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Material Requirements for Future Deployment Levels of Photovoltaics

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supervised by
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Affidavit

I, **GILBERT GUNTSCHNIG**, hereby declare

1. that I am the sole author of the present Master's Thesis, "MATERIAL REQUIREMENTS FOR FUTURE DEPLOYMENT LEVELS OF PHOTOVOLTAICS", 65 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's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Even though the photovoltaic industry has entered a phase of consolidation, growth projections still remain strong and photovoltaics is expected to contribute significantly to decarbonising future electricity generation. As photosensitive layers and contacts of solar modules contain metals, which are relatively scarce and used in other important electrical applications, the large-scale deployment of photovoltaics could potentially influence the metal availability and demand considerably.

Technological development in the field has recently rendered photovoltaics competitive to other conventional electricity generation methods in favourable locations. Consequently, grid parity events are expected to occur across Europe in coming years thereby facilitating large-scale deployment.

Evaluating growth scenarios proposed by the EPIA has shown that such projections are unlikely to be fulfilled based on known reserves and current annual production of the metals used in solar modules. Cadmium telluride turned out to face the most serious material restrictions among the examined solar technologies.

Annual production limits for the technologies CdTe and CIGS were determined to be less than 10 GW in both cases. Hence, under the assumptions of this study both technologies fall short of providing deployment levels required for fulfilling ambitious growth scenarios.

Maximum cumulative installed capacity for CdTe have been calculated to range from 94 to 207 GW and from 347 to 1230 GW for CIGS.

Recycling of metals used in photosensitive layers will not provide a means to solve the availability problem. Moreover, price fluctuations of the metals are expected while PV manufacturers will need to compete against other industries.

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Ag	silver
a-Si	amorphous silicon
C	cumulative installed capacity [GW_p]
CdTe	cadmium telluride
CIGS	copper-indium-gallium selenide
c-Si	crystalline silicon
CSP	concentrating solar power
EPIA	European Photovoltaic Industry Association
Ga	gallium
Ge	germanium
GR	growth rate [%]
IEA	International Energy Agency
In	indium
L	layer thickness [µm]
LCOE	levelized cost of electricity
M	material demand [t]
MS	market share [%]
NREL	National Renewable Energy Laboratory
PV	Photovoltaic(s)
Si	silicon
STC	Standard Test Conditions (1000 W/m^2)
Te	tellurium
U	material utilization rate [%]
W_p	Watt peak
α	area specific material intensity [g/m^2]
η	module efficiency [%]

1. Introduction

The photovoltaic industry has recently experienced rapid technological development which enabled the deployment of solar modules at an unprecedented pace. As of 2011, 67 GW of photovoltaic systems have been installed, which means that the cumulative capacity has increased by a factor of ten in the last five years (EPIA 2011b). This has earned PV the title of third-ranking renewable energy generation technology in terms of globally installed capacity after hydro and wind power. Even though the PV industry has now entered a phase of consolidation, growth projections remain strong and experts in the field expect PV to play a major role in the electricity mix of the future.

While PV generates electricity from a source of renewable energy that seems inexhaustible, the materials used for the photosensitive layers of photovoltaic modules are not so abundant. If this technology is to contribute to decarbonising the energy sector, the material intensity of module fabrication will require optimization. In this study the impact of future large-scale PV deployment on the availability of materials used in solar modules will be investigated. The discussion will focus on the metals which have been identified as the metals which could potentially restrict future deployment of PV. These include silver, which is used for the contacts of crystalline silicon cells, indium, tellurium and gallium. The latter metals are contained in the metal alloys used in cadmium telluride and copper-indium-gallium selenide thin-film modules.

In order to assess the effect of large-scale solar module fabrication, the study is structured in the following way. In the introductory section, the current state of the art for the relevant technologies in terms of solar cell efficiency is presented. Moreover, the status quo of photovoltaic technology is examined by determining levelized cost of electricity for PV installations and evaluating the competitiveness of this renewable energy generation method. In the chapter thereafter the most important studies in the field of material constraints in the PV industry are reviewed to get an overview of up to date scientific knowledge. This chapter also contains information about the refining, the annual production and the estimated reserves of the metals examined in this study. Chapter 3 aims at describing the methodology which has been used to evaluate potential material limitations encountered under large-scale solar deployment scenarios. The subsequent section presents the calculated material requirements for the fulfilment of EPIA growth scenarios. In addition, it comprises the evaluation of annual production limits of PV technologies and the achievable cumulative capacity based on known reserves of the metals of concern. The work concludes with an analysis of the importance of recycling and an outlook for the development of future metal prices.

1.1 Cell Efficiency and Market Shares

The following chapter aims at providing the basis for the further discussion in that current state-of-the-art solar cell efficiencies are given and trends of the development of those efficiencies are depicted. Furthermore, current market shares of the relevant PV conversion technologies are presented including an outlook into the development of the field in the near future.

The conversion efficiency of solar cells is one of the most important parameters based on which the progress in research and technology in the field of PV is evaluated. Additionally, cell efficiency is one of the main drivers for the price development of PV electricity as higher efficiency means less area required for the same energy output. The thorough examination of this parameter will therefore establish an indispensable pillar for the further discussion in this study.

The thermodynamic efficiency for a single junction silicon solar cell was first calculated to be around 33% by Shockley and Queisser (Shockley&Queisser 1961). This value was determined for a crystalline silicon (c-Si) solar cell. Swanson and other researchers have refined these efficiency calculations and have established a limit efficiency of 29% for Si solar cells under standard conditions (Kazmerski, 2006; Swanson, 2005).

Current commercial c-Si solar cells and modules are well below this limit with efficiencies of 25% and 22.9% respectively (Green et al., 2012). Kazmerski mentions several reasons for this gap between theoretical and attainable values and gives explanations for the differences between commercially available modules and those produced under laboratory conditions (Kazmerski, 2006). On the one hand these differences represent the trade-off between efficiency and production cost. On the other hand, the scale-up of production lines leads to less controlled conditions of cell production in comparison to laboratory-scale production. Regarding the differences between cell and module efficiencies, which have already been mentioned above for c-Si, the author mentions potential losses caused by wiring, low optical transmission of protective and structural layers between cells and changes in incident sunlight. Swanson lists different reasons and their respective contributions to the difference between theoretical limits and attained module efficiencies in another publication (Swanson, 2007). These reasons include electron recombination at the top surface of the silicon, at the back contact and in the bulk before collection as well as absorption of light in the back contact. The mentioned losses total 14.3%. Due to the significant gap between cell and module efficiencies, research in the field of photovoltaics is aiming at closing this gap to further enhance the competitiveness of this technology.

When examining conversion efficiencies in the PV industry, it is not enough to solely mention c-Si cells because the solar cell market has become increasingly diversified over the last decade. While c-Si has dominated the technology mix for 30 years, a temporary shortage in silicon availability and significant developments in the thin-film industry have lead to a considerable increase in thin-film capacities. The market share of thin-film technologies increased from 6% in 2005 to 16-20% in 2010 (Jäger-Waldau, 2011b). Another source confirms these numbers by stating market shares of roughly 10% for cadmium telluride (CdTe), 7% for amorphous silicon (a-Si) and 2% for copper-indium-gallium selenide (CIGS) for the year 2009 (Razykov et al., 2011). This trend is very likely to be sustained in the future as an EPIA report shows. The EPIA expects a market share of 33% for thin-film technologies, 6% for emerging technologies such as Concentrator PV, organics and dye-sensitized cells and only 61% for wafer-based silicon technologies by the year 2020 (EPIA, 2011). The International Energy Agency depicts a comparable scenario for the year 2020. According to the Photovoltaic Roadmap the market share of c-Si modules is expected to decrease to about 50% (IEA, 2010). This is explained by the increase of thin-film technologies such as CdTe and CIGS. However, the forecast of future market shares is rather difficult and many experts in the field disagree even about market shares of 2012 as a report issued by the US Department of Energy shows (Price et al., 2010). The aforementioned trends of increasing market shares for thin-film technologies are confirmed by this publication but expected market shares of c-Si range from 66% to 84%. These findings indicate that any forecasts of technology market shares like the ones issued by EPIA and IEA are rather rough estimates and comprise high uncertainties.

Another way of determining future growth trajectories in the field of photovoltaic technology is presented in a recent publication (Liu et al., 2011). In this article, researchers analyzed patent data for the different PV technologies based on which the maturity state and the future growth trajectory of the respective technology were identified. In order to be able to distinguish between the PV technologies, patents were classified into five groups. The analysis showed that thin film technologies such as CdTe or CIGS have reached a maturity state of their lifecycle. Higher patent activities for other technologies such as silicon suggest that those PV options are still in the growing phase of their development. This result is quite unexpected as the silicon technology has reigned over the PV market over the last decades.

The current state-of-the-art regarding solar cell and module efficiencies is regularly published in the journal *Progress in Photovoltaics* (Green et al., 2012). These publications serve as a standardised basis for the scientific community as only independently in recognised test centres measured results are included. The above mentioned numbers for c-Si are taken from these solar efficiency tables. In addition to this source, the National Renewable Energy Laboratory issues a so-called best research-cell efficiencies chart which is updated regularly (NREL, 2012). It includes various PV conversion technologies, ranging from well established ones such as c-Si, CdTe and CIGS to emerging applications such as multijunction cells, gallium arsenide (GaAs), dye sensitized and organic cells. The valuable feature of this chart is the illustration of how the different technologies have evolved over the years. Moreover, it depicts a trend that is common to all the above mention technologies. Research in this field has resulted in continuous improvement of cell efficiencies across all the different technologies.

According to the aforementioned Solar cell efficiency tables version 39 by Green et al. (Green et al., 2012), the following records of cell efficiencies in the various technologies are acknowledged. Single crystalline silicon cells reach 25.0% while the respective modules currently achieve conversion rates of 22.9%. Multi crystalline silicon cells are well below these numbers as they only reach 20.4% and 18.2% respectively. The chart issued by the NREL shows that single c-Si technology has progressed extensively since 1980 as efficiencies have increased from approximately 15% to 25% in 1999. However, higher efficiencies have not been acknowledged since then. The record for multi crystalline Si cells has not been broken since 2004 but progress has been made in the module efficiency as the latest result stems from 2011. The IEA predicts single c-Si module efficiencies of 23% for the year 2020, which would represent a significant progress in technology as this number is seen as a mean value (IEA, 2010). The aforementioned value of 22.9%, presented in the Solar cell efficiency tables, is the record efficiency achieved with this technology. Actual numbers of commercially available modules range from 14 to 20%.

The second most important technology in terms of market share, namely CdTe, currently reaches record efficiencies of 16.7% for solar cells and 12.8% for modules (Green et al., 2012). The NREL chart displays a higher value of 17.3%, which is not yet included in the tables by Green et al. (NREL, 2012). Similar to the trend depicted for the c-Si technology, CdTe has evolved tremendously over the last decades. While best cell efficiencies were at approximately 9% back in 1980, this number has almost doubled since then. According to the IEA´s PV Roadmap, efficiencies of 14% are predicted for the year 2020 (IEA, 2010). Just recently a new record efficiency of 14.4% for CdTe modules was announced by First Solar Inc. The record was confirmed by the NREL and thus eclipsed the earlier record, which was also held by First Solar Inc., by one percent (PV-Tech, 2012). This clearly shows that this technology is evolving rapidly at the moment and represents a promising alternative for the near future.

The CIGS as the more expensive type of solar cell in the thin-film segment has achieved record efficiencies of 19.6 and 15.7 respectively (Green et al., 2012). This technology has also developed greatly over the last decades, bringing efficiencies from roughly 7% in 1980 to almost 20% nowadays (NREL, 2012). In contrast to the two aforementioned technologies, the best cell efficiencies have been topped in relatively short intervals. This indicates that there is plenty of room for improvement and that this technology is still in its youth. According to the IEA, commercially available modules are expected to reach 15% mean efficiency by the year 2020 (IEA, 2010).

The record efficiencies for emerging technologies with low market shares such as single-junction GaAs, dye sensitized, organic and multi-junction cells are summarized in Table 1 together with the aforementioned types of solar cells and modules.

Table 1: Cell and module efficiencies for solar technologies

	cell efficiency [%]	module efficiency [%]
single c-Si	25.0	22.9
multi c-Si	20.4	18.2
a-Si	10.1	7.1 (EPIA, 2011)
CdTe	16.7	12.8
CIGS	19.6	15.7
GaAs (thin film)	28.	23.5
dye-sensitized	11.0	9.9 (submodule)
Organic	10.0	4.2 (submodule)
multi-junction GaInP/GaInAs/Ge	34.1	27.0

1.2 PV Electricity Price and Grid Parity

The following section briefly outlines the methodology for the calculation of PV electricity generation costs. Moreover, it encompasses details concerning future grid parity of PV electricity.

