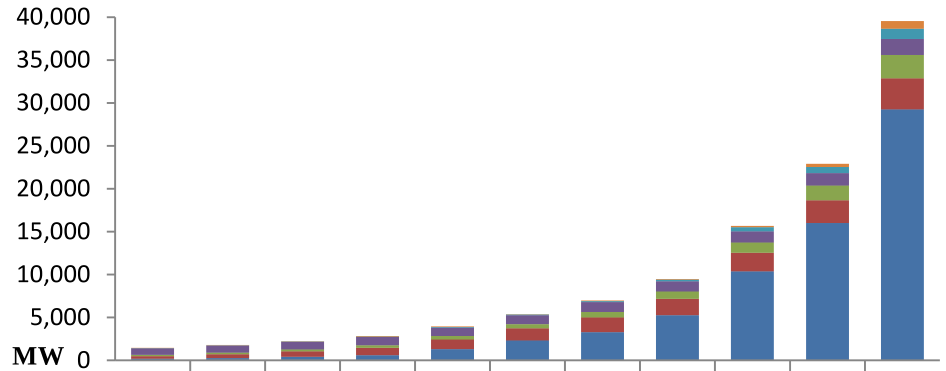
Although there are significant differences in terms of power output and efficiency between crystalline and CdTe modules, it is inaccurate to compare absolute figures, but rather should one evaluate the levelised cost of energy (LCOE) and balance of systems cost, which will be analysed in chapter 5. One should however note that due to the characteristics of the different materials used, the two technologies perform in different ways under diverse conditions. Especially temperature and radiation are the two major factors affecting the performance of PV system during operation. Given their properties CdTe modules have proven to cope better with lower solar irradiation levels and increasing temperatures than crystalline modules. (Mehta, November 2010) These characteristics are and should therefore be considered when determining which technology better suits a given location.

3. Global PV market

3.1. Installed capacity and market size

In 2010 the global cumulative installed PV capacity reached 39.5 GW. (EPIA, May 2011) A closer analysis of the global cumulative installed PV capacity shows significant regional imbalances and how limited PV energy is distributed throughout the world. Figure 3.1 shows the evolution of the cumulative installed PV capacity by region, from which one can clearly deduct that the EU is the most significant PV market worldwide, followed by Japan and North America. In 2010 the EU alone had an installed capacity of 29.3 GW thus accounting for 74% of the global installed PV capacity. (EPIA, May 2011) Although accounting for nearly three quarters of the global installed capacity the EU only accounts for less than 5% of the world’s land surface area and roughly 7% of the global population. (www.cia.gov) Moreover the regional imbalance pattern seen on a global scale also holds true when looking at the country shares of the installed PV capacity within the EU. As seen in Figure 3.2 the cumulative installed PV capacity in Germany represents a market share of over 58%. This being said, over 83% of the entire EU PV energy market is accounted for by the three largest markets, Germany, Spain and Italy.

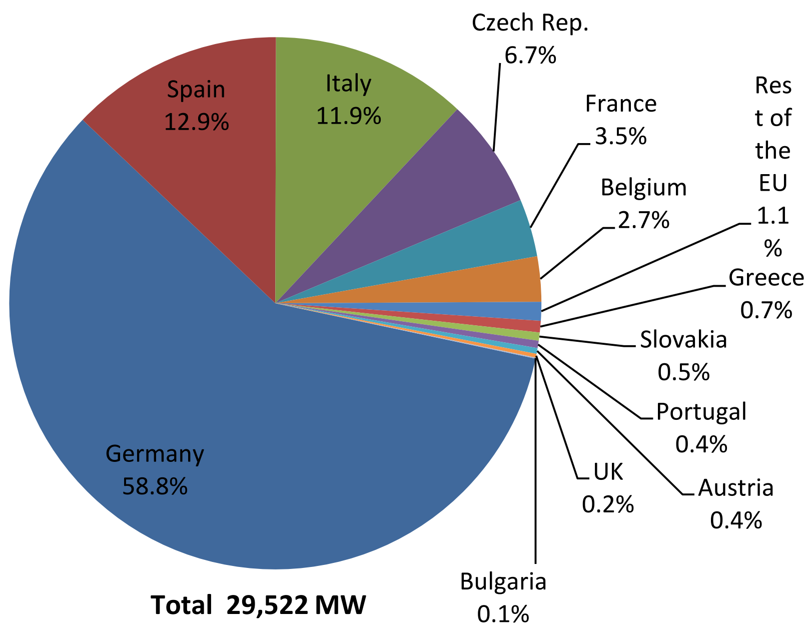
Figure 3.1 – Cumulative installed PV capacity by region



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
China	19	30	45	55	64	68	80	100	145	373	893
APEC	38	43	49	57	66	80	112	170	466	718	1,191
Rest of World	758	814	894	971	1,000	1,010	1,128	1,190	1,303	1,427	1,844
North America	146	177	222	287	379	496	645	856	1,205	1,744	2,727
Japan	318	452	637	860	1,132	1,422	1,708	1,919	2,149	2,632	3,622
EU	181	275	414	613	1,319	2,324	3,307	5,257	10,387	16,006	29,252

Source: EPIA 2011

Figure 3.2 – Cumulative installed PV capacity within the EU 2010

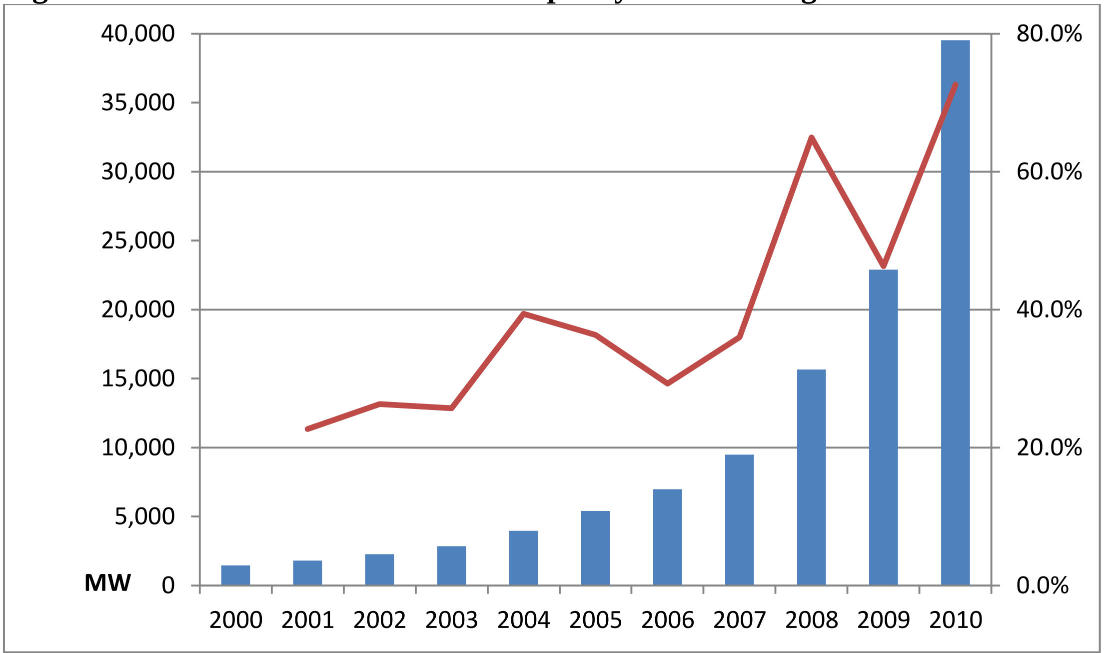


Source: EPIA 2011

3.2. Developments and growth of the PV market

The PV market has experienced extraordinary growth over the past decade especially through the implementation of support schemes in a number of countries as well as the growing awareness for renewable energies. While only having a cumulative installed capacity of 1.5 GW in the year 2000, the global PV market reached 39.5 GW in 2010. (EPIA, May 2011) This growth translates into a CAGR of 39.1% over the respective time period. Moreover when evaluating the year on year growth rates of the past decade, significantly different dynamics can be identified. Especially in the second half of the past decade the cumulative installed capacity grew substantially faster than in the first half despite the financial crisis and global recession. Whereas the CAGR from 2000-2005 is 29.9% the CAGR from 2005-2010 is 48.9%, which clearly underlines the significance of the past five years for the PV market. A further breakdown of the growth of the past five years shows that the PV market experienced its largest year-on year growth in 2010, during which the cumulative installed capacity increased by 72.6%. Figure 3.3 shows the cumulative installed PV capacity and year on year growth for the past ten years.

