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Thin Film Implementation Scenarios

Advanced Thin Film Technologies for Cost Effective Photovoltaics (ATHLET)

Timon Wehnert, Volker Handke

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Vorwort

Innerhalb der Projektlaufzeit von 2006 bis 2009 sind einschneidende Änderungen bei einigen Rahmenbedingungen eingetreten, die maßgeblichen Einfluss auf die Entwicklung der Photovoltaikmärkte besitzen. Dabei handelt es sich insbesondere um Veränderungen der ökonomischen Rahmenbedingungen, von denen die globale Wirtschaftskrise sowie die Reduktion und Neuausrichtung der öffentliche Förderung besonders wirksam sind.

Die geplatzte Spekulationsblase des Finanzsektors hat zu einer globalen Wirtschaftkrise mit einer Verschlechterung von Finanzierungsmöglichkeiten und Investitionsbereitschaft geführt, welche insbesondere das Wachstum der Dünnschichttechnologie dämpft. Diese veränderte ökonomische Rahmenbedingung, erschwert der Photovoltaikbranche den Zugang zu Krediten, führt somit zu erhöhten Investitionskosten und bremst damit den Ausbau der Produktionskapazitäten. Dieser Effekt macht sich für die Dünnschicht-PV stärker bemerkbar, da deren Fertigungstechnik noch eine geringere industrielle Reife besitzt, zudem auch wesentlich vielfältiger und komplexer ist und entsprechende Produktionskapazitäten daher eher riskante Investitionen darstellen und in der gegenwärtigen Situation der Finanzmärkte auf eine verringerte Risikobereitschaft trifft.

Im Zuge der globale Wirtschaftkrise ist es auch zu erheblichen Preisschwankungen bei Erdöl gekommen mit entsprechenden Auswirkungen. Der rasante Preisverfall hat auf der Nachfrageseite eine wesentliche Motivation erneuerbare Energien und die Photovoltaik zu nutzen, geschwächt.

Darüber hinaus sind Änderungen bei den Förderbedingungen der öffentlichen Hand eingetreten. Diese haben zum Zusammenbruch von nationalen Märkten geführt (z.B. Spanien) oder beeinflussen die Entwicklungschancen von Teilmärkten wie Freiflächenanlagen oder Gebäudeintegration welche wiederum technologiespezifische Implikationen nach sich ziehen.

Ein weiterer wichtiger Einflussfaktor der sich während der Projektlaufzeit erheblich geändert hat, ist die Rolle Chinas als Hersteller und Exporteur von Photovoltaikprodukten. So importiert China sowohl Know How als auch Technologie zur Fertigung von Photovoltaik, produziert kostengünstiger und exportiert die photovoltaischen Produkte.

Des weiteren hat sich die Situation auf dem Rohstoffmarkt für Solarsilizium erheblich gewandelt. So hat das zurückliegende dynamische Marktwachstum zu einer Verknappung und Verteuerung von Solarsilizium geführt. Dieser konnte aber unter anderen durch den Ausbau von Produktionskapazitäten begegnet werden, so dass der Preis für Solarsilizium inzwischen stark gefallen ist. Allerdings können nicht alle Photovoltaikhersteller davon profitieren, da sie sich teilweise an langfristige Lieferverträge gebunden haben, die oberhalb der aktuellen Preise der Spotmärkte liegen.

Der Preisverfall beim Silizium hat dabei einen wesentlichen Vorteil der Silizium-freien Dünnschicht-Technologie wegfallen lassen. Zusammen mit den gesunkenen Rohstoffpreisen verringert sich damit eine besondere Chance, welche die energie- und ressourceneffiziente Dünnschicht-PV bis dato besessen hatte.

Insgesamt ist zu beobachten, dass das Angebot die Nachfrage zunehmend übersteigt und Photovoltaik Produkte einem erheblichen Preisverfall unterliegen. Dabei dürfte es zu einem stärkeren Wettbewerb unter den Anbietern mit einem entsprechenden Preisdruck kommen und der Markt in eine Konsolidierungsphase eintreten.

Wie die Märkte auf diese Änderungen der Rahmenbedingungen reagieren ist ungewiss. Zwei mögliche Entwicklungslinien lassen sich zusammenfassen:

- Einerseits ist eine erhebliche Diversifizierung der PV-Marktes denkbar, bei dem sich das Angebot stärker auf spezifische Marktsegmente spezialisiert und Wettbewerbvorteile durch eine stärkere Ausprägung von Alleinstellungsmerkmalen realisiert werden.
- Andererseits ist auch ein Preiswettbewerb möglich, in dessen Folge einzig die Kosten des Betreibers Solarstrom zu erzeugen ausschlaggebend sind und der Markterfolg überwiegend von der Maximierung der Modulflächen, der Anlagengröße und der energetischen Effizienz abhängt.

Beide Entwicklungspfade bergen spezifische Chancen und Risiken für die einzelnen PV-Technologien und damit auch für die Dünnschicht PV.

Ob sich eine PV-Technologie zukünftig am Markt besonders durchsetzen wird und welche dies langfristig sein wird, lässt sich unter den derzeitig sich dynamisch wandelnden Rahmenbedingungen nicht eindeutig bestimmen oder gar belastbar quantifizieren.

Allerdings besitzen die einzelnen photovoltaischen Technologien spezifische Umweltauswirkungen die je nach Marktanteil erhebliche Größenordnungen erlangen können. Insbesondere die einzelnen Dünnschichttechnologien unterliegen zudem spezifischen Abhängigkeiten von strategischen, überwiegen metallischen Rohstoffen. Diese Abhängigkeiten können je nach Marktanteil, aber auch entsprechend dem Grad der ressourceneffizienten Nutzung dieser strategischen Metalle, erhebliche Wirksamkeiten entfalten, die bis hin zu einer technologiespezifischen Limitierung des Marktwachstums reichen können.

Ursprüngliches Ziel der Szenarien war es, die langfristigen Anforderungen und die Folgen unterschiedlicher Entwicklungspfade insbesondere der Dünnschicht-Photovoltaik zu beschreiben. Dazu wurde auf Prognosen hinsichtlich der zukünftigen Marktgröße und ihrer technologischen Zusammensetzung zurückgegriffen sowie Abschätzungen über die damit verbundenen Umweltauswirkungen und Rohstoffbedarfe vorgenommen.

In der aktuellen politischen Debatte um die Kürzung der EEG-Vergütung für Photovoltaik, gewinnen die Szenarien aber eine wesentlich grundlegendere strategische Bedeutung für die Positionierung des Solarstandortes Deutschland. Denn die Ausgestaltung der öffentliche Förderung entscheidet maßgeblich über die Entwicklung der Marktsegmentente, in deren Folge über die eingeschlagenen technologischen Entwicklungspfade und damit wiederum über die Zukunftsfähigkeit der nationalen Standorte zur Erzeugung von solarer Energie und solaren Produkten

Berlin, 21. April 2010

Volker Handke und Timon Wehnert

IZT - Institut für Zukunftsstudien und Technologiebewertung
Institute for Futures Studies and Technology Assessment
Schopenhauerstr. 26 in 14129 Berlin
Tel.: 030-803088-19/-13, Fax: 030-803088-88
Mail: v.handke@izt.de /t.wehnert@izt.de

Kurzfassung

Der vorliegende Werkstattbericht fasst die Ergebnisse aus dem Arbeitspaket *„Implementierungsszenarien"* zusammen, das im Rahmen des europäischen Projektes *„Fortschrittliche Dünnschichttechnologien für eine kostengünstige Photovoltaik"* im Teilprojekt VI *„Nachhaltigkeit, Training und Mobilität"*, durchgeführt wurde.

Ziel des in den Jahren 2006 bis 2009 im Rahmen des 6. Forschungsrahmenprogramms der EU durchgeführten integrierten Projektes, war die Entwicklung und Markteinführung von Solarzellen der zweiten Generation – die sogenannten Dünnschichtzellen.

Insgesamt wurden durch 24 internationale Partner von Universitäten, Forschungseinrichtungen und Unternehmen aus 11 europäischen Ländern zwei aussichtsreiche Technologiepfade der Dünnschichtzellen weiterentwickelt und in die industrielle Fertigung überführt.

Zum einen handelt es sich um die sogenannte CI(G)S-Technologie bei der statt Silizium eine auf ein Substrat (Glas, Metall oder Folie) aufgebrachte sehr dünne Halbleiterschicht aus den Elementen Kupfer, Indium, Gallium und Selen bzw. Schwefel zur Absorption der Sonnenstrahlung genutzt wird. Zum anderen handelt es sich um sogenannte mikromorphe Dünnschichtzellen welche als Tandem- oder Stapelzellen unterschiedliche Absorptionsspektren kombinieren. Sie sind damit in der Lage, ein breiteres Spektrum des Sonnenlichts zu nutzen und entsprechend höhere Wirkungsgrade zu erreichen.

Zusammen mit der University of Northumbria at Newcastle und dem Helmholtz-Zentrum Berlin für Materialien und Energie (vormals Berliner Hahn Meitner Institut) hat das IZT das Subproject VI: *„Sustainability, Training and Mobility"* übernommen. Aufgabe des IZT war es dabei vor dem Hintergrund der Nachhaltigkeitseffekte, Szenarien für eine breite Markteinführung der Dünnschichttechnologie zu entwickeln (*„Implementation Sceanrios").*

In einem ersten Arbeitsschritt wurden dafür existierende wissenschaftliche Studien zu zukünftigen Markt- und Technologieentwicklung gesichtet und ausgewertet. Aus diesen bestehenden Roadmaps, Marktanalysen und sonstigen prognostischen Studien, wurden besonders relevante Publikationen identifiziert und detaillierter analysiert. Ein wesentliches Analyseergebnis war dabei die Identifizierung von Schlüsseltreiber für die zukünftige Entwicklung der Photovoltaik im allgemeinen und der Dünnschichttechnologie im besonderen. Diese identifizierten Treiber wurden hinsichtlich ihres Einflusses näher beschrieben und in mehreren Expertenworkshops bezüglich ihrer Wirkungsweise und ihrer Wechselwirkung modelliert. Anhand der Schlüsseltreiber wurde die zwei qualitativen Szenarien *„Diversity Rules"* und *„Size Matters"* entwickelt sowie eine quantitative Abschätzung über die zukünftigen Umweltauswirkungen und Rohstoffbedarfe vorgenommen. In einem Back-Casting-Ansatz wurden anschließend strategische Optionen abgeleitet.

Abstract

The photovoltaic markets have been growing tremendously in recent years – and growth is expected to continue in the decades to come. However, there is a large uncertainty on the overall market size development – the variation between the most optimistic and most pessimistic scenarios is greater than a factor 10. Furthermore, most scenarios make statements only on the total market size. Specifications according to technology type are very rare. Generally, a long-term co-existence of the different PV cell technologies (crystalline silicon, thin-film, new emergent technologies) is assumed. Within the next 20 years the share of thin-film is believed to increase – in very optimistic estimates up to a market share of 45% in 2030.

An issue that is not described (or only very superficially) in long-term PV market scenarios is the *structure* of the markets themselves. It is often pointed out that the different technologies do have properties which give them specific advantages and disadvantages in the various market segments. This is one of the reasons why a long-term coexistence of different PV cell types is commonly assumed. However, to our knowledge, no study exists to date that defines scenarios for market segments and stringently assesses the potentials of the various PV technologies in these scenarios.

The aim of this study is to at least partly fill this gap. Based on a systematic literature review and targeted expert consultations, four archetypal PV market segments are identified and key performance indicators for PV products in these markets are described:

- **Large-scale (ground mounted) PV farms:** Key performance indicator is low cost per W_P. Thin-film technologies have great potentials in this market segment.
- **Roof top installations**: Besides costs, high efficiency is a key requirement in this market, as space is a limiting factor. Consequently, technologies with higher efficiencies (e.g. crystalline silicon cells) have advantages to gain market shares in this sector.
- **Building integrated:** Key demands are functionality, aesthetics and flexible design options. In contrast to the majority opinion that thin-film technologies are superior in this respect, it is actually heavily disputed among experts which technologies are the best fit to respond to the requirements of this market. Although thin-film products could deliver suitable solutions, this would hardly be possible within mass-production schemes, which in return would forfeit the advantages over wafer based silicon products.
- **Off-grid**: Key indicators are reliability of performance as well as costs. The potential for the different PV technologies to enter this market are very similar.

In a scenario exercise two narratives are given which describe two alternative worlds with distinct differences in the distribution of shares between these market segments resulting in very different PV products.

- *Diversity Rules* describes a world in which the markets for PV products are very diverse and also differ regionally. Consequently there is a necessity for specific products for the diverse market segments. Most important are roof-top and building integrated applications. The demand on the functionality of the products is high. In addition to customised solutions for specific applications there is a high level of standardisation that allows the building of a plan with a mixture of products from different producers.
- In the *Size Matters* scenario the biggest market segments are large scale PV plants, many of them in multi-megawatt parks on green fields or large roofs of commercial and industrial buildings. Square flat plate modules dominate the market and technological development almost exclusively aims at reducing cost per W_P. Production is largely concentrated and dominated by a few multinational players.

Conclusions are drawn for both PV companies and policy makers:

- Company strategies
  PV producers should use the scenarios to test the robustness of their company strategy and there technology development plans. Specifically for thin-film the question arises whether the separation of cell and module production could be a strategic option which could be beneficial in specific market segments.
- Support mechanisms for PV
  The details of the support mechanisms to promote renewable energies will largely influence the *shape* of future PV markets in Europe. Beyond the question of the *size* of the PV market, the share of the different market segments may strongly impact on prices for solar power, demands for grid extensions (and subsequent costs) as well as the job creating potential of the PV industry in Europe.

Content

1 Objectives of this Study

The aim of the scenario exercise within the Athlet project[1] is to explore possible futures for thin film photovoltaics with a time horizon of 20 years. It is important to point out that it is not the intention of this exercise to make predictions. Results are not a roadmap but different future *scenarios*. The idea is to analyse "what could happen" as it is impossible to foresee "what will happen". The aim is to open up our thinking, and consider alternative futures as a sound basis for today's strategic decisions.[2]

The approach taken is to develop qualitative scenarios which illustrate two possible futures and tell plausible storylines how the world might develop in this way. To this means the chosen scenarios mark extremes of possible developments. In between it would be possible to construct a myriad of scenarios containing aspects of either of the two archetypes. However, looking at the extremes helps to identify the distinctive features of possible different developments.[3]

It is important to note that the scenarios have been constructed in a way to point out possible developments which would affect the development of thin film PV differently than PV as a whole. To explore this difference – thin film PV vs. crystalline silicon PV – the two scenarios differ with respect to the market structures. Thus the scenarios illustrate qualitatively what future PV markets might look like, e.g. in which applications / market segments photovoltaics is used. They do not – as most other scenarios do – differ with respect to market size.

Underlying the whole scenario exercise is one fundamental assumption: It is currently not possible to identify one winner PV technology. Even more, we assume that the parallel co-existence of various PV technologies will continue in the next 20 years. Although individual technological paths may die out (and new ones emerge), we do not assume that one single PV cell type will dominate in terms of energy yield per costs (kWh/€) in the near to mid-term future. This set of assumptions is in line with existing scenario work and foresight exercises (see chapters 2.2 and 2.4). Although being generally unchallenged, this assumption is stressed at this point, because it is fundamental to our scenario work. It is the reason why it makes sense to analyse possible future market structures and specify different requirements for PV products in the various market segments.

Structure of this report

Chapter 2 of this study gives an overview of the status, trends as well as existing PV market scenarios. The question of market size and market share for individual PV technologies is analysed in this chapter based on an extensive literature review. Additionally, abstracts of key studies, which have been analysed in depth, are given in the annex (pp 47). In chapter 1 key sustainability indicators are analysed and the question of potential raw material scarcity is assessed. Chapter 4 sketches four key market segments for PV and assesses the different potentials of wafer based silicon technologies vs. thin film technologies qualitatively in these market segments. The scenarios themselves are given in chapter 1, followed by a brief comparison of the two scenarios (in chapter 5.3) and a first assessment of the challenges thin film development faces in the two different scenario paths (chapter 5.4). The methodological approach of the scenario exercise is outlined in the annex (chapter 7). Conclusions for private companies as well as policy makers are summarised in chapter 6.

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1 The project Athlet - Advanced Thin Film Technologies for Cost Effective Photovoltaics was co-funded within the 6th Framework Program by the European Commission (Project no. 019670). See also http://www.ip-athlet.eu

2 An easy to read description of why and how to use scenarios is also given in the executive summary of the Shell Global Scenarios to 2025 [Shell 2005]

3 For the different methodological approaches in scenario work, with respect to energy scenarios see also [IEA 2003]. It is important to distinguish between quantitative scenarios, like e.g. [Mantzos et al. 2003] which are made by computer modelling and mainly qualitative energy scenarios (e.g. [CIA 2004] or [UNU 2006]) which illustrate different futures by narratives.

2 Status, Trends and Existing Scenarios

In preparation of the scenarios an extensive literature review has been conducted including a wide variety of recent energy scenarios, roadmaps and articles (see literature – chapter 9).[4] For 18 of the most important studies, which highlight especially PV and specifically thin film PV developments, short abstracts were drafted (see Annex B – Abstracts of Reviewed Literature). The studies analysed in depth were selected according to the following criteria:

- Specific information contained on PV development perspectives and specifically thin film PV development.
- Do studies name key drivers which strongly influence PV development? Are trends and drivers described which could be used in the scenario building process?
- Geographical coverage – studies should give insights on EU or global developments.
- Time coverage – studies should include long-term outlooks, i.e. beyond 2020.
- The reliability, actuality and the prominence of the studies

The analysis of the reviewed papers shows that there are substantial differences within the reviewed scenarios concerning PV market development. There are however also commonalities, e.g. the fact that all scenarios stress the importance of support schemes for the further development of PV. In general there is quite extensive data on overall PV development possibilities. However, only a few studies address the different types of solar cells and their individual prospects. Challenges and R&D needs for thin film PV are clearly formulated (and show great coherence between the various studies analysed). Generally not addressed is the question how certain scenarios might impact the development of thin film PV or what the specific thin film potential would be within a certain scenario.

Key messages from the literature review are summarized below.

2.1 Overall PV Market Status and Outlook

PV market size – scenario review

There is a big insecurity on future market developments for PV. A Meta study by [Krewitt 2005][5] analyses existing PV-scenarios and develops three sets of scenarios: a bottom line “MIN”, an ambitious but realistic scenario “SEE” and an upper ceiling “MAX” (compare Table 2-1). Underlying these scenarios are mainly different assumptions concerning energy prices and policy actions towards CO_2 reduction (often expressed in CO_2 mitigation costs) as well as learning curves (cost developments) for different power production technologies. The figures for the globally installed capacity (GW_p) for the year 2050 vary between MIN and MAX by more than a factor of 10! Taking into account that the assumed annual growth rate in 2050 is (less than) 3%, this corresponds to a substantial and long lasting difference.

The EU-FP6 NEEDS project, which dealt with external costs of energy technologies (www.needs-project.org) also developed PV scenarios [NEEDS 2009]. They follow a similar approach giving upper and lower ceilings (which are more extreme than the Krewitt MAX & MIN scenarios) and develop furthermore an “optimistic/realistic” scenario which is quite in line with the Krewitt SEE scenario (compare Table 2-1).