The further development of the PV industry and the deployment of PV solar energy depend very much on the actual price this technology achieves per unit of electricity. In order to be able to compare PV electricity with other sources of electricity generation, the Levelised Cost of Electricity (LCOE) parameter is commonly used. It can therefore be seen as a means to determine the cost-effectiveness of PV electricity. In general, this approach is favoured by system operators over the simple cost per Watt analysis as it reflects present cost of electricity production. This fact is easily understood because cost per Watt only estimates the value of investment at the time of purchase while LCOE determines the current price of electricity of the respective installation. The LCOE parameter is defined as the ratio of total costs over the system lifetime to the electricity produced during that time. The total costs include investment costs as well as operational and maintenance expenditures. This approach allows comparing the costs of various power generation technologies with PV electricity as the LCOE also includes the location of the installation which strongly influences annual solar irradiation. In Europe, for example, solar irradiance may vary from values like 1000 kWh/m^2 in Scandinavia to almost 2000 kWh/m^2 in Southern European countries. These differences have a strong impact on LCOE because the same module may produce up to double the electricity in Southern Europe than in Scandinavia (EPIA, 2011).

According to the EPIA, LCOE for PV electricity ranged from 35 ct/kWh to 18 ct/kWh in 2010 (EPIA, 2011a). The average European LCOE was calculated being 23.9 ct/kWh for 2010 and 20.3 ct/kWh for 2011. Another publication calculated LCOEs for specific locations around the world which ranged from 27.5 ct/kWh in Stuttgart (Germany) to 14.9 ct/kWh in Daggett (USA) for crystalline silicon PV (Peters et al., 2011). Moreover, the authors present different electricity costs for c-Si, CdTe PV and concentrating solar power (CSP). The thin-film technology achieves the lowest LCOE, which is mainly due to lower module costs in relation to the other technologies, followed by c-Si and CSP. An interesting trend is expected for the year 2020. CSP will then be cheaper in certain regions than crystalline silicon PV.

The dramatic price decrease that was mentioned in the cited EPIA publication is due to several influencing factors. The oft-cited experience or learning factor of PV is one of the reasons why this sector has managed to decrease prices dramatically over the past decades (EPIA, 2011; Wawer et al., 2011). This theory is based on the fact that experience gained in an industry translates into more cost efficient production processes and therefore lower costs. This approach originated in the field of economics but can easily be applied to the PV sector. When the price per Watt peak is plotted over the cumulative production of PV (e.g. in MW) on a log-log scale, a linear function is obtained. The slope of this function is the so-called learning coefficient and gives the percentage at which prices decrease when cumulative output is increasing (Nemet, 2006). Several studies have shown that the learning curve for PV is a graphical illustration of the fact that the prices of modules decrease by approximately 20% every time the cumulative capacity installed is doubled (EPIA, 2011; Nemet, 2006; Wawer et al., 2011). This learning rate is the highest among all energy generation technologies over such a long period of time (Breyer&Gerlach, 2012). Typical learning rates in the energy sector are around 10% which has been shown for wind and solar thermal energy.

According to the EPIA, the average module price in Europe has come down from 4.2 €/W in the year 2000 to 1.2 €/W in July 2011, representing a price decline of 70% over this time span (EPIA, 2011a). This seems to be on the lower side of the spectrum because Solarbuzz, a renowned consulting firm in the field, publishes an average retail module price of 2.17€/W (Solarbuzz, 2012). This difference could be related to the fact that Solarbuzz is mainly focussing on the US market while the EPIA study was intended to reflect European numbers. However, one has to bear in mind that module prices for thin-film modules are lower in general and it is possible that this technology was included in the above mentioned average module price reported by the EPIA while the value published by Solarbuzz is only including Si modules.

A publication by R. Swanson summarizes the reasons for the dramatic price decrease for PV modules over the last decades (Swanson, 2007). The significant decrease in the price of poly-silicon is identified as an important price driver which was responsible for the ten-fold decrease in module price from 1979 to 2002. Many renowned analysts predict even further decreases of the polysilicon price in the near future (Osbourne, 2012). The imbalance between demand and supply of the material is the main driver for this development. After the silicon shortage of 2004-2007, production capacities have been ramped up too aggressively leading to an overshot. This development is likely to drive many polysilicon manufacturers out of the market as they will not be able to compete at the expected costs of US$20/kg. Moreover, the supply/demand imbalance is aggravated by increasingly lower amounts of silicon used in module production. As a result, module prices are also expected to drop since the market price of silicon has a huge impact on the price of PV modules. GTM Research forecasts module prices below US$0.70 per Watt (Osbourne, 2012).

The second reason put forward in the document concerns the cell and module efficiency. As already has been shown in the chapter above, efficiency of solar cells has been steadily increasing over the last decades. The rates at which these efficiencies have developed over time may be different for the different technologies but the constant increase of that parameter is a common feature to all of them. Research efforts in the field of PV technology have often times been bundled in the cell and module efficiency area because the efficiency of a cell affects the whole value chain to a great extent. Higher efficiency results in less area required for the same amount of energy output. This automatically translates into lower costs for manufacturing materials such as glass, silicon and other components of PV modules.

Decreasing wafer thickness is obviously another major contributor to the price decrease of modules described by the experience curve. In essence, lower wafer thickness results in a similar outcome as for increased efficiency because a thinner layer of photosensitive material translates into lower material costs. The importance of this parameter for the price of modules in PV manufacturing is reflected by the 'bump' which can be seen in the experience curve. This feature of the learning curve serves as a good example for the significant impact the price of silicon has on module cost. Hence, decreasing wafer thickness is crucial in further decreasing PV costs. Since 1990 the wafer thickness has decreased from 400 µm to around 200 µm (EPIA, 2011). According to the EPIA, wafer thickness will further decrease to values around 100 µm by the year 2020.

The remaining reasons mentioned by Swanson include the progress in wafer sawing, automation and crystal growth (Swanson, 2007). The commonly used wire saws minimize kerf loss, i.e. material loss during the sawing process.

When the experience curve is plotted, it becomes apparent that this curve can also be seen as a representation of market dynamics. The polysilicon shortage, which hampered PV production in 2005-2007, resulted in higher prices for module production and hence to a non-linear behaviour between prices per Watt peak and cumulative installed capacity during that time. Recent studies explicitly show this 'bump' in the experience curve (EPIA, 2011; Breyer&Gerlach, 2012; Swanson, 2007).

In the past, the slope of the experience curve was often expected to flatten with increasing cumulative capacity as this behaviour is characteristic for many industries (Breyer&Gerlach, 2012). However, apart from the aforementioned event caused by the silicon shortage, this has not been observed in the PV industry. The reason for the flattening of the experience curve is directly related to so-called floor costs for PV production meaning that it gets increasingly difficult to decrease prices with increasing optimisation of the product. From this one can infer that the actual floor costs for PV systems are yet far from being reached today.

The name ‘experience curve’ and the manner it is referred to automatically suggest that learning from experience is the main mechanism which is responsible for cost reductions in PV technology. However, a publication by Nemet has shown that the relationship between cumulative capacity and cost is rather weak (Nemet, 2006). The argumentation is based on the following cornerstones. Firstly, reductions in the cost of solar grade silicon were not linked to a learning process within the PV industry because silicon was only produced by the microprocessor industry and not by the PV industry itself during the considered time frame. Secondly, the ability to manage investment risk and expected future growth rates of demand have been identified to play a more significant role in explaining the cost reductions in the PV industry. This argument is based on the fact that several companies expanded their production facilities rapidly after having entered the market. Thirdly, there is only a weak link between increasing module efficiency and production experience because most of the advances in cell efficiency were accomplished by universities rather than manufacturing companies. In essence these findings suggest that not only experience but a myriad of influential parameters have to be considered in order to describe cost evolution in the PV industry. Hence, decisions on potential future investments in this sector should be based on a set of variables rather than on experience only.

As the experience curve only captures the module price, more costs are needed in order to be able to determine the PV system price. According to the EPIA, the module price accounts for 45-60% of the installed system price depending on the PV technology (EPIA, 2011). For c-Si rooftop installations the module price share of the entire system has reached 60% (EPIA, 2011). Thin-film installations have a lower module price share of 51%. Due to the significant influence module prices exert on the installed system price, research efforts are focussed on this area in order to bring down module costs by increasing efficiency and decreasing manufacturing costs. The remaining part of the system price consists of inverter price (10%), structural components (23% for c-Si, 32% for thin-film) and engineering and procurement with 7% (EPIA, 2011).

Grid parity is widely considered to be the key parameter on which the assessment of the maturity of an energy generation technology is based. The term grid parity describes the moment at which PV generation costs are equal or lower than electricity generation costs using traditional fossil fuels. The generation costs are determined using the aforementioned LCOE approach which takes into account all costs incurred in the generation process (see section above). The EPIA further distinguishes two concepts of grid-parity, namely 'dynamic grid parity' and 'generation value competitiveness' (EPIA, 2011a). While the generation value concept describes the definition of grid parity given above, dynamic grid parity is defined as the moment at which long-term revenues of PV electricity are equal to the long-term costs of traditionally supplied electricity.

The general concept of grid parity is quite complex as many influencing factors have to be considered in order to determine the moment at which PV is competitive. Firstly, the wholesale electricity price obviously plays a major role in assessing grid parity because this is the value the LCOE of PV is compared to. According to Eurostat, electricity prices in the EU are on a steady rise with an increase of 18% including VAT from the year 1997 to 2007 (Eurostat, 2007). This trend remains unchanged even though the economic crisis slowed down the price increase between 2008 and 2010.

Secondly, grid parity is earlier reached in regions with high solar insolation as the latter directly influences the LCOE. Consequently, the concept grid parity is always interlinked with the location of the PV installation.

Thirdly, the aforementioned experience curve has also to be considered as it describes the development of module price with increasing installed capacity. Since the module price is a significant part of the overall system price of PV, it affects the calculation of LCOE and therefore the outcome of the grid parity assessment.

Fourthly, expected growth rates of the PV industry have to be taken into account because of the direct link to the experience curve. During the last 15 years the PV industry grew at a tremendous pace reaching an average annual growth rate of 45% (Breyer&Gerlach, 2012). The consensus among the scientific community is a future annual growth rate of 30% even though this number sounds like a rather conservative estimate.

In general, all factors influencing the LCOE also have an impact on the grid parity assessment. For further details the reader is referred to the section dealing with LCOE above.

Recently published studies like the one by Q-Cells point out, that grid parity events are already occurring in Europe with Italy and Cyprus being the first to reach this stage due to their privileged locations regarding solar insolation (Breyer&Gerlach, 2012). The analysis also reveals that, although solar conditions are crucial, other parameters greatly influence the moment at which grid parity is reached. Even though Portugal and Denmark receive significantly different amounts of solar insolation, grid parity is expected at about the same time in both countries due to relatively high electricity prices in Denmark. By 2020, 80% of the residential and 75% of the industrial market is expected to be beyond grid parity in Europe. Assuming a progress ratio of 0.8, levelized costs of electricity for residential systems break through the 20 ct barrier per kWh in 2013 for an electricity yield of 1000 kWh/kWp (Breyer&Gerlach, 2012). In 2020 the LCOE for PV is calculated to be 9.9 ct/kWh, 6.6 ct/kWh and 5.7 ct/kWh for electricity yields of 1000, 1400 and 1700 kWh/kWp in the residential sector. Under the same conditions the 10 ct barrier per kWh is reached in 2018 in the industrial sector for an electricity yield of 1000 kWh/kWp. This milestone is achieved in 2014 for 1400 kWh/kWp and already in 2012 for 1700 kWh/kWp. The milestones of 20 ct/kWh for residential systems and 10 ct/kWh for industrial facilities have been chosen because they reflect present electricity prices in Austria.

The following figure compares the average European LCOE according to the EPIA with the ranges of electricity price for residential and industrial consumers in European countries for the year 2011. The mentioned values apply for residential consumers with an annual electricity consumption of 3500 kWh ± 25% and industrial consumers with an annual consumption of 2 GWh ± 50%. Electricity prices are obtained from Europe´s Energy Portal (EU Energy Portal).