Figure 3.3 – Cumulative installed PV capacity and annual growth 2000-2010



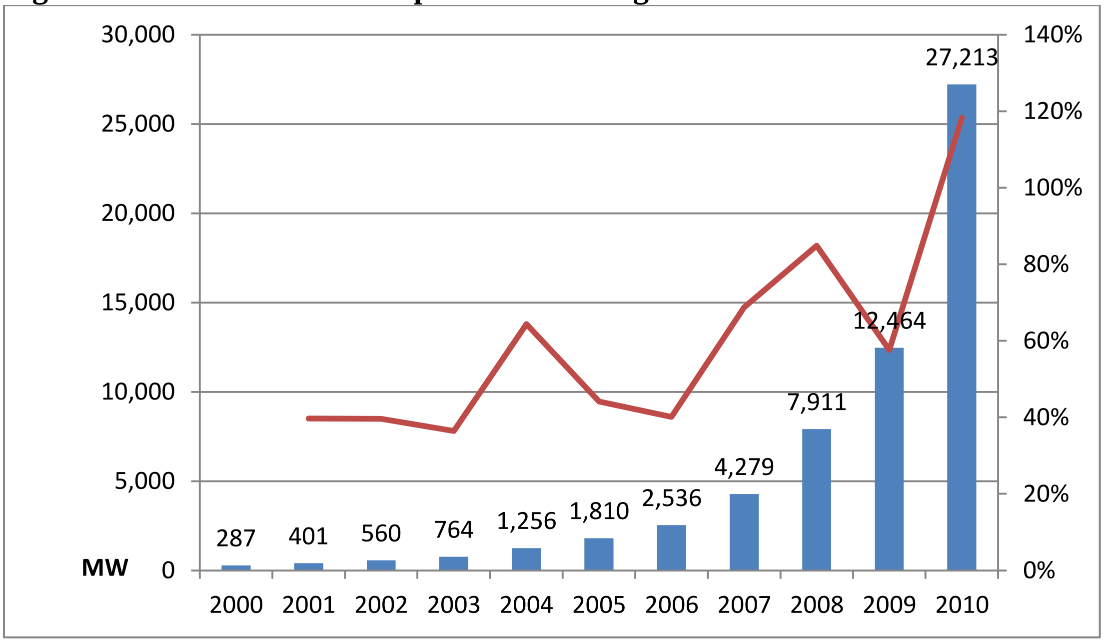
Source: EPIA 2011

3.3. Market shares of crystalline and CdTe cell production

Moreover the analysis of the crystalline and CdTe market shares of annual PV cell production over the past ten years is necessary to evaluate the future prospects of the respective technologies. The following findings give light to a significantly imbalanced market in favour of crystalline cells. Before commenting on the actual market shares of the production of PV cells one should note that CdTe PV technology has not been commercially available for as long as crystalline PV technology. The first commercially available CdTe modules were produced in the 1990s whereas crystalline PV modules have been used for over half a century, albeit mainly for off-grid and space purposes for the majority of that time period, thus justifying a certain degree of imbalance in the market shares. Therefore the analysis should consider both the growth in market share and the market share itself over the past decade when trying to determine the prospects and trends of CdTe compared with those of crystalline cells.

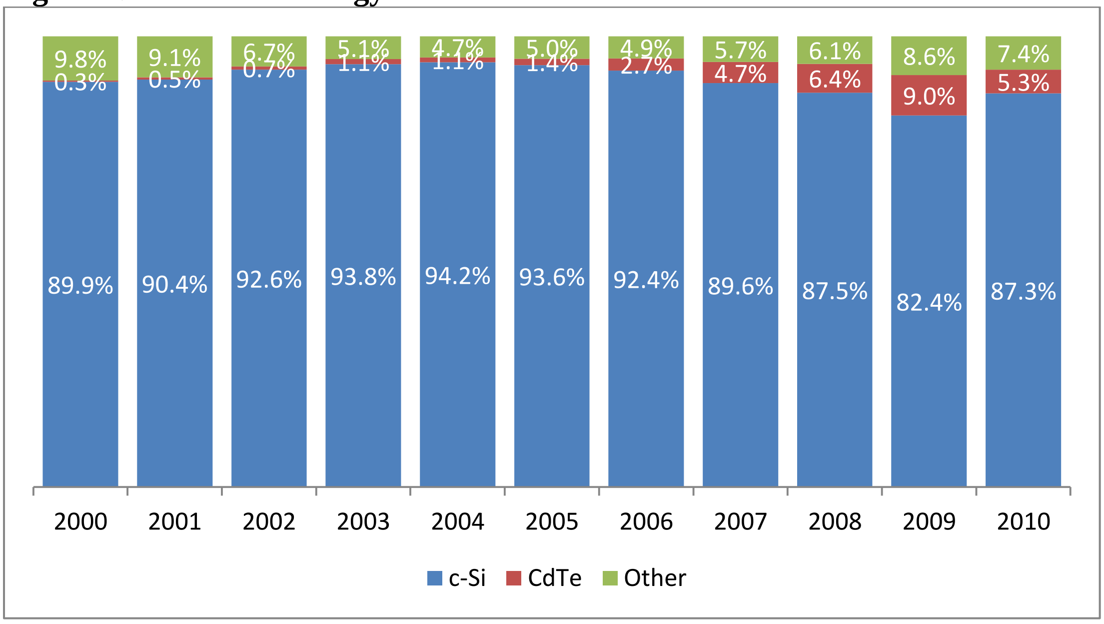
The market shares of the PV cell production over the past decade as seen in Figure 3.4 show the dominating role of crystalline modules compared to thin film PV technologies including CdTe cells. In the year 2000 crystalline cell production accounted for 89.9% whereas the CdTe cell production was nearly non-existent with a market share of only 0.3%. (Hering, March 2011) However, the rapid development and increasing CdTe cell production can be observed as the market share increased in every year until staying flat at 1.4% in 2004. Over the same time-period crystalline cell technology steadily increased its market share to reach 94.2% in 2004, marking the highest market share over the entire decade. (Hering, March 2011) Midway into the last decade CdTe cell production was able to increase its market share while that of crystalline cells experienced a decrease to reach its lowest share of 82.4% in 2009. In 2009 CdTe cell production experienced its height with a market share of 9%, which was a result of the large-scale ramp up of CdTe market leading First Solar, which also ranked number one in terms of cell production of the entire PV market. (Hering, March 2011) Another milestone was also reached a year earlier in 2008, when CdTe cell production had the largest market share of all thin-film technologies with 6.4%. (Hering, March 2011) Although CdTe cell production experienced a growth of 30% in absolute terms in 2010, its market share slipped to 5.3% thus stopping the trend that had developed from 2004. (Hering, March 2011) Nevertheless CdTe cell production remained in the top spot among all thin film technologies. Crystalline cell production was the clear winner of 2010 and saw its market share recover from the previous year low to reach 87.3%. (Hering, March 2011) Within the crystalline sector multi-crystalline cell production with a market share of 52.9% clearly outpaced the mono-crystalline cell production, which accounted for 33.2%. (Hering, March 2011)

Figure 3.4 – Annual solar cell production and growth 2000-2010



Source: Photon International, March 2011

Figure 3.5 – Cell technology market shares 2000-2010



Source: Photon International, March 2011

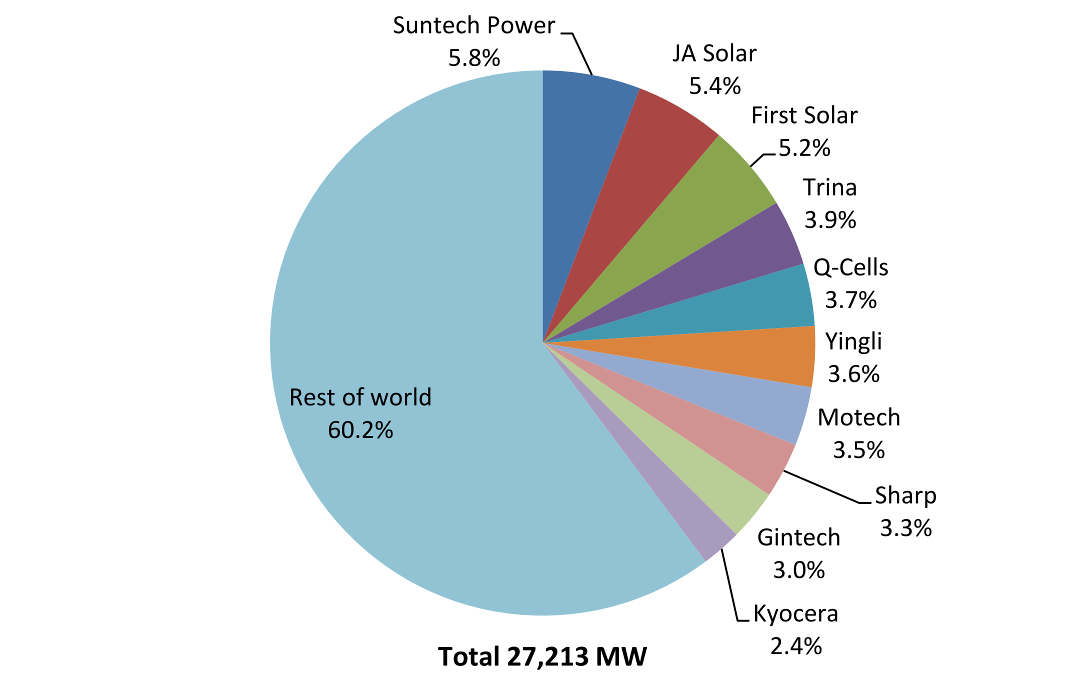
The production figures over the past ten years clearly demonstrate the leading position of the crystalline cell industry. Although losing some momentum in the second half of the decade the share of crystalline cell production never dropped below 80% and was able to rehabilitate itself in the record year 2010. Nevertheless CdTe PV technology also is a winner of the past decade as it was able to establish itself as the leading thin film technology. However remarkable the trend of CdTe cell production was from 2004 until 2009, the market faces a number of challenges, which is underlined by a decline in market share in 2010. Firstly as explained in section 3.4 the large increase in CdTe cell production can be attributed to a single company, rather than numerous companies carrying out large ramp-ups as was the case in crystalline cell industry. In addition a significant consolidation in crystalline cell prices also led to the remarkable cell output in 2010. Even though the recent developments in PV cell production show that CdTe PV is a highly prospective technology, it remains doubtful whether it will realistically be in a position to challenge the crystalline cell industry and possibly becoming the leading PV technology.

3.4. Crystalline vs. CdTe cell production and number of producers

Further to the evaluation in chapter 3.3 regarding the market shares of PV cell production in terms of technology, the evaluation of the number of cell manufacturers and production capacities is another important aspect in determining whether the supply-side of CdTe has a potential of substantially increasing its market share and possibly reach levels as seen in the crystalline cell production. Whereas the crystalline cell market consists of a large number of multinational manufacturers throughout the world, the CdTe cell market is characterised by only a small number of producers.