[4] The results of this review were summarized and made available for the Athlet consortium in deliverable No: 97 („Report on existing roadmaps and scenario material“ D VI .2.1).

[5] The study furthermore assesses economic potentials for PV and explicitly analyses thin-film potentials For more details on [Krewitt 2005] see also Annex, p. 52ff.

Cumulated global capacities of PV (GWp) up to 2050

Source	Szenario	Status	2010	2020	2030	2040	2050
Krewitt 2005	Max	3 (2003)	22,4	302	1916	4174	6015
	SEE - Solar Energy Economy	**3 (2003)**	**21,2**	**199**	**775**	**1618**	**2477**
	Min	3 (2003)	19,5	120	315	511	708
NEEDS 2006	Very Optimistic / Technological Breakthrough	6 (2006)	22,5	230	1270	4080	8.930
	Optimistic / Realistic	**6 (2006)**	**22,5**	**206**	**755**	**1520**	**2.360**
	Pessimistic	6 (2006)	22,5	105	236	384	532
EPIA, Greenpeace 2008	Advanced	9 (2008)	25,4	278	1864	-	-
	Moderate	9 (2008)	21,6	211	912	-	-
EREC Greenpeace 2008	energy(R)evolution	5 (2005)	21	269	921	1799	2911

Table 2-1: Cumulated global capacities of PV (GWp) up to 2050
Most optimistic scenarios differ from most pessimistic scenarios for more than a factor 16! Highlighted are mid-range scenarios which will be used as references for the scenario development in this study.
Sources: [Krewitt 2005], [NEEDS 2009], [EPIA, Greenpeace 2008], [EREC Greenpeace 2008]

We consider both mid-range scenarios (Krewitt “SEE - Solar Energy Economy” and NEEDS ”optimistic/realistic”) to be good starting points for a reasonable estimate for a long-term PV market size development.

- Comparison to other scenarios
  Comparing these two “medium” scenarios to ambitious and recent PV-scenarios, the “Advanced Scenario” in [EPIA, Greenpeace 2008] exceeds both “realistic” scenarios. The EPIA/Greenpeace “Moderate Scenario” which is based on general assumptions of IEA World Energy Outlook 2007, is close to the SEE projection, although with the significant difference of larger growth rates in later years. The latest “energy [r]evolution” scenario by [EREC, Greenpeace 2008] envisions a cumulated capacity of 2,900 GW_p in 2050 which is 20% above the SEE scenario and well below the MAX scenario of 6000 GW_p.

- Comparison to status data
  A comparison between past scenarios and the current market development shows, that most scenarios generally underestimated the growth of the PV market. This is also true for rather ambitious scenarios like the European Photovoltaic Industry Association (EPIA) / Greenpeace “Solar Generation” scenario series [EPIA, Greenpeace 2008]. However, comparing factual market development to [Krewitt 2005] shows that the market development stays within the corridor outlined by Krewitt up till 2007. The globally new installed capacity in 2008 of 5,6 GW_p as given by [EPIA 2009] is significantly higher than the MAX scenario (it is almost as high as it’s 2010 figure). However, 2008 was an exceptional year due the market development in Spain and is – in its extreme development – most likely not representative for the general long-term trend.

- Comparison to EPIA goal 12% in 2020
  EPIA has set a very ambitious goal for PV in Europe: by 2020 the share of PV of the European electricity production should be 12%. It has to be mentioned that EPIA itself points out that this target is beyond usual high growth scenarios and would require a major “paradigm shift”. For comparison: the installed capacity (in Europe!) corresponding to 12% of Europe’s electricity demand in 2020 is significantly higher than the PV capacity installed globally in the most daring scenario (Krewitt 2005 MAX). It is also dramatically higher than the [EPIA/Greenpeace 2008] “advanced” scenario. The 12% goal can only be reached if in the next decade annual growth rates are significantly above the 30%

growth rate assumed by Krewitt 2005 MAX. Higher growth rates are indeed possible (as they e.g. have been higher in the years 2007/2008). However, it seems very unlikely that growth rates beyond 40% could be sustained over a longer time horizon.

- With a mid- to long-term perspective a 12% PV share in Europe's electricity production is quite realistic. In 2030 this could even be possible within the boundaries of the moderately optimistic scenarios (Krewitt "SEE - Solar Energy Economy" and NEEDS "optimistic/realistic"). This would be possible by very high growth rates in early years and a strong focus of PV markets in Europe (slower growth in other world regions) followed by decline in growth rates after 2020. However, generally speaking, the more ambitious scenarios would become more likely if the 12% goal was reached by 2020.
- Concluding from this it can be said that the EPIA 12% goal is outside the above outline scenario corridors for the next 15 to 20 years. However, in the time frame 2030 – 2050 the 12% goal is compatible with a scenario corridor marked by the optimistic / realistic scenarios as floors and the very ambitious / very optimistic scenarios as ceilings. However, the 12% goal implies a dramatic paradigm shift for the whole energy sector in Europe.

In conclusion of the above we adopt the market development outlined by Krewitt SEE and NEEDS "optimistic/realistic" as the underlying assumption for our own scenario development. However, it needs to be pointed out that that these projections are *scenarios* and not *predictions*! And although we consider them to be realistic and suitable for a reference in our scenario development, we do NOT consider them to be *most likely*!

We want to point out, that for our scenario work we explicitly do not assume that the 12% goal will be reached by 2020. In contrast, the scenarios described in 1 would become rather unrealistic and partly inconsistent if the 12% goal was reached as early as 2020. Thus, although our scenarios are compatible with significant changes in the energy sector and continuously high growth rates for PV, they are not based on a total paradigm shift.

Trendbreaks in 2008?

Since the beginning of the Athlet project three major developments have happened which could have strong impacts on PV market developments:

1. The **economic crisis**: among others it has stopped the extreme growth of energy prices as well as raw material prices and will impact both on PV markets (demand) as well as on the availability of capital (especially venture capital for cutting edge technologies).
2. After a boom in 2008, there was a break down of the **Spanish PV market**
3. The **new US government** under Barack Obama engages in a stronger support for PV.

It is not within the scope (and possibilities) of the Athlet scenario process to give a detailed, quantitative (econometric) assessment of the impacts of the above named factors on the quoted PV-market scenarios. However, qualitatively the following assessments can be made:

- The economic crisis has a strong short term impact both reducing the demand for energy and decreasing energy investments substantially [IEA 2009]. Most economic forecasts however, anticipate that the bottom of the crisis is (soon) reached and that the economy will recover within the next years. Thus, a likely impact of the economic crisis could be a timely delay of energy investments, including PV-market growth rates.
- With a short term perspective all three events appear to be earthquakes which ask for major corrections in PV-market scenarios. But with a mid- to long-term perspective, these developments largely have a notion of levelling-off previously extreme developments (growth of energy prices between 2003 and 2008, boom of Spanish market, US denial of climate change). Thus, scenarios developed before 2006 could even be perceived more realistic (again) today (late 2009), than they appeared in early 2008.
- Furthermore, some of these events may play each other off: while the economic crisis brings down investments, the counter measures by the Obama government explicitly support certain green technologies, PV being one of them.

Assuming that the economic crisis would lead to a time delay in PV market growth equivalent to 2 years of stagnation[6] in 2030 this time lag would amount to less than a 15% reduction of the total installed capacity. For comparison total installed capacity in 2030 in the [Krewitt 2005] MAX scenario is > 600% higher than in the [Krewitt 2005] MIN scenario. Furthermore, in 2008 the PV market was already almost the size anticipated for 2010. Thus a time delay of two years due to the economic crisis would only balance off very recent high growth years.

Concluding from this, we judge that – although the short term impact of these developments may be huge – with a time horizon of 2030 and beyond, the impact of these developments may be rather **marginal for the overall size of the global PV market.** The MIN and MAX scenarios given by [Krewitt 2005] still mark realistic boundaries for the long-term PV market development. Under the assumption of energy prices just slightly above the IEA 2008 reference case [IEA 2008] and globally concerted climate protection actions, the SEE scenario can be considered a very realistic estimate for long-term developments.

However, the above mentioned 2008/2009 developments could have strong impacts in the short to mid-term, which are of relevance for the Athlet scenarios:

- The current shortage for venture capital (and thin film is perceived more adventurous compared to c-Si) favours c-Si development, compared to scenarios developed two to four years ago.
- The US market will develop more strongly than anticipated two years ago and PV receives stronger technology support (for research and companies) in the US. Thus, the strength of US based companies may increase compared to predictions made two to four years ago.
- The economic crisis may trigger mergers of PV producing companies faster than was anticipated in 2007 (see also below).

Shift from supply to demand side market

As an immediate result of the above named developments there is an oversupply of PV modules in 2009. Consequently module prices in Germany decreased in 2009 about 20% (see Graph 2-1). Also spot market prices for raw silicon have dropped drastically in 2009 (which is a result of both the PV market development and the ramping up of silicon supply industry). In short, the whole PV market has shifted from a supply market, where the amount of PV modules being installed totally depended on production capacity (and raw-silicon availability) to a demand side market, where producers have to actively find customers for their PV products. In this situation, companies dramatically change their strategies. Cost reductions (e.g. by increasing automation of production processes) become more important than the extension of production capacity. Furthermore, producers may have to adapt their products to specific market segments to be competitive in this changing market environment.

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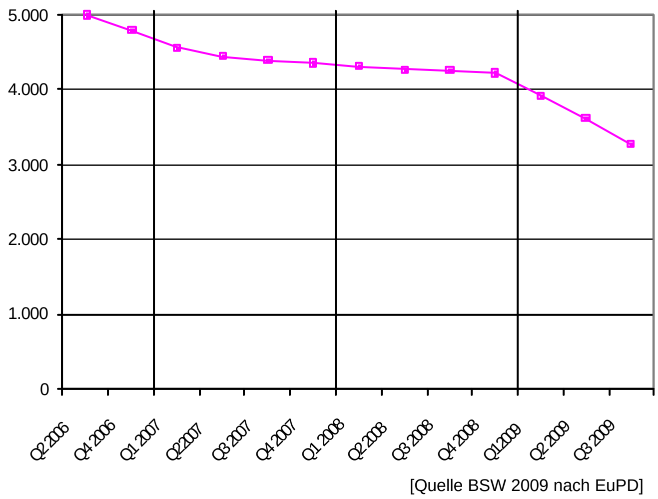
[6] This could for example happen in a dramatic break down of the market in 2009 and slow catch up on 2010 and 2011 resulting in a net growth of 0% over this two year period and 25% + growth rates from 2012 on.

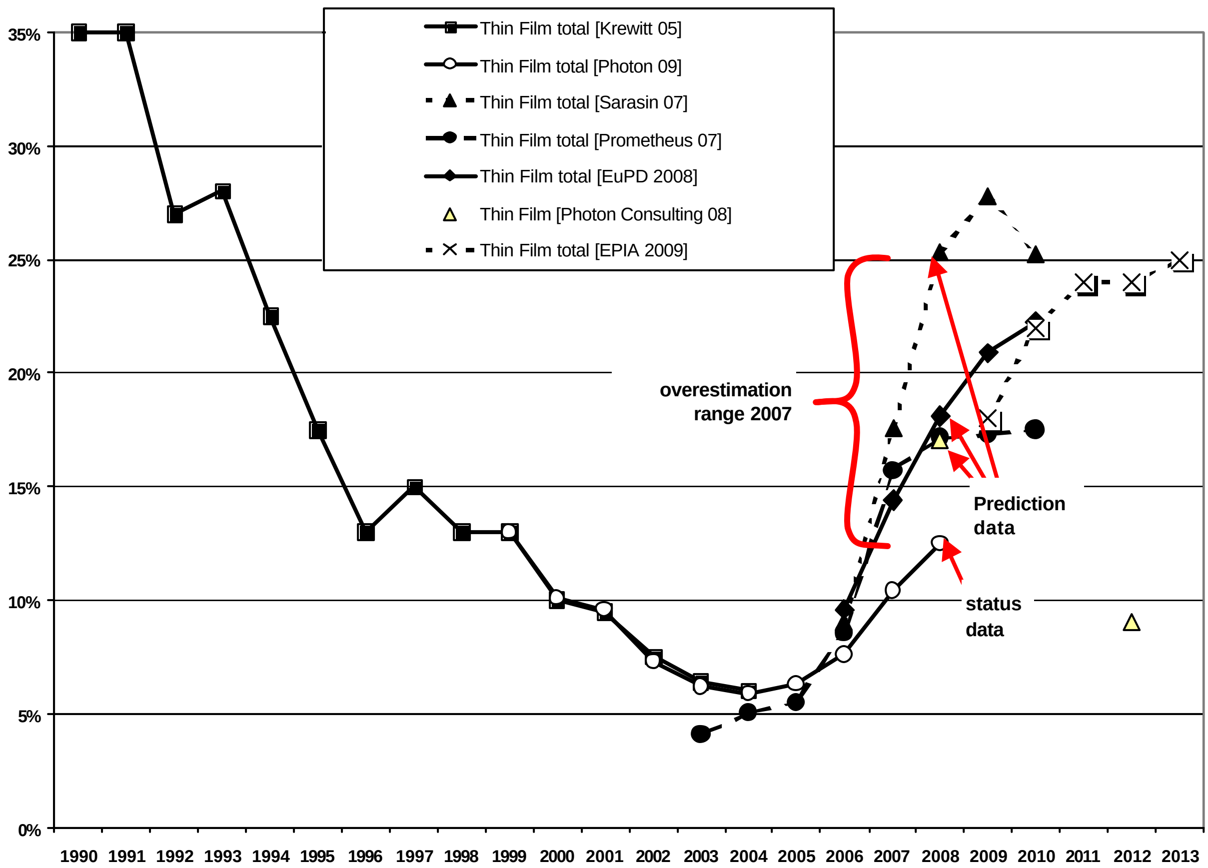


Graph 2-1: PV price index (in € pro kWp)
Mean consumer price (total system) in Germany for roof top systems with less than 100 kWp. [BSW 2009]

2.2 Thin film Market Shares and Players

PV market development – choice of technologies

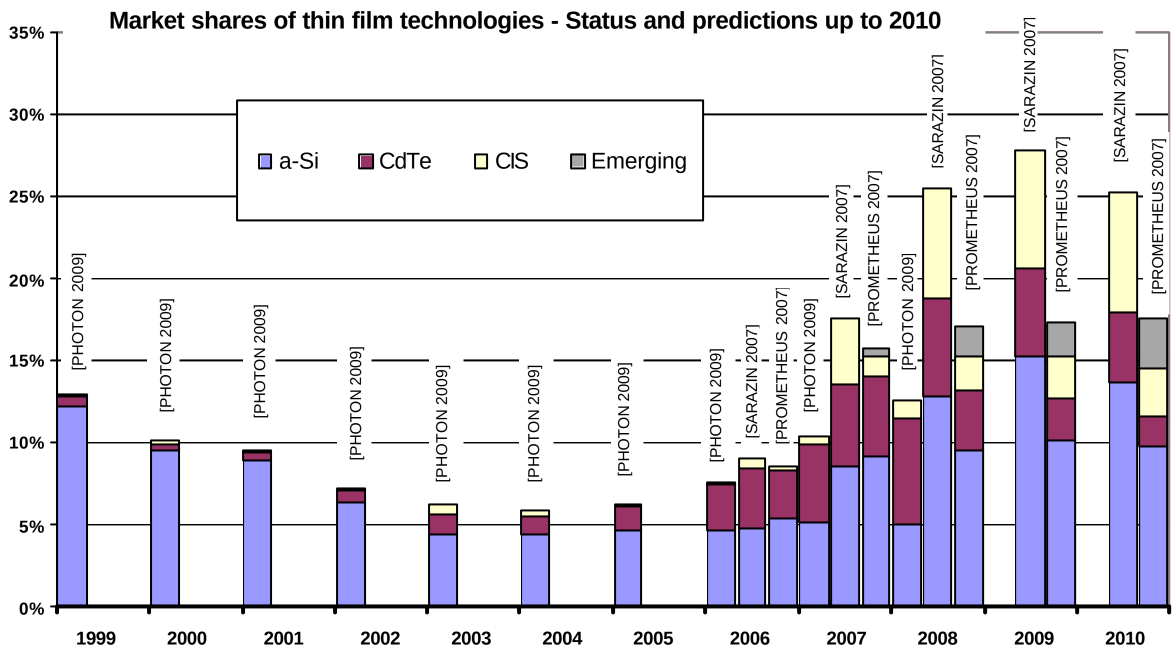
Within the various scenarios on PV market development there is again a wide range of possible market developments for thin film PV. They range from confinement into niche markets, through equal growth of the overall PV market and up to a thin film take-off, where thin film PV could conquer a share of 45% of the overall PV market by 2025 (NEEDS 2009).



Graph 2-2: Thin film market share of total PV market (annually production in MW_p) - status and prediction up to 2010
Recent forecasts overestimated t he expected share of thin film technologies.
Status data according to [Photon 2009 and Krewitt 2005]. Projecions according to [Sarasin 2007, Prometheus 2007, EuPD 2008, Photon Consulting 2008, EPIA 2009].

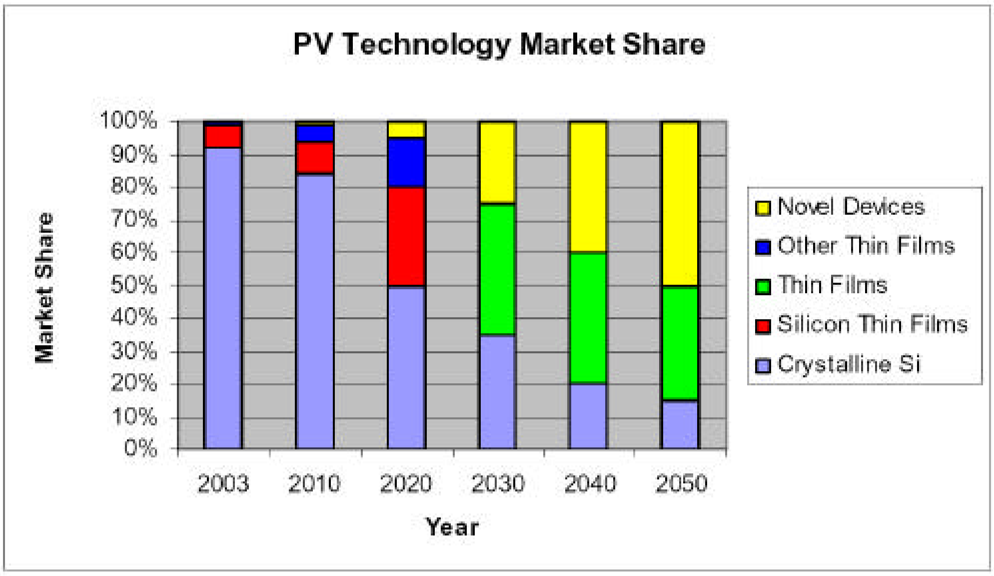
In 1990 the market share of thin film technologies was relatively high (see Graph 2-2) but on a very low level in terms of absolute production (MW_p). With the fast growth in production of crystalline silicon cells the market share of thin film declined very rapidly. During the years 1999 to 2003 the average market growth of thin film was around 15% while the PV production in total grew by 35%. The market shares stabilised in 2003 – 2005. In recent years (2006 to 2008) thin film technologies gained market share again, mainly due to the growth of CdTe modules (see Graph 2-3). In this period, thin film technologies strongly benefited from the limited growth of crystalline silicon technologies due to the raw silicon shortage. In absolute terms, CdTe production rose from $1MW_p$ in 2000 up to 200 MW_p in 2007. This dramatic growth was mainly due to the activities of one single company (First Solar), which illustrates that the market can be significantly influenced by the commercial decisions of a very few companies at its present size.