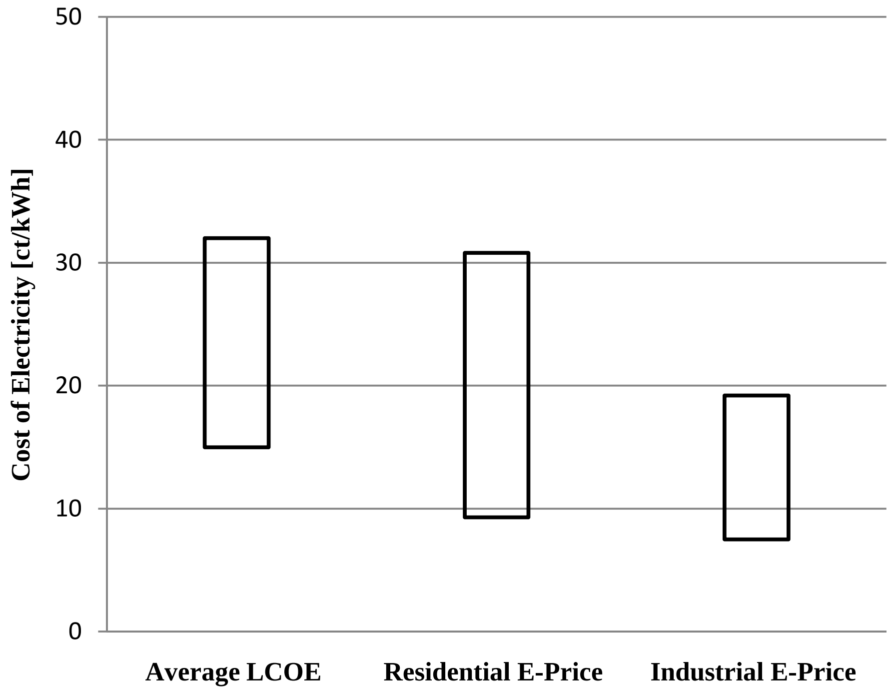

Figure 1: Average European LCOE compared to Residential and Industrial Electricity Price

The above mentioned report published by the EPIA presents a similar outlook although dynamic grid parity is expected later than in the Q-Cells study. The reason for this is the difference in system price on which the calculations for the grid parity assessment is based. While the Q-Cells study calculates with system prices of 2.7 and 2.4 €/Wp for the residential and for the industrial sector, the figures on which the EPIA study is based are higher. In the latter case PV system prices between 3.14 and 5.92 €/Wp are determined and then used for the grid parity calculation. Since the Q-Cells scenario reflects the price situation in Germany, which can be considered as the most mature photovoltaics market, the difference becomes clearer. The authors argue that the German market sets the global price for PV just because of its enormous size. This might have been the case some years ago but is increasingly changing due to significant deployment in China and the US.

In a recent press release a renowned PV analyst points out that the concept of grid parity does great harm to the PV industry (Mints, 2012). Since the electricity cost of PV was always perceived to be high by the public, great pressure was put on the PV industry to lower prices. The ultimate goal was to reach a point where PV is able to compete against conventional energy even without receiving subsidies. However, the fossil fuel industry itself is still the beneficiary of several support mechanisms. The price pressure is mainly transferred to the module manufacturing industries because the costs of the other system parts have largely been neglected. Consequently, many manufacturers face serious problems to compete in this environment. The result of this development is already visible. More and more PV companies fail because they just are no longer profitable as prices tumble down. The author therefore suggests that rather than overstressing the concept of grid parity the focus should be placed on the realization of healthy margins across the whole value chain. If the current imbalance in the share of the cost burden is upheld, manufacturers will continue to fail, especially in Europe and the US.

In conclusion, the concepts of levelized cost of electricity (LCOE) and grid parity for PV have been examined in this chapter. According to the EPIA, the average LCOE in Europe is approaching the 20 ct/kWh barrier while PV can be much less expensive in more favourable locations. The module cost was identified as being the major price driver in PV representing 45-60% of the overall system price. Moreover, the parameters influencing the module price such as cell efficiency, learning rate, photosensitive layer thickness and polysilicon price have been investigated. The key concept of grid parity has been discussed differentiating between dynamic grid parity and generation value competitiveness. Finally, grid parity events have been identified to occur already in Europe especially under good PV conditions.

2 State of the Art

The following chapter contains an overview of several key publications regarding material considerations and possible material limitations in the photovoltaic industry. The studies will be presented in chronological order in order to illustrate the development of scientific knowledge in this field over the years. As photovoltaics is a rather young technology this overview only includes more recent studies and thus is not a complete literature review of publications issued in this field. Due to the rapid developments, which take place in this industry at the moment, it only makes sense to discuss the latest publications.

The earliest study considered deals with material constraints for thin-film solar cells (Andersson et al., 1998). Based on the assumption that 100000 TWh of electricity will be generated by solar cells in 2100, four different thin-film technologies are examined in order to determine potential material constraints. However, market shares of the various PV technologies are not taken into account meaning that material constraints are calculated based on the assumption that every technology produces 100000 TWh. The investigated thin-film technologies include amorphous silicon, cadmium telluride, copper indium gallium diselenide and the Grätzel cell for all of which an overall conversion efficiency of 10% is assumed. The calculations of these scenarios yield an interesting result. Each of the aforementioned technologies uses at least one element to the extent that the requirements exceed known reserves. Indium was identified to be the most critical element in that respect, having a requirement to reserve ratio of 650. Tellurium, germanium, selenium, gallium and cadmium follow with ratios of 110, 51, 30, 25 and 4.6, respectively. However, the large scale deployment of PV is not only restricted by the high requirement to reserve ratio but also due to the fact that they are by-products of the mining process of more common metals. The authors highlight in the concluding statement that other technologies like a-Si (without Ge) and polycrystalline silicon do not face such material constraints. Moreover, they suggest high utilization and recycling rates of the investigated elements in order to alleviate resource bottlenecks.

Another study examines at which deployment rate scarce metals used in PV become a limiting factor in the year 2020 (Andersson, 2000). For this purpose the material requirements for the seven elements tellurium, cadmium, germanium, indium, gallium, selenium and ruthenium for four thin-film PV technologies (CdTe, aSiGe, CIGS, and nano-crystalline dye-sensitised cells) are evaluated. The numbers are calculated taking into account several assumptions that lead to decreased material requirements in 2020. Firstly, the efficiencies of PV technologies are increased to 12% for CdTe, 14% for CIGS and 11% for aSiGe along with a reduction in layer thickness. Secondly, material demand for indium in CIGS is lowered significantly without considering a change in efficiency. Thirdly, the recovery from mining operations of more common metals is increased. Based on these assumptions critical deployment rates are calculated to be 20 GWp/year for CdTe and dye sensitized cells, 70 GWp/year for CIGS and 200 GWp/year for aSiGe. Consequently, CdTe is the technology that faces the most decisive material limitations followed by CIGS and aSiGe. CdTe deployment is restricted by tellurium availability while CIGS is limited due to its indium content.

Keshner and Arya studied the availability of thin-film materials in one part of a broader study (Keshner et al., 2004). Based on data provided by the US Geological Survey, they calculated that the limit of annual production is reached for CdTe at 29 GWp due to restricted Te availability, while CIGS can provide 65 GWp. However, the figure for CIGS is based on shortages of selenium rather than on an indium constraint. Would only the indium availability be considered, the production potential increased to 676 GWp for CIGS.

In a more recent study not only thin-film PV are analyzed but the other remaining technologies such as silicon, multi-junction and concentrator cells are included in the evaluation (Feltrin et al., 2008). For these technologies electricity production limits are calculated based on the following assumptions. Solar modules are assumed to operate at champion cell efficiencies meaning that they reach the values achieved under laboratory conditions. In order to be able to determine the deployment limits, only 25% of the global material reserves are assumed to be available for the production of solar cells. This is mainly explained by the competing material use for other products such as batteries. The results of this study showed that indium and cadmium availability create serious restrictions towards large-scale deployment of thin-film PV. For CdTe and CIGS power generation potentials of about 100 GWp were determined. However, material shortages are also encountered in the conventional silicon PV mainly due to restricted availability of silver which is used for the electrodes.

The US Department of Energy primarily mentions indium and tellurium as the metals of concern in its Solar Technologies Market Report (Price et al., 2010). Due to projected deployment of 3.1 GW in 2012, CIGS will require 12% of the current annual production of indium. In order to alleviate the pressure CIGS production puts on indium availability and price, some measures are suggested to be implemented. The degree of recycling should be increased and indium could be substituted by another metal such as gallium. However, the change in alloy composition may influence the cell performance in a negative way. Tellurium, which is used in CdTe PV, is expected to show similar characteristics as indium. But unlike the latter the prices of tellurium have dramatically increased over the last years, rising from $50/kg in 2004 to $225/kg in 2008.

Another study investigating material availability for thin-film PV demonstrates a more optimistic view (Fthenakis, 2009). The author examines technology growth potentials based on refining rates of indium and tellurium during base metal processing. As the supply of tellurium and indium is directly linked to the amount of the base metal extracted, the demand for these common metals (copper, zinc) strongly influences the availability of the metals needed for PV. Tellurium for example is mainly recouped from the anode slimes in copper refining. Currently, recovery rates of tellurium are estimated to be well below 50%. However, it is technologically feasible to recoup 80% or more depending on the market price. Gold for example is extracted at recovery rates greater than 95%. Assuming that the photosensitive layer thickness can be reduced from 3.3 µm to 1.5 µm for CdTe and from 1.6 µm to 1.2 µm for CIGS in 2020 along with a significant increase in performance of thin-film modules, the further deployment of PV using these technologies is not expected to be restrained by material constraints. The study predicts an annual production limit of 14-38 GWp for CdTe and 13-22 GWp for CIGS which is sufficient to supply modules at current PV growth rates. Under these considerations the prices of In and Te become the limiting factors. The projected growth scenarios are expected not to be sustainable if prices increase to levels which are ten times higher than the maximum prices.

Alternatives to the leading thin-film materials have also been studied recently (Wadia et al., 2009). The authors examine annual PV electricity production potentials of 23 inorganic materials. Compared to many of the materials considered the leading thin-film materials of today perform poorly. However, known economic reserves of In and Te are identified to suffice for annual electricity production of 17000 TWh which corresponds to today´s worldwide electricity consumption. Among the investigated materials iron pyrite (FeS_2) displayed the best performance in terms of raw material cost and annual electricity production potential.

A study published in Science demonstrates that Te shortages can successfully be addressed by changing some parameters which are characteristic for today´s thin-film industry (Zweibel, 2010). In order to produce 10% of world-wide electricity in 2030, an annual production of CdTe modules of 200 GWp is required. For the fabrication of these modules 19000 metric tons of Te would be used. Since the present annual production is at about 640 tons, a more than 40-fold increase in supply is required. However, this gap between material demand and supply can be closed by enhancing module efficiency, increasing recovery rates from copper refining and decreasing layer thickness. Even though current thin-film modules use a 3 µm thick photosensitive layer, this value is expected to decrease dramatically in the near future according to the author of the study.

Another recently published paper reaches the conclusion that material constraints will not play a major role in hindering future large-scale deployment of PV (Candelise et al., 2011). This argument is based on a comparison of the future PV market size according to the IEA technology roadmap with annual production limits of thin-film technologies derived from literature. Even if only one of the dominant thin-film technologies was to produce electricity, the projected 10.2 GWp/yr could be met. Considering that the PV market is segmented into different technologies and accounting for the fact that thin-film deployment trails that of c-Si quite a bit, shows that material constraints are found to be unlikely. However, increasing demand may lead to significant price increases which might hinder future expansion. As the PV industry currently only uses a minor part of the global annual production of these metals, other industries have an even greater impact on price dynamics at the moment. As an example, only 2% of global indium demand is being used in module manufacturing.

Not only considerations of material constraints in the thin-film industry find their way into literature but also silver requirements of silicon PV are undergoing examination (Green, 2011). Due to the recent price surge of the silver market price, the author expects that changes to the design and manufacturing of silicon cells regarding the amount of silver use will be required in the near to medium term. In 2010, PV accounted for approximately 7% of global silver supply but this number is likely to increase as the industry grows at a rapid pace.

A further study depicts a comprehensive picture regarding resource scarcity in PV by evaluating the cumulative material demand for a PV electricity production of 10000 TWh in 2040 (Zuser et al., 2011). This represents 25% of the worldwide electricity demand in the year 2040 according to the EREC Council. Depending on three scenarios, which represent the level of technological progress, an installed capacity of 8369 GWp for the pessimistic case to 5908 GWp is required to supply the aforementioned electricity needs. Unlike many other studies, this one takes market shares of the technologies c-Si, CdTe, CIGS and a-Si into consideration. In 2040, all technologies are expected to have a market share of 25% which is explained by the fact that the c-Si market share shrinks because of the rapid expansion of thin-film technology. The market share values for the calculations between 2010 and 2040 are derived from linear interpolation. According to these assumptions and the methodology laid out in the paper, the predicted electricity production is unlikely to be reached in 2040. Especially for the technologies CdTe and CIGS severe material shortages have been identified. Similar to the above mentioned studies, In and Te are considered to be the elemental species of concern. In order to reach the electricity production goal in 2040, Te production needs to be ramped up by a factor of 30-180. Material restrictions for In are less pronounced but today´s production rates are still insufficient to cover future demand. Unlike other works, this study also expects serious material constraints for CIGS due to limited gallium availability. Furthermore, recycling efforts can only contribute to alleviate material shortages after 2030. This is only intuitive as the cumulative installed capacity in 2010 was at 40 GWp and solar modules are expected to last at least 20 years. Considering that the study assumes that some thousands of GWp are to be installed in order to meet the energy needs of the future, recycling is expected to play a negligible role in the near to medium term.