A look at the top ten solar cell production shares as seen in Figure 3.6 clearly shows how imbalanced PV cell production is and the disparity between crystalline and CdTe cell production. Among the top ten First Solar is the only company to produce CdTe cells, whereas the remaining nine companies are all specialised on crystalline cell production. (Hering, March 2011) Especially the two industry leaders in terms of cell production were able to significantly increase their production and capacities in 2010 thus taking the number one and number two spot respectively. Moreover one should note that among the top ten Sharp is the only other company also producing thin-film PV cells made from a-Si.

Figure 3.6 – Top 10 PV cell producer market shares in 2010



Source: Photon International, March 2011

Although the analysis of the top ten PV cell manufacturers can lead to early conclusions dismissing the potential of CdTe cell output further increasing and having the possible prospects of replacing crystalline cells in the future, one must always evaluate the entire market and analyse where the strengths and possible opportunities lie. As of 2009 there are only four commercially operating CdTe cell producers. (EPIA and Greenpeace, February 2011) Moreover it is important to point out that of the small number of producers, market leading First Solar accounts for almost all global CdTe cell production. With its overall market share of 5.2% in 2010, Frist Solar accounted for approximately 98% of CdTe PV cell production. In addition to being the largest CdTe cell producer, First Solar was also the number one PV cell producer overall in 2009, ahead of today's first ranked Suntech and second placed JA Solar. (Hering, March 2011) From this market share one can conclude that the CdTe market is characterised by a monopoly.

Among the most significant problems of a monopoly are the high barriers to entry for prospective companies aiming to enter the market. Ultimately, these high barriers to entry eliminate future competition, one of the most important drivers for continued and sustainable growth of markets. Firstly, the more competitive an industry is, the quicker technological advances and product innovations take place as the companies try to become the industry leader. In addition if smaller competitors are unable to survive as a result of a monopoly, the monopoly company is in a strong position to acquire the smaller competitors and thus practically eliminate near to all competition in the market. Furthermore, in a competitive market environment companies will also engage in price warfare thus causing prices to systematically decrease over time. As a result demand for the offered goods and services increases and enables further growth of the market.

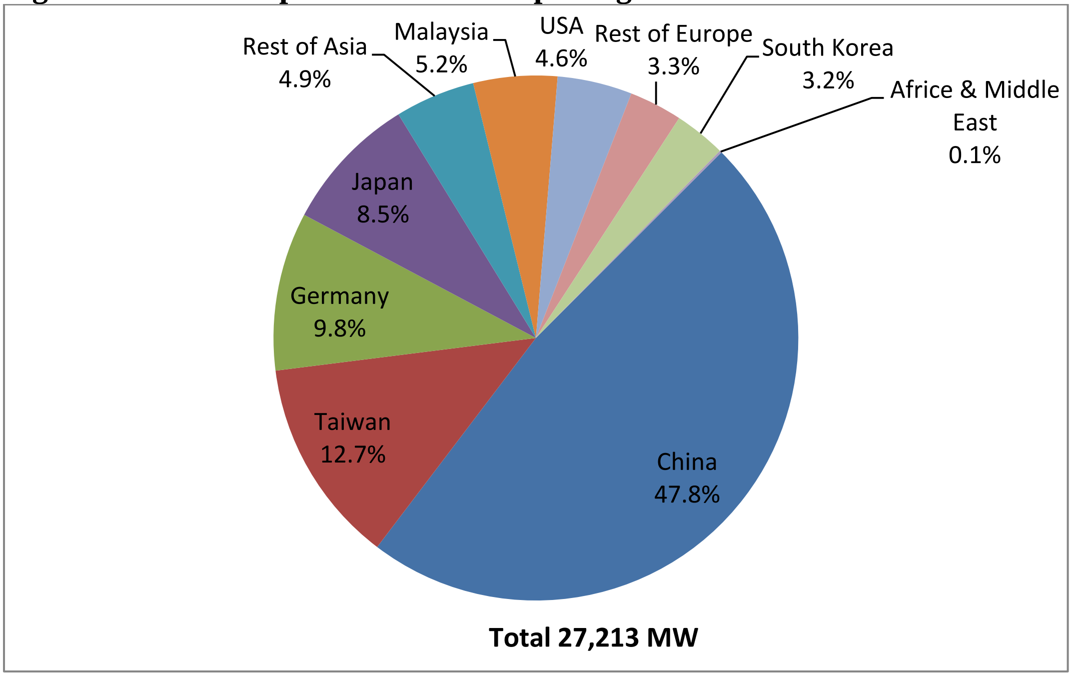
From the current monopoly structure in the CdTe market one can therefore deduce that there are a number of weaknesses and threats to the future growth prospects of CdTe PV technology. The dominant position of First Solar makes it almost impossible for new competitors to enter the market, which can cause a major obstacle for possible technological innovations and limit the output of CdTe PV cells and modules. Although a monopoly, First Solar was able to systematically reduce price and costs of CdTe, due to the competition from crystalline PV cells, which has been positive for the CdTe market. However it is therefore questionable whether other CdTe cell producers, which have the financial strength to enter the market, will be able to withstand both the price pressure from First Solar as well as the continually consolidating prices of crystalline cell manufacturers. The effects of the negative impact of the monopoly situation can also be observed by the fact that as a result of the market share of CdTe cells of overall PV cell production decreased in a growing market, due to the fact that First Solar did not carry out any significant capacity ramp-ups. (Hering, March 2011) Thus the future development and prospects of CdTe technology replacing crystalline technology in years to come is at jeopardy if the production of CdTe cells continues to rely on a single company.

In addition there are very few drivers that enable an industry to become competitive and attract more players. The quickest and most efficient way of enabling competition is through government subsidies and beneficial legislation for prospective market entrants. Among government support, the United States stands out as one of the greatest supporters of CdTe PV technology through the loan guarantees the Department of Energy (DoE) distributes to CdTe cell manufacturers. One could note that although the loan guarantees act as subsidies they are a more effective way of financing competition as companies are motivated to become profitable sooner rather than later.

Despite the disadvantageous market structure for CdTe cells, recent developments show that existing players have committed large investments for major production ramp-ups. General Electric announced in 2011 that it would be investing into a new CdTe module factory with a yearly capacity of 400 MW. Although this is still only a fraction of First Solar's production capacity, it signals the an important step into the right direction for the future development of the CdTe market and diluting First Solar's dominance. (Enkhardt, 2008) In addition Calyxo, a former Q-Cells subsidiary that was fully acquired by Solar Fields LLC in 2011, has also completed a ramp up to increase its annual production capacity to 135 MW. (www.calyxo-solar.com) The move by General Electric, one of the world's largest industrial companies, may prove to be one of the most crucial developments in the CdTe market as it may serve as a precedent for other large multinational companies considering a possible market entry. Although these developments enhance the competition to some degrees it remains doubtful that the CdTe will actually move towards a more competitive market structure as it will be dominated by large multinational corporations and may make a market entry for new smaller companies even more difficult in the future. Therefore, the prospects of the CdTe market will continue to ride on the performance of a select few players.

On the other hand the crystalline module market has many well-established companies with large production capacities that by themselves encourage competition and innovation, which is reflected in the size of the market itself. As seen in Figure 3.6 the majority of the crystalline cell manufacturers in the top ten have similar market shares. However, recent PV cell production figures show the shifting power towards Asia, especially China, which accounted for over 47% of global PV cell production as seen in Figure 3.7. (Hering, March 2011) On one hand this can be considered a risk as the majority of the production is concentrated n one region, which could dictate supply to PV markets around the world. In contrast the growing importance of China can also be seen as a benefit as the module prices are significantly lower than those of other producers from western countries as further discussed in section 5.

Figure 3.7 – PV cell production shares per region 2010



Source: Photon International, March 2011

Given these premises the market shares and structure give reasonable doubt as to how much further the CdTe market will be able to grow in order to catch up and potentially overtake the crystalline module market in years to come. The CdTe will have to outperform and add more production capacities than the crystalline market in coming years if it is to overtake the latter. Finally the prospect of the CdTe market becoming more competitive and attracting further players will also play a significant role as to the prospects of becoming the leading PV technology. As long as the development of the CdTe market relies solely on Frist Solar, the market will remain a niche sector and never fulfil the prospects of substantially increasing its market share.

3.5. Future outlooks and prospects for PV energy

In order to help achieve the global climate goals at the lowest cost, PV will need to play a significant role in the world's energy mix in 2050. (IEA, October 2010) The momentum of the PV market is expected to carry on in forthcoming years, especially as PV energy moves closer towards grid parity and countries implement PV systems to reach renewable energy and carbon emission reduction targets. Due to an array of factors affecting the development of the PV market there are a number of growth scenarios and figures the PV market will actually reach. EPIA and Greenpeace

(February 2011) have established three scenarios, the reference, accelerated and paradigm shift scenarios, to predict the cumulative installed PV capacity until 2050. According to the reference, accelerated and paradigm shift scenarios the global installed PV capacity is expected to grow at a CAGR of 5.1%, 10.7% and 11.9% respectively until 2050, whereby the installed capacity in 2050 is expected to reach only 377 GW under the reference scenario and levels of 2,988 GW and 4,669 GW under the accelerated and paradigm shift scenarios respectively. (EPIA and Greenpeace, February 2011)

The evaluation of the market shares crystalline and CdTe modules will have in the future is significantly more problematic, as technological advances and raw material price developments cannot be accurately predicted. Crystalline PV modules are expected to remain a dominant PV technology until at least 2020, with a forecasted market share of about 50% by that time. (IEA, October 2010) Under a different scenario crystalline modules are expected to only drop to a market share of 61% in 2020, whereby thin-film modules as a whole will account for about 33% of the entire market. (EPIA and Greenpeace, February 2011) Despite remarkable growth to a market share 13% from 2005 until 2010 CdTe modules are expected to account for ca. 10% in 2020. (EPIA and Greenpeace, February 2011) Albeit only forecasted until 2020, these figures suggest that it will remain unlikely for CdTe modules to gain a market share similar to that of crystalline modules post 2020. It is important to note that CdTe modules also face competition from other thin film technologies such as CIS or CIGS, which have proven to have higher efficiencies. Furthermore, as mentioned earlier the low number of CdTe module manufacturers also makes future growth more difficult. Even if the aforementioned scenarios do not hold about the future growth of the CdTe market, it would have to grow at a significantly faster pace than the crystalline module market and the entire PV market to increase its market share, which under current circumstances is questionable.