However, the total thin film market share of less than 13% in 2008 fell short of the optimistic predictions which were between 17 and 25% (see Graph 2-2). A closer look into the predictions reveals that mainly the growth potentials of a-Si and CIS have been overestimated in the recent past (see Graph 2-3). For the short-term future, EPIA predicts an increase up to 24% in 2012 [EPIA 2009]. However, the EPIA outlook did not anticipate the current decrease in raw silicon prices. In contrast, Photon Consulting predicts a decline down to 9% market share for thin film PV in 2012 [Photon Consulting 2008]



Graph 2-3: Market shares of thin film technologies - status and prediction up to 2010 Status data according to [Photon 2009 and Krewitt 2005]. Projections according to [Sarasin 2007, Prometheus 2007, EuPD 2008]. The Sarasin projections were quite adequate for CdTe, but too optimistic for both a-Si and CIS technologies.

Many long-term projections indicate increases of the share of thin film technologies. A good comparative assessment of the role of the different PV technologies in key energy scenarios is given in [Krewitt et al 2009, pp 135]. The [NEEDS 2009] scenarios strongly link thin film development to the overall PV development (fast growing market size being interlinked with technological breakthroughs). In the very optimistic scenario thin film technologies would reach a maximum market share of 45% which they would hold in the time period 2020 till 2040. After that novel devices would become market leaders. In the pessimistic [Needs 2009] scenario, thin film technologies would reach their maximum 45% market share only in 2050.



Graph 2-4: Market shares of different PV technologies up to 2050
According to the very optimistic [Needs 2009] scenario with high growth and fast technological development.

New players – and soon mergers?

Pushed by the scarcity of raw silicon on the one hand and the availability of venture capital for PV on the other, a lot of new thin film production capacity was built or planned in the years 2005 to 2008. Many of these plants were planned by absolute newcomers with so far no experience in PV production. On the other hand, established silicon cell manufacturers who are extended their portfolio (e.g. Sharp, Q-Cell joint-ventures). Sarasin lists 29 thin film producers who are active [Sarasin 2007]. EuPD research counts 92 companies who have announced to ramp up thin film PV production [EuPD 2008a].

By 2010 / 2012 first experiences will be gained with most of the production sites built or planned today. There will still be a significant co-existence of various technological approaches (within thin film and others, see above). However, some of the approaches followed today may already die out, because others have proven to be more viable.

Especially new and small companies are now more vulnerable than they would have been with the market situation that existed two years ago. Start-up thin film producers are threatened by two developments: decreasing availability of venture capital and decreasing raw silicon prices. Thus the economic crisis may trigger a phase of consolidation and we may see a series of take-overs and mergers sooner than we would have expected two years ago.

Big business – and slower changes?

In technological innovations processes we often witness an “entrenchment” effect. Shifts from established technologies towards new and better technologies are hindered by entrance barriers.[7] Market share is an entrenchment factor, because the technology with the highest market share profits most from scale effects.

So far this was not an important factor for the PV industry. The overall market has been small. It has been possible to enter the market as a newcomer / with a new technology and growth rates could be achieved to keep up with the general pace. Looking at thin film, currently there are many pilot plants with just a few MW of capacity. After two to five years of piloting a next step with some 20 to 50 MW could be envisioned.

7 E.g. computer users do not necessarily choose Windows because they consider it the best available technology. Among many reasons the large market share of Windows promotes the product. A benefit for users is for example that compatibility problems with other users are perceived to be lower than with other alternatives.

Now, with a dramatically growing market, the picture will soon change. If 1GW PV-cell plants are being built, a new technology must be extremely superior to be competitive on a 30 MW level. Consequently the risk for investors to try and bring new PV technologies into market will rise with the size of the overall PV market.

Thus, the faster the market grows, the more difficult it could be for new technologies to enter the market, or to get to the point of competitiveness (with other PV technologies). This is of course not only dependent on size alone, but also on how different the two alternatives are (e.g. substituting just the cell and leaving the whole module production process unaltered would be less of a barrier than fundamentally changing all production steps). Likewise, synergy effects from other industries (e.g. display production) influence the innovation framework.

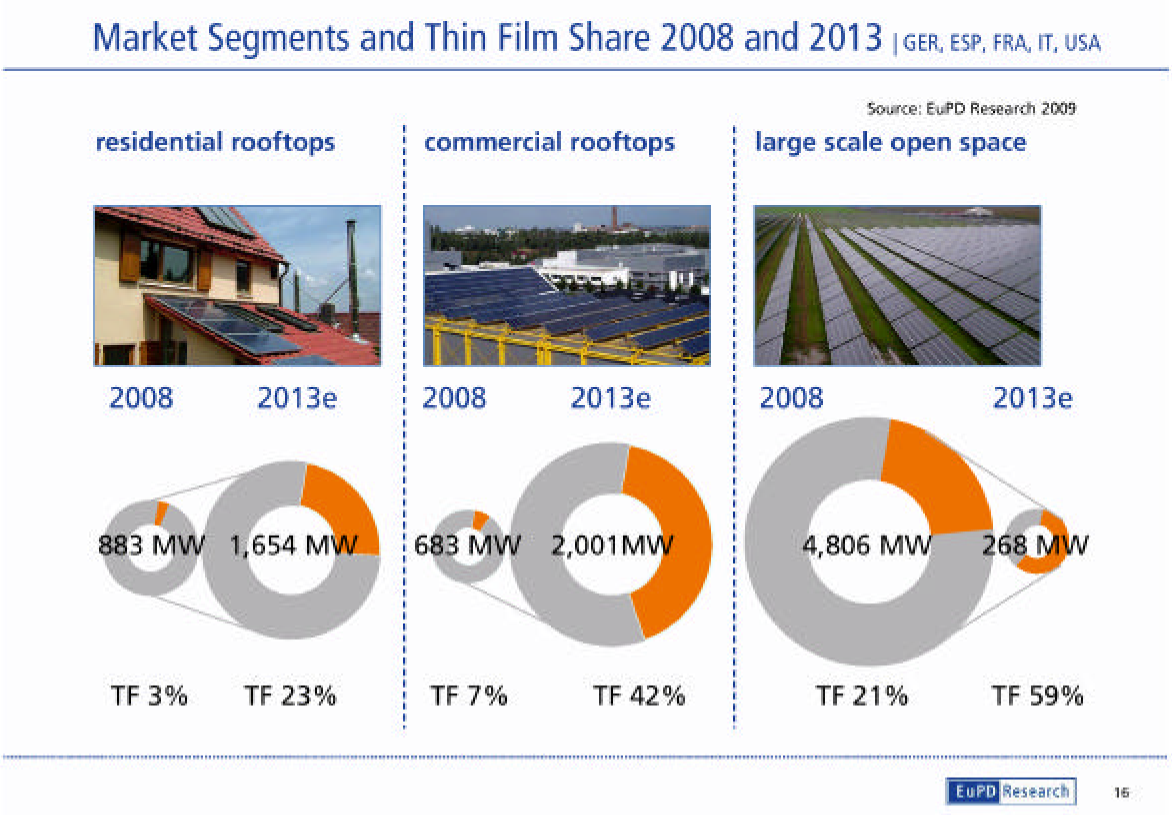
On this background it will be important who will invest in PV in the future? When will big Oil and Gas companies really make significant investments in the PV market was the question raised in [Sarasin 2006])? And what would this mean for the PV markets? Would this lead to more centralised PV power plants? What about players in other sectors? What will be the future influence of the chemical industry? Will they restrict themselves to be material providers or go for the whole value chain? How about big players in the semiconductor business? Will they eventually buy-in to the many new thin film start-ups? Which strategies will the (re)-emerging giants China and possibly the US choose? A vast range of options exist and it is not possible to make predictions. However, it seems almost certain that the investors in PV will strongly influence the final products and the chosen technology.

2.3 Market Segments and Support Mechanisms

Market segments

The structure of the future PV market could become quite important for thin film PV prospects. Thin film PV cells show several specific technical characteristics such as the possibility to create flexible cells or a lower impact of ambient temperature on the efficiency. This could give them advantages over crystalline silicon cells in certain market segments.

However, the structure of the future PV market is quite debated. How will the off-grid share develop compared to on-grid solutions? How important will markets in developing countries become? How big will certain “niches” become (e.g. embedded power supply in appliances)? The literature analysed does point out that dramatic shifts in market segments could happen. EuPD for example predicts a collapse of large scale open space PV farms in established markets (Ger, Esp, Fr, It, USA) [EuPD 2009]. The EuPD study estimates distinctively different market share of the different technologies (thin film vs. crystalline Si) in the different market segments (see Graph 2-5).



Graph 2-5: Future PV market segments – status and 2013 predictions
Figures refer to newly installed capacity in the respective year for "established markets". Share of thin film (TF) technologies is highlighted in orange. Source: [EuPD 2009]

However, in most other studies which were analysed, market segments are hardly ever quantified; drivers for shifts are rather loosely motivated but not strictly derived, and reliable long-term assessments are missing.

Markets in developing countries

According to [Sarasin 2005] the main market for PV in the mid to long-term future will be in developing countries, mainly off-grid. Currently the main bottleneck to tap the off-grid market is appropriate financing schemes (for very customers, who cannot bring up initial investments) and business models (including low-cost maintenance concepts for remote areas).

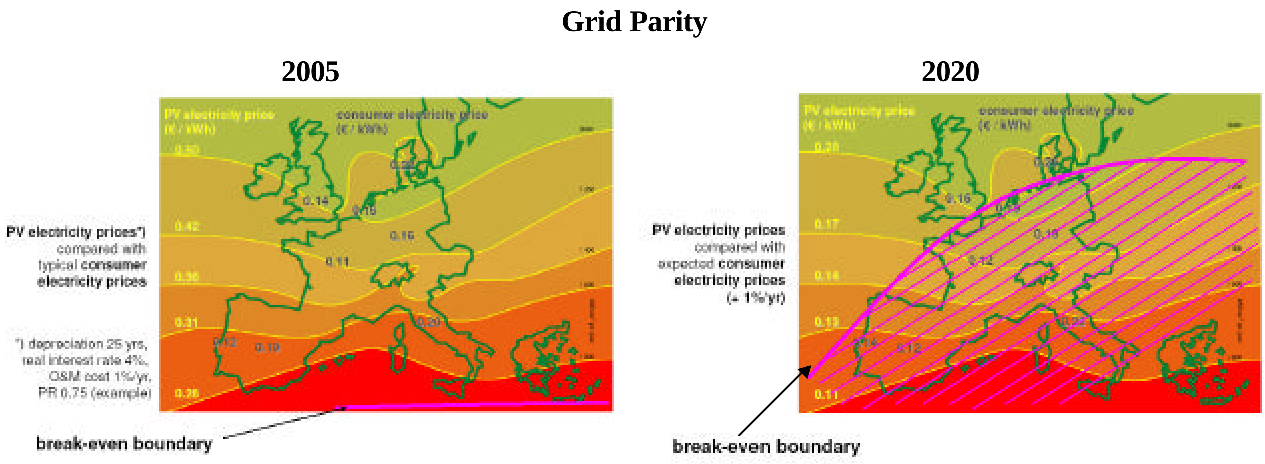
Market support and policy instruments

It is stressed in all scenarios that PV market development strongly depends on political support for PV and the introduction of respective instruments. However, hardly any implications are ever made regarding whether different types of solar cells might benefit differently from specific market support approaches or instruments.

Grid parity

Once the production costs of PV generated electricity are equal or lower than the consumer price of electricity (so-called "grid parity"), then private investors can build PV on their premises using the electricity themselves and make an economic benefit without relying on support mechanisms.

It must be noted that grid parity is not an on-off process but will evolve gradually. Graph 2-6 shows predictions for regional distributions. In Europe this will most likely be the case first in certain southern European countries with relatively high electricity costs.



Graph 2-6: PV electricity price (colour coding) vs. end-customers electricity costs in Europe for 2005 and 2020 projections
By 2020 in most of southern and central Europe "grid parity" could be reached.
Source: [Sinke 2006]

But even in regions where grid parity exists in principle at a certain point in time, it is not inevitable that PV systems are being financed through this scheme. The willingness of the various actors to invest into PV depends not only on the ratio of PV prices to electricity costs but also on perceived benefits and burdens (administrative barriers, lack of suitable business models, image etc.). It can also be assumed that the established electricity providers will develop counter measures to keep competition low. A simple approach would be to charge high fixed costs (per month) with minimal prices per electricity (kWh) consumed. Thus, the development of grid parity will strongly depend on policy, regulation, taxation and PV support schemes.

Consequently, successful business models based on grid parity will most likely evolve in small niches, e.g. for certain plant sizes, customers etc. – some of which may grow rapidly in size and market share while others could be confined to niches.

2.4 Technology Assessment

Challenges for thin film PV

Various scenarios and roadmaps refer to challenges which need to be overcome in order for thin film PV to reach higher market shares. Most prominent are:

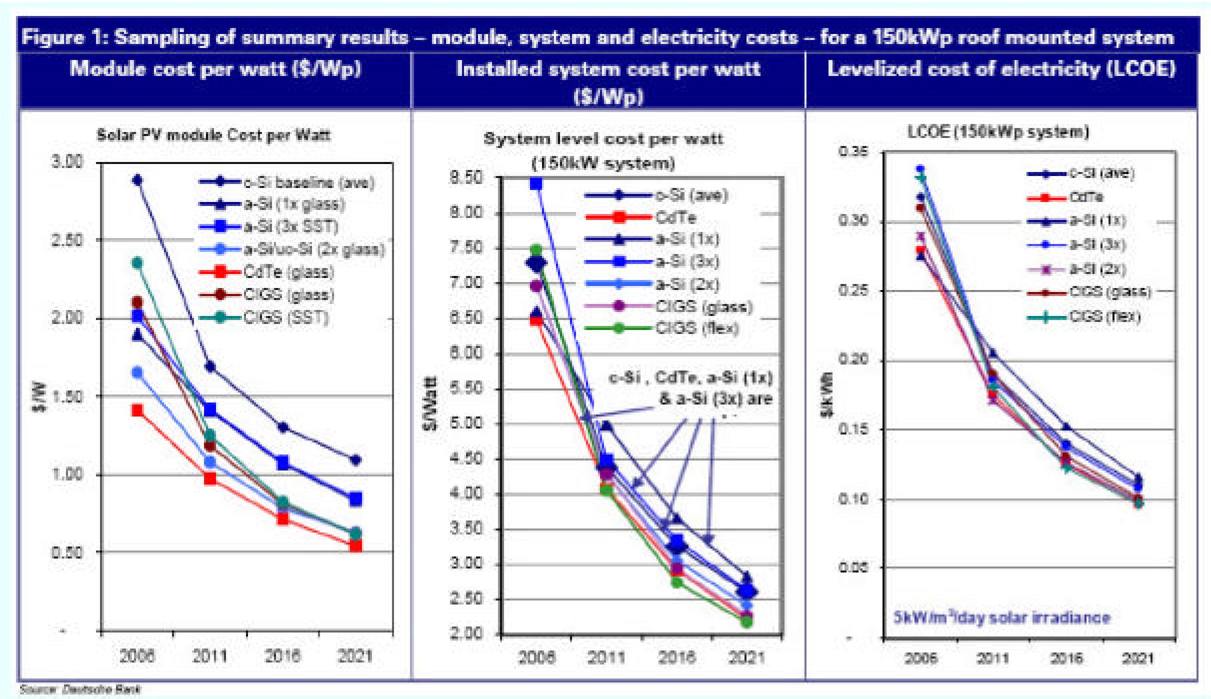
- still a relatively low efficiency for commercial modules
- lack of standard production equipment; high costs and longer time to start-up production
- the relatively low yield in production related to the use of prototype equipment and quality control systems still in use
- expected module lifetime (poor image from the first, amorphous silicon products)
- safety requirements of some materials in production (CIS, CdTe), availability and cost of materials (Ga, Ge, In, Te)
- reduction of material purity and material yield

Learning curves / Cost developments

Underlying most PV development scenarios are certain assumptions on cost reductions to be achieved in connection to a growth of production capacity / size of PV markets. From historic data of market development so called "learning curves" have been developed to mirror cost reduction potential for various technologies.

Whether or not the factual development will stick to the predictions from learning curves approaches will be decisive for the cost development of the various technologies and thus their respective market shares. However, inside information which is fed into learning curve models and which discriminates between different PV cell types is rare and generally not publicly available.

In Graph 2-7 cost curve projections for various PV cell technologies are given. Costs are declining for all technologies, but CdTe and CIGS are expected to reach lowest costs in a 2020 time horizon. However, the apparently strong advantages of CdTe and CIGS in terms of cost per W_p on module level become extremely narrowed down if cost per kWh produced is compared. Our overall conclusion is that in a short to mid term time horizon (10 to 20 years) there is no single “winning” technology visible. In terms of levelized cost of electricity (€/kWh) the differences are too small to secure a clear leadership for certain cell types, unless further technological breakthroughs occur.



Graph 2-7: Cost projections till 2021 for different PV cell types [Deutsche Bank 2007]

Bottlenecks

As major bottlenecks for thin film development resource scarcity is named. This concerns especially Indium for CIS cells, but also other raw materials like Tellurium, Gallium and Germanium (see also chapter 1). Implicitly, labour capacity (skills, installation knowledge etc.) is considered a limiting factor for PV market growth.

Competition by concentrated solar-thermal power?

After a long pause there is a growing dynamic in the field of concentrated solar-thermal power (CSP). Within the last few years several new CSP plants have been built or are being planned, especially in southern Spain and northern Africa (see [Ragwitz, 2007] and [Richter, Teske, Short 2009]). The technology has attracted strong attention stimulated by announcements of big German financial and energy players who expressed interest in the Desertec concept (see [SZ 2009] and www.desertec.org).

If a significant capacity of concentrated solar thermal power plants was installed and major technical breakthroughs were achieved in the next years, then this could lead to strong competition for PV on the on-grid market in countries with high direct radiation. Eventually this could lead to a reduction of support by funding schemes and research for PV in many countries (if CSP is perceived as the better alternative). Globally such a development may even reduce the growth rate of the PV industry.

2.5 Conclusion

Based on the literature research augmented with results gained in interviews and workshops, it can be stated that it is not predictable which PV technology will turn out to be "the winner". All have potentials but also challenges to overcome.

- Many experts and studies state the opinion that wafer-based silicon PV will be superseded by new technologies, one branch of which might be thin film technologies. The main argument is that the cost reduction potential in silicon PV is too small. However, many new technologies to improve silicon PV are been developed and tested. It is undisputed that wafer-based silicon PV will have a large PV market share for the next ten years and it is quite likely that wafer-based silicon PV will be on the market for many more years to come.
- Thin film PV technologies (a-Si, CdTe, CIS) had low market shares in the beginning of this decade but are currently catching up again. Up to 2012 a market share of 15 to 20% could be possible. However, falling raw silicon prices could slow down market share gains of thin film technologies and even lead to a short- to mid-term decrease in thin film market shares.
- The experiences with thin film production plants which are currently planned and built, will be decisive for the further development. Consequently, with a longer time perspective, it is unpredictable which thin film technology might win the race or if even all technologies, which are currently pursued will exist in parallel.