The last study considered in this literature overview evaluates potential material shortages of c-Si, CdTe, CIGS and dye-sensitised solar cells by calculating best-case scenarios (Tao et al., 2011). For this purpose the reserve base, which per definition also includes sub-economic resources apart from the known reserves, of the investigated metals is used. Additionally, layer thicknesses are taken on the lower range of what is found in commercially available modules, namely 2 µm for CdTe and CIGS. Assuming that the entire reserve base is available for PV production, the maximal cumulative capacity and the maximal annual growth rate of the technologies is calculated. The authors conclude that under these conditions PV is not capable of supplying sufficient electricity to play a major role in the future technology mix. For example, the maximum capacity for CdTe and CIGS are determined being 816 and 650 GWp respectively.

In conclusion, several research projects have already dealt with the research question of how future PV growth is going to affect the availability of materials used for the fabrication of solar modules. The methodologies used differ to a great extent as do the results. However, the research endeavours can be grouped together based on the parameters evaluated. Firstly, studies have focused on the determination of the maximum level of cumulative installed capacity. Some have concentrated on the maximum amount of electricity produced which is mainly given in TWh. As this value can be easily transformed into capacity (GWp), these projects can be grouped together. Secondly, maximum levels of annual PV production of the various technologies have been evaluated. As such, this parameter is described as GWp per year. Thirdly, another approach consists of calculating material demands for a certain level of PV deployment and relating the result to current production rates of the metals of concern.

Since the methodologies and the underlying assumptions are different in every study, the results vary as well. However, indium, tellurium, gallium and silver have been identified as the showstoppers of large-scale PV deployment based on the fact that they are recouped as by-products of the refining process of more commonly used metals such as copper or zinc. This explains why it is a complex issue to ramp up production rates of these metals. Interestingly, the resource constraint issue for CIGS is not as clear-cut as for the other technologies. While c-Si growth is clearly restrained by silver availability and the low production rates of tellurium pose restrictions for CdTe, results differ for CIGS. Most consider indium constraints as the main issue advocating a substitution by gallium in the alloy employed in CIGS. Others indicate that the element gallium is the limiting factor to CIGS deployment.

The results for cumulative installed capacity range from 120 GWp (Feltrin et al., 2008) to approximately 11,000 GWp (Wadia et al., 2009) for CdTe and from 90 GWp (Andersson, 2000) to approximately 11,000 GWp for CIGS (Wadia et al., 2009). Similarly, estimates of achievable annual production range from 20 GWp/yr (Andersson, 2000) to 211 GWp/yr (Fthenakis, 2009) for CdTe and from 17 GWp/yr to 152 GWp/yr (Fthenakis, 2009).

This bandwidth of results clearly shows the uncertainties encountered when dealing with potential future material restrictions in the field of PV.

2.1 Metal availability

As outlined in the section dealing with the state of the art, several elements have been identified being of crucial importance for a further development of the PV industry. While silver availability poses a challenge to the established crystalline silicon technology, the thin film industry´s metals of concern include indium, tellurium and gallium. These are also the metals this study will focus on. In order to get a better understanding of the deployment restrictions the availability of these elements might potentially create, it is necessary to illustrate how these metals are mined and refined. This section will also include an analysis of available metal production rates and reserves which will be used to in the following calculations.

Silver, which is used for wafer-based silicon PV, is produced as a by-product of copper, gold and lead-zinc mining. Global mine production of Ag amounted to 23,800 tons in 2011 and has been gradually increasing in recent years (USGS, 2012). According to the US Geological Survey, reserves are estimated being 530,000 tons. Compared to the base metals with which silver is extracted these production figures are rather small. In 2011 12.4 million tons of zinc have been produced and reserve estimates amounted to 250 million tons.

Indium is primarily obtained as a by-product of zinc production. Additionally, deposits have been identified which might warrant direct mining (Green, 2009). However, these sources are unsuited for the extraction of indium at prices which are consistent with PV. According to the US Geological Survey, global primary production of indium was 640 tons in 2011 (USGS, 2012). Numbers for the reserves of indium were removed from the USGS reports since 2009. The last estimates from 2008 have indicated reserves of 11,000 tons and a reserve base of 16,000 tons of indium (USGS, 2008). The Indium Corporation published a study estimating the indium reserve being almost 50,000 tons (Mikolajczak, 2009). The publication also points out that only 30% of the worldwide amount of indium mined is refined to indium metal. The reason for this is the low recovery rate of only 50% of indium out of the indium refined in smelters. The author concludes that the recovery rates will adapt to demand. As the metal price rises, higher recovery rates are warranted. Due to the low recovery rates during the production process of the base metals such as zinc, indium smelters have accumulated indium-containing tailings which amount to an estimated 15,000 tons worldwide with 500 tons added every year (EU-Commission, 2010). For the calculations in this study, an indium reserve of 50,000 tons is taken as this seems to be the only available figure at the moment.

Tellurium, which is used in CdTe PV, is mainly produced as a by-product of copper mining. Studies conducted on the recovery rates of tellurium during copper refining have shown that only 30-40% of the metal are recouped (Fthenakis, 2009). However, current technology would allow for extraction rates as high as 80%. As the demand of tellurium will be higher in the future, recovery rates are expected to increase as well bearing in mind that gold for example is recovered at 95%. The USGS discontinued publishing the refinery production of tellurium in 2008 in order to avoid the disclosure of private company data. The last value obtained from the USGS reports stems from 2008 and amounts to 135 tons of primary production not including US production (USGS, 2008). However, some distinguished authors in the field have estimated production rates of some 480 tons of tellurium per year. A publication of the European JRC also indicates that refinery production is at 500 tons (Jäger-Waldau, 2011c). Even though reporting of annual production of tellurium was discontinued by the USGS, reserves data are still available (Fthenakis, 2009) (Zweibel, 2010). In the report from 2012 the reserves estimate amounts to 24,000 tons (USGS, 2012). These figures are based on the tellurium content in copper reserves and neglect reserves from potential direct mining of tellurium. This source of tellurium was described comprehensively by Green (Green, 2009).

The last metal of concern which is considered in this study is gallium. As shown in the section dealing with the state of the art, it has been identified as rare material potentially posing restrictions to high level deployment of CIGS PV. Gallium is primarily obtained as a by-product from bauxite refining (USGS, 2012). It is contained in bauxite ores only in very low concentrations and can only partly be extracted from these ores. Since the reserves of bauxite are so large that only a part of them is expected to be mined in the near future, reserves cannot be estimated according to the commonly used definition of the word. The Indium Corporation claims in a report that material restrictions based on gallium availability are unlikely to impose limits to CIGS growth because recovery rates of gallium out of bauxite ores are still as low as 10% (Mikolajczak, 2009). According to the USGS report, annual production amounted to 216 tons in 2011.

The data presented in this section is mainly based on USGS publications. The uncertainties of such estimates are rather high considering that some of these numbers are purely derived from certain assumptions. In the case of tellurium for example, only the content of the metal in copper ores is considered when deriving the reserves data. Moreover, certain data such as tellurium production rates is not available due to the protection of sensible company information. In addition, cross-validation is not possible as the USGS reports are the only official publications on metal production rates and reserves.

The gathered metal data, which will be further used in this study to evaluate possible material restrictions in PV, is summarized in Table 2.

Table 2: Recent production and reserves data for Ag, Ga, In and Te

	Annual production [t]	Reserves [t]
Ag	23800	530000
Ga	216	NA
In	640	50000
Te	480	24000

3 Methodology

The following section describes the methodology which is used for the realization of the study. The aim of the presented work is to evaluate the impact of future levels of deployment of solar cells on the availability of the metals gallium, indium, silver and tellurium until the year 2030. The PV technologies considered in this study are limited to c-Si, CdTe and CIGS as they represent the major part of solar cells which are operational today. About 5-7% of the present market share is occupied by a-Si which is taken into consideration in the calculation (Razykov, 2011; EPIA, 2011). However, material constraints for a-Si are not evaluated as potential bottlenecks for this technology have not been identified in the reviewed literature. In order to achieve the outlined goals, the study will be divided in three parts with each of them covering a different aspect. In the first part the material demand for potential scenarios of future PV growth are calculated and compared to known reserves. The second part aims at determining the highest achievable level of annual production of the different PV technologies based on the production data for the metals used. In the third part the installed capacity which can be deployed based on the reserves data will be determined.

3.1 Evaluating growth rate scenarios

In a first step, the material requirements to fulfill two different growth scenarios, published by the EPIA for the technologies c-Si, CdTe and CIGS, are calculated (EPIA, 2011). The so-called accelerated and paradigm shift scenarios have been worked out by Greenpeace and the EPIA in order to provide insights into how PV will evolve in the future. The accelerated scenario is described as a continuation of the status quo regarding support policies and political commitment. It can be achieved even if no major technological changes are implemented. The paradigm shift scenario, on the other hand, foresees a dramatic improvement in the way PV is supported and deployed allowing PV to generate 12% of European electricity demand in 2020. Based on the growth rates published in the above cited report and world-wide PV capacity of 67.4 GW (EPIA, 2011b), the cumulative installed capacity for the year 2030 has been determined. The following table summarizes the characteristics of the scenarios used in this study.

Table 3: Average growth rates under the accelerated and paradigm shift scenario

	2011-2020 [%]	2021-2025 [%]	2026-2030 [%]	Cumulative capacity 2030 [GW_p]
Average growth rates accelerated scenario	26	14	10	1673
Average growth rates paradigm shift scenario	42	11	9	4102

In order to be able to calculate the material demand for the depicted scenarios, several parameters such as the market shares of the technologies, the layer thickness and the efficiency have to be taken into account. The known market shares of the PV technologies are linearly extrapolated into the future using market projections published by the EPIA (EPIA, 2011). However, the EPIA only forecasts market share until the year 2020. In the study at hand it is assumed that the market share of c-Si will decline to 50% by 2030 as the other three thin film technologies will divide the remaining 50% evenly amongst them. As mentioned before, the market share occupied by a-Si will be considered in the calculations but material requirements will not be evaluated in this case.

For the parameters layer thickness and efficiency three different scenarios are used to reflect different levels of progress of the respective technology in the future. These scenarios will be referred to as the conservative, the neutral and the progressive scenario. In the case of c-Si, the scenarios represent an efficiency of 20% for the pessimistic, 22% for the neutral and 25% by the year 2030. These projections are mainly based on the findings established by the PV Roadmap of the IEA (IEA, 2010). The efficiency values for the years between 2011 and 2030 are derived by linear interpolation between the current average efficiency of 15% and the expected values for 2030 under the different scenarios. The current average module efficiency was determined by checking the product portfolios of the largest PV manufacturing companies which are described in a report published by the Joint Research Centre of the European Commission (Jäger-Waldau, 2010). The average efficiency has to be considered as an estimate because an average value cannot be determined so easily. Most companies produce several different sets of modules which also have different characteristics and efficiencies.

The same procedure was used for CdTe and CIGS. While First Solar, the leading CdTe PV manufacturing company, has recently demonstrated that their modules achieve efficiencies of 14% and beyond, other companies do not reach this benchmark yet. These companies produce CdTe modules in the range of 10-11% conversion efficiency. The specifications of the modules produced by First Solar are at the time of writing not available on the official website of the company. Based on this information, an average CdTe module efficiency of 12% was estimated for this study. Based on the prospects of technology development published in the IEA PV roadmap report, efficiencies of 14%, 15% and 16% by the year 2030 have been assumed under the conservative, neutral and progressive scenario. A screening of product specifications of several CIGS producing companies has shown that 12% is suitable in order to represent the current average conversion efficiency of CIGS modules. The conservative, neutral and progressive scenarios stand for 15%, 18% and 20% conversion efficiency for CIGS by the year 2030.

The parameter layer thickness is of crucial importance for this study as the material demand is linearly dependent on it. As the crystalline technology is not examined upon its polysilicon use, only the amount of silver, which is used for a specified capacity, needed to be identified. According to Green, approximately 100 mg silver per Watt is used during the production of silicon modules. This corresponds to 100 metric tons of silver for one GW (Green, 2011). Since this estimate is derived from the solar market volume and the corresponding silver use in the PV industry, there is no need to factor in the material utilization rate. In order to account for technological progress in the material use efficiency, the amount of silver consumed during the production process is estimated to be reduced significantly by the year 2030. Similar to the other technologies, three scenarios are developed for the silver content in crystalline silicon modules. However, these scenarios account for different amounts of silver usage per module as opposed to material utilization rates because the latter value is not available for c-Si. The conservative, neutral and progressive scenarios represent 60 t, 50 t and 40 t of silver used per GW in the year 2030. The values between the amount used in the base year and the target values established by the scenarios are derived from linear interpolation.