4. Evaluation of the sustainability of crystalline vs. CdTe PV modules

4.1. Raw materials

4.1.1. Crystalline modules

4.1.1.1. Silicon – the second most abundant element in the Earth's crust

The most important raw material needed for the production of crystalline modules is silicon. Silicon is the second most common element in the Earth's crust, comprising 25.7% of the Earth's crust by weight. (www.eoearth.org) Despite its high abundance, silicon is hardly ever found in its pure, natural state, but rather as a silicate ion in silica-rich rocks such obsidian, granite, diorite and sandstone. (www.eoearth.org) The most common resource, from which silicon is recovered, is sand. The purest form of sand is quartz, which is also known as silicon oxide (SiO_2). Due to the ample supply and the relatively uncomplicated mining and processing of sand, it is the most common supply of silicon. Moreover, the abundant reserves of silicon are expected to easily supply demand for many decades to come. (www.eoearth.org)

To recover silicon the sand undergoes a special reduction method, namely melting electrolysis, though which metallurgical grade silicon with purity between 98% and a maximum of 99% is won. However, metallurgical grade silicon still contains too many impurities to be used to produce crystalline PV modules. Hence a further treatment procedure is required to gain solar grade silicon, for which the impurity content must not exceed 10^{-9}. (Kaltschmitt et al, 2007) The most common method used to purify and transform metallurgical grade silicon into solar grade silicon is the Siemens process. "This purification method starts with the conversion of metallurgical grade silicon into trichlorosilane using hydrochloric acid. The subsequent fractional distillation ensures compliance with the extreme purity requirements. Afterwards silicon is again obtained by pyrolysis of the purified trichlorosilane. In appropriate pyrolysis reactors within a reducing atmosphere the trichlorosilane is decomposed at hot bars. Elementary silicon is separated as polycrystalline material." (Kaltschmitt et al, 2007)

4.1.1.2. Issues concerning c-Si

Although quartz is a readily available resource there are a number of limitations and constraints regarding the downstream market including the supply and production capacities of solar grade silicon and its treatment process. Firstly, the Siemens process used to gain solar silicon is a costly, energy intensive, long-lasting and sometimes inefficient purification process thus resulting in high material costs for the crystalline module industry. In terms of energy, the Siemens process requires approximately 100 kWh to produce one kg of solar grade silicon. (Kreutzmann, February 2007) The main reason for the energy intensity results in the fact that the process takes place over hours, during which the high temperatures in the boilers need to be maintained. In addition to the time and energy consumption come the discrepancies in efficiencies among different producers. Although the most efficient production processes require about 1.3 to 1.6 tons of metallurgical silicon to produce one ton of solar silicon, less efficient processes can require as much as six tons of metallurgical silicon. (Sollmann, January 2009) As a result one of the weaknesses of solar silicon production are potentially inefficient processes, which in return would cause material costs to increase and thus pose a threat to the continued growth of the crystalline PV market.

Although the Siemens process currently still is the most common and effective method of producing high quality solar grade silicon, a number of companies are using alternative treatment processes or developing new ones. One of the commercially feasible and available methods being used is the Vapour-to-Liquid method used by Japanese Tokuyama. (Kreutzmann, February 2007) While being around ten times faster than the Siemens process, whereby drastically reducing energy costs, the produced solar silicon is of lower quality. (Kreutzmann, February 2007) Although the absolute value of the productions costs is reduced, the actual savings are in fact lower, due to the lower efficiencies of the produced crystalline cells. (Kreutzmann, February 2007) A more prospective method of producing solar grade silicon is therefore believed to be the direct purification treatment of metallurgical silicon introduced in 2006. (Sollman, May 2009) The main difference between this process and the energy intensive Siemens process is that fact that the silicon is purified via a physical rather than a chemical reaction. (Sollmann, May 2009) Whereas initial studies show that the energy consumption of the direct purification method is reduced to approximately 15 kWh/kg, the efficiencies of PV cells produced from this form of solar silicon are not as efficient as cells produced from solar silicon purified through the Siemens process. (Kreutzmann, February

2007) These recent developments show the prospects of replacing the Siemens process with the aforementioned purification method thereby highlighting a significant opportunity for the crystalline market to further grow as a result of lower material costs. Nevertheless the true cost savings potential of the direct purification method remains yet to be realised for commercial operation.

Further limitations along the downstream market of solar silicon production become evident when analysing the actual production capacities. Due to the rapid growth in demand for PV energy, especially crystalline modules, the module producers face severe bottlenecks in the supply of solar silicon, which in turn led to production capacity limits as well as extremely high spot prices thus causing high module prices. (Kreutzmann, February 2007) Consequently many solar silicon producers initiated and continue to carry out large ramp-ups of production capacities to meet the heightened demand and ensure sufficient supply for the growing crystalline module industry. (Kreutzmann, February 2007) In light of the financial crisis the capital intensive production capacity expansions were however in jeopardy as a number of producers did not have available the necessary funding sources to follow through with their plans or at best had to delay these. While the production capacities of solar silicon have in fact been successfully increased over past years, continued expansion will be necessary to ensure a sound basis and opportunity for further growth potential of crystalline module producers as well as support reaching the target of making PV electricity from crystalline modules cheaper and thus more available.

Moreover bottlenecks of metallurgical grade silicon are another risk and cause for concern along the solar grade silicon supply chain. Metallurgical silicon can be considered the crucial raw material for the crystalline module industry since solar silicon is won by purifying metallurgical silicon. As a result of the increased crystalline PV module production metallurgical grade silicon is believed to become an even more scarce resource than it currently is. (Sollmann, January 2009) On one hand the problem with metallurgical silicon is that a number of industries, some of which are more mature than the crystalline module industry, demand the material and therefore compete for sufficient and secure supplies. According to some analysts approximately 50% goes to the aluminium industry, 40% is required by the chemical industry and only the remaining 10%, ca. 170,000 to 190,000 tons per year, is shared by the semiconductor and PV industries. (Sollmann, 2009) Although exact production figures are uncertain and the industry relies on estimates it is widely believed that demand for metallurgical silicon has come very close to current supply capacities. (Sollmann, 2009) According to some studies it is estimated that the PV industry will require an additional production capacity between 230,000 and 580,000 tons of metallurgical silicon by 2012 given that there is no excess capacity. (Sollmann, 2009) Therefore, a number of threats concerning future supply levels exist. If other industries should require additional capacities of metallurgical silicon, the PV industry might lose out and face serious bottlenecks. On the other hand it takes time and significant capital to expand the production capacities of metallurgical silicon, which as a result of slow economic recovery or possibly further financial turmoil may not be achieved in the near to short-term. (Sollmann, 2009) These outcomes all have the potential of harming the crystalline module industry from becoming more competitive and growing further through effectively lowering the costs. Nevertheless, if the price of metallurgical silicon increases as a result of higher demand, the PV industry has the advantage that one kg of polysilicon is sold at about four times the price of one kg of metallurgical silicon. (Sollmann, 2009) Thus any price increases resulting from supply constraints can be more easily absorbed and passed on to solar grade silicon manufacturers in the short-term. The supply should therefore be secured for the short to medium term.

Although the downstream market of solar grade silicon may be a reason for concern, due to productions limitations and supply bottlenecks, the upstream market benefits from one of the most widely available resources on Earth. Therefore one should consider the aforementioned issues concerning the raw material only as short-term risks to the crystalline module industry, since production capacity ramp-ups take somewhere between two and three years and quartz is an abundant resource. (Sollmann, 2009) In addition the rapidly increasing demand for crystalline modules should ensure current silicon manufacturers to continue to increase supply and attract new investments by companies willing to invest in the market, thus securing supply for the PV industry.

4.1.2. CdTe modules

The production of CdTe modules requires two relatively rare and scarce elements, cadmium and tellurium. While being able to meet the demand for the PV industry in the foreseeable future, the global reserves of cadmium and tellurium are much smaller than silicon. Similar to silicon though, cadmium and tellurium are not found in their elementary form, but are refined as by-products during the production of other metals and materials.

4.1.2.1. Cadmium

4.1.2.1.1. Characteristics, sources and occurrence

Cadmium is a chemical element found in most zinc ores. Zinc-to-cadmium ratios in typical zinc ores range from 200:1 to 400:1. (USGS, January 2010) The production of cadmium decreased to an estimated 18,800 tons in 2009 from 19,600 tons in 2008. (USGS, January 2010) The global reserves of cadmium, which were calculated as a percentage of zinc reserves, are estimated to amount to 590,000 tons. (USGS, January 2010) Even though there are a number of producing countries of cadmium, China accounted for 22.9% of the global production in 2009, followed by the republic of Korea and Kazakhstan with shares of 12.2% and 11.2% respectively. Although the majority of the production is concentrated in a few countries, there are significant reserves located in countries, which in 2008 and 2009 only produced small amounts of cadmium. Nevertheless the fact that cadmium production is virtually controlled by a few countries can be considered a risk for the future development of the CdTe module production.