It is almost certain that the PV market in 10 to 20 years will be dominated by technologies which are at least in the demonstration phase today. Thus, concluding from the above, both wafer-based silicon and thin film PV technologies are likely to have substantial market shares. However, with a 20 year perspective it may well be that some of today's thin film PV technologies will have died out or are reduced to niche markets.

Consequently, for the scenario exercise, it is interesting to explore whether certain technologies are better fit to serve specific market segments than others. In the light of the extremely fast shift from a supply to a demand-oriented market, this assessment may be of interest for PV manufacturers both from a long-term strategic as well as a short-term marketing perspective.

3 Sustainability Assessment and Resources

The following chapter contains the results of the sustainability assessment of the large scale implementation of thin film PV technologies to provide an estimate for the absolute magnitude of environmental impacts. In the first part, the environmental impact of PV as a renewable energy source is compared to conventional energy systems. In the second part, the environmental impact of different PV-Technologies is shown. Furthermore this chapter shows the demand for specific rare materials of different thin film technologies and to which extent measures of material-effectiveness can lower the demand. Finally the use of fluorinated gases in the production of PV is described to point out a crucial factor influencing the overall climatic impact of thin film PV.

3.1 LCA Results

In a sustainability assessment of thin film PV, a renewable energy source has to be compared to conventional energy systems. For this purpose the following figures illustrate selected LCA results.

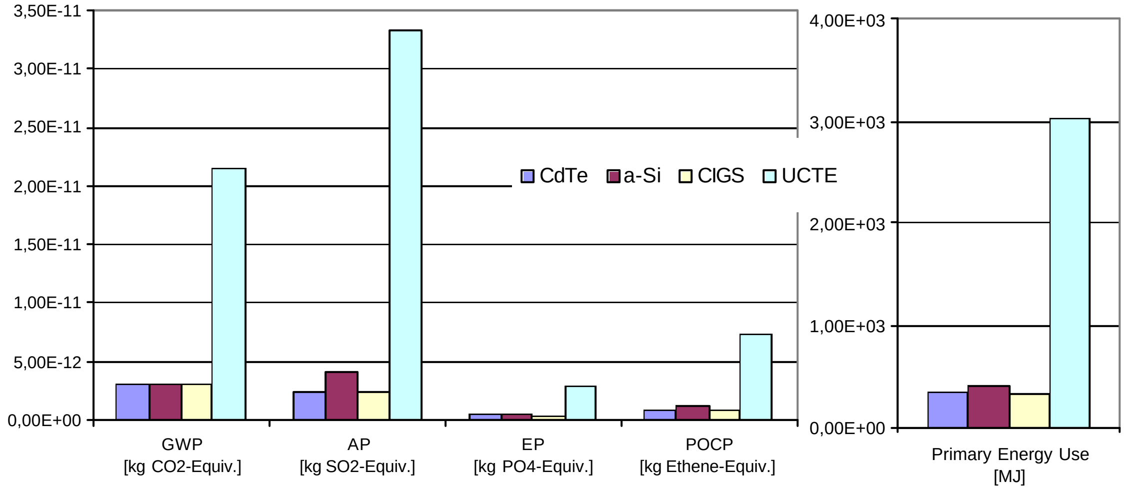


Figure 3-1: Thin Film power plant compared to UCTE power mix [referred to 1 GJ] [SENSE 2008]

The results of environmental assessment shown in the figure above underlines that, as a whole, the environmental impacts (GWP[8], AP[9], EP[10] and POCP[11]) caused by thin film PV-modules as well as the Primary Energy Use are definitely lower than those caused by conventional energy supply systems (UCTE power mix)[12.]

The environmental performance of a PV-system depends on its application type (power plant, mobile, building integrated etc.) and the solar radiation of the location. Nevertheless, regardless of the application type and location, thin film PV modules cause significantly less environmental burdens than conventional energy carriers.

[8] WP: Global Warming Potential,

[9] P: Acidification Potential

[10] P: Eutrophication Potential

[11] OCP: Photochemical oxidation Potential

[12] CTE (Union for the Co-ordination of Transmission of Electricity) - average electricity generation mix of main European countries, diesel generator etc.

Moreover, the environmental impact differs significantly among the PV technologies. The following table shows the specific environmental impacts of different photovoltaic technologies.

Impact per kWp	PV-Panel at plant						Dimension	Sources/ Approach
	Single-Si	Multi-Si	a-Si	CdTe	CIS	Ribbon-Si		
Climate change	18	13	4,10	4,09	12	10	kg CO_2-Equ.	IPCC 2001: GWP 100
Cumulative energy demand	355	264	66	73	215	191	MJ-Equ.	VDI-guideline 4600
Eutrophication potential	9,2	7,2	1,4	2,6	3,8	5,5	g PO_4-Equ.	CML 2001
Aquatic eutrophication	2,4	1,7	0,1	0,2	0,4	1	g PO_4-Equ.	IMPACT 2002+ (Midpoint)
Acidification potential	72	53	22	31	41	42	g PO_4-Equ.	CML 2001
Depletion of abiotic resources	132	101	29	46	118	72	g Sb-Equ.	CML 2001
photochemical oxidation potential	3,4	2,6	1,1	1,2	1,7	1,9	kg ethylene-Eq	CML 2001 high NOx POCP
Stratospheric ozone depletion	6,6	6,1	0,1	0,3	0,7	4,9	mg CFC-11-Equ.	CML 2001: ODP 25a
Human toxicity	7,4	6,5	3,7	5,5	3,9	5,1	kg 1,4-DCB-Equ.	CML 2001: HTP 100a
Human health	0,38	0,28	0,11	0,16	0,23	0,21	eco-Points	Eco-indicator 99, (H,A)

Table 3-1: LCA Result of different PV Technologies [ECOINVENT 2007]

The table above shows the LCA results of the main environmental impact categories. The analysis is based on data from standard production lines in the United States (a-Si), Germany (CIS, CdTe) and Western Europe (mc-, sc- and ribbon-Si). The time of data collection differs among the cell types. Investigation starts 1997 and ends 2007. The data concerning the producing of a-Si panels were collected from 1997 to 2005, production data of mc-, sc- and ribbon-Si-panels refer to the year 2005, data of CIS-panels refer to the production period 1998 to 2007, respectively from 2002 to 2006 and for CdTe-panels.

The table above shows very impressively how values of the environmental impact categories vary between the different PV technologies. Especially for the stratospheric ozone depletion and the eutrophication potential the spreads of the values between the sc-Si and the a-Si are very broad. In the other categories the values between sc-Si and the a-Si still vary with a factor 2 to 7. In summary the producing of sc-Si-panels has the highest and a-Si the lowest environmental impacts with regard to the analysed categories. Furthermore it can be seen that production of thin film PV panels is more environmentally friendly than the production of wafer based PV panels. An exception is the depletion of abiotic resources for CIS-PV-panels. Within the thin film technologies the picture is not very clear. But in the most environmental categories considered, the production of ribbon-Si-panels has the highest environmental impact of all. Exceptions are the categories human health, climate change, the cumulative energy demand and, again, the depletion of abiotic resources. Here CIS-panels have higher values.

Beside these results of common LCA´s, the emission of fluorinated gases through the photovoltaic industry emerges as an issue. [Photon 2008b] Fluorinated gases like CF_4, C_2F_6, SF_6, NF_3, ClF_3 and F_2 are used by the photovoltaic industry for etching silicon wafers and cleaning the (PE)CVD chamber. Because of their high global warming potential and high atmospheric life time, the emission of F-gases from the module production can increase the overall climatic impact of thin film PV significantly.

Whether the use of F-gases has a significant influence on the overall carbon footprint of thin film PV depends on the gas types used, the abatement system and its cleaning efficiency, the handling of the gases and the circumstances of their production. The losses of F-gases are in most cases unavoidable either for physical or economic reasons: e.g. there is no better selectivity of the synthesis process available, no efficient separation process is known or investment in better separation cannot be not justified by the price of the product.

A possible approach is the use of on-site synthesised F_2 with an obligatory implemented back up of the running abatement system. [UBA 2009]

Taking the market split of the described scenarios (see chapter 5) into account, the environmental impacts have a higher influence for the residential roof top and the building integration market than for the commercial roof top and the green field market.

It seems more certain that the environmental impact has a higher influence on an investor's decision if the asset location is close to the living place of the investor. As well the scale of the investment has an influence on the consideration of environmental issues. The higher an investment is, the stronger the role played by the economic conditions and environmental issues lose influence. This correlation sustains the thesis that in the "Diversity Rules" scenario the environmental performance of a PV-technology plays a more important role than in the "Size Matters" scenario.

3.2 Rare material

In the last few years the continuously increasing demand for photovoltaic modules has generated a silicon supply shortage. During that shortage the price of solar grade silicon increased dramatically. On the other hand this shortage provided an opportunity for thin film photovoltaic manufacturers to enter the market with significant quantities. Since mid 2008 the shortage of solar grade silicon has been more and more overcome by new production capacities and new production processes, but some PV manufactures are still bound to long term supply contracts with high price conditions. Due to the collapse of the market grow in 2009, the expanded capacity of module production and a rise of imports especially from China, the market situation has changed from a supply market to a demand market. As a result module prices dropped in 2009 (see Figure 3-2).

With the change of the market, the window of opportunity for thin-film PV seems to be getting smaller, as the independency of thin film PV from the silicon feedstock is no longer as advantageous.

Beside cost efficiency and the potential to improve the production processes and the module efficiency, the availability of rare material will become increasingly important. This is particularly true for a PV market with decreasing module prices and a reduction of feed in tariffs.

However, the silicon shortage brought attention to material availability as a possible bottleneck for the development of the photovoltaic market. Together with other emerging technologies thin film PV will have a significant impact on the material demand of so called strategic metals. These metals are characterised by:

- Small global mass flow
- Produced as by-product of major metals
- Dissipative use profile (small amounts of material in mass products)
- Volatile price formation by demand or supply changes
- Utilisation competition with other emerging technologies
- Limited possibilities for substitution
- Poor commercial recyclability

The following table shows thin film cell types, their demand for strategic metals and their resource-economic skeleton data:

Cell type	strategic metals	Requirements [t/GWp]	Global Refinery Production 2007 [t]	Reserve[13] 2008 [t]	Reserve base[14] 2008 [t]
CdTe	Cadmium	100	20,800	490,000	1,200,000
	Tellurium	44	300	21,300	47,300
CIGS	Indium	34	563	11,000	16,000
	Gallium	44	103	110	NA
	Selenium	46	1,560	86,000	172,000
a-Si Ge/GaAs	Germanium	37	105[15]	405	500
Dye-sensitised	Ruthenium	0-1	40[16]	6,000	NA

Table 3-2: Thin film cell type and their demand for strategic metals
[Kautsch 2005, Falk 2006, Andersson 2000, USGS 2008, 2009]

Note that the data in the table above possesses high uncertainties. Reserve and reserve base are strongly related to the current economic situation including prices, exploration, mining and finishing technology. Furthermore the cell specific requirements reflect the current technology status. It can be expected that the cell specific requirements will decrease as a result of technological progress and industrialisation of the cell production.

To assess the availability of strategic metals it is necessary to make at least a rough estimate of the demand for strategic materials used by the different thin film technologies. Therefore three quantitative scenarios from the NEEDS study are used to show the development corridors of the future PV market in general and their technological differentiation.[17] The following figure gives an overview:

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[13] Reserves.—That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative.

[14] Reserve Base.—That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth.

[15] Only US-Refinery

[16] 2006

[17] The NEEDs-scenarios distinguish the market sizes of thin film, wafer based-Si and novel devices. To differentiate the thin film internal technologies, the market shares from [SARAZIN 2009] about the year 2012 are taken and kept constant up to 2050. This manner contents high uncertainties. The adjust thin film internal technology market shares are: CdTe: 46%, a-Si: 39% and CIS: 15%.[Sarasin 2009]

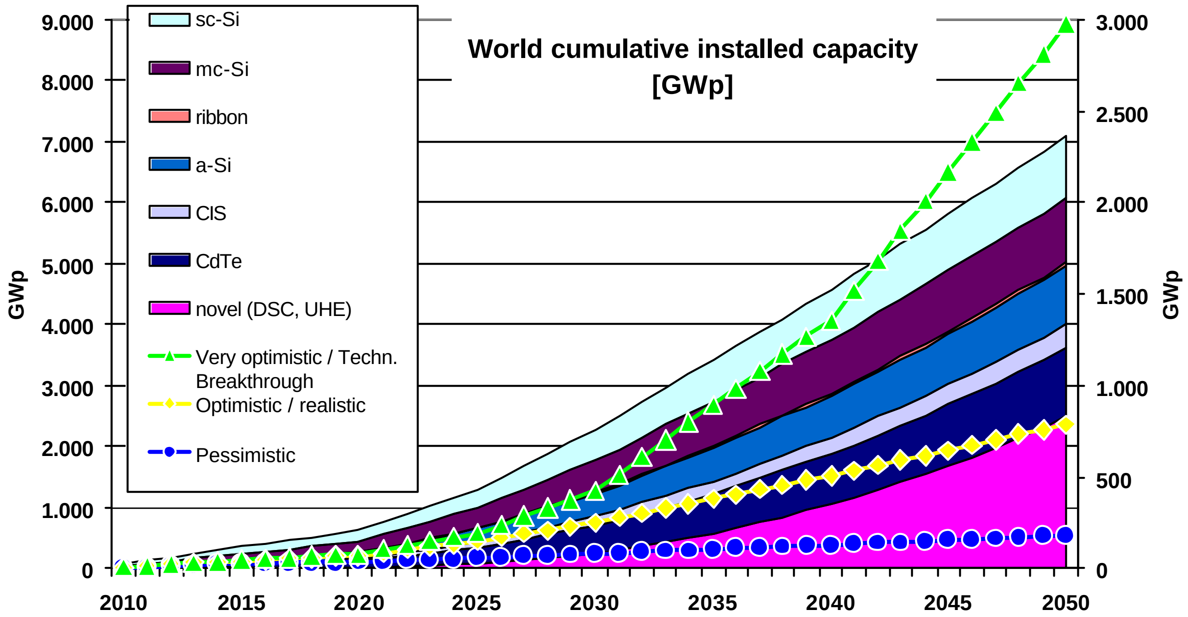


Figure 3-3: World cumulative installed capacity in general according to three scenarios (left axis). Cumulative installed capacity by technology to the realistic scenario (right axis)

Based on these scenarios the demand of different thin film technologies for strategic materials is estimated.

To draw a differentiated picture of the future material needs estimates about the demand generated from the content of the product and the demand generated from the production process to be made separately.

To get a better understanding of the impact of material efficiency measures, estimates are made about the reduced demand in the case of

- recycling of production waste,
- material-effectiveness production and
- recycling of end-of-life waste

Furthermore the impact of combining efficiency measures and material needs is estimated. At the least, the actual world primary production of the materials is shown to come to a rough estimation about the future availability of the material.

To give a more dynamic picture several assumptions are made:

- The product specific demand decreases by 10% per decade due to incremental technological improvements
- The current material yield of production processes is assumed to be 50% for all cell technologies
- The recycling quota of production waste is assumed to be 50% in 2010 and increases 10% per decade
- The material yield is assumed to increase by 10% per decade due material-efficiency measures active taken in the production

To estimate the impact of recycling end of life modules for the future material demand, the following assumptions are made.

Year	Collecting quota	Recycling quota			
		Indium	Gallium	Selenium	Tellurium
2007	10%	10%	60%	10%	80%
2010	10%	10%	60%	10%	80%
2020	25%	50%	70%	30%	85%
2030	50%	75%	70%	50%	95%
2040	75%	90%	80%	75%	95%
2050	90%	50%	90%	90%	95%

Table 3-3: Collecting and Recycling quotas of EoL-Recycling to 2050

The values in the table above reflect different assumptions about the actual recycling situation, the ongoing development of recycling activity, a life expectancy of 30 years and the value of the materials.

The collection quota starts on a very low level because currently no end of life recycling is established except for CdTe cells. Furthermore, there is not a sufficient amount of end of life modules as yet.

The recycling quota of Gallium and especially of Tellurium starts on a high level because both materials are very valuable and recycling processes are already established and practiced.

The results concerning the future demand of Indium to CIS PV are shown in the following graph:

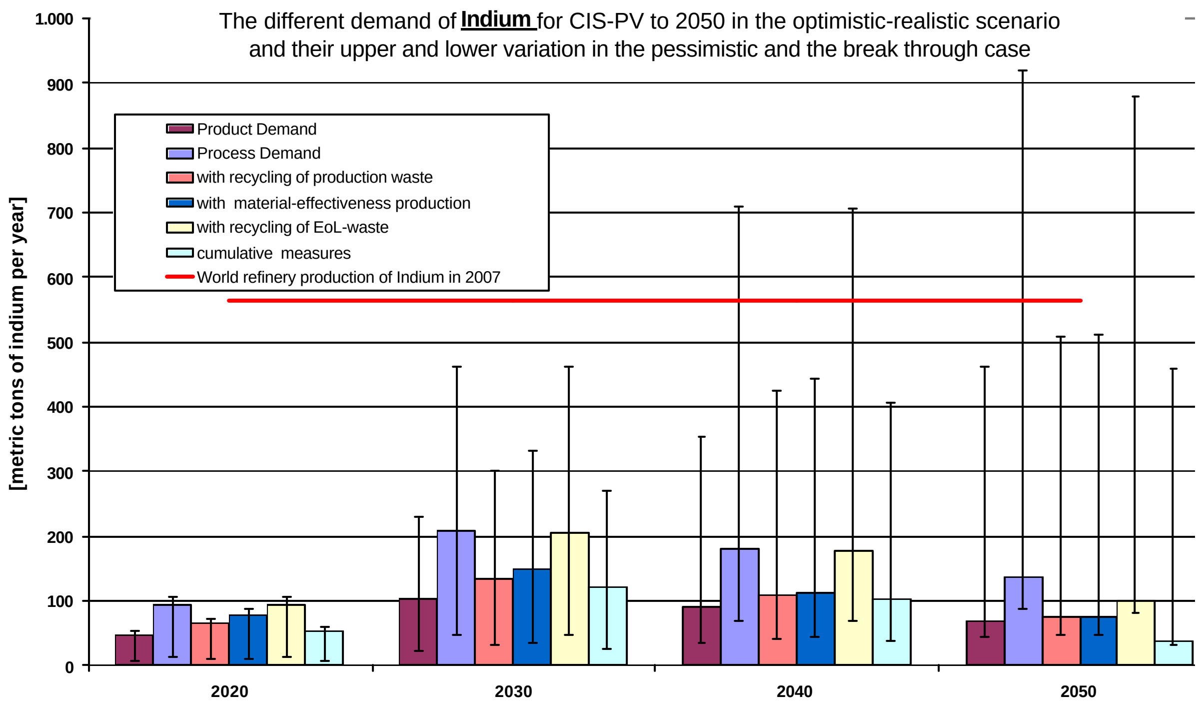


Figure 3-4: Demand of Indium to CIS-PV up to 2050

As the graph shows, the production of CIS-PV requires, in the realistic scenario, between a quarter to a third of the global primary production from 2007. In the very optimistic scenario that share can increase until 2050 up to nearly the double the actual primary production. Even in the case of cumulative resource efficiency measures, CIS PV requires in the very optimistic scenario three quarters of the refinery production from 2007. In the pessimistic scenario the Indium demand of CIS-PV is very moderate and in all cases mostly less than 10%. But it has to be mentioned that CIS-PV stands in strong competition with other Indium consuming technology products. In particular these are the LCD as well as the white LED.