The layer thickness values for CdTe and CIGS have been chosen according to recently published information (Fthenakis, 2009; Woodhouse et al., 2012; Zuser et al., 2011; Zweibel, 2010). Current CdTe modules were found to have a 3 µm thick photosensitive layer, modern CIGS devices exhibit 2 µm of photosensitive material. These figures will most likely decrease in the future as manufacturers strive for higher profits. Under the conservative, neutral and progressive scenarios layer thickness amounts to 2 µm, 1.5 µm and 1 µm for CdTe, and 1.5 µm, 1.25 µm and 1 µm for CIGS in 2030.

The material utilization rates during the fabrication process of thin film modules are still rather low. The values for this parameter vary wildly in scientific publications. In the case of CdTe for example, values ranging from 40% to 90% have been published (Green, 2011a; Woodhouse et al., 2012). Due to the fact that Green´s publication focuses on First Solar, the leading CdTe manufacturer, the material utilization rate of 40% derived in this publication is used for this study. This part of the fabrication process will most likely experience major progress in the future because certain deposition techniques have already demonstrated to have utilization rates of about 70% (Bubenzer et al., 2003). Therefore, under the scenarios for 2030 material utilization is assumed to increase to 70%, 80% and 90% for the conservative, neutral and progressive case. Published information on the utilization rate of indium during the fabrication process of CIGS modules is more coherent than in the tellurium case (Candelise et al., 2011; Fthenakis, 2009; Green, 2009). Based on the cited studies, the utilization rate for indium is assumed to be 40% and will increase to 70%, 80% and 90% under the three different scenarios. In the following table the parameters efficiency, layer thickness, material utilization rate and their development according to the scenarios are summarized.

Table 4: Parameter inputs for scenarios

	2011	2030		
		Conservative	Neutral	Progressive
Module Efficiency [%]				
c-Si	15	20	33	25
CdTe	12	14	15	16
CIGS	12	15	18	20
Layer thickness [µm]				
CdTe	3	2	1.5	1
CIGS	2	1.5	1.25	1
Material utilization [%]				
CdTe	40	70	80	90
CIGS	40	70	80	90
Material use per GW [t]				
Ag in c-Si	100	60	50	40

In the next step the amounts of minor metal used in the thin film solar modules have to be determined. As these are part of metal alloys in such devices, the mass fraction of the metal within the alloy has to be taken into account in order to be able to determine the material demand for a specific area of solar modules. In the case of CdTe, tellurium accounts for 53% of the weight of the cadmium telluride alloy which has a density of 5.85 g/cm³. With the assumptions made for the baseline scenario for the year 2011, one square meter of CdTe modules thus contains 9.3 grams of tellurium.

The procedure is less straight forward for CIGS modules because a wide variety of metal alloys with slightly different compositions form the photosensitive layer in such devices. The indium demand was calculated based on the alloy with the composition $CuIn_{0.7}Ga_{0.3}Se_2$ which is a common material in CIGS modules (Tao et al., 2011). Indium accounts for 25% of the weight of this substrate which has a density of 5.7 g/cm³. Under the baseline scenario one square meter of CIGS modules thus contains 2.85 grams of indium.

The same metal alloy as in the indium case is used for the calculation of gallium material demand of CIGS. The weight fraction of gallium in this alloy is 6.5% which translates into an area specific material demand of 0.74 g/m².

Since all of the input parameters have now been determined and quantified, the required material demand for the accelerated and the paradigm shift scenario can be calculated. In order to be able to account for the change of the parameters with time, the material demand needs to be calculated for each year using the following generalised equation:

$$M_{nij} = \frac{C_{n-1} \cdot MS_{ni} \cdot (GR_n - 1)}{\eta_{ni} \cdot STC} \cdot \alpha_{ij} \cdot \frac{1}{U_{ni}} \cdot \frac{L_{ni}}{L_{n=1,i}} \cdot 10^6$$

where M stands for material demand in metric tons, C for cumulative installed capacity in GWp, MS for market share of the respective technology, GR for growth rate of the solar market, η for module efficiency, STC for standard test conditions (1000 W/m²), α for the area-specific material demand in g/m², U for the utilization rate of material and L for the layer thickness (μm) of the respective solar technology. The index n describes the year with n=1 being the base year 2011. The solar cell technology is described with the index i, and j is used to refer to the material. When calculating the material demand for the capacity installed in 2011, the above mentioned equation needs to be adjusted as the capacity of the base year can be used without having to consider growth rates.

3.2 Annual production limits

Based on the parameters and the scenarios established in the previous section, the annual production limits for the solar cell technologies are calculated. For this purpose the material demand, which is dependent on time, is compared to annual production of the minor metals. Future production rates are derived from literature since this topic has been extensively discussed by some authors. Since no information about the future production of silver and the portion that will be available for PV is known to the author, this part of the study will focus on the thin film technology, which is anyhow expected to be more limited than the conventional. Fthenakis estimates that more than 1400 tons of tellurium will be available by the year 2020 as the production and demand of copper is expected to increase by 3% on average per year and due to the fact that the recovery rates for tellurium will gradually increase to 80% (Fthenakis, 2009). Currently, the major part of tellurium production is used in iron and steel fabrication as well as in the chemicals industry. Fthenakis therefore assigns the entire increase in tellurium production to PV arguing that the demand for the above mentioned industries will remain flat in the future. Since such a material consumption percentage of tellurium in the PV sector is hardly conceivable, 50% of the increase in production is assigned to PV. This means that under these assumptions approximately 600 tons of Te will be available for module fabrication in 2020.

The PV industry currently only consumes about 5% of indium production. Since the demand in higher value added products such as cell phones, liquid crystal displays and computers is expected to increase, only 25% of metal consumption is assumed to be available for the PV industry. Hence, approximately 200 tons of indium would be available for CIGS module production under these assumptions (Fthenakis, 2009).

There is no need to examine potential bottlenecks for gallium as indium is considered the limiting factor for large scale deployment of CIGS.

4 Results

In the subsequent section the results based on the outlined methodology are presented. Starting with the outcomes for the EPIA scenarios, this part also includes the results for annual production limits for thin film technologies as well as the achievable cumulative installed capacity based on reserves data.

4.1 Material demand for growth rate scenarios

The material demand for two scenarios published by the EPIA in cooperation with Greenpeace has been determined. The accelerated scenario foresees lower growth rates in the near future than the other prediction. This characteristic is reversed towards the end of the period 2011-2030 when the growth rates of the accelerated scenario eventually overtake those of the paradigm shift prediction. In the year 2030, the accelerated scenario results in cumulative capacity of 1673 GW_p which significantly lags behind the 4102 GW_p expected under the paradigm shift scenario. Compared to other prospects of future market development, these figures are significantly higher. The most progressive scenario developed by the IEA, expects a market size of 870 GW by 2030, which represents roughly one fifth of what is foreseen under the paradigm shift scenario that is used in this study (Jäger-Waldau, 2011a). Since the aim of the study is to investigate whether the PV industry could potentially be restrained by a lack of minor metal availability, it only makes sense to focus on scenarios which are at the higher end of the broad range of predictions.

In order to be able to assess the impact of future PV deployment levels on the availability of the considered metals, the cumulative material demand is checked against known reserves and the maximum annual material demand is related to current annual production.

Based on the assumptions outlined in the methodology section, the following tables depict the cumulative demand and the maximum annual material demand of the metals gallium, indium, silver and tellurium for the accelerated scenario. The numbers are rounded to three significant digits.

Table 5: Cumulative material demand [t] for accelerated scenario by 2030

	Conservative	Neutral	Progressive	Reserves [t]
Ag	58900	54100	49200	530000
Ga	2050	1490	1150	NA
In	7890	5740	4410	50000
Te	24500	18400	13700	24000

Table 6: Maximum annual material demand [t/yr] for the accelerated scenario in the period 2011-2030

	Conservative	Neutral	Progressive	Annual Production [t/yr]
Ag	4770	4490	3630	23800
Ga	180	140	110	216
In	680	530	430	640
Te	1940	1320	1040	480

The figures given in table 5 represent the future material requirement for the fulfilment of the accelerated scenario. Thus, the material demand for the base year 2011 has not been included in the calculation. This means that the metal consumption of the PV industry for the deployment of the current 67 GW is not considered.

Clearly, the future deployment of modules will require a significant part of reserves being used by the PV industry. In the case of silver, for example, roughly 10% of reserves are consumed by the fabrication of c-Si modules. However, reserves estimations have been gradually increased in the past years and this trend is very likely to be sustained in the future. Today about 7% of the annual silver production is used in PV (Resnick, 2011). It can be seen from table 6 that this percentage will increase under these assumptions. In the neutral scenario approximately 19% of the annual silver production would be required to fulfil the accelerated scenario. Such a high demand in silver might have adverse effects on the competitiveness of solar modules as prices will follow demand and increase as well. This aspect will be looked into more deeply in a later chapter. For the other technologies resource constraints are much more severe compared to the latter example. Especially, CdTe will require a major portion of known tellurium reserves, even under the progressive scenario. Additionally, maximum annual material demand exceeds current production rates in all scenarios. In order to satisfy such a growth scenario, annual metal production needs to be significantly expanded. This does not only apply for tellurium but also for the metals indium and gallium as such material demands would inevitably lead to significant price implications.

The material constraints become clearly evident once material requirements for the paradigm shift scenario are calculated. The summary of results is given in the following two tables.

Table 7: Cumulative material demand [t] for paradigm shift scenario by 2030

	Conservative	Neutral	Progressive	Reserves [t]
Ag	153000	141000	129000	530000
Ga	5110	3730	2880	NA
In	19700	14300	11100	50000
Te	62600	47300	35600	24000

Table 8: Maximum annual material demand [t/yr] for the paradigm shift scenario in the period 2011-2030

	Conservative	Neutral	Progressive	Annual Production [t/yr]
Ag	21200	20000	18700	23800
Ga	668	519	419	216
In	2570	2000	1610	640
Te	6790	5460	4380	480

Even though the paradigm shift scenario represents a very ambitious expectation of the future development of the PV market, only the material demand for CdTe exceeds known reserves. Under this scenario more than a quarter of silver reserves is consumed by silicon solar modules. The limitations for CdTe become even more pronounced when the maximum annual material demand for the period 2011-2030 is compared with current annual production. The latter is surpassed by a factor of 9-14 depending on the scenario. Due to the specific design of the paradigm shift scenario, maximum demand values peak around the year 2020 because the growth rate is assumed to be 42% until then. As the growth rates decrease significantly after 2020, so do the annual material requirements. In the case of tellurium under the conservative scenario, for example, only two annual material demands exceed 4500 t/yr. This characteristic is shared across all evaluated technologies and can mainly be attributed to the design of the scenario.

Unlike under the accelerated scenario, production rates for all metals would need to increase significantly under the paradigm shift scenario. The silver requirements could theoretically be met but only if almost 100% of silver produced would be available for the PV industry. In addition, the annual production of both metals, which are used in the alloys of CIGS modules, would need to be ramped up if this scenario was to be met.

The ratio of maximum annual material demand to current annual production is a good indicator for the material limitations created by such deployment levels of solar power. The following table depicts this ratio for the paradigm shift scenario.

Table 9: Ratio maximum annual material demand/annual production for paradigm shift scenario

	Annual material demand/Annual production			
	Conservative	Neutral	Progressive	Annual production [t/yr]
Ag	0.89	0.84	0.79	23800
Ga	3.09	2.40	1.94	216
In	4.01	3.13	2.52	640
Te	14.1	11.4	9.13	480

In summary, tellurium has been identified to be the minor metal which imposes the most severe resource constraints upon solar technology deployment. Thus, cadmium telluride faces the biggest challenge among all of the technologies examined in this study. The considered growth scenarios, which have been developed by EPIA in cooperation with Greenpeace, also affect the metal availability for CIGS and the traditional silicon technology. However, these effects are far less pronounced in comparison to the tellurium containing thin film option.

4.1.1 Sensitivity Analysis

After evaluating the proposed growth scenarios under the assumptions described in the methodology section, it is clear that restricted material availability poses a threat to the large-scale deployment of solar modules. In this section ways to address this problem are explored by identifying and characterising the parameters, which affect the cumulative material demand the most. Moreover, varying the parameters also allows gaining insights about the sensitivity of the model towards the initial assumptions. The sensitivity analysis is carried out for CdTe only as the other technologies are expected to yield the similar result. However, the accelerated and the paradigm shift scenario are treated separately because they are likely to react differently due to design differences. The initial values for the variables layer thickness, module efficiency and material utilization rate are varied by 15% in order to be able to assess the impact on the result for cumulative material demand. As one variable is varied the others remain unchanged. In addition, the expected market share of CdTe by the year 2030 is changed by 15%. Since the market shares for the base year 2011 are given, the influence of market share on the final result can only be determined by varying the values for the year 2030. As the three scenarios already represent variations of layer thickness, efficiency and material utilization rate in the year 2030, the sensitivity of the model can be tested by changing the initial values.
The layer thickness turns out to be parameter which the model reacts most sensitive to. The change of the initial values results under both growth scenarios in a twofold response of the model towards variations in layer thickness as compared to material

utilization rate. If the layer thickness is reduced by 15%, the cumulative tellurium demand decreases by roughly 8%. An increase in material utilization rate by 15% on the other hand only yields a 4% decrease in metal demand. The mentioned numbers apply for the accelerated scenario under the neutral setting.