Cadmium is not found in its natural state, but in zinc ores. During the refining of ores and the subsequent production of zinc, cadmium is produced as a by-product. Hence one can deduce that the supply of cadmium is derived from the supply of zinc. In 2009 the production levels of cadmium were estimated to decrease as a result of production cutbacks at several zinc smelters. (USGS, January 2010) Despite its dependency on zinc production, the production levels have however remained relatively stable since the 1990s. (www.mmta.co.uk) A secondary source of cadmium is the recycling of NiCd batteries, which were the major driver of demand for cadmium in the middle of the 20th century. (www.mmta.co.uk)

The fact that the use of cadmium is relatively limited can be both considered a benefit as well as a threat to the CdTe industry. On one hand the CdTe module industry benefits from fairly little competition in demand for cadmium, thus allowing potential production increases without necessarily causing significant increases in price for the material; the majority of cadmium is used for NiCd batteries and CdTe modules and smaller amounts are used in pigments, coatings and plating and stabilizers for plastics. (USGS, January 2010) Furthermore, although NiCd batteries still account for a large portion of the demand for cadmium, the demand for NiCd batteries is expected to decrease in years to come, due to the increased use of li-ion lithium batteries. (USGS, January 2010) On the other hand a less competitive market and falling demand levels for cadmium from other industries could result in production cuts thus causing the price to increase and consequently cause the price of CdTe modules to increase. The prices for cadmium over the past decade have increased from about 20¢/lb in 2000 to a high of $6.10/lb in the summer of 2007. (www.mmta.co.uk) However, the relatively low production cost of CdTe modules and the cadmium price increase over the past decade show that a significant further increase in cadmium is required to realistically threaten the supply of cadmium for CdTe modules.

4.1.2.1.2. Issues concerning the toxicity and safety of cadmium

There are numerous differentiating opinions regarding the safety of environmental friendliness of CdTe modules due to the high toxicity of cadmium. The fact that cadmium is a highly toxic heavy metal is undisputed as its use in electronics is also forbidden according to the 2002/95/EG directive, also known as RoHS (Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment). (Sollmann and Podewils, March 2009) However, as this law explicitly exclude cadmium-based coatings such as those used in PV modules. Although claims cannot be verified, some observers believe that successful lobbying from First Solar in Brussels led to the exception. (Sollmann and Podewils, March 2009) Due to the toxicity of cadmium various figures claim that its use in CdTe modules is unsafe and therefore should be forbidden. Especially prominent figures from the crystalline PV sector support this view, although it is unclear whether they express this view out of concern for health and safety issues or rather as a means of trying to eliminate one of the most fierce competitors and successful PV companies. (Sollmann and Podewils, March 2009) A fact is that each First Solar module, the leading CdTe module in the market, contains 7g of cadmium, which in the event of leaking from the modules pose a serious environmental threat. (Sollmann and Podewils, March 2009) Three risks, namely fire, module pieces in waste dumps or elsewhere and broken modules, have been identified and also tested in an extensive study to evaluate the potential of cadmium escaping from CdTe modules. (Sollmann and Podewils, March 2009)

Fire is one of the most significant threats both in theory and in reality, especially for roof mounted or building integrated CdTe PV systems. In its pure form cadmium melts at 321°C, but when it is combined with tellurium in one compound, CdTe does not melt below 1,041°C. (Sollmann and Podewils, March 2009) Since fires in buildings are generally perceived not to exceed temperatures of 1,000°C, some views claim that temperatures that exceed 1,000°C are possible and not unheard of, for which case the the modules pose a significant hazardous risk for the environment and people. (Sollmann and Podewils, March 2009) The study goes on to claim that even if temperatures exceed the melting point of CdTe, there is however no threat as the cadmium can evaporate into the glass covering the CdTe layer when this is softened during the fire. Some observers however claim that since the modules are never installed horizontally, but at a slight angle, different parts of the modules are exposed to different temperatures, whereby the ethylene vinyl acetate (EVA) holding the glass sheets together could melt and thus cause cadmium to be released into the environment. (Sollmann and Podewils, March 2009) In 2008 a CdTe PV system burned down in Germany when a fire broke out in the barn, on which the system was installed. Although the building was completely destroyed 90% of the modules were unaffected and the remaining 10% were incinerated as these were mixed with animal cadavers and faeces thus being determined as hazardous waste. The temperature of the fire however was so low that no cadmium was released into the environment. (Sollmann and Podewils, March 2009) Although, based on this case, some would dismiss the threat of cadmium being released during a fire, one fire was recorded during which the installed crystalline modules burst and were scattered around the site. One can only guess as to what damage could have been done to the environment had CdTe modules been installed instead.

The implications of CdTe modules ending up in dumps or other places as well as broken modules are in practice relatively uncertain. (Sollmann and Podewils, March 2009) A test, during which the CdTe module is placed in a specific solution for 24 hours, showed that the cadmium in the modules did not leech out and therefore a threat of groundwater contamination is ruled out. (Sollmann and Podewils, March 2009) However one should note that this test only reflects one situation whereas the modules may in fact be exposed to different conditions whose risks have not been identified. The threat to the environment from broken glass is relatively unexplored as real life tests would risk possible threats to the environment and people. It is however important to note that due to these concerns First Solar has implemented an effective recycling programme, which should assure the safe and successful disposal of CdTe modules. (www.firstsolar.com)

The aforementioned threats and risks undoubtedly cast a negative shadow on the use and especially the sustainability of CdTe modules. Although there have been no known accidents involving cadmium contamination from PV modules, the potential that such an event could occur in reality questions whether CdTe is an efficient and safe PV technology for the future. (Sollmann and Podewils, March 2009) The only plausible solution to avert these risks would be to cease CdTe module production. On the other hand one could also argue that the probability of the environment being exposed to cadmium from CdTe modules is rather small. Moreover a strong argument in favour of the CdTe industry is the fact that cadmium is produced regardless of the PV industry as it is a by-product of zinc smelting and therefore needs to be stored in slags, which in theory could lead to more serious contaminations if not handled or disposed of correctly. (Sollmann and Podewils, March 2009) The use of cadmium in PV modules could therefore be a safe and suitable alternative storage for the produced cadmium. Finally, the combustion of coal in old, inefficient and badly maintained power plants is responsible for the most serious emission of cadmium into the environment and therefore could be considered a more significant than CdTe modules. (Sollmann and Podewils, March 2009) Regardless of the opposing views, the issues surrounding cadmium and the implications of a possible cadmium contamination will in the long-run most likely prevent the industry from becoming the leading PV technology and possibly replacing crystalline modules.

4.1.2.2. Tellurium

4.1.2.2.1. Characteristics, sources and occurrence

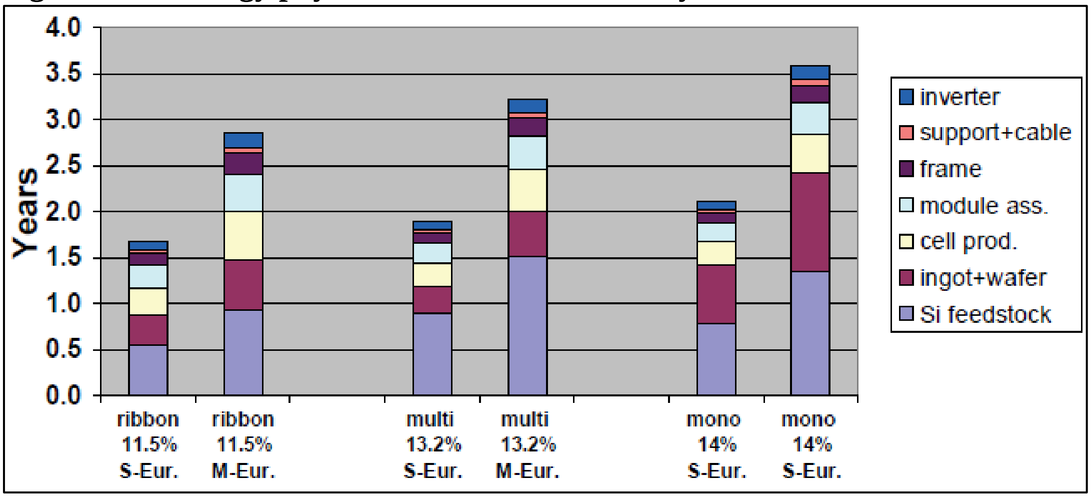
Tellurium is a metallic element, which is not found in its natural pure state, but mainly recovered during copper refining. It is very brittle and does not react with air or water. More than 90% of tellurium is produced from anode slimes collected from electrolytic copper refining. (USGS, January 2010) Remaining sources of tellurium are skimmings from lead refineries and flue dusts and gases generated during the smelting of bismuth, copper and lead ores. (USGS, January 2010) Further sources of tellurium, which are however not refined, also include some lead and gold deposits. In addition, tellurium is present in coal and some lower-grade copper deposits, but the cost of recovering the tellurium from these deposits is too high to make it worth the effort. (USGS, January 2010) Unfortunately there are significant uncertainties concerning the globally available reserves and production figures of tellurium. Based on the tellurium contained in copper only, an estimated 22,000 tons of tellurium reserves are known to exist worldwide. (USGS, January 2010) Since production figures for the majority of countries are not published there are no figures available as to the global production levels. The few production figures and estimates available amount to less than 100 tons.