However, the graph shows that resource efficiency measures have a significant impact on future demand for Indium of CIS PV.

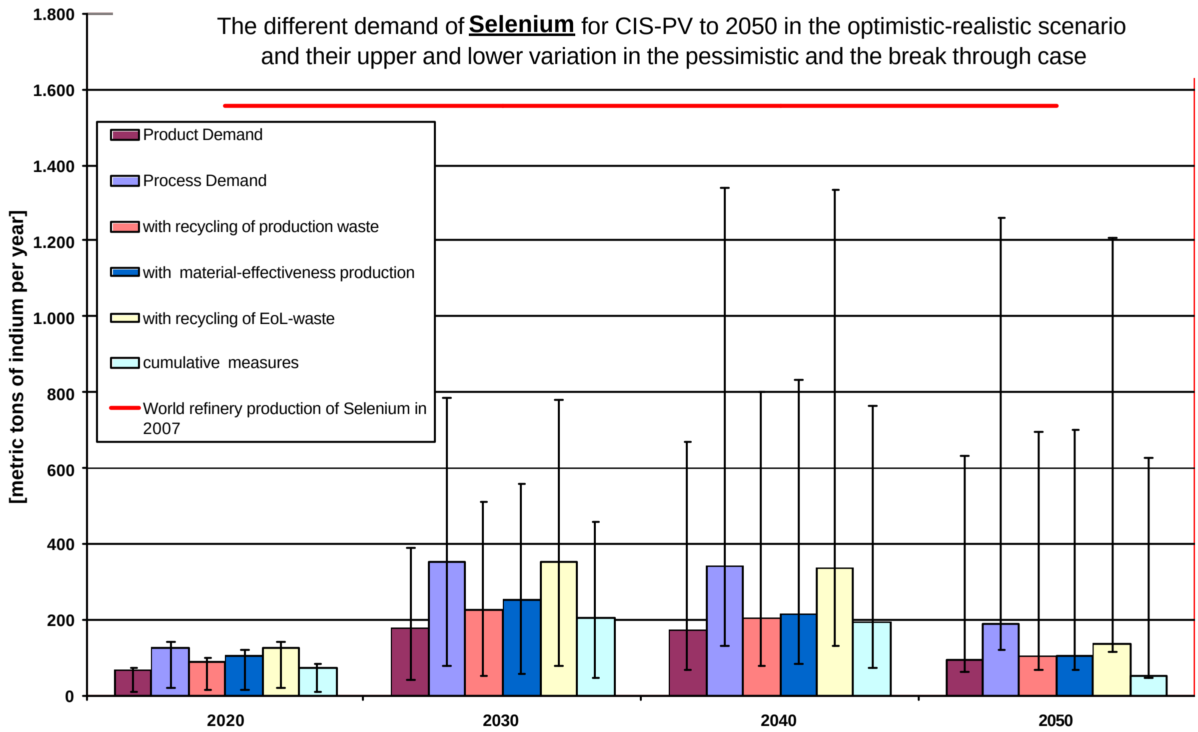


Figure 3-5: Demand for Selenium from CIS-PV up to 2050

The effects caused by Selenium demand from CIS-PV are less than those caused by Indium demand. In all scenarios and timeframes, the demand does not exceed the primary production of Selenium in 2007. Furthermore the amount of Selenium produced is nearly triple that of Indium. Therefore and because the Selenium is a by-product of copper, the supply can follow increasing demands much more easily. Furthermore the usage profile as well as the production sites of Selenium are much more diverse than for Indium. Particularly due to the latter, the supply can follow an increasing demand much more easily. Nevertheless material efficiency measures can decrease the material requirements significantly. In particular the recycling of production waste can halve the demand. The recycling of EoL-waste reduces the demand significantly only in the long term when a sufficient amount of CIS-Modules reach their life expectancy.

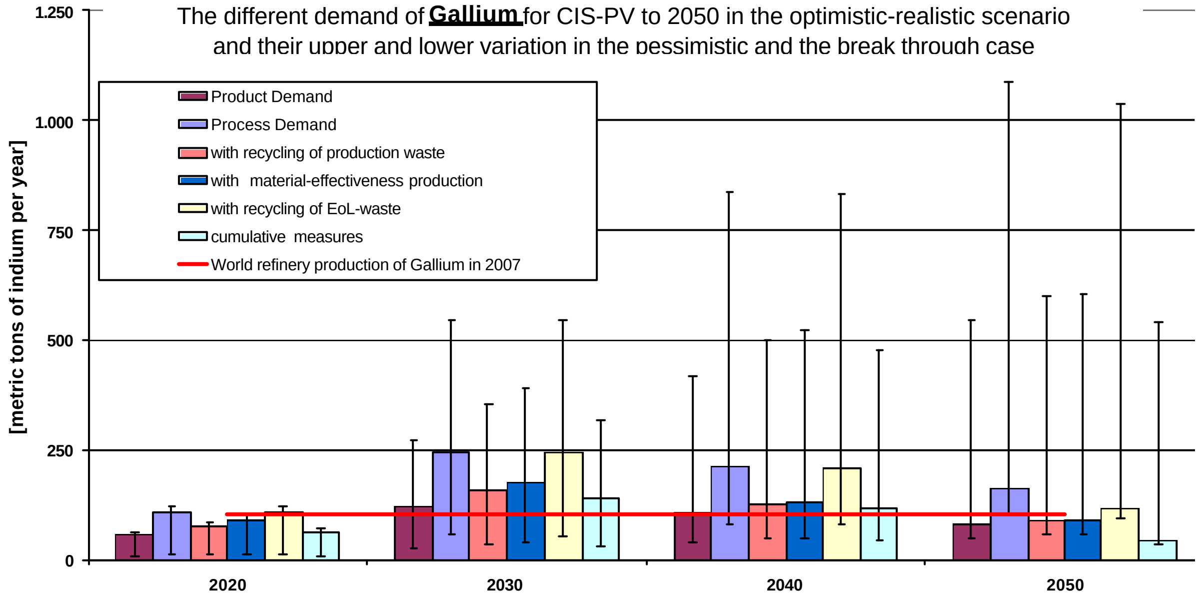


Figure 3-6: Demand for Gallium from CIS-PV up to 2050

The figure above shows dramatically how the weak availability of Gallium can be a key bottle neck of the broad market implementation of CIS-PV. From the year 2030 in all cases of the realistic and the very optimistic scenario, the demand of Gallium from CIS PV exceeds the global primary production of 2007. In the very optimistic scenario the process demand will be more than 6 times higher than the primary production in 2007. Furthermore the relatively small production volume of Gallium makes an increase of supply more difficult even if the production sites of Gallium geographical are well diverse.

Because of the very high price and the already existing recycling facilities, the recycling of Gallium from production and EoL-waste is a highly recommend material efficiency measure.

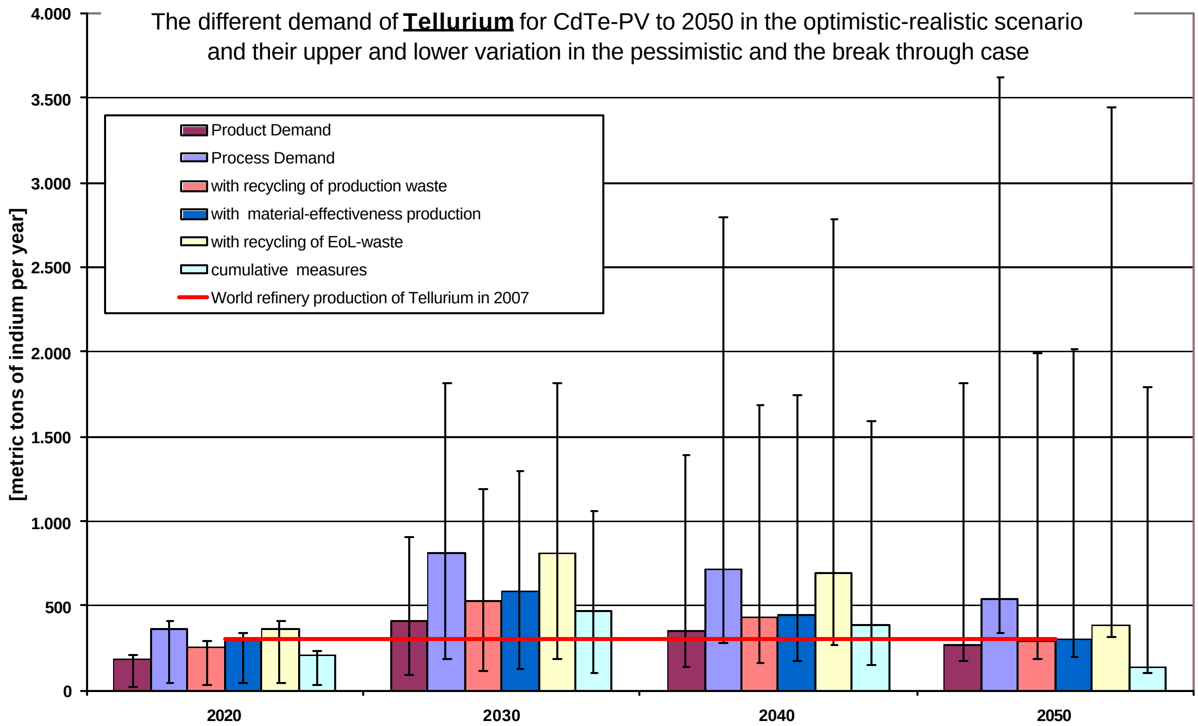


Figure 3-7: Demand for Tellurium from CdTe-PV up to 2050

For a broad market implementation of CdTe-PV the availability of Tellurium can be a key constraint.

As shown in the figure above, from 2020 the demand for Tellurium from CdTe-PV exceeds the primary production line of the year 2007 in all cases of the realistic and the very optimistic scenarios. In 2030 and 2040, even with cumulative efficiency measures, we are not able to reduce the demand under the production line of 2007. In the very optimistic scenario the process demand is 6 times higher than the worldwide production output of Tellurium in 2007. Furthermore it has to be realised that with the current consumption profile over 80% of the Tellurium is consumed by iron and steel applications and the chemical industry. Similar to Gallium, the recycling of Tellurium is already very common, mainly because of the high value of Tellurium. To overcome the certain constraints of CdTe-PV material, efficiency measures have to focus mainly on the recycling of production waste.

In summary the availability of strategic materials can be a serious constraint for the broader implementation of thin film PV. Particular the increasing demand for Indium and especially for Gallium can handicap the market grow of CIS-PV and the rising demand of Tellurium can limit the market share of CdTe-PV. Material efficiency measures can have a significant impact to reduce future demand and help to overcome material constraints and are therefore strictly recommended.

Core elements of a main strategy to improve the material efficiency are:

- Minimising the material demand of the product
- Maximising the material yield in all steps of the production process
- Maximising the input to recycling process
- Maximising the material yield in the recycling process

3.3 Conclusion

The environmental assessment underlines that the environmental impacts caused by thin film PV-modules and the Primary Energy Use are definitely lower than those caused by conventional energy supply systems. Compared to wafer based PV panels the production of thin film PV panels is more environmentally friendly with the exception of the depletion of abiotic resources by the production of CIS-PV-panels. In comparing the thin film technologies, the picture is not very clear. But in most environmental categories considered, the production of ribbon-Si-panels has the highest and a-Si the lowest environmental impacts of all thin film technologies with regard to the analysed impact categories

Concerning the availability of rare material, the assessment underlines that a growing use of thin film PV will have a significant impact on the demand for strategic metals. In particular, the market for high purity metals in semiconductor quality will grow in order of one to two orders of magnitude. With a mass roll-out of thin film PV cells, the security of material supply in mid and long term will play a crucial role. Furthermore the demand effect of thin film PV will have also a significant influence on the prices of the materials. A crucial influence on the prices of semiconductor materials will come from competitor markets like micro-electronics which are more resistant to price fluctuations.

Most likely is an overhang of demand for gallium and indium from CIGS-cells and tellurium from CdTe-cells. If the supply can not satisfy these keen increases of demand, the material availability can be a serious constraint for the thin film technologies involved.

Therefore activities to improve the efficiency of material use are highly recommended. Measures relating to efficiency of material usage should include the reduction of the material content in the product, maximising the material yield in the production and the recycling of production waste as well as end of life modules.

4 Thin film Potential in Key PV Markets

In this chapter the characteristics of the various PV market segments are analysed. The underlying assumption is that specific requirements exist so that one product does not necessarily perform best for all applications. The key indicator of performance for a PV system is of course energy yield per cost (kWh/€) or for simplicity reasons kW_p/€. However, system cost may vary for different PV technologies in different market segments. And more importantly, we assume that other factors may influence customer choices – if the difference in kWh/€ stays within reasonable margins. Thus, in this chapter, the key requirements (performance indicators) for four archetype PV market segments are characterised:

- Large-scale (ground mounted) PV farms
  Large (>> 100 kW_p) PV installations on previously not built-up areas.
- Roof top installations
  PV modules are mounted on roofs of buildings (grid connected). This would include standard flat panel modules as well as foil type modules which could be rolled out on flat roofs. This segment could be subdivided into two sub-segments: large roof top installation on flat roofs and small scale installations (< 10 kW_p) with a large share of pitched roofs.
- Building integrated
  The PV module is an integrated part of the building envelope. Facades are a typical example. We would also define PV roof tiles as building integrated.
- Off-grid
  The consumer is not connected to a larger electricity grid. The PV system is a stand alone solution (e.g. Solar Home System) or part of a micro grid. Markets would be in remote areas or in developing countries.

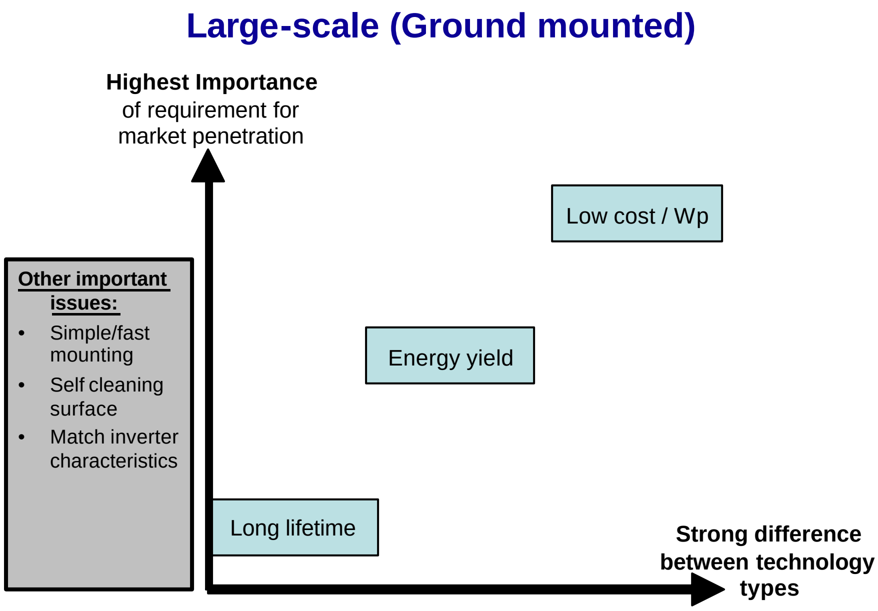
There is another market segment: Consumer Appliances and Pervasive Micro Applications. This comprises small scale appliances like mobile phone chargers or products in which small PV modules already embedded (watches, pocket calculators etc.). This market could grow in the future and it may be a substantial market in terms of profits. It furthermore poses quite specific challenges (e.g. dissipation of electronic goods / recycling strategies) and needs to be considered in sustainability analyses of PV products. However, it will not be analysed further in this study as the overall market size (in MWp) was considered to be marginal within a 20 year time horizon, at least in comparison to the other four markets.

4.1 Large-scale (ground mounted) PV farms

In the market segment of large-scale, ground mounted PV farms the key indicator is the system cost per kWh produced or for simplicity reasons costs per W_p (including: modules, wiring, mounts, inverters etc.). Efficiency is not a decisive factor, as space of the system is generally not the limiting factor. However, efficiency impacts beyond the module costs by wiring and mounting costs. Adding to the system costs are mounting costs (labour and material) which need to be reduced. Self cleaning module surfaces help to increase the electricity output, without creating high maintenance needs.

It has to be noted that the energy yield (in kWh) is not always proportional to the W_p characteristic of the module (full light behaviour etc.). This difference can impact quite heavily for large-scale PV farms. Therefore it can be assumed that better estimates of on-site performance (beyond the W_p indicator) will be used in the future to base technology choices on.

The *net* energy yield (energy output of the module over life time minus energy used in production of the module) could become an increasingly important factor for large-scale PV systems for the following reasons. It can be assumed that within the next 10, may be even within the next 20 years or longer, large scale PV systems rely on some sort of support scheme. The reason is that they have to compete against production costs of other large power plants, while small scale PV systems have to compete only against consumer prices. The minimal long-term support scheme would be carbon credits in a CO_2-emission trading scheme. But with a short to mid-term perspective, large scale systems will only be implemented with massive public support or within a strong beneficial regulatory framework. As the intention of this support is CO_2 mitigation, it is very plausible that support schemes in the future could encompass the net CO_2-reduction (or net energy yield) as one indicator which defines the support level. Thus PV technologies with high net energy yield could have an additional advantage in large scale systems.



Graph 4-1: Key requirements for PV technologies to enter market segment of large-scale (ground mounted) PV farms. Assessment of importance and differences between technologies was given by participants of the scenarios workshop [Athlet WS 2009]

In general thin film technologies have advantages in the market segment of large scale (ground mounted) PV farms. Cost (per W_p or kWh) are more decisive than efficiency. Currently CdTe modules seem to be leading in terms of cost per W_p and the respective prices and is also performing well with respect to costs per energy yield (€/kWh) due to its full light behaviour. Other thin film technologies have good mid to long-term perspectives (see Graph 2-7). In terms of net energy yield, amorphous silicon and CdTe modules currently often have best the performance indicators (see

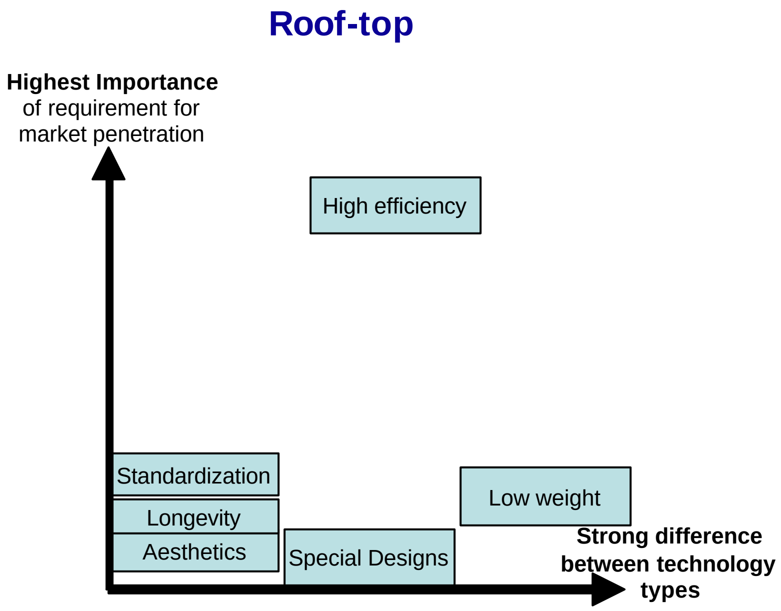
Table 3-1 in chapter 3) depending on system and location characteristics.