The model is far more sensitive towards variations in market share of CdTe. If the market share in the year 2030 is reduced by 15%, the model responds with an almost 12% decrease of cumulative metal demand. Consequently, this parameter has the greatest impact on the final result. Should the CdTe industry continue to grow at a high pace and account for a higher market share than assumed in this study, the material constraints will be even more serious. The following table provides a comprehensive overview of the results of the sensitivity analysis based on the neutral scenario.

Table 10: Sensitivity Analysis of input parameters

	Advanced scenario		Paradigm shift scenario	
	Cum. material demand [t]	Model response [%]	Cum. material demand [t]	Model response [%]
Layer thickness: 2.55µm	16900	-7.9	43400	-8.2
Efficiency: 13.8%	17400	-5.1	44800	-5.3
Material utilization rate: 46%	17600	-4.1	45300	-4.2
Market share CdTe 2030: 14.1%	16200	-12	41900	-11

4.2 Annual production limits

The annual production limits for the thin film technologies CdTe and CIGS have been calculated. This section presents the results and compares them to values found in literature.

Unlike in some published studies on this topic, the approach applied in this work considers the fact that the annual metal production will only partly be available to the PV industry. Thus, published annual production limits vary over a wide range of values. As already mentioned in the methodology section, 600 tons of tellurium and 200 tons of indium are expected to be available by 2020. These figures are based on estimates published by Fthenakis (Fthenakis, 2009).

In a first step the metal requirement for one GW of the respective solar technology under the conservative, neutral and progressive scenario was calculated. For this purpose the values of the relevant parameters from the year 2020 have been used. An overview of the input data is provided by the table below.

Table 11: Input for Annual Production Limit Calculation

	Conservative	Neutral	Progressive
CdTe:			
Layer thickness [µm]	2.53	2.29	2.05
Module efficiency [%]	13	13.4	13.9
Mat utilization rate [%]	54.2	58.9	63.7
CIGS:			
Layer thickness [µm]	1.76	1.64	1.53
Module efficiency [%]	13.4	14.8	15.8
Mat utilization rate [%]	54.2	58.9	63.7

Based on this input, annual production limits, which are the depicted in the following table, have been evaluated.

Table 12: Metal Requirements and production limits for CdTe and CIGS

	CdTe (Te)	CIGS (In)
Metal requirement 2011 [t/GW]	194	59
Metal requirement 2020 conservative scenario [t/GW]	112	34.5
Metal requirement 2020 neutral scenario [t/GW]	89.7	26.8
Metal requirement 2020 progressive scenario [t/GW]	71.9	21.6
Metal available 2020 [t]	600	200
Annual PV production limit [GW/yr]	5.4-8.3	5.8-9.2

The annual production limits for CdTe and CIGS are considerably lower under the assumptions made in this study than in most publications dealing with the same topic. The reasons for this are twofold. First of all, these studies have assumed that 100% of the metal production is available to the PV industry (Andersson et al., 1998; Andersson, 2000; Wadia et al., 2009). The studies, which did not assign the entire metal production to the PV industry, have estimated that the metals indium and tellurium will predominantly be used for module fabrication. Fthenakis, for example, assumed that almost 80% of tellurium and more than 32% of indium will be used in the PV industry by the year 2020 (Fthenakis, 2009). For now, these assumptions seem rather unrealistic especially considering the effect on module price. Secondly, these studies have also been designed around very optimistic assumptions about technological progress in the field. Andersson evaluated growth restrictions based on a 100% material utilization rate and 1 µm layer thickness for CdTe by the year 2020. CIGS was predicted to reach a layer thickness of 0.5 µm by that time. Due to such assumptions, annual production limits in the range of 14 - 38 GW/yr have been calculated for CdTe (Andersson, 2000; Fthenakis, 2009; Keshner & Arya, 2004). CIGS was evaluated to be restricted at an annual production of 13 - 676 GW/yr.

Table 12 shows that neither technology has the potential to satisfy the material demands of the growth scenarios discussed in this work. According to the model developed for the calculation of the cumulative material demand, 70 GW of both thin film technologies would be needed to achieve the accelerated scenario. The paradigm shift scenario demands a contribution of 206 GW from CdTe and CIGS. Since these numbers exceed the calculated production limits by a factor of 10 even in the case of the accelerated scenario, the following part of the study is dedicated to exploring ways to reduce the impact of this material restriction. The range of annual production limits for CdTe and CIGS are depicted in the following figure and related to the required deployment under the accelerated scenario.

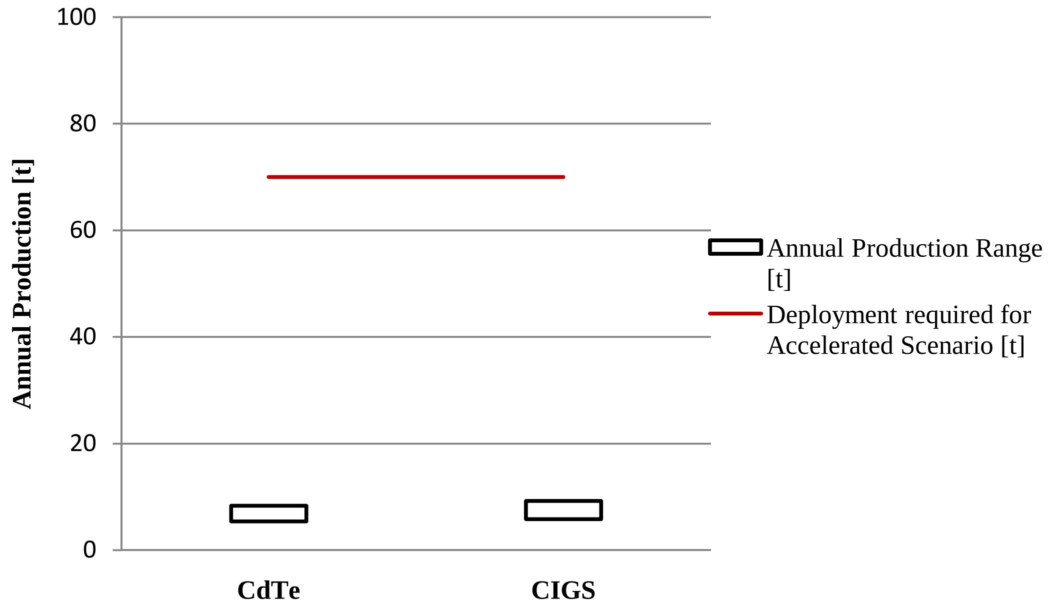

Figure 2: Range of Annual Production for CdTe and CIGS in relation to deployment required for Accelerated Scenario

To this end, the variables layer thickness, module efficiency, material utilization rate are varied until an annual production limit of 70 GW is achieved. At the beginning, only one parameter will be adapted without changing the others. The neutral scenario will be taken as the starting point. The values for the parameters are presented in table 11. Then, a solution involving a change of all three parameters will be explored.

In order to reach a capacity of 70 GW, the examined variables need to be changed drastically. The layer thickness would have to decrease to below 0.25 µm for CdTe. The benchmark of 70 GW cannot be reached by adapting module efficiency only. Even CdTe modules with an efficiency of 20% could only provide 10 GW per year. The similar argument applies for the variation of the material utilization rate. Even if this parameter was changed to 100%, CdTe would provide just below 12 GW.

Thus, a solution involving adaption of all three parameters is required in order to stay within limits which are realistic from the technological point of view. Clearly, processes will still have process losses in 2020 and a layer thickness of 0.25 µm is equally unimaginable by that time. Although only CdTe has been considered in this analysis the same argument applies to CIGS. The goal of 70 GW capacity increase in 2020, will only be feasible if all three parameters are adjusted.

With an assumed layer thickness of 0.75 µm, a module efficiency of 18% and a material utilization rate of 95%, the tellurium material demand amounts to about 13 tons per GW installed capacity. Hence, 44 GW could potentially be installed if these parameters were achieved. However, this scenario still falls short of supplying the 70 GW required for the fulfilment of the accelerated scenario.

For CIGS the metal requirements impose similar restrictions on annual deployment like in the CdTe case. If the layer thickness was decreased to 0.75 µm and the module efficiency and the material utilization rate was increased to 20% and 95% respectively, the capacity potential would reach 35 GW.

Thus, the required 70 GW can be deployed neither by CdTe nor by CIGS under these conditions. The values which have been taken for the calculation of the scenarios in the last two paragraphs are very optimistic and it is highly unlikely that such progress can be achieved until 2020. Therefore, the only solution to the material restriction seems to be an expansion of annual metal refining. In addition, greater capacities could be deployed if the PV industry had a greater portion of these metals available. If the amount of tellurium would increase from 600 to 1000 tons for example, the benchmark of 70 GW was reached by 2020. Consequently, the contribution of thin film technologies to ambitious growth scenarios such as the ones applied in this study very much depends on the amount of metal available for the PV industry.

In conclusion, the evaluation of annual production limits of the thin film technologies CdTe and CIGS has shown that less than 10 GW per year can be deployed based on the assumption that 600 tons of tellurium and 200 tons of indium are available to the PV industry by the year 2020. Since the model requires deployment of 70 GW from both technologies under the accelerated growth scenario, the actual production limits turn out to be only one tenth of the requirement. Even if both thin film technologies experience dramatic technological progress until 2020, the benchmark of 70 GW will not be met. However, the material constraints can be appropriately addressed by increasing the amount of material available for the PV industry, either by expanding annual refining or increasing the portion of total metal available for module fabrication.

4.3 Maximum cumulative installed capacity

In this section the maximum cumulative installed capacity, which can be achieved under the assumptions included in the conservative, neutral and progressive scenarios, is examined for the thin film technologies CdTe and CIGS. To this end, it is assumed that the known reserves are only partly available for PV module fabrication as it is highly unrealistic that the PV industry can dispose of the entire metal reserves. Since no information on such data is published or known to the author, 50% of tellurium reserves and 25% of indium reserves are assigned to be available for CdTe and CIGS production. In order to factor in the time dependency of the variables layer thickness, module efficiency and material utilization rate, the model used for the calculation of the material demand for growth scenario (see chapter 4.1) is applied. A complete collection of model data is printed in the appendix.

The accelerated and the paradigm shift scenario are expected to deliver different results regarding maximum cumulative installed capacity. Since the growth rates are significantly different in both cases but the parameters values are the same for both models in the same year, the reason for this difference becomes clear. In essence, the paradigm shift scenario is expected to deliver lower maximum cumulative capacity because it features high growth rates until 2020 when the progress in technology is still moderate. The accelerated scenario, on the other hand, has lower growth rates in the same period. Hence, more capacity is produced under the accelerated scenario at a later stage when technological development is more advanced.

Under the outlined assumptions, CIGS turns out to be less restricted in terms of maximum cumulative installed capacity than CdTe. As the cumulative material demand of indium under the accelerated scenario does not reach the 12500 tons, which are available for CIGS fabrication, the maximum cumulative capacity cannot be determined on the basis of the market size assumed by this scenario. Since the model predicts a CIGS capacity of 278 GW in 2030, the achievable maximum capacity is higher than this. If the metal resources, which remain after the production of 278 GW of modules, were used for module fabrication under the conditions described by the conservative, neutral and progressive scenario in the year 2030, an additional 225 GW, 550 GW and 1020 GW could be deployed. The actual values of layer thickness, module efficiency and material utilization rate in 2030 are presented in table 4.

As expected, the evaluation of maximum capacity based on the paradigm shift scenario yields a different result. In this case, a CIGS capacity of 350 GW and 540 GW can be achieved under the conservative and neutral scenario. The market size of 681 GW for CIGS in 2030 does not consume the entire indium reserves available for module production under the progressive scenario. Using the parameter values for the year 2030 an additional 185 GW of CIGS modules could be deployed.

The whole situation is quite different for CdTe in that the metal availability restricts deployment to a greater extent than in the CIGS case. Under the accelerated scenario the maximum installed capacity amounts to 110 GW, 142 GW and 207 GW for the conservative, neutral and progressive scenario. Thus, the market size of CdTe by the year 2030, which is required to fulfill the accelerated growth scenario, cannot be reached under these conditions. The material restriction for CdTe is even more pronounced in the case of the paradigm shift scenario. As a matter of fact, CdTe can only contribute 94 GW, 107 GW and 124 GW under the conservative, neutral and progressive scenario respectively. Thus, this technology would fall short of deploying capacity levels, which are required to satisfy ambitious PV growth scenarios such as the ones scrutinized in this study, if the amount of metal available for the PV industry remained the same in the future. Since the reserves estimates are constantly revised upwards, more tellurium should be available for the production of CdTe than today.