Besides being a relatively small market there are a number of other limitations the use of tellurium can have for the future growth of CdTe module production. (USGS, January 2010) Firstly, as mentioned tellurium is neither found in its elementary form nor is it directly refined, but dependent on copper refining. Since the use and demand patterns for copper, an important industrial metal, can differ from that for CdTe modules, there is a significant supply-side risk, which can limit the production capacities of CdTe cell manufacturers. Furthermore, the use of tellurium for PV applications is expected to be approximately 11% of the global tellurium consumption. (Shon-Roy, December 2009) Given the current production of crystalline cells, which has a market share approximately 14 times greater than that of CdTe cell production, significant tellurium supply capacities need to be added in coming years should CdTe modules become the leading PV technology. However, on one hand since the majority of tellurium is used for metal alloying applications, which are large cyclical markets with single digit growth rates, additional supply capacities may not be added as quickly as the PV industry might require. On the other hand the copper refining facilities are unlikely to increase copper supplies they know they cannot sell, which would also obstruct further supply of tellurium. (Shon-Roy, December 2009) Thus when the PV market grew seven times faster in 2007 and 2008, the supply chain for CdTe modules suffered from severe bottlenecks. (Shon-Roy, December 2009) These bottlenecks do not only limit the production capacity of CdTe modules, but can also lead to increasing raw material costs, which in turn will adversely affect future growth of the CdTe module industry.

4.2. Energy payback – crystalline vs. CdTe PV

In addition to analysing the raw materials used in the production of CdTe and crystalline module, the energy payback time is another important measure in evaluating the sustainability of said modules. Although no CO_2 emissions are released during the operation of PV systems, CO_2 emissions are in fact released during the production of crystalline and CdTe modules in sometimes energy intensive processes. To measure how long it takes for each module to generate the energy that was required to produce it the energy payback time is calculated. There are a number of different factors affecting the energy payback time thus making it impossible to calculate an industry wide standard figure. Firstly the value chain includes a number of different processes and involves numerous companies across the world. Secondly the production characteristics of PV systems depend on the solar irradiation, system application and performance ratio. (Alsema et al, September 2006) For example a PV system operating in a location with higher solar irradiation will have a shorter energy payback time than a PV system installed in a location with less irradiation. Therefore the following findings are based on a number of predefined factors.

Figure 4.1 – Energy payback time for silicon PV systems[1]



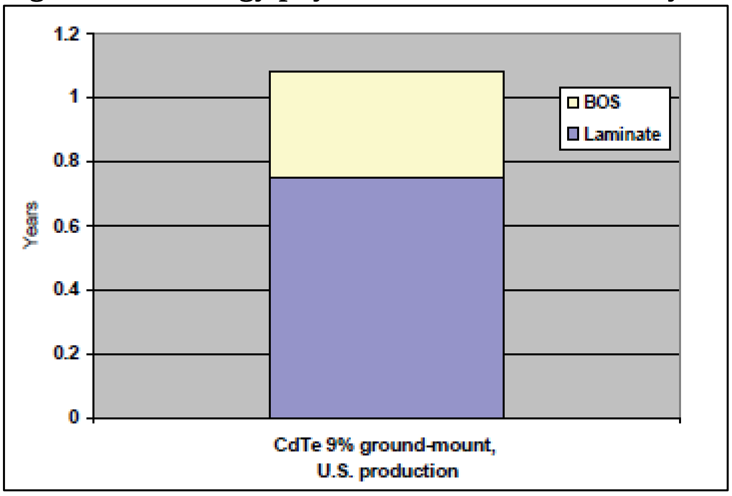
Source: Alsema et al, September 2006

As seen in Figure 4.1 the energy payback times among the different crystalline technologies as well as the two locations vary significantly. From the data it is evident that installing PV systems in sunnier locations clearly has the largest impact on reducing the energy payback time. The energy payback time is reduced significantly as the solar irradiation is increased. Furthermore, one can observe that the higher the efficiency the longer the energy payback period lasts. This anomaly can be explained by the fact that production of solar silicon with less impurities requires more energy consumption as was discussed in section 4.1, for which reason the energy payback of systems containing cells produced from said feedstock will be longer. Moreover the data shows the solar silicon feedstock, accounts for approximately 30% of the primary energy usage thus representing the longest energy payback time along the value chain. (Fthenakis et al, October 2011) As more efficient ways of producing purified solar grade silicon become available and less energy is consumed during the production of wafers and cells, the energy payback time may under southern European conditions be reduced to below one year. The opportunities of reducing the energy consumption in the production of crystalline PV modules as well as an increased number of such system installations in high solar irradiation regions may enable the energy payback period to be significantly shortened and allow crystalline PV technology to become a more sustainable form of

[1] Energy payback time of rooftop PV systems based on crystalline silicon technology at two different locations. Southern Europe and middle Europe with solar irradiation of 1700 kWh/m²/year and 1000 kWh/m²year respectively. Module efficiencies are shown for each technology; system performance ratio 0.75

energy thus allowing it to keep its market leading position. If however the energy intensive processes regarding crystalline modules cannot be made more efficient in the future the widespread use of said technology may decline.

Figure 4.2 – Energy payback time for CdTe PV systems[2]

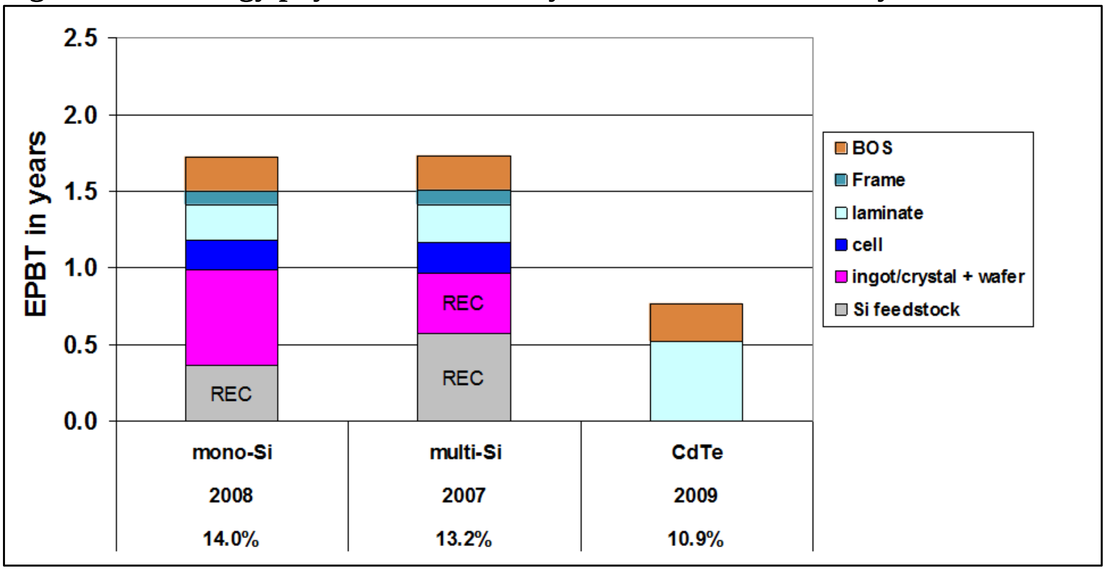


Source: Alsema et al, September 2006

The data in Figure 4.2 shows the energy payback time of a CdTe roof mounted PV system installed in southern Europe. According to said data a CdTe under such conditions requires a little more than a year to produce the energy required during its manufacturing. In contrast to crystalline silicon PV modules under the same conditions the payback time is approximately six to twelve months shorter than the various crystalline silicon PV modules shown in Figure 4.1. Similar to crystalline silicon the majority of the energy is needed to produce the semiconductor laminate, which requires roughly nine months of operation to recover the energy consumption during production. From this information it becomes evident that under the predefined specifications of the mentioned study, CdTe is a more sustainable PV technology in terms of energy payback time. This specific strength of CdTe PV over crystalline PV may also be an opportunity for the share of CdTe modules of overall installed PV capacity to increase as more stringent carbon emission goals and energy consumption policies are introduced.

[2] Energy payback time of rooftop PV system based on CdTe technology in southern Europe with a solar irradiation of 1700 kWh/m²/year. System performance ratio 0.75

Figure 4.3 – Energy payback time for crystalline and CdTe PV systems[3]



Source: Fthenakis et al, October 2011

Figure 4.3 shows more recent data and a direct comparison of the energy payback times of crystalline and CdTe PV technologies. Before commenting on the data it is important to note that the figures for the crystalline silicon PV systems are based on the production statistics of REC and are therefore not to be regarded as an industry average. (Fthenakis et al, October 2011) Regardless of this fact one can clearly identify that the energy payback time for CdTe is about half of that for crystalline PV. Comparing Figures 4.2 and 4.3 also show a decrease in energy payback time of less than a year for CdTe. One can therefore conclude that if sustainability alone was used to measure the potential of CdTe and crystalline silicon PV technologies, the former has the opportunity of possibly establishing itself as the leading PV technology and replacing the latter.

4.3. Power generation capacity of crystalline vs. CdTe modules

In terms of power generation capacity there are significant differences between crystalline and CdTe modules. Regardless of the efficiency of the respective modules, the power generation capacity of crystalline modules is significantly higher than that of CdTe modules. Resulting from the difference in power output, a CdTe PV system with the same installed capacity as a crystalline PV system would

[3] Energy payback time of rooftop PV systems based on crystalline and CdTe technology in southern Europe with a solar irradiation of 1700 kWh/m²/year. System performance ratio 0.75

therefore require more modules and more area. However land is a scarce resource and limited thus requiring its use and purpose to be both sustainable and efficient.

Today there are a number of modules by numerous manufacturers available. The typical power output of commercial crystalline modules range between 150W and 250W under STC[4]. There are also industry leading crystalline modules with energy outputs that exceed 300W under STC. On the contrary CdTe modules only have a power output of less than 100W under STC. Since crystalline modules are generally produced in greater dimensions than CdTe modules one has to calculate the power output as W/m²under STC.