4.2 Roof top applications

Roof top markets for PV modules show two very specific characteristics: 1) the space which is available is limited and 2) the static and construction properties of the roof restrict mounting options. Consequently the efficiency of the module (W_p/m^2) becomes a very important factor (assuming that the costs per W_p of the alternatives are within reasonable ranges) in order to maximise the energy yield on the roof.

Furthermore there is a demand of low weight and easy to mount modules. Low weight is crucial for certain building types, especially for retrofitting of PV systems on large flat roofs of commercial and industrial building. Here the static properties of the roof often do not allow installation of heavy PV modules. The mounting itself can also be difficult. Screwed or bolted-on mounting solutions may cause difficulties with rain water leakage. Weight based solutions are limited to roofs with strong static properties. Consequently, light weight modules are generally favourable for roof top installations and would be a very competitive option in specific sub markets. Low-cost mounting solutions profit from standardisation of modules and corresponding mounting components.

Aesthetics and design questions could be an issue in individual projects / applications, but this reaches already into building integration and is described in section 4.3.



Graph 4-2: Key requirements for PV technologies to enter market segment of roof top applications. Assessment of importance and differences between technologies was given by participants of the scenarios workshop [Athlet WS 2009]

In terms of efficiency, wafer based silicon technologies currently have strong advantages over thin film technologies – and most likely will continue to do so in the mid-term future. Thus, unless thin film beats alternatives heavily in price, the low efficiency is a strong disadvantage in this market segment.

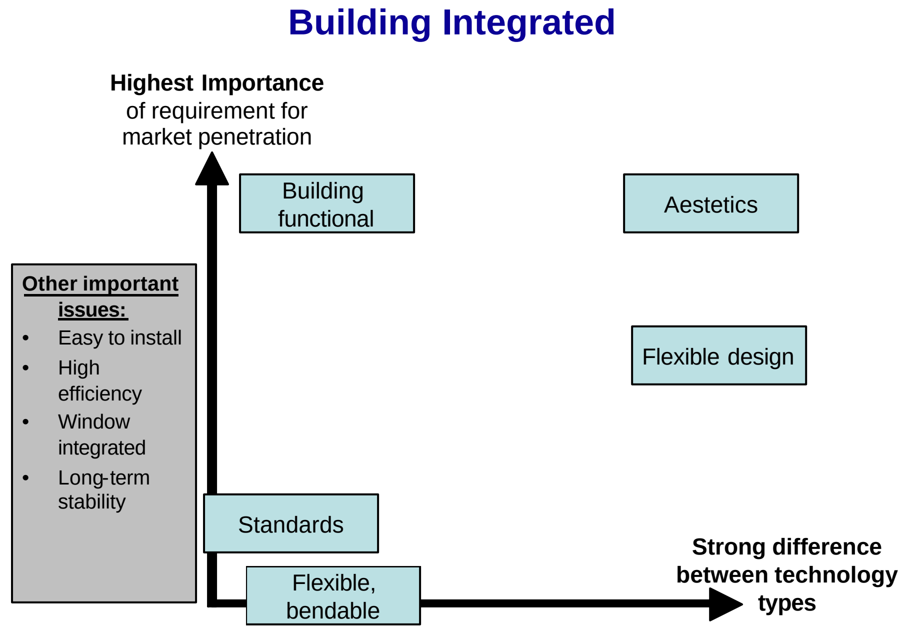
With respect to low weight modules, the most important factor is the encapsulation. Glass based solutions are generally heavy. Low-weight alternatives could be PV-foils, which then would not even need heavy mounting gear. Although low-weight encapsulation techniques could be applied to a wide variety of PV cell types, thin film technologies have specific advantages in this field, bendability being one of them. The technological challenge is to develop low-weight, low-cost encapsulations with long lifetimes.

In conclusion it can be said that the low efficiency poses a disadvantage for thin film PV in roof top markets and would need to be compensated by attractive prices. Low-cost and low-weight mounting options could help to secure at least sub-market segments.

4.3 Building integrated systems

For building integrated PV systems the most important requirements are functionality and design of PV modules. In terms of functionality the modules have to be easily mountable in the building envelope. Furthermore they have to satisfy building specific demands (in addition to being an electricity generator): insulation, water resistance, sound absorption etc.. Consequently the modules have to be designed to fulfil common standards and norms of the building sector. Furthermore, manufacturers have to specify (e.g. in module leaflets) standard building material characteristics (e.g. fire resistance) for their modules so that planners can fulfil declaration obligations.

The aesthetic requirements are difficult to specify, being highly subjective. Many are linked to functional requirements: sizes and shapes need to fit the proportions of the building. Thus, flexibility in design is definitely a key advantage in the market segment of building integrated PV. Bendability of cells could be beneficial for non-flat plate uses. This however would be a high quality / high price market. With respect to the optical appearance of the modules the colour itself may not be as decisive as the overall visible structure – e.g. heterogeneously chequered versus homogeneously uniform. Transparency and shading ability could be other important features of building integrated PV modules.



Graph 4-3: Key requirements for PV technologies to enter market segment of building integrated systems (e.g. facades). Assessment of importance and differences between technologies was given by participants of the scenarios workshop [Athlet WS 2009]

The above stated requirements refer to the PV *module*. Some of them are rather independent of the respective cell type (e.g. noise absorbance, water resistance). Module manufacturers have to fulfil these requirements if they want to tap the market of building integrated PV. But there are no advantages or disadvantages for thin film over crystalline silicon PV technologies.

For other requirements there are dramatic differences in what the various cell technologies could contribute. However, the experts we consulted had highly controversial views on which technology performs better in building integration:

- Thin film modules can in principle respond best to design requirements (size, shape, bendability, homogeneity). However, the foreseeable improvements in the production processes (increasing automation, optimising production parameters for high efficiency and low material use / costs) contradict flexible solutions since cell production is inseparable from module production for thin film technologies. Consequently flexibility in design will almost certainly result in higher costs, higher material use and/or losses in module efficiency unless cell and module production are separated into independent processes.
- The production of crystalline silicon PV cells is independent from the module production and can thus be optimised separately. In this respect the production of wafer-based PV modules is more flexible regarding shapes and sizes. Higher costs stem only from adaptations in the module production, not the cell production.

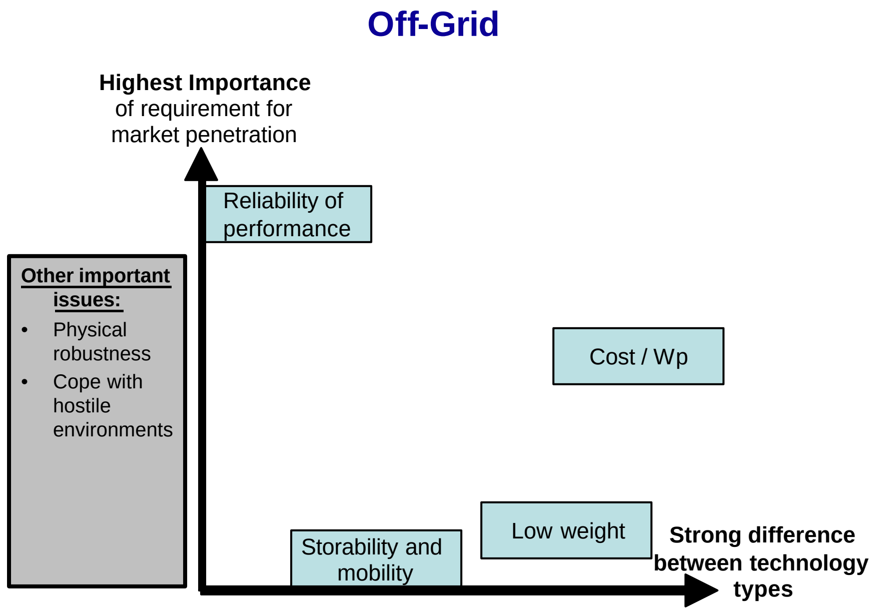
As a consequence we consider it likely that in a scenario with high share of building integrated PV (e.g. Diversity Rules scenario, see chapter 5.1) this market could split into three sub-segments:

- Highly standardised products
  With standard sizes and shapes – Thin film products could gain a significant market share here, as efficiency would less decisive than design options like colour and structure.
- Flexible sizes and shapes
  Under the aesthetic paradigm of „making PV visible“ in shelter and (semi-transparent) shading elements, wafer based silicon PV could gain major market shares in this sub-segment.
- Specialised designer products
  The high-end market of building integrated PV could possibly be an attractive niche for very specialised thin film producers. Both costs and energy yield would be secondary to the very specific design requirement of largely tailor-made PV modules.

4.4 Off-grid applications

As off-grid applications we define relatively small systems (however, > $10W_p$) which are not grid connected. One major market could be village power supply in developing countries where previously no electricity grid existed. In this segment, off-grid solution would encompass both stand alone systems (e.g. solar home systems) as well as micro-grid solutions (e.g. power supply for one village). Additional markets are very remote areas in industrialised countries (e.g. individual houses in remote mountain regions), consumer applications (e.g. caravan or boat) as well as remote commercial applications (e.g. power supply for telecommunications).

This market segment in itself is rather inhomogeneous. The individual sub segments could develop very differently. The market development of consumer and commercial off-grid applications will largely depend on the technical and cost development of PV. For off-grid solutions in developing countries, the bottleneck is not the PV technology itself, but rather appropriate funding and maintenance schemes.



Graph 4-4: Key requirements for PV technologies to enter market segment of off-grid applications (e.g. Solar Home Systems, independent micro grids).
Assessment of importance and differences between technologies was given by participants of the scenarios workshop [Athlet WS 2009]

The most important requirement for off-grid solutions is the reliability of the system. It has to be physically robust, be able to cope with hostile environments and must function with minimal on-site maintenance. Once reliability is ensured then costs per W_p (or kWh produced) become the next decisive factor. Low-weight solutions are a rather marginal requirement for most sub-market segments.

The potential for the different PV technologies to enter this market are very similar. Reliability of performance is key – however, there is no significant differences between the different cell types visible today. A life-span of more than 20 years does not seem to be a key performance indicator for most sub-market segments. The different energy behaviour of the various PV technologies was not seen as a decisive discrimination factor by the experts involved in this scenario process. It was expressed that for the vast majority of applications in this market segment W_P would be an appropriate indicator. Consequently, thin film technologies could gain important market shares in this segment if cost reductions were achieved.

It needs to be stressed that the off-grid market in developing countries (including China and India), is a strongly politically driven market, which, for many years to come, will largely be influenced by public support or framework conditions (e.g. rural electrification programs, concession areas for PV-electrification). Consequently, it is quite likely that certain developing countries may ask for high local content of the PV systems installed. Especially countries with strong state regulation may do so. If this was the case then a separation of cell and module production could be beneficial to enter the market. The reason is that is possible and reasonable to manufacture modules locally. However, most countries with high potentials for off-grid applications are not suitable for a large, efficient and reliable – high tech – cell production. This is obviously not the case for China and India, but may well be the case for most African countries.

5 Two Scenarios

Within Athlet two scenarios were developed, which describe the structure of the PV market in 20 years qualitatively. The scenarios were built, based on an analysis of key drivers which shape future PV markets (for details on the methodology, see chapter 7). In this chapter the two scenarios - *Diversity Rules* and *Size Matters* - are presented in the form of newspaper articles written in 2029. In section 5.3 the two scenarios are compared to each other and key commonalities and differences are highlighted. Section 5.4 assesses the potential for thin film technologies within the scenarios.

5.1 Diversity Rules

EUROfacts – online feature, 24.11.2029

Global voices on key technologies No.11 – Solar Energy

"The United Arab Emirates are an exception globally when it comes to solar energy. We use both Photovoltaics and CSP (*concentrated solar-thermal power – large arrays of mirrors concentrating solar light to produce steam which conventional steam turbines use to produce electricity*). In most other regions of the world it is either/or. 'You have so much sunshine' is what people normally say and it is true: You need a lot of direct sunshine for CSP, which you do not have too much in Europe or the northern parts of the US. But in my view, more important is the demand. With a lot of solar electricity you do get nasty over-supply peaks during the day. Differently here in Abu Dhabi – there is an excessive cooling demand during the day. Abu Dhabi didn't do well enough on efficient cooling and climate effective building – which is great for the solar business, but actually a shame."

Leila Mernissi is a professor at Masdar University, free lance consultant for large solar settlement projects internationally and a board member to the International Renewable Energy Agency (IRENA) in Masdar City.

"If you want to give an overview of electricity from solar, you have to distinguish regions where the markets developed very differently. In the southwest of the US it is CSP. In the urban agglomerations of the US coasts it is photovoltaics. In Europe, being densely populated, the market is almost totally dominated by small to medium sized PV systems on houses. In my home country, Morocco, there are large CSP power plants in the desert that feed into the national grid - to supply the cities. And soon we will export to Europe big time. That is, if they finally come to an agreement on the high voltage connections. In Morocco PV is something for the small villages. There are still many of them not connected to the national electricity grid. Currently, many villagers start upgrading their old stand-alone solar home systems and connect them into micro grids. Apart from that there is hardly any PV – city houses have solar water heaters. We used to have a feed-in tariff for PV, but with the uptake of CSP plants, the law was dumped again. The market situation for solar in fact is pretty much the same as in China – PV is used for off-grid applications and some big CSP plants in high irradiation regions – however, the market size is a little bit bigger in China compared to Morocco." *Ms. Mernissi adds with a smile.*

According to the 2029 IRENA PV Status Report, almost 50% of the world PV market goes into roof mounted applications. Another 15 – 20% is building integrated, in terms of facades etc. The remainder is almost exclusively off-grid and mini-grid installations mainly in rural areas of developing countries. Large solar farms are niche market today.

"That is of course directly linked to the breakthroughs in CSP." *Ms Mernissi continues.* "Who would want to build large PV farms if you can do it cheaper with concentrated solar power? Let's be honest here, there is direct competition between the technologies – at least in regions with plenty of land and direct sunshine. CSP has the advantage that you can store the heat and produce power also at night time - and in fact efficient storing systems were an important factor to make the technology competitive - but still, the more power you can sell during the day, the better your return on investment. So in regions with a large share of CSP electricity, you normally do not have too much Photovoltaics.

PV power on the other hand is best, when it is produced close to the user. I saw Europe for much too long supporting large, green-field PV-farms. Which was fine at the time, I guess, to give the solar business a jump start. But you almost missed out on the real market. I remember when the Masdar Initiative really took off: when they signed their first contracts to develop a dozen solar settlements in Arab countries. All of them were holistic sustainable energy concepts. PV was an integral part of it – masterly embedded in the housing concept. I had been studying in Zürich at the time. The Swiss had been very good at research on building integration of PV. But the rest of Europe? And then, in the early teens of the century: within two years all the major PV countries twisted their support schemes. PV on buildings received massive support. In Europe this was backed by European regulation for the electricity markets. Someone must have pulled the threads behind the scene masterly to make this happen. In 2015 the last feed-in tariff had been transferred to a "grid-parity enabling scheme".

But off-course not all of it was politics. Looking at the solar industry I must say it really grew smart in the last two decades. I remember in 2010 there were hundreds of modules on the market – all dull, square modules, but not two of them had the same size, voltage or output. Standardisation was nil at the time! It took some time before the industry did their homework, before they even realised that they too had to play according to the rules in the buildings sector. But look at the products now: Well established standards – sizes for examples. As an architect you can plan a solar façade, knowing that there are different standardised products from several producers to choose from. Can you imagine, 20 years ago, you would have to decide on the PV-module *before* you could plan the façade of your house – or buy expensive tailor-made solutions – ridiculous!

Today you have a wide variety of PV-products, which truly differ in functionality: Low-weight and low-cost foils for flat roofs. Roll them out, plug them in, ready! Some of them are so easy to dismantle that it pays off to have them on the roof only for 6 years – knowing that you can take them down and resell them afterwards. Ideal for industrial buildings with fast changing uses. PV had an enormous breakthrough after sensible standardisation. There are for example a wide variety of façade products: flexible, coloured, semi-transparent, water-proof, sound absorbing, shatterproof – you name it – all of them with well specified characteristics according to buildings norms – architects paradise! But even if you look at "common" square modules, there is an established standard[18] of seven common modules, with specific sizes and output ranges, frames and hook points. For some of these common sizes, you would find modules from as many as eight different producers and could mix them within one PV system and it would work! But in addition to that there are of course, what they call optimised output modules which differ from company to company – some very efficient with respect to size (kWh_R per m^2)[19] others focus on revenue per investment cost (kWh_R per €) only. The choice of the costumer then could strongly depend on the purpose of the system (e.g. share of self-use vs. selling to the grid) and the availability of roof space.

What will be the key challenge for PV in the future? Well, it always was cost per kWh produced. Environmental performance became also important, mainly energy yield. For the future? There are different opinions, but I see the race for efficiency, thus kWh per square meter still to be the biggest issue. Let's chat on this in 20 years again!"

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[18] The IRENA S892 norm defines key properties for fixed frame square PV modules. A series of seven "interchangeable" modules with very strict specifications is defined with in the norm. These specifications are defined by industry representatives in IRENA's PV producers forum and adapted every five years – thus the current 2025 series will soon be replaced by the 2030 series of the norm.

[19] The 2016 established kWh_R standard defines the expected yearly energy yield of a PV module based on four characteristics: direct and indirect radiation, air temperature and wind speed. 26 so called "global archetypes" of factor combinations are defined and the world is classified in archetype regions (The index "R" refers to these regions). Thus, a reasonable estimate of the expected energy yield per year can be obtained by multiplying the kWh_R value of the module with the local annual radiation index.

5.2 Size Matters

EUscience, 24.11.2029

"What ever happened to…?" Tracing urban myths - feature of the month

"Grid parity?" *Guiseppe Vendetti allows himself a very ironic laugh.* "Grid parity? Yes, I remember it very well! The solar-buzz-word at the beginning of this century. I am amazed you still remember this term – nobody dares to use it anymore. So many hopes and unrealistic dreams – and business plans in fact – were connected to that PV-paradise on earth: grid parity."

Shaking his head in amusement he continues: "Now, in retrospect it is of course obvious that it would not work out that easily. But I am amazed that so few dared to doubt at the time. I guess it was too promising: 'Once the cost of PV generated power is cheaper than what private households pay for power from the grid – then everybody would buy PV systems like mad – no more support needed.' But wasn't it obvious that the power producers would not like this? Wasn't it obvious that they would not just sit and watch that market developing around their backs? I guess the solar community did not dare to be critical in order to avoid scaring off their investors – and forgot to secure the political support grid parity would have needed. As you know, the PV market grew tremendously in the last few decades, but definitely not from grid parity.

Guiseppe Vendetti is the manager of an energy service company based in Milan, Italy, which specialised in PV power plants. The company, SolVeni, plans, builds and runs solar systems on the roofs of industrial buildings and premises of private companies. SolVeni cooperates with Decarbonate, an international investor which specialises in carbon emission trading and CO_2-emission reduction projects. Decarbonate finances and owns the PV systems. The owner of the premise where the system is built has a long-term contract to buy the solar power produced at a fixed price, which is lower than the cost of electricity from the utility. Grid parity!