In conclusion, it has been found that CdTe is the thin film technology which is most restricted in terms of maximum cumulative installed capacity. The progress projections of technology represented by the accelerated and the paradigm shift scenario yielded different results. Due to the high growth rates under the paradigm shift scenario until 2020, the achievable capacity turned out to be lower than under the other setting. This is mainly due to the fact that in this case growth is assumed to take place in a period with little to moderate technological progress. The following table summarizes the findings from the evaluation of maximum cumulative installed capacity of CdTe and CIGS.

Table 13: Maximum cumulative installed capacity for CdTe and CIGS

Maximum cumulative capacity [GW]	CdTe	CIGS
Accelerated scenario		
Conservative	110	503
Neutral	142	825
Progressive	207	1230
Paradigm shift scenario		
Conservative	94	347
Neutral	107	538
Progressive	124	863

5 Conclusion and Outlook

The final chapter discusses the importance of recycling in the examined setting. Moreover, an outlook for future metal prices and the summary of the results of the study is included.

5.1 Recycling

The relevance of recycling of decommissioned solar modules for the recovery of primary materials is negligible for the period considered in this study. In publications, recycling has been put forward as an option to reduce material demand, thus increasing material availability for the PV sector. However, this aspect will not come into play until 2030 as life time expectancy of solar modules of 25 to 30 years represents current state of the art. Since 67 GW of solar modules have been reported to be installed world-wide in 2011, this capacity is so small in comparison to the expected market size in 2030 that recycling of old modules will hardly make any difference. Compared to the 2030 market sizes of 1700 GW and 4100 GW according to the accelerated and the paradigm shift scenario the material amounts contained in the current cumulative installed capacity is negligible. The European association for the recovery of photovoltaic modules, which was founded in July 2007, published in an annual report that the expected waste stream from old modules in 2030 will be 20 times larger than the one in 2010 (PV-Cycle, 2011). This shows that PV recycling is expected to provide significant amounts of material in the future. However, for the scope of this study, recycling does not play a major role.

Nonetheless, recycling of old PV modules is absolutely advisable because they contain many hazardous substances such as cadmium, lead, selenium and tellurium (McDonald & Pearce, 2010). Many PV manufacturing companies have therefore started to set up recycling initiatives such as the above cited PV CYCLE. Modern recycling techniques allow for high rates of recovery beyond 90% (Fthenakis &

Wang, 2006). Small scale operations are proven to achieve complete separation of cadmium and tellurium at the cost of 2 cents per W_p. Recycling processes on the industrial scale achieve recovery rates of roughly 90% (Fthenakis, 2009). PV-CYCLE reports that 90% of the glass and 95% of the semiconductor material contained in CdTe modules can be recycled.

The recycling process developed by First Solar, the leading CdTe manufacturing company, represents the state of the art in solar module recycling. The method involves six process steps (Berger et al., 2010). At the beginning, the glass, on which the semiconductor film is deposited, is broken into small pieces by a shredder and a mill. Then, the photosensitive material is leached from the glass using aggressive solvents such as sulphuric acids. In the next step, the glass is separated from the liquid solution containing the dissolved metals. After that, the glass is separated from the ethylene vinyl acetate and any semiconductor material is removed from the glass surface. In the last step the dissolved metals are precipitated using sodium hydroxide and subsequently concentrated to yield a filter cake which can be used to produce new solar modules.

In conclusion, recycling has not been considered in this study mainly due to the time lag between the deployment and the decommissioning of solar modules. Since current installed capacity accounts only for a minor portion of expected deployment levels in 2030, recycling will not provide a solution to the metal availability issue in the period 2011 to 2030.

5.2 Metal price considerations

The evaluated growth scenarios for the PV market have revealed the limited metal availability which might restrict future large-scale deployment ambitions. In fact, the material requirements for the fulfilment of such scenarios even exceed today´s known reserves and annual production for some metals. However, one has to bear in mind that the metals used in solar modules are also used in other industries, in most cases to a much larger extent. For example, photovoltaic module manufacturing currently accounts for only 2% of total indium demand while more than 50% is used to produce indium tin oxide, a material used in LCD screens (Candelise et al., 2011). But potential material limitations have not only been identified in the thin-film PV industry but also in the traditional silicon sector. The material requirements for silver, a material used for contacts in c-Si modules would constitute a major part of silver reserves and annual production under the investigated scenarios.

Certainly, such a demand in metals would inevitably lead to price fluctuations and eventual price increases. Since higher metal prices would automatically render photovoltaic electricity more expensive, this development would also affect the competitiveness of this renewable energy option. This effect has already been observed in the c-Si market. While in 2009 approximately 900 tons of silver went into module fabrication, this amount more than doubled in the year thereafter in which 1984 tons of silver were used in the c-Si industry (Resnick, 2011). This accounts for 8.6% of mined silver production. In 2011, the price skyrocketed to unprecedented levels. Although this surge cannot be entirely attributed to the increase in demand of the PV industry, it certainly played an important role. As a result of the significant price increase, the price of solar modules went up by almost 5% (Resnick, 2011). Even though the price surge of silver seems potentially unsustainable, economists still expect the price of silver to remain at a high level in the near future (Michelson, 2011). It is well imaginable that such price scenarios like the one just described above are also affecting other PV technologies.

Since the module and the material contained in it still account for a major share of the total module price, price fluctuations of these materials also affect the competitiveness of the respective technology. In fact, this is what currently can be observed on the PV market. Due to the oversupply of polysilicon, which is a consequence of a temporary supply bottleneck, the silicon technology managed to decrease module prices by over 50 percent in the year 2011 (Stuart, 2012b). Consequently, module prices dropped to an average of $0.87 per watt in 2012, which basically eroded the cost advantage of the thin-film industry. It turned out that CdTe manufacturing companies are hit most seriously when First Solar, the leading CdTe company, decided to close down its production facility in Frankfurt (Oder) in April, laying off 2000 employees (Stuart, 2012a).

Unlike in the silver case, future demand prospects for tellurium are less clear. Compared to indium, a larger fraction of 11% of worldwide consumption is used in PV module fabrication (Candelise et al., 2011). While the PV industry needs to compete with other sector for indium, the demand in tellurium of non- PV industries is decreasing. After the significant price increase in 2005, the metallurgical industry started to substitute tellurium by other metals. Thus, the demand in many non-PV applications is decreasing.

The evaluation of the growth scenarios in this study has shown that the limited metal availability of tellurium would impose the most serious constraints on PV deployment. Due to the fact that demand for tellurium is decreasing in its traditional applications, investment in tellurium production might seem a risky business, especially because of the limited share of global consumption by the PV industry. Despite of the decreasing use in traditional applications, tellurium is still considered being one of the most critical metals in terms of availability. Thus, some studies dealing with material availability considerations have focused on tellurium and the impact a price increase would have on the price of CdTe modules (Candelise et al., 2011; Woodhouse, et al., 2012). A higher tellurium price would provide an incentive to increase recovery rates from copper mining. However, the production of tellurium cannot be easily ramped up because it is considered a by-product of the refining of more precious metals such as copper or gold. In fact, tellurium generates a mere 0.2% of the overall revenues gained from electrolytic copper refinery (Woodhouse, et al., 2012). In essence, the availability of tellurium for the PV industry will mainly depend on the expansion of copper mining rather than on increased demand from module manufacturers.

The above cited study examines the impact a higher tellurium price might have on the CdTe industry. The authors conclude that a price increase of up to an order of magnitude above 2011 prices could be absorbed by CdTe manufacturers (Woodhouse, et al., 2012) under certain circumstances. In other words, the CdTe industry would retain its cost advantage over conventional silicon module manufacturing. In order to absorb this dramatic price increase, substantial progress in CdTe technology needs to be achieved. Not only the module efficiency would need to increase to 18% but the layer thickness would also need to drop to 1 µm. However, recent events have shown that this price advantage of thin-film modules has been eroded as the silicon manufacturers have managed to significantly reduce the price of their modules.

The other scarce metal used in thin-film module fabrication, indium, faces a rather clear future demand trend. While PV usage of indium accounts only for a tiny fraction of overall consumption, the major part is used for the production of LCDs and other electrical appliances. The demand for these industries is projected to continue growing in the future. Thus, the demand for indium is most likely also going to increase. As such, the investment perspectives for indium suppliers seem more promising than for their tellurium-producing counterparts. The expected surge in demand for indium might trigger price responses, in particular when supply falls short of satisfying demand. Such an upward pressure on price may also render higher recovery rates from refining of base metals economically viable. In fact, the strong demand for indium tin oxides has recently supported the indium supply (Candelise et al., 2011). As a result, indium production and refining capacity has been steadily increasing.

In conclusion, the PV industry still only accounts for a minor fraction of the total consumption of the metals indium, silver and tellurium as it has to compete with other industries over material resources. While the traditional use of tellurium as a steel alloy additive is declining, the industries competing with the PV sector over indium are steadily expanding. In particular, the use in electrical appliances, which consumes the major part of today´s overall indium consumption, is expected to become an even greater factor in terms of indium demand. The demand in silver will most likely remain at a high level due to applications in electronic equipment and the projected growth in fabrication of silicon solar cells (EU-Commission, 2010). Based on these demand prospects the following price projections are possible. The indium market might face an upward pressure on price, particularly if supply is unable to meet demand. For tellurium the situation is less clear-cut because the traditional metallurgical usage is declining and the development of demand from the PV thin-film is unclear. For both metals, the decision to expand production capacities will certainly not be taken based solely on the demand of the PV industry. As many other industries promise higher value added per unit of material, PV manufacturers will need to compete for these metals. Moreover, expansion of production capacities will largely depend on the market price of the respective metal as they are produced as by-products of base metal refining. According to experts the price of silver will probably remain at a high level even though the price surge of 2011 might appear unsustainable.

5.3 Summary

In the first part of the study the status quo of the PV industry and technological progress in the field has been presented. A myriad of reasons suggest that this sector of renewable energy has an optimistic future ahead. Firstly, cell and module efficiencies have been greatly improved recently. Thin-film technologies such as cadmium telluride and copper-indium-gallium selenide have emerged and have proven that they can compete against the established silicon technology. Secondly, recently published studies have shown that grid parity is already reached under favourable conditions and that more grid parity events are expected to occur across Europe in the following years. Thirdly, the PV industry has managed to decrease module prices significantly by profiting from economies-of-scale advantages. As of 2011, 67 GW of PV capacity has been installed around the world.

Under such conditions the PV industry is expected to expand at a quick pace. This study examined the impact of projected large-scale deployment of PV on the availability of metals used in the fabrication process of solar modules. Literature has identified the metals gallium, indium, tellurium and silver being the materials of concerns for the PV industry as their limited availability might restrict PV deployment beyond a certain level. Thus, the material requirements for the fulfilment of EPIA growth scenarios for the solar technologies crystalline silicon, cadmium telluride and copper-indium-gallium selenide have been examined in this study. For this purpose a model needed to be developed which takes into account the market shares, the module efficiency, the material utilization rate and the layer thickness of the different technologies. All of these parameters were assumed to be time-dependent, i.e. they are expected to change with technological progress.

With the use of this model potential material restrictions have been evaluated by calculating the material requirements for the EPIA scenarios, the annual production limits and the maximum cumulative installed capacity.

Tellurium turned out to be the metal which imposes the most severe limitations upon large-scale PV deployment. In order to satisfy the material requirements for the paradigm shift scenario of the EPIA, the amount of tellurium needed exceeds the known reserves by a factor of 2. Considering the fact that tellurium is only partly available for the PV industry as it is also used in other applications, cadmium telluride is the solar technology which is most restricted in terms of material availability. However, ambitious growth scenarios such as the ones investigated in this study, also require a significant part of the metals which are used in the other technologies.

The analysis of annual production limits of the thin-film technologies established that neither technology would be capable of contributing significantly to the EPIA growth scenarios under the assumptions that have been incorporated into the model. The annual production limits for both thin-film technologies were calculated to be below 10 GW in the year 2020. Unlike in most other studies dealing with this topic, the fact that the metals are only partly available for module manufacturing has been taken into account. In order for the PV industry to be able to deploy thin-film technology on a large scale, several criteria need to be met. Not only the performance of the modules needs to be enhanced but also the material requirements per unit need to be lowered significantly. Moreover, it is crucial that the amount of metal available for module fabrication is increased, either by expanding refining capacities or by directing more resources to the PV sector.

Based on the assumption that 50% of tellurium reserves and 25% of indium reserves are available for solar module manufacturing, the maximum cumulative installed capacity of CdTe and CIGS has been evaluated. The results range from 94 GW to 207 GW for CdTe and from 347 GW to 1230 GW for CIGS depending on different scenarios reflecting differences in technological development.