This analysis will compare the most powerful commercial crystalline and CdTe modules. Due to the high number of crystalline module producers the average output W/m²/module of most powerful commercial module of the top five manufacturers, who have a market share of over 22%, will be used. On the other hand the highest output First Solar module will be used to represent CdTe technology as the said company has the largest market share.

Figure 4.4 – Power output of crystalline vs. CdTe modules

Technology	Manufacturer	W/module (STC)	Module area (m²)	W/m²/(STC)
Crystalline	Suntech	250	1.65	151.52
	JA Solar	325	1.96	165.82
	Trina	285	1.94	146.90
	Q-Cells	265	1.67	158.68
	Yingli	290	1.95	148.72
CdTe	First Solar	87.5	0.72	121.53

Source: Suntech, JA Solar, Trina, Q-Cells, Yingli and First Solar company information, September 2011

As can be seen form the data in Figure 4.4 the power output W/m² of CdTe is the lowest of all the compared modules. The average power output of all listed crystalline modules is 154.33 W/m² compared with an output of 121.53 W/m² for First Solar's CdTe most powerful FS series 3 modules. Therefore the average crystalline module output is 27% higher than that of the CdTe modules. One could

[4] Standard testing conditions: 1000W/m², AM 1.5, 25°C

therefore conclude that if one were to erect two PV systems of same size under STC conditions, the CdTe PV system would require nearly 30% more in land space thus making its use more critical from a sustainable land usage perspective. Hence if CdTe is to become the market leading PV technology the power output would have to reach the output of crystalline modules as the land area on Earth is limited.

4.4. Recycling of crystalline and CdTe modules

Another important aspect to consider when discussing the sustainability of PV modules is recycling. As mentioned earlier in this section there are a number of processes along the value chain of PV modules that affect the environment in different ways. Before directly comparing the strengths and weaknesses of recycling of crystalline and CdTe PV modules, one should understand what merits recycling of PV modules can have in general. One of the major benefits of recycling is the reduction of the energy payback time of PV modules. (www.pvcycle.org) As discussed earlier energy payback time of modules varies significantly dependent on the technology and operating location of the PV system. This being said one a significant issue with energy payback time regardless of the parameters is the fact that the silicon feedstock for crystalline modules and the semiconductor laminate for CdTe modules is the most energy intensive process and therefore has the longest energy payback time. Recycling can help reduce the time as the raw materials, which can be recovered with less energy intensive processes, can be reused in the production of new modules thus effectively reducing the energy payback time. Thus the recovery of the valuable materials during recycling also acts as supply security of raw materials for the production of new modules. (www.pvcycle.org) This is not only important aspect in terms of securing the supply of the necessary raw materials for the continued success of the PV industry, but also protects the environment because less raw materials have to be processed through energy intensive treatments. On the other hand it is important to note that the full potential and merits of PV module recycling will only be realised towards the end of this decade when the larger quantities of modules will near their life and hence increase the annual waste figures. (Konrad, 2009) Nonetheless the majority of the industry leading PV companies have taken the initiative of preparing industry wide recycling standards through the establishment of PV Cycle, a non-profit organisation supported by the EPIA and numerous PV companies.

When taking a closer at the prospects of crystalline module recycling there are a number of strengths and weaknesses. PV modules are not yet a standardised good and produced by various module manufacturers often using different production methods. (Müller, August 2009) Unfortunately this is a significant weakness and needs to be improved if the crystalline module industry is to become more environmentally sustainable. Although it currently might be difficult to establish an industry wide recycling standard the aforementioned founding of PV Cycle is a strong step in the right direction as the a large share of module manufacturers can work together for the most feasible outcome. There a number of strengths as well, which allow for great potential and opportunities of recycling. If during the recycling process in tact wafers can be recovered and reused, the energy payback time of the module is roughly only 30% of the energy payback time of a new module of similar output and efficiency. (Müller, August 2009) This is one of the best examples underlining the opportunities and potentials of recycling. From a sustainability perspective recycling is therefore a crucial issue for the continued success of crystalline modules. Furthermore, the recycling of older crystalline PV cells from the 1980s is even more beneficial and can achieve even greater savings in energy payback time as these cells were generally 300 microns thus requiring more silicon. (Müller, august 2009) Although this currently poses to be a great opportunity one must also acknowledge that it will not last as today's modules already require less silicon and it is unclear as to how much the silicon amount in future crystalline modules can be reduced. Nonetheless in the near term this will definitely help make crystalline PV technology more sustainable.

On the other hand the prospects of CdTe modules are different for which reason their recycling has to be portrayed from a different perspective, albeit with the same goal. As seen in section 4.2 the energy payback time is significantly lower for CdTe modules, therefore recycling does not have the same marginal effect on reducing the energy payback time. However, the raw materials used in CdTe PV modules are rare and toxics. (Müller, August 2009) Therefore one can argue that CdTe PV module recycling can on one hand make sure that toxic materials do not harm the environment if modules are disposed of incorrectly and by reducing the environmental impact of recovering the raw materials when recycled materials re-enter the value chain. As mentioned earlier the CdTe module market is led by First Solar, who is not only a member of PV Cycle, but also has a fully operational recycling program. The program is pre-financed by First Solar through payments made with each module sale. (Müller, August 2009) The strength and benefit of this system is that even if the company should not exist when the last operating CdTe module nears its life-time end, the recycling will be financially guaranteed.

The aforementioned shows that while the recycling of both, crystalline and CdTe modules, has its benefits and weaknesses, the overall outcome is more or less the same. For example the fact that energy payback time is reduced is valid for both technologies. Moreover the fact that the re-entrance of the raw materials has a positive impact on the environment by reducing the energy intensity along the value chain also holds true for both technologies. It is therefore difficult to argue for which technology recycling is more sustainable. One should therefore conclude that regardless of the PV technology recycling is a crucial aspect of the development of both the crystalline and CdTe markets and will become one of the most important issues as the waste from PV systems increases in years to come. Nonetheless the technology, for which recycling will be the most effective and environmental friendly in the future, will most likely succeed as the market leader in terms of sustainability.

5. The Economics of PV

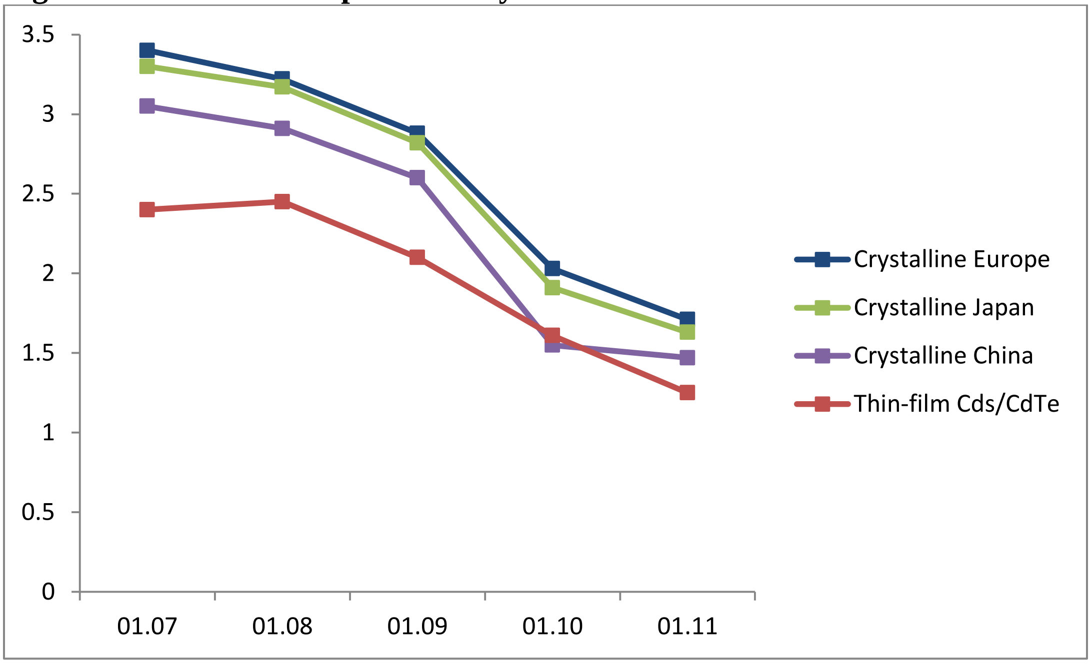
In addition to the evaluation of the supply and demand patterns and the aspects of sustainability the price developments must also be considered when trying to establish the prospects of CdTe becoming the leading PV technology. Price is one of the most important factors affecting demand therefore making it crucial for the future development of an industry.

5.1. Price developments of crystalline vs. CdTe modules

Until 2009 CdTe modules were significantly less expensive than and held an economic advantage over crystalline module. Due to a number of substantial events and developments towards the end of the past decade crystalline module prices underwent a considerable consolidation causing prices to drop to all-time lows; these events include, but were not limited only to the financial crisis, recession and problems with key solar markets such as Spain. (Fawer and Magyar, November 2010)

As can be seen in Figure 5.1 the price of CdTe modules in 2007 and 2008 were significantly lower than crystalline modules from Europe, Japan and China. Due to the advantageous price the demand for CdTe increased, which sub-sequentially lead to the major increases in market share of CdTe cell production as mentioned earlier. However, the price advantage CdTe modules had over crystalline modules started to diminish during the course of 2009 up until 2011 and shrunk dramatically. As a matter of fact the price for crystalline modules from China even dropped below the price of CdTe modules. Nevertheless the CdTe prices have so far been able to regain their price advantage and are still cheaper than crystalline modules. However, as discussed in section 4.3 crystalline and CdTe modules from different manufacturers have different power outputs (W/m^2). Therefore, as mentioned in section 2 investors mainly calculate the LCOE instead of comparing the absolute module price. As was established earlier the power output of CdTe modules is approximately 30% less than the average crystalline modules. To account for this lower output a lower price of CdTe modules is necessary to ensure that the LCOE of CdTe PV remains lower than the LCOE for crystalline PV. (Mehta, November 2010) The shrinking cost advantage of CdTe modules can therefore be considered a significant threat to further increasing demand in the bid to possibly become the market leading PV technology. On the other hand the significant price decay of crystalline modules can be regarded as a major opportunity to ensure further growth and remain atop the PV market.