"Sure, if you look at what we are doing, you could call it grid parity." Mr. Vendetti continues, "but the point is that this is a niche market. Look at it this way: The overall PV market grew by a factor of 100 in the last 25 years. We will reach more than 60 GW_p newly installed capacity globally this year. It is amazing! And I am not complaining, Solveni is making a good living out of it! But the big PV market is that of large-scale solarfarms.

I guess the US was leading the way – and the situation is much more extreme over there than here in Europe. Some states had been playing with quota systems that basically forced the energy utilities to have a certain share of solar power in their portfolio. I would have always guessed that CSP *(concentrated solar-thermal power)* would win the race, but it never really took off economically. In a critical transition period the support schemes were favourable for PV – as it was considered the true long-term option to develop." China joined in shortly after the Johannesburg treaty was signed. They promoted it as climate protection, but to me it was always clear that they wanted to build a home market to promote their PV industry in the light of the 08/09 economic crisis – and large scale PV farms fitted better than anything else with the five-year-plan thinking at the time."

Currently the biggest market for Photovoltaics world wide is the United States. Here the so called "green field" installations – which to a large extent are built on brown desert soil – contribute almost 60% of the solar power generated in the US. The remainder comes mainly from PV systems on large flat roofs like shopping malls and industrial buildings. Shining solar roofs on small private homes are seldom seen in the US.

"We traditionally have a different market structure for PV in Europe", *Mr. Vendetti explains.* "We have less space, so roof tops are a natural option. Twenty years ago, some countries like France even put a heavy emphasis on supporting building integration. I think, the turning point was when EPIA announced its ambitious targets – I remember well, it must have been 2009 or even 2008: 12% PV power in Europe by 2020 – I was struck by lightning! And so were the big utilities. PV was not peanuts anymore: No longer relegated to micro niches but something to have a closer look at! The power producers feared to lose peak time market shares. And grid-wise: if this growth had come from grid parity – who would pay for the costs connected to the grid? So some utilities came up with flat rate offers – just like in the telephone business – 4000 kWh per year for a fixed price. The European Commission ruled that out after some time – it did not fit with the energy efficiency policy. But the scene was set: high connection fees, minimal prices per kWh consumed. That killed grid parity in Italy over night.

Do you remember all this talk that solar would bring big changes in the energy business – democratic utopia: everyone produces the energy they need themselves – big rubbish. And on the other side it is funny to see that the big power producers actually fought renewables in the beginning. It took them some time, but then they realised that they could be part of the game. So they turned around and said: ‘Look at us! We are the real green guys!’ Heavy investments in off-shore wind and a big fuss about solar power from northern Africa – as you know, most of the plans were quickly dropped when the Maghreb turmoil started. I would not have invested in Morocco or Tunisia at the time. And finally they said: ‘We’ll do PV big time – just like in the U.S.’

Today it has become an industry of large players. Looking at the manufacturers, the market is totally dominated by the ‘big six’. Between 2010 and 2020 we saw a tremendous series of mergers. All the small companies and new concepts were bought up by the big ones. Large industrial players: semiconductor giants, utilities and few gas and oil multinationals have formed strategic alliances. Consequently production shifted to Asia. Manufacturing standardised mass-products is just not competitive in Europe or the US. Size matters was the credo and kW_p per $ was – and still is – all that counts. It’s funny to think of architects dreaming of PV facades in all different colours 30 years ago. PV is a grown-up industrial product that fits the needs of the energy sector: reliable and climate friendly power.

Looking at my company, SolVeni, we are one of the few small players in this business – and have been for decades, with good profits. So as a businessman I am happy. But more importantly I am also a green idealist. The important thing always was that Photovoltaics would take off fast enough to make the world fit for the coming solar age. And we are on a good path.”

5.3 Two Scenarios – Brief Comparison

The two scenarios "Diversity Rules" and "Size Matters" sketch two possible futures of photovoltaic market developments within a 20 year time horizon. The scenarios were built based on an assessment of developments/drivers that impact future PV markets. The key drivers to frame the scenarios were chosen in such a way that the markets show different opportunities for thin film PV vs. crystalline silicon PV (for the methodology of the scenario construction see chapter 7). Thus the scenarios describe two markets which differ with respect to their structure. They do not – as most other scenarios do – differ with respect to their size, but they describe qualitatively in which applications / market segments photovoltaics are used. In fact, fast growth or slow growth versions of the two scenarios could be constructed.

Diversity Rules	Size Matters
o Public funding and **regulation focuses on building related applications** (special feed-in tariffs) o **Grid parity** is main financing scheme o **CSP high** (technological breakthrough including efficient heat storage systems, growing market size) → Building integrated and roof top applications dominate PV market	o Government hands responsibility to utilities through **quotas and renewable obligations** o **Utilities and big investors** go for large scale projects o **CSP low** little cost reductions, still only demonstration projects → Green field and large roof top applications dominate PV market

Table 5-1: Key characteristics of Athlet scenarios

The key drivers and main features which are juxtaposed in the two scenarios are summarised in

Table 5-1. The starting points are funding and financing schemes for PV – and here again not the overall magnitude but structural features which also include the question of who the key players are, and who will invest in and use PV systems. Concentrated Solar-thermal Power Plants (CSP) were considered to be a likely competitor whose impact would be quite different in the different market segments (large-scale PV farms vs. small scale & roof-top applications).

Market size

Many scenarios use market size to discriminate possible future developments. In the [Needs 2009] scenarios for example, market size is strongly linked to technological development (stronger innovation provides lower cost which leads to a faster growing market). Consequently, in the NEEDS scenarios the shares for the various PV technologies differ with market size (see p. 14). This scenario exercise however, aims to illustrate that independently from different market size trajectories, the opportunities of crystalline silicon versus thin film technologies can also be substantially different, based on other developments which shape the PV market structure.

As pointed out above, the overall PV market size is not a factor used to discriminate between the two scenarios. In contrary the market sizes are assumed to be similar. Both scenarios assume constant and substantial growth of PV capacity being installed. In the current form they would be in line with the SEE scenario developed by [Krewitt 2005] – see also

Table 5-2. Note that the figures given are input to the scenarios and not output data of our analysis!

	2008	2020	2030
annually installed capacity (GWp / a)	5.6	30	60
cumulated capacity (GWp)	15	200	780

Table 5-2: Assumed PV market size and total installed capacity up to 2030
Status data 2008 according to [EPIA 2009]. Projections according to SEE scenario in [Krewitt 2005]; see also page 10.

The key features of the scenarios would be robust on a wide range of market size scenarios. Thus, high growth or low growth versions could be constructed with very limited changes. However, it has to be noted that there are limits. Both extremes – minimal growth as well as maximum growth – are not compatible with the storylines. In this respect it has to be pointed out that the scenarios are not compatible with the EPIA goal of reaching 12% PV power production in Europe by 2020. The EPIA goal is linked to a major paradigm shift with joined forces of all actors which leads to a dramatically fast and simultaneous exploration of all market potentials. This is obviously not the case in either of the scenarios.

Economic Implications

Generally cost for PV power is linked to marked size – following the reasoning that scale effects bring down prices. In the Athlet scenarios the market size is assumed to be equal. Still we would see distinct differences in the economic parameters:

- Costs per W_p
  The costs per W_p of the PV system (including, mounting, maintenance & end-of life) is generally higher for small scale systems on roofs or building integrated compared to large-scale systems on green field installations. Consequently the average cost for PV power (€/kWh) will be lower in the scenario Size Matters.
- Avoided System Cost
  From the perspective of costs for the whole energy system, the scenario "Diversity Rules" could reduce grid costs as the decentralised production of PV power on buildings is closer to urban demand centres. However, this is not necessarily the case. The development of a smart electricity grid and optimised grid extension planning would be prerequisites to achieve substantial grid cost reductions.
- Local Content
  In the scenario "Size Matters" production of PV modules will be extremely standardised and most likely also strongly centralised. It can be assumed that the current "shift to Asia" of PV production will be accelerated in this scenario. A significant share of the cost reductions achieved in this scenario is due to a minimisation of local services (e.g. installation and maintenance). In contrast the scenario "Diversity Rules" implies a larger share of local content in the system costs. The production of modules could to a larger degree be close to the market, especially for the market segment of customised solutions. Consequently there could be a larger share of PV module production in Europe in the "Diversity Rules" compared to the "Size Matters" alternative.

It is beyond the scope of this study to quantitatively weight the above factors against each other. However, we consider it to be possible that gains in the field of avoided system costs could balance the losses in the costs per W_p of the PV installation. From a job creation perspective we consider it likely that the "Diversity Rules" scenario is beneficial for Europe. In conclusion, we estimate that the economic benefit for Europe could be comparable in both scenarios, given appropriate framework conditions – an adequate establishment of a smart grid and a consequent strategic grid optimization being one.

5.4 Thin film potential in scenarios

In the scenarios market shares of the different possible PV cell technologies are – purposely – not mentioned. The scenarios describe the market segments and leave it open, which technology may be more apt to respond to these specific demands. Consequently, the design of black and white scenarios (e.g. "Thin film Paradise" versus "Thin film Doomsday") was avoided. Instead thin film technologies have potentials in both scenarios. Whether these can be tapped – or are left to competing technologies – strongly depends on strategic decisions of thin film producers and the respective successes in

In the following section research and development. potentials for thin film technologies are assessed based on the general market segment analysis of chapter 4.

Diversity Rules

There is no obvious conclusion whether or not the developments described in the "Diversity Rules" scenario would favour thin film technologies or not. The main market segment is roof top applications. Here, thin film is struggling with its low efficiencies (kWh/m^2). Thin film technologies can only gain a strong share in this market segment by offering modules at significantly lower costs or by offering strong advantages for mounting (e.g. low weight PV foils).

Another important market in this scenario is that of building integrated applications. Here, thin film could offer unique solutions if production processes can be optimised accordingly. But also in this segment competition from wafer based silicon is high, since the separation of cell and module production offers advantages for flexible design (shapes and sizes) of PV modules. One strategic approach to address this market could be to separate cell and module production for thin film technologies also. Small to medium sized cells on (bendable) metal foils, which could then be cut into individual cell structures, could be one solution. This would allow the development of thin film cell production lines which are highly standardised and efficient. At the same time it would be possible to use the cells in very different modules. These modules could be produced in specialised production processes. The separation of cell and module production would also allow centralisation of cell production – and tapping of the economies of scale. While module production facilities could be close to the respective markets which in this scenario would show strong regional differences.

Size Matters

In the scenario Size Matters large, ground mounted solar farms and large-scale roof-top applications dominate the market. Those thin film technologies which meet their expectations of reducing costs (in terms of system costs or €/kWh produced), will be apt to gain high market shares. Products would be highly standardised and production largely centralised to tap scale effects. In order to reduce shipping and handling costs, weight and size (thickness) of modules would need to be minimised. However, the urge to separate cell from module production is much lower in this scenario compared to Diversity Rules.

Concentrating PV modules, using high efficiency cells on tracking systems, could gain high market shares in this scenario, assuming that the technology development in this field is successful.

6 Conclusions

The photovoltaic markets have been growing tremendously in recent years – and growth is expected to continue in the decades to come. Moderately optimistic scenarios assume a growth in production capacity by a factor of hundred between 2010 and 2050. However, there is a huge uncertainty on the overall market size development – both more optimistic and pessimistic scenarios exist, with variations greater than a factor 10 between the extremes.

Most scenarios make statements only on the total market size. Specifications according to technology type are very rare. Currently a variety of PV technologies exist in parallel – crystalline silicon, various thin-film technologies are already established, other technologies are in a research stage (e.g. dye sensitised cells). Concerning the long-term potentials of these technologies, there is no "winning" technology visible yet. Some experts have quite controversial views on the perspectives of individual technologies. However generally, technology foresight results indicate that the parallel co-existence of several technologies will continue even in the long-term future. Scenarios which specify different PV technologies assume a decreasing share of crystalline silicon PV cells (which still equals a strong total growth in a strongly growing market environment). Thin-film technologies (a-Si, CdTe, CIGS) are assumed to grow in market share. Under very optimistic assumptions a peak share of 45% for thin-film technologies in 2030 seems possible. With a very long-term perspective (> 2030) other emergent technologies are believed to gain importance.

Generally the development of the different technologies is attributed to factors like technological improvement of the respective technology and to overall market size development. The linkage being: fast market growth stems from cost reduction; highest potential for cost reductions are within new PV technologies like thin-film. Thus scenarios with strong growth rates include early breakthroughs and high market shares for thin-film technologies.

An issue that is not described (or only very superficially) in long-term PV market scenarios is the *structure* of the markets themselves. It is often pointed out that the different technologies do have properties which give them specific advantages and disadvantages in the various market segments. This is one of the reasons why a long-term coexistence of different PV cell types is commonly assumed. However, to our knowledge, no study that defines scenarios for market segments and stringently assesses the potentials of the various PV technologies in these scenarios exists to date.

For this study we define four archetype PV market segments. For each of which we identified key performance indicators for PV products in these markets and link these to characteristics of thin-film technologies. Major findings of this assessment are:

- Large-scale (ground mounted) PV farms
  Key performance indicator is low cost per W_P. Thin-film technologies have great potentials in this market segment.
- Roof top installations
  Besides costs, high efficiency is a key requirement in this market, as space is a limiting factor. Consequently, technologies with higher efficiencies (e.g. crystalline silicon cells) have advantages in this sector. Thin-film could gain market shares with specific low-weight and easy to install products, like PV foils.
- Building integrated
  Key demands are functionality, aesthetics and flexible design options. In contrast to the majority opinion that thin-film technologies are superior in this respect, it is actually heavily disputed among experts which technologies are best suited to respond to the requirements of this market. Although thin-film products could deliver suitable solutions, this would hardly be possible within mass-production schemes, which in return would forfeit the advantages over wafer based silicon products.
- Off-grid
  Key indicators are reliability of performance as well as costs. The potential for the different PV technologies to enter this market are very similar.

In conclusion it can be stated that despite the different requirements, thin-film technologies have the potential to tap significant shares in all of the above market segment (or at least in major sub segments). However, it is important to note that specific technological developments are necessary to become competitive in any of the above market segments. Cost reductions (in terms of €/W_P or more specifically €/kWh PV power) are the main goal for future PV technological development. However, within certain margins other factors can be decisive for competitiveness.

The Athlet scenario exercise describes two alternative (juxtaposed) development paths for PV markets. We consider both scenarios equally likely or unlikely.[20] The scenarios – not being predictions – serve firstly to show that the above named market segments could develop very differently and secondly to illustrate two out of a myriad of possible paths how they could develop. Both scenarios offer opportunities for thin-film PV but with quite different challenges.

- Scenario A - *Diversity Rules*
  Diversity Rules describes a world in which the markets for PV products are very diverse and also differ regionally. Consequently there is a necessity for specific products for the diverse market segments. Most important are roof-top and building integrated applications. The demand on the functionality of the products is high. In addition to customised solutions for specific applications there is a high level of standardisation that allow build an plan with mixes of products from different producers.

- Scenario B - *Size Matters*
  In the *Size Matters* scenario the biggest market segments are large scale PV plants, many of them in multi-megawatt parks on green fields or large roofs of commercial and industrial buildings. Square flat plate modules dominate the market and technological development almost exclusively aims at reducing cost per W_P. Production is largely concentrated and dominated by few multinational players.

Strategic Options for the Private Sector

Different developments of the various PV market segments – two alternatives being sketched in the Athlet scenarios – ask for and evoke specific strategic responses by companies of the PV industry:

- PV producers need to tailor their products and services to the shape of future markets. But as technology development has long lead times, market assessments with a mid- to long term time horizon are vital. In this respect the Athlet scenarios can be used by each individual company to improve their long-term strategy:
  - **Test the robustness of the companies strategy** against the scenarios: What would it mean for our company if the world became rather like *"Diversity Rules"* – or rather like *"Size Matters"*? How would we need to change our strategy if scenario A / or scenario B became actually reality? Which new products would we need to develop? How would we need to improve existing products and services?
  - **Scan for "early warning signs":** Are trends becoming visible which indicate that either of the scenarios becomes more likely? The table of scenario drivers (Table 5-1) can be used as a first reference – which of these drivers can be observed to actually materialize?
- Companies might find the one or the other scenario as more desirable. Although it is not within the powers of any company to shape the future, there are means of influence. If one of the scenarios is perceived as being more favourable for the European PV industry as a whole, the European PV industry association may lobby policy to adapt support mechanisms which induce a specific market development.
- In the *Diversity Rules* scenario standards for a wide range of module properties (size, shape but also building related functionalities like sound absorption, fire resistance, scatter proof etc.) will need to be

[20] Actually we consider it extremely unlikely that the future will *exactly* look like any of the two scenarios. In fact an infinite number of scenarios could be constructed which are somewhere between the two sketched extremes. The future will most likely contain shades of the one and more or less shade of the other scenario – and definitely additional aspects, which we have not considered in the scenario exercise.

developed. If the PV industry fails to establish these standards the path towards the *Diversity Rules* scenario will dead end in low growth rates of the PV market.

One issue which becomes apparent from our analysis, is that cost in €/W_P is of course an important, but not necessarily the only parameter towards which module production needs to be optimised. Depending on how the different market segments develop, other issues may become of importance. Specifically for the producers of thin-film modules these are:

- Separation of cell and module production:
  In the scenario *Diversity Rules* most PV products require very specific functionalities. Although very elaborate, international standards exist, there is a market for a wide variety of customised PV modules with quite different functionalities. Thin-film technologies in principle are capable of delivering very adequate solutions to satisfy the demand. However, an integrate cell and module production process limits cost reductions through economies of scale. In a Diversity Rules world, we see a large potential for a separation of cell and module production: Small (wafer like) thin-film cells can be produced centrally – with maximal cost reduction - and are being shipped to regional module production facilities which produce a variety of customised products for the specific markets.
- Improvement of material efficiency:
  Availability and price of semiconductor material can have a significant influence and can limit a broad market implementation of thin film photovoltaic. Therefore activities to improve the efficiency of material use are highly recommend. Measures of material efficiencies should include the reduction of the material content in the product, maximising the material yield in the production and the recycling of production waste as well as end of life modules.

Policy Recommendations

Photovoltaic technologies are supported in Europe to provide in the long-term a carbon-free source of energy supply at reasonable costs. Increasing the share of PV power is mainly perceived as a means to decrease Europe's CO_2 emissions. From this perspective, cost reductions are the key objective for future PV technology development. At the same time, photovoltaics is a globally booming industry with a huge economic potential. For Europe it offers both the opportunity to export high-tech goods and to reduce import costs for energy.

The two Athlet scenarios were qualitatively assessed with respect to the above named potentials of PV technology use and production. (A quantified economic assessment is beyond the scope of the Athlet scenario exercise, see research recommendations below.) The economic benefit for Europe of a future PV development largely depends on the overall market size and the speed of technological innovation – which was to be assumed equal in both Athlet scenarios. But also the structure of future PV markets will have economic consequences for Europe:

- We anticipate a higher share of local content in the Scenario A - *Diversity Rules*. Due to a larger share of smaller systems, most of which are roof-top or truly building integrated, a larger share of the costs goes into installation (local workforce). The regionalisation of markets and the need for customised solutions could result in a larger share of PV production closer to the consumer. At least for the module production this could slow down the current shift of production facilities to Asia.
- In Scenario B - *Size Matters* the costs of PV Modules (€ / W_P) will be lower than in the *Diversity Rules* scenario. However, due to a higher share of large PV-farms mainly in rural areas, with longer distances to load centres (cities), the grid costs for electricity distribution are likely to be higher, possibly balancing off large parts of the higher PV costs. The current trend of production facilities of PV equipment moving to Asia would most likely accelerate. Europe's PV industry would most probably increasingly focus on the development of production equipment, automation technologies, system integration and specific high tech components.