The attainable deployment level of PV will eventually depend on the technological progress the industry manages to achieve and the development of recovery rates of minor metals from base metal refining. Furthermore, the allocation of resources among the industries, which use these minor metals, will play a key role in assuring the availability of the scarce resources for module manufacturing. While PV manufacturers will need to compete against other industries, price fluctuations of the metals of interest are expected.

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7 Appendix

This section contains the numbers based on which the results in chapter have been calculated.

Table 14: Capacities for the accelerated and paradigm shift scenario, MS=market share

	Capacity accelerated [GW]	Capacity paradigm [GW]	MS c-Si [%]	MS CdTe [%]	MS CIGS [%]	MS a-Si [%]
2011	67	67	80.0	13.0	2.0	5.0
2012	85	96	77.9	13.0	3.2	5.9
2013	107	136	75.8	13.0	4.4	6.8
2014	135	193	73.7	13.0	5.7	7.7
2015	170	274	71.6	13.0	6.9	8.6
2016	214	389	69.4	13.0	8.1	9.4
2017	270	553	67.3	13.0	9.3	10.3
2018	340	785	65.2	13.0	10.6	11.2
2019	428	1114	63.1	13.0	11.8	12.1
2020	540	1582	61.0	13.0	13.0	13.0
2021	615	1756	59.9	13.4	13.4	13.4
2022	701	1949	58.8	13.7	13.7	13.7
2023	799	2164	57.7	14.1	14.1	14.1
2024	911	2402	56.6	14.4	14.4	14.4
2025	1039	2666	55.5	14.8	14.8	14.8
2026	1143	2906	54.4	15.2	15.2	15.2
2027	1257	3168	53.3	15.5	15.5	15.5
2028	1383	3453	52.2	15.9	15.9	15.9
2029	1521	3763	51.1	16.2	16.2	16.2
2030	1673	4102	50.0	16.6	16.6	16.6

Table 15: Layer thickness for CdTe and CIGS under conservative, neutral and progressive scenarios

	CdTe con [µm]	CdTe neut [µm]	CdTe pro [µm]	CIGS con [µm]	CIGS neut [µm]	CIGS pro [µm]
2011	3.0	3.0	3.0	2.0	2.0	2.0
2012	2.9	2.9	2.9	2.0	2.0	1.9
2013	2.9	2.8	2.8	1.9	1.9	1.9
2014	2.8	2.8	2.7	1.9	1.9	1.8
2015	2.8	2.7	2.6	1.9	1.8	1.8
2016	2.7	2.6	2.5	1.9	1.8	1.7
2017	2.7	2.5	2.4	1.8	1.8	1.7
2018	2.6	2.4	2.3	1.8	1.7	1.6
2019	2.6	2.4	2.2	1.8	1.7	1.6
2020	2.5	2.3	2.1	1.8	1.6	1.5
2021	2.5	2.2	1.9	1.7	1.6	1.5
2022	2.4	2.1	1.8	1.7	1.6	1.4
2023	2.4	2.1	1.7	1.7	1.5	1.4
2024	2.3	2.0	1.6	1.7	1.5	1.3
2025	2.3	1.9	1.5	1.6	1.4	1.3
2026	2.2	1.8	1.4	1.6	1.4	1.2
2027	2.2	1.7	1.3	1.6	1.4	1.2
2028	2.1	1.7	1.2	1.6	1.3	1.1
2029	2.1	1.6	1.1	1.5	1.3	1.1
2030	2.0	1.5	1.0	1.5	1.3	1.0

Table 16: Module efficiencies for c-Si, CdTe and CIGS under conservative, neutral and progressive scenarios

	η c-Si con [%]	η c-Si neut [%]	η c-Si pro [%]	η CdTe con [%]	η CdTe neut [%]	η CdTe pro [%]	η CIGS con [%]	η CIGS neut [%]	η CIGS pro [%]
2011	15.0	15.0	15.0	12.0	12.0	12.0	12.0	12.0	12.0
2012	15.3	15.4	15.5	12.1	12.2	12.2	12.2	12.3	12.4
2013	15.5	15.7	16.1	12.2	12.3	12.4	12.3	12.6	12.8
2014	15.8	16.1	16.6	12.3	12.5	12.6	12.5	12.9	13.3
2015	16.1	16.5	17.1	12.4	12.6	12.8	12.6	13.3	13.7
2016	16.3	16.8	17.6	12.5	12.8	13.1	12.8	13.6	14.1
2017	16.6	17.2	18.2	12.6	12.9	13.3	12.9	13.9	14.5
2018	16.8	17.6	18.7	12.7	13.1	13.5	13.1	14.2	14.9
2019	17.1	17.9	19.2	12.8	13.3	13.7	13.3	14.5	15.4
2020	17.4	18.3	19.7	12.9	13.4	13.9	13.4	14.8	15.8
2021	17.6	18.7	20.3	13.1	13.6	14.1	13.6	15.2	16.2
2022	17.9	19.1	20.8	13.2	13.7	14.3	13.7	15.5	16.6
2023	18.2	19.4	21.3	13.3	13.9	14.5	13.9	15.8	17.1
2024	18.4	19.8	21.8	13.4	14.1	14.7	14.1	16.1	17.5
2025	18.7	20.2	22.4	13.5	14.2	14.9	14.2	16.4	17.9
2026	18.9	20.5	22.9	13.6	14.4	15.2	14.4	16.7	18.3
2027	19.2	20.9	23.4	13.7	14.5	15.4	14.5	17.1	18.7
2028	19.5	21.3	23.9	13.8	14.7	15.6	14.7	17.4	19.2
2029	19.7	21.6	24.5	13.9	14.8	15.8	14.8	17.7	19.6
2030	20.0	22.0	25.0	14.0	15.0	16.0	15.0	18.0	20.0

Table 17: Material utilization rate for CdTe and CIGS under conservative, neutral and progressive scenarios

	U CdTe con [%]	U CdTe neut [%]	U CdTe pro [%]	U CIGS con [%]	U CIGS neut [%]	U CIGS pro [%]
2011	40.0	40.0	40.0	40.0	40.0	40.0
2012	41.6	42.1	42.6	41.6	42.1	42.6
2013	43.2	44.2	45.3	43.2	44.2	45.3
2014	44.7	46.3	47.9	44.7	46.3	47.9
2015	46.3	48.4	50.5	46.3	48.4	50.5
2016	47.9	50.5	53.2	47.9	50.5	53.2
2017	49.5	52.6	55.8	49.5	52.6	55.8
2018	51.1	54.7	58.4	51.1	54.7	58.4
2019	52.6	56.8	61.1	52.6	56.8	61.1
2020	54.2	58.9	63.7	54.2	58.9	63.7
2021	55.8	61.1	66.3	55.8	61.1	66.3
2022	57.4	63.2	68.9	57.4	63.2	68.9
2023	58.9	65.3	71.6	58.9	65.3	71.6
2024	60.5	67.4	74.2	60.5	67.4	74.2
2025	62.1	69.5	76.8	62.1	69.5	76.8
2026	63.7	71.6	79.5	63.7	71.6	79.5
2027	65.3	73.7	82.1	65.3	73.7	82.1
2028	66.8	75.8	84.7	66.8	75.8	84.7
2029	68.4	77.9	87.4	68.4	77.9	87.4
2030	70.0	80.0	90.0	70.0	80.0	90.0

Table 18: Silver demand per GW under conservative, neutral and progressive scenarios

	Ag use per GW con [t]	Ag use per GW neut [t]	Ag use per GW pro [t]
2011	100.0	100.0	100.0
2012	97.9	97.4	96.8
2013	95.8	94.7	93.7
2014	93.7	92.1	90.5
2015	91.6	89.5	87.4
2016	89.5	86.8	84.2
2017	87.4	84.2	81.1
2018	85.3	81.6	77.9
2019	83.2	78.9	74.7
2020	81.1	76.3	71.6
2021	78.9	73.7	68.4
2022	76.8	71.1	65.3
2023	74.7	68.4	62.1
2024	72.6	65.8	58.9
2025	70.5	63.2	55.8
2026	68.4	60.5	52.6
2027	66.3	57.9	49.5
2028	64.2	55.3	46.3
2029	62.1	52.6	43.2
2030	60.0	50.0	40.0

Table 19: Material intensity of c-Si, CdTe and CIGS; material utilization rate unconsidered

	Ag use per GW c-Si [t]	Te use per GW CdTe [t]	In use per GW CIGS [t]	GA use per GW CIGS [t]
2011	100	77.5	23.8	6.2

Table 20: Material requirements for CdTe and CIGS under accelerated scenario

	Te use con [t]	Te use neut [t]	Te use pro [t]	In use con [t]	In use neut [t]	In use pro [t]
2011	1698	1698	1698	80	80	80
2012	414	403	393	77	75	73
2013	489	465	442	105	99	94
2014	578	536	498	141	129	119
2015	685	620	562	187	166	150
2016	812	718	635	246	212	187
2017	963	832	718	320	268	231
2018	1144	964	813	414	338	285
2019	1359	1119	920	532	423	349
2020	1615	1299	1041	680	528	426
2021	1267	995	777	393	297	235
2022	1395	1069	812	434	320	248
2023	1535	1147	847	479	345	261
2024	1689	1230	881	529	372	275
2025	1858	1319	913	584	401	290
2026	1544	1067	713	487	326	231
2027	1637	1099	706	519	339	234
2028	1734	1131	696	552	352	238
2029	1836	1162	681	588	366	241
2030	1944	1191	661	625	380	243

Table 21: Material requirements for c-Si and CIGS under accelerated scenario

	Ag use con [t]	Ag use neut [t]	Ag use pro [t]	Ga use con [t]	Ga use neut [t]	Ga use pro [t]
2011	5392	5392	5392	21	21	21
2012	1197	1190	1184	20	19	19
2013	1431	1415	1400	27	26	24
2014	1708	1680	1651	37	34	31
2015	2036	1990	1943	49	43	39
2016	2424	2352	2281	64	55	49
2017	2879	2775	2671	83	70	60
2018	3414	3267	3119	108	88	74
2019	4040	3836	3631	138	110	91
2020	4772	4493	4214	177	137	111
2021	3103	2896	2690	102	77	61
2022	3371	3117	2863	113	83	64
2023	3657	3348	3039	125	90	68
2024	3962	3588	3215	137	97	72
2025	4286	3839	3391	152	104	75
2026	3085	2729	2373	127	85	60
2027	3205	2798	2391	135	88	61
2028	3325	2862	2398	143	92	62
2029	3443	2918	2393	153	95	63
2030	3559	2966	2373	163	99	63

Table 22: Material requirements for CdTe and CIGS under paradigm shift scenario

	Te use con [t]	Te use neut [t]	Te use pro [t]	In use con [t]	In use neut [t]	In use pro[t]
2011	1698	1698	1698	80	80	80
2012	668	651	634	97	94	91
2013	890	846	804	154	145	137
2014	1187	1100	1021	240	219	202
2015	1584	1434	1298	367	325	293
2016	2116	1870	1654	551	475	419
2017	2830	2442	2109	820	687	593
2018	3786	3191	2690	1209	987	832
2019	5068	4173	3431	1768	1407	1161
2020	6789	5459	4375	2571	1995	1610
2021	3049	2393	1868	946	716	565
2022	3264	2501	1900	1015	749	580
2023	3495	2611	1927	1090	785	594
2024	3741	2725	1950	1171	823	610
2025	4004	2841	1967	1258	863	625
2026	3644	2517	1681	1149	770	545
2027	3825	2569	1651	1212	792	548
2028	4013	2618	1611	1278	815	550
2029	4210	2663	1562	1347	839	552
2030	4415	2704	1502	1420	863	552

Table 23: Material requirements for c-Si and CIGS under paradigm shift scenario

	Ag use con [t]	Ag use neut [t]	Ag use pro [t]	Ga use con [t]	Ga use neut [t]	Ga use pro [t]
2011	5392	5392	5392	21	21	21
2012	2019	2008	1997	25	24	24
2013	2724	2694	2664	40	38	36
2014	3671	3609	3547	62	57	53
2015	4938	4825	4711	95	84	76
2016	6634	6439	6244	143	123	109
2017	8897	8575	8254	213	179	154
2018	11912	11397	10882	314	257	216
2019	15918	15112	14306	460	366	302
2020	21231	19990	18749	668	519	419
2021	6856	6399	5942	246	186	147
2022	7244	6698	6153	264	195	151
2023	7644	6998	6352	283	204	155
2024	8056	7297	6538	304	214	158
2025	8478	7592	6707	327	224	163
2026	6924	6125	5327	299	200	142
2027	7125	6220	5315	315	206	142
2028	7318	6298	5279	332	212	143
2029	7503	6358	5214	350	218	143
2030	7677	6398	5118	369	224	144