Figure 5.1 – Price development of crystalline and CdTe modules[5]



Source: Solarserver, pvXchange, September 2011

5.2. Major factors affecting the price of crystalline and CdTe modules

There are a number of drivers and factors of crystalline and CdTe modules. A look at the value chain of the two different module technologies shows the complexity of the price composition. However, due to the difference in technology the factors affecting crystalline and CdTe modules are somewhat different.

The value chain of crystalline module production includes polysilicon, wafer, cell and finally module production. (O'Rourke et al, January 2009) Each part of the value chain therefore has a different influence on the price of the end product, in this case the crystalline module. Additionally the weighting of each component and its effect on the module price is very different. The greatest cost component in crystalline modules is the polysilicon feedstock. (Fawer and Magyar, November 2010) As a result of the significant capacity increases in polysilicon production, the price for polysilicon has declined from its all-time highs, which in turn was one of the reasons for the significant consolidation of crystalline module prices as shown in section 5.1. (Fawer and Magyar, November 2010) Despite this favourable development, the fact that the price of polysilicon will continue to be a major price driver of crystalline modules is a weakness, which could surface in coming years and threaten the growth of the crystalline module market. Moreover, as also discussed in section 4, the

[5] Average selling price, wholesale spot market price of for PV module only

production capacities for polysilicon are not increased in the short-term, but are a lengthy process. Following earlier supply shortages and price spikes, polysilicon is therefore mainly sold in long-term contracts, which allows better planning for the silicon production capacity increases, price stability for the module manufacturers and effectively calculable prices for the end user. (Fawer and Magyar, November 2010) If however the demand for crystalline modules picks up and grows too quickly in the future, the situation concerning silicon could prevent the market from growing and hold it hostage.

On the other hand there is also a non-silicon price component of crystalline modules. With probably little room for further significant price reductions of silicon, the non-material related costs have grown considerably in importance. (Fawer and Magyar, November 2010) The main reason for dominance of the crystalline market by Asian companies is the more competitive price, which can be seen in Figure 5.1. Given differences, the silicon price component among European and Asian firms is roughly the same; but Asian companies benefit from more streamlined corporate structures, allowing them to effectively reduce the non-silicon related price component. (Fawer and Magyar, November 2010 Although not all crystalline companies benefit from this trend, the market itself can continue to maintain its market leading position based on competitive prices for modules from Asia. The question however is whether Asian companies will be able to maintain this situation or whether growing prosperity and increasing wealth will put pressure on the non-silicon price component. Due to the favourable market structure of crystalline PV it is questionable though how much minor price increases will affect growth. Nonetheless further price consolidation is the greatest opportunity for crystalline PV manufacturers to remain atop of the PV market.

Contrary to crystalline PV CdTe modules require less semiconductor material and are therefore less dependent on raw material prices thus allowing for lower prices. Whereas this is a significant benefit of the CdTe market, there are also some weaknesses. Since cadmium and tellurium used in CdTe modules are scarcer than silicon exponential demand growth for CdTe modules could cause prices to increases in coming years. This could therefore significantly limit the future growth perspectives of CdTe PV.

Furthermore, according to a study by Bank Sarasin there are a number of crucial targets such as a low cost structure, low investment costs and low balance of system costs, which need to be met by CdTe module manufacturers to ensure future success. (Fawer and Magyar, November 2010) The study further goes on to estimate that current and contending CdTe manufactures must set production costs of $ 0.5/W as their ultimate target in order to establish themselves in the market and ensure growth; market leading First Solar produces at approximately $ 0.8/W. (Fawer and Magyar, November 2010) In addition is argued that investment costs for new production lines and competitive prices for the balance of system are a necessity for CdTe manufacturers to withstand future price pressures. (Fawer and Magyar, November 2010) These arguments suggest that the future progress and success of the CdTe industry will depend a lot on price. In connection with the monopoly market structure identified earlier it may therefore become difficult for CdTe PV to become the market leading technology.

Given current market conditions price is a greater issue for crystalline modules, especially since the majority of it depends on the price of polysilicon. On the other hand CdTe currently benefits from its price advantage, but will need to find ways in further reducing its prices if it is to not only remain a feasible alternative to crystalline PV, but actual make a run for the top of the PV market. Similar to crystalline PV the CdTe market could also face raw material price pressure if the market experiences further exponential growth. Achieving further economies of scale will therefore be the key for economic success for each PV technology.

6. Conclusion

The findings of this analysis show that the weaknesses and threats outweigh the strengths and opportunities of CdTe PV compared with crystalline PV thus undermining the prospects of the former becoming the market leading PV technology. The results of this analysis are also presented visually in the SWOT table below.

Three specific areas, namely market structure and dynamics, sustainability and economics, were evaluated in this analysis to prove whether CdTe modules could surpass market leading crystalline modules. Each of these aspects brought forth different results for both technologies.

A highly competitive market structure with numerous multinational module producers and large production capacities are the greatest strengths of the crystalline PV market. These premises underline the leading and dominant position of said technology in the PV market. On the other hand the thin-film market leader CdTe market is much smaller in size and characterised by a monopoly situation. Even though the increasing of production capacities by other CdTe players is an opportunity to further develop the market, it is still only a fraction of the size of the crystalline market.

With regards to sustainability the results were not as clear as in the preceding market analysis. Considering the raw materials used in crystalline and CdTe modules, the former is at a significant advantage due to the highly abundant raw material silicon. Nonetheless a weakness of the crystalline market is the high energy intensity of the Siemens process to produce polysilicon. Promising alternative treatment processes are an opportunity for the crystalline market to reduce the energy demand thus becoming more environmentally sustainable. On the other hand cadmium and tellurium are far more scarce resources, for which the production capacity depends on zinc and copper mining activities. One of the greatest weaknesses however is the toxicity of cadmium. Since the use of cadmium in CdTe PV is criticised and its use in other electronic products in forbidden, there is a threat that its use could be forbidden in PV modules in future years. The analysis of the energy payback time showed a significant strength of CdTe modules in terms of sustainability. In all presented scenarios the energy payback time of CdTe systems was significantly shorter than crystalline systems. The opportunity for the crystalline market therefore lies in the success of alternative silicon treatment processes that can reduce the energy intensity along the value chain. Another important measure analysed was the power output (W/m^2) of CdTe and crystalline modules. The results showed that as a result of a higher output crystalline modules require less area to produce the same amount of energy as a CdTe PV system. Due to the fact that land too is a scarce resource and needs to be used efficiently and in a sustainable manner, crystalline modules show the greater strength. If the power output of CdTe modules can be increased to reduce the gap to crystalline modules then CdTe has the opportunity of becoming a more sustainable PV technology. Finally, findings concerning recycling are neither specifically a strength nor weakness for either technology, but rather an opportunity for both to increase sustainability.

Similar to sustainability the analysis of the prices and factors affecting prices show a mixed result for crystalline and CdTe modules. Clearly a great strength of the CdTe market is therefore the lower prices. However, results also showed that the difference in prices between crystalline and CdTe modules has shrunk over the past years and especially Chinese manufacturers have had great success in offering highly competitive prices for crystalline modules. The technology able to further reduce its price over time will therefore have the greater growth prospects. When considering some of the most important factors affecting the price the high silicon price component is a weakness of the crystalline industry. A lot of emphasis and opportunity therefore lies in how the non-silicon price component is reduced. On the other hand the CdTe market benefits from a smaller material related price component. Since the competitive prices are one of the greatest strengths of CdTe PV, a failure to further reduce prices would be a significant threat to future growth of the industry. The findings show how much further CdTe producers have reduce their prices than currently leading pioneer First Solar.

Thus it is highly unlikely that in consideration of the aspects analysed in this work CdTe modules can become the market leader and replace crystalline modules atop of the PV market.

Strengths		Weaknesses	
Crystalline	**CdTe**	**Crystalline**	**CdTe**
<u>Market</u> • Highly competitive market • Large number of multinational players • High production capacities <u>Sustainability</u> • Silicon is an abundant raw material • Higher module power output W/m^2 <u>Economics</u> -	<u>Market</u> - <u>Sustainability</u> • Lower requirement of raw materials • Shorter energy payback time <u>Economics</u> • Lower module prices	<u>Market</u> - <u>Sustainability</u> • Raw material intensive • Complex production value chain • Longer energy payback time <u>Economics</u> • High module prices	<u>Market</u> • Monopoly situation • Very few prospective market entrants <u>Sustainability</u> • Cadmium is highly toxic and dangerous • Cadmium and Tellurium are scarce resources • Production of Cadmium and Tellurium depend on other mining activities <u>Economics</u> -

Opportunities		Threats	
Crystalline	**CdTe**	**Crystalline**	**CdTe**
<u>Market</u> - <u>Sustainability</u> • More efficient production of solar grade silicon • Improvement of energy payback time <u>Economics</u> • Further consolidation of prices	<u>Market</u> • Production capacity increases by CdTe producers <u>Sustainability</u> • Increased module power output W/m^2 <u>Economics</u> • Further consolidation of prices	<u>Market</u> • Movement to a more monopolistic market <u>Sustainability</u> • Capital and energy intensive raw material production <u>Economics</u> • No improvement in module prices	<u>Market</u> • No market entrants and little competition <u>Sustainability</u> • Possible legislation banning use of cadmium <u>Economics</u> • Price pressure due to scarce raw materials

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