As highlighted in the narratives of the scenarios, the development of the various PV market segments strongly depends on general energy and electricity regulations as well as specifically on the details of the support mechanisms employed to promote solar power or renewables in general. It has to be acknowledged that support schemes are per se never "technology-neutral". They always, at least implicitly and at a certain stage of development, favour certain technological solutions. For this reason, most feed-in tariff systems in Europe offer different rates depending on the size of the PV system – due to the economies of scale an equal rate for all would favour large-scale, green field projects, with certain technological solutions.

Consequently the details of support schemes define the growth and structure of the various PV market segments. Parameters to promote certain market segments are (among others) different funding rates:[21]

- according to the size of the system,
- which differentiate between green field applications, roof top or building integrated (façade) solutions, or
- which differentiate between power fed into the grid and self-consumption.

In our view there is a growing need to fine tune support mechanisms for solar energy in European countries. In the past the magnitude of market stimulation (versus costs of the support scheme) was seen as the key indicator for success. However, as PV emerges from its role of being a niche product in Europe's energy supply, it becomes more important to consider other targets, which are in our view closely linked to the structure of the PV market. The characteristics and sizes of the different market *segments* may in future heavily impact on local content and value added for European PV companies as well as grid costs connected to an increasing share of photovoltaic power in Europe's energy mix.

Open Questions and Research Needs

Resulting from the assessment undertaken in this study we identified several open questions and derived research needs for the most important issues:

- Existing energy scenarios hardly differentiate between the different market segments for PV although this may heavily impact the structure and the economics of Europe's future energy system. Therefore, a detailed analysis of economic impacts (including both energy costs and job opportunities for Europe) of different development paths for Europe's and the worlds PV market should be conducted, especially considering various growth alternatives for the different PV market segments (green-field farms, roof top, building integrated etc.). This assessment should be linked to the current support mechanisms for PV. Conclusions for a future adaptation of regulation and support mechanisms could be derived.
- If the PV market follows a high growth scenario (or if even more extreme the EPIA goal of 12% power produced by PV was reached in 2020) then PV power will result in heavy extensions and transformations of Europe's electricity grid. The question of where PV systems are being installed (rural areas distant to load centres or close to the consumer in urban areas) will strongly impact on the grid costs induced by PV. An economic assessment of different PV market scenarios and its consequences for the electricity grid needs to be linked to the development of targeted regulations which both promote fast PV implementation, but keep grid costs down simultaneously.
- To provide a better base for export opportunities, the potentials of off-grid markets (mainly in developing countries) for European PV companies need to be assessed, especially with respect to resulting technological demands and the development of adequate business models.

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[21] For example, the German feed-in tariff encompasses all of the above parameters, the 2009 adaptation of the law explicitly promotes self-consumption to bridge towards grid parity financing approaches ([EEG 2009], see also [EC 2008] and [Wiki PV 2009] for overview on international support schemes).

7 Annex A - Methodological Approach

The scenario exercise was run according to the following methodological steps:

Step 1 - Overview of existing scenarios and roadmaps

Existing scenarios, roadmaps and other relevant studies were screened and analysed. Important trends and developments within the thin film field and with impact on thin film (market and technology) development were identified (See chapter 7 for abstracts of reviewed literature).

Step 2 - Comparative Analysis

A comparative analysis of the reviewed studies was conducted with regards to future developments described or claimed in the studies. Although no clear cut division can be made, future developments can be characterised into two groups:

- Likely trends
  include developments which are considered quite likely by a majority of experts (studies). The variation is rather small with respect to the impact the variation would have on the development of thin film PV. These trends serve as framework conditions which are equal in all scenarios.[22] Some of them could be explicitly named in the scenarios, while many of them would not be made explicit.
- Drivers
  are developments which are possible, but which are disputed among experts. By varying the magnitude of a driver the impact on thin film development should vary significantly.[23] Different values or polarities for the drivers are used to construct significantly different scenarios.

Chapter 2 gives an overview of the key findings of the comparative analysis of the reviewed studies and points to commonly agreed and disputed possible developments.

Step 3 - Identifying possible key drivers

Based on the comparative analysis of existing scenarios, possible scenario drivers were identified and a list of key drivers was compiled by the scenario team at IZT/UNN-NPAC (see

Table 7-1). The following list of possible scenario drivers is structured along the field of "production – cost and prices" (drivers 1 through 6) and "markets for PV" (drivers 7 through 14). Some of the drivers have strong interconnections. In this case we generally start with the more general driver (e.g. "Global Energy and climate policy") becoming more specific ("Public support schemes"). Drivers which have been used to construct the scenarios are highlighted in grey shading.

No.	Driver Title	Description (Explanation)
1	Energy prices	Energy prices define achievable prices of PV (competing with other energy sources) but also production costs. Energy prices impact differently on the production costs of the various PV technologies. Values (e.g.€ / barrel oil): High / Low

[22] An example could be the global population. Although predictions of the world's population differ quite strongly, it may be reasonable to assume the same population growth rates for all scenarios. There may be differences in the market shares of a world with 7 billion people compared to a world with 9 billion people, however other drivers may be more decisive when it comes to comparing crystalline silicon PV to thin-film PV.

[23] An example could be resource scarcities. Massive price changes for key resources of different photovoltaic technologies (e.g. silicon, indium) would have strong impacts on thin-film market shares.

No.	Driver Title	Description (Explanation)
2	Silicon prices	Availability and prices of silicon are crucial factors for the market prospects of c-Si PV cells. Thus defining the competitive framework of thin film PV. Values (€ / kg): High / Low
3	Prices of mineral resources (Indium, Selenium, Gallium, Tellurium)	The production of thin film PV requires several specific mineral resources e.g. Indium, Selenide, Gallium, Tellurium. The availability and prices of these minerals can become a crucial bottleneck for thin film PV markets. Typically these resources are produced as by-products in small quantities and the elasticity to respond to growing demand is limited. Furthermore, there may be strong competition from other fast growing technology sectors e.g. electronic devices or display production. The possible impacts are very technology specific: CIS-PV-cells depend on the availability of Indium, Selenium and Gallium CdTe-PV-cells depends on the availability of Tellurium PV cells using ITO as TCO layer depends on the availability of Indium. Values (€ / kg): High / Low prices for specific minerals
4	Material use per kWp	The amount of critical materials (see above) used in thin film modules determines how vulnerable the thin film industry is to price increases of the respective materials Value (g/kWh): High / Low
5	Technological breakthroughs c-Si	In general a learning curve behaviour of innovation is assumed (e.g. 20% cost reduction for every doubling of the production size). Technological breakthroughs could increase this ratio (or in contrast – technological innovation could reach barriers which decrease this ratio). Value: High / Low technical innovation in c-Si
6	Technological breakthroughs thin film PV	Same as 5, but specifically for thin film PV Value: High / Low technical innovation thin film PV
7	Turnkey production facilities	Turnkey production facilities can currently be bought for crystalline silicon cells but not for thin film PV. With growing market size system integrators may enter the thin film market. The share of production facilities bought (turnkey) or self-made depends not only on the thin film market size but also on strategies of manufacturers and their willingness to cooperate. An interesting time horizon for this driver could be 2010 - 2015 Values: Turnkey / self-made thin film production facilities (specify for types: a-Si, CIS, CdTe)
8	Availability of skilled labour	The availability of skilled labour could become a bottleneck for the growth of production capacity Values: sufficient / insufficient skilled labour
9	Global energy and climate policy	The energy sector as a whole is strongly dependent on policy framework setting. Global and local framework conditions will set the scene for the PV market.
10	Acceptance & risk perception	How does the public perceive technological risks (e.g. toxic materials) high / low perception
11	Public support schemes (magnitude)	Public support schemes (feed-in tariffs, quotas, tax incentives etc.) currently determine the size of the global PV market and will do so for the coming years. Values: Strong & growing support / weak or decreasing support

No.	Driver Title	Description (Explanation)
13	Public support schemes (types and technology specific support)	Public support schemes often favour certain technological options (e.g. higher funding for roof top vs. green field). Even if support is per se technology neutral, some concepts benefit stronger than others. The structure of public support schemes, shape the market of PV and thus provide different opportunities or c-Si vs. thin film PV. Values: This is driver with multiple dimensions. Values have to be given qualitatively.
13	Public support – research	Research has a long-term effect on both global efficiency of cells and the development of new concepts as well as on the local knowledge base.
14	Development of specific market segments – functional products	Standard PV today is on glass. However new cells, especially thin film would allow for different PV products (flexible cells). The question is: Will there be significant markets for such new products and applications (e.g. building integrated vs. green field)? Values: Small niches / significant market shares
15	Markets in developing countries	Developing countries have a huge market potential for PV, especially in off-grid applications. Market barriers are mainly due to lack of financing instruments and organizational issues. If these were overcome by innovative concepts, aligned with governmental, or global support schemes then this market could grow rapidly. Interesting time horizon: 2020 Values: fast growing markets / stagnant markets
16	Solar-thermal power plants	Solar-thermal power plants are a direct competitor to large scale PV farms in high solar regions. The development in this sector (prices) may strongly influence the PV market. Interesting time horizon: 2015 Values: accelerated growth / restricted to niches
17	Business models for grid parity	Grid parity: end-user electricity prices are equal or higher then costs for electricity produced with PV. When grid parity is reached it is generally assumed that a large market would be opened in that region. However, there may be other impeding factors then just the PV prices: regulatory restrictions, counter measures by power companies, lack-of acceptance or hesitation of end-users. Interesting time horizon for Europe 2015 Values: Acknowledged and wide-spread business models / restriction to niches

Table 7-1: List of possible scenario drivers.
Marked in grey are those key drivers which were chosen to construct the Athlet scenarios.

Step 4 – Selection of final scenario drivers

In an iterative process involving stakeholder participation (including four workshops with Athlet consortium members and external experts - see chapter 9) the final set of scenario drivers was selected. The drivers were chosen to lead to strong differences in the respective scenarios. The influence of the drivers on the energy system and their interdependence was analysed in a cross-impact analysis, employing the MIC-MAC software [MICMAC 2009]

Furthermore, the drivers were selected according to three key characteristics:

- They should be considered "disputed" in the sense that the community of thin film experts disputes the magnitude that the driver may gain in coming years.

- They should impact the various PV technologies differently.
  Compare Table 7-2, where two examples are given: the first driver would impact all PV technologies equally, while the second would impact differently on Si-based vs. non-Si-based PV technologies.

Event (Driver & Magnitude)	Impact on PV	Impact on thin film PV
e.g. breakdown of PV support schemes in Europe	Severe breakdown of market	Severe breakdown of market
e.g. Breakthrough of cheap raw silicon production method	Increase in market growth	Loss of competitiveness compared to silicon PV

Table 7-3: Examples possible scenario drivers and impacts on PV as well as thin film PV market development.
While the first driver would impact all PV technologies equally, the second would impact differently on Si-based vs. non-Si-based PV technologies.

- They should be considered "interesting" in the sense that the impact is rather complex and not too one dimensional / foreseeable. Example: A technological breakthrough in thin film PV production (cheap and high efficient modules) would lead to higher market shares of the respective technology. This, however, is so obvious that it is not necessary to explore this in a scenario exercise.

The key driver chosen was that of "*Development of specific market segments – functional products*" (driver 14 in Table 7-4). The rationale behind it is that this driver differentiates the most between thin film and c-Si PV technologies. With the current situation of production costs being similar for the available PV technologies and no clear winner being visible, the decision was taken to explore specific market constellations and segments.

In the next step it was analysed which other drivers would align with the polar values of the key driver. Drivers 13 (Public support schemes - types and technology specific support); 15 (Markets in developing countries); 16 (Solar-thermal power plants) and 17 (Business models for grid parity) were chosen to form a cluster of consistent scenario drivers. (See chapter 5.3 for summary).

It has to be noted that the developments in the scenarios described are not mutually exclusive. Different combinations are possible. A scenario where PV is equally used in large PV farms and on roof tops (and where CSP fails to become competitive) could be constructed. Again, the market size could vary substantially for such a scenario and could indeed be both higher and lower than in the given scenarios types. However, such a scenario was not considered

Step 5 – Scenario writing
Based on the identified clusters of scenario drivers two story lines were developed which describe the different future and the paths towards them in a pointed and stimulating way.

8 Annex B – Abstracts of Reviewed Literature

In the beginning of the scenario development process a thorough literature review was carried out (see chapter 9 for full list).For 18 studies brief abstracts were compiled. They are documented in this chapter and highlight especially PV and specifically thin film PV developments. The studies analysed in depth were selected according to the following criteria:

- Specific information contained on PV development perspectives and specifically thin film PV development.
- Do studies name key drivers which strongly influence PV development? Are trends and drivers described which could be used in the scenario building process?
- Geographical coverage – studies should give insights on EU or global developments.
- Time coverage – studies should include long-term outlooks, i.e. beyond 2020.
- The reliability, actuality and the prominence of the studies

The studies are grouped in three categories: energy scenarios, roadmaps and articles. Although no clear cut distinction can be made in every case, generally scenarios explore possibilities and dependencies ("If abc happens, what will be the share of PV in 2020?"), while we define roadmaps to be more normative mainly stating targets (e.g. white papers, research agendas etc.). Articles have been given a separate category since they generally explore more individual aspects and do not provide so much of an overall picture.

8.1 Energy Scenarios

8.1.1 DLR - Energy economic perspectives of PV

The Study “Energiewirtschaftliche Perspektiven der Fotovoltaik” [Krewitt et.al. 2005] deals with economic perspectives of PV on a global scale with a time horizon up to 2050.

A set of existing scenarios (by Shell, WEC, WBGU, EREC, DLR and others) are analysed to define the range of PV production capacity (per year) and installed capacity and other key figures of PV development up to 2050:

	2003	2010	2020	2030	2040	2050
MIN						
annually installed capacity (GWp / a)	0,68	4,5	14,3	21,3	29,9	39,6
growth rate *) (% / a)	25,0	27,0	11,6	4,0	3,4	2,8
cumulated capacity (GWp)	2,88	19,5	120,3	314,6	511,4	708,0
energy (TWh / a)	3,8	27	170	445	723	1000
share of electricity production **)	0,023	0,14	0,66	1,44	1,99	2,47
SEE						
annually installed capacity (GWp / a)	0,68	5,4	29,6	59,6	102,2	142,2
growth rate *) (% / a)	25,0	29,7	17,0	7,0	5,4	3,3
cumulated capacity (GWp)	2,88	21,2	199,5	775,0	1617,7	2477,0
energy (TWh / a)	3,8	30	282	1096	2287	3501
share of electricity production **)	0,023	0,15	**1,09**	3,55	6,29	**8,64**
share in SEE scenario ***)	0,023	0,16	1,29	4,41	8,26	11,48
MAX						
annually installed capacity (GWp / a)	0,68	5,8	60,2	163,5	253,9	336,6
growth rate *) (% / a)	25,0	30,7	23,4	10,0	4,4	2,8
cumulated capacity (GWp)	2,88	22,4	301,7	1915,7	4174,3	6015,0
energy (TWh / a)	3,8	31	426	2708	5900	8502
share of electricity production **)	0,023	0,16	1,65	8,78	16,23	20,99

*) column "2003" mean value of 1993-2003; column "2010" mean value of 2003-2010
**) share of electricity production in reference case (40,5 TWh in 2050)
***) share of electricity production in scenario SEE (30,5 TWh/a in 2050)

Table 8-1: Key figures of three PV market scenarios.
The scenario SEE – Solar Energy Economy claims to be an optimistic but realistic scenario for renewable energy market development. Source: [Krewitt 2005]

The installed capacity ranges from approx. 700 to 6000 GW_p in 2050 (see Table 2-1). However the 6000 GW_p is considered an upper ceiling, which is considered rather unlikely as it is more than 2000 times the capacity installed in 2003.

In addition to the scenarios displayed here, two even more extreme scenarios are introduced: a pessimistic case and an optimistic case. The optimistic case falls in line with some scenarios published by pro renewables associations. The pessimistic case however did not mark the bottom line.[24]

Competition with concentrated solar thermal (CST) power production

The study points out that there is a competition between PV and concentrated solar thermal (CST) power production. If major breakthroughs are to be achieved in CST technology and a capacity of significant size is to be installed within the next few years then this might hinder the further growth of PV. There could be strong competition in the on-grid market in countries with high direct radiation. This might reduce investments (and research) in PV.

[24] eg.: [Sarasin 2005] gave more conservative predictions. However, in the meantime Sarasin published a way more optimisic outlook for the near future development [Sarasin 2007] which assumes yearly installation rates (8.25 GWp/a for 2010) which are even more optimistic than the optimistic scenarios assessed by [Krewitt 2005]. For details see below.

Thin film technology

The study summarises major challenges for thin film technology. Highlighted are especially the needs to

- increase the efficiency of cells to overcome cost restraints which are linked to high area demands of thin film modules
- improve the knowledge base of manufacturers of thin film production lines. Currently production lines are tailor made and small in number, which slows the learning curves of thin film PV.

Thin film technologies are mentioned to have specific features to allow them to conquer niche markets. However, it is pointed out that these niche markets may be economically interesting for manufacturers, but will be insignificant from the perspective of global energy markets.

Indium bottleneck

The study addresses also the issue of a possible indium bottleneck for CIS[25] production. Based on manufacturer interviews it is concluded that the future specific indium requirement in CIS cells (g/kW_p) will be the determining factor as to whether or not indium could become a serious bottleneck for the production of CIS cells. An indium requirement of 6 g/kW_p could allow for an ambitious growth scenario (SEE scenario, with a CIS share of 10%) with no major indium shortage up to the year 2050. An indium requirement of 35 g/kW_p could lead to major restraints of CIS production and increase costs for CIS cells significantly.

Market prospects for thin film PV

Historically, the market share of thin film PV has decreased: From 35% in 1990 down to 6.4% in 2004. Production was almost constant between 1990 and 1999 at roughly 15 MW_p/a. For the years 1999 – 2003 the growth rates in thin film PV production of 15% was only half of the overall PV market growth rate (almost 30%).

In order to achieve a significant market share of the overall PV market, thin film PV must reach growth rates of more than 25% annually (or higher, possibly 45%) up to the year 2020. However great efforts are needed soon in order to reach significant market shares which allow it to compete with learning dynamics of the silicon technologies.

Learning costs and break-even points

The study calculates learning costs and break-even points for the three PV development scenarios based on a variation of learning factors (scenario variants I to III). Case I assumes a learning factor of 0.8 up to 2050 (continued historic learning factor). Case II assumes slower learning after 2020 (continuously down to 0.95 in 2050). Case II assumes starting with a learning factor of 0.84 today which will reduce down to 0.95 in 2050.

[25] If no explicit distinction is made, in this paper the term CIS is generally used as an abbreviation for all chalcopyrite cell types.

Scenario	PV share of global electricity prodution	Break-even point	Learning costs till break-even (in billion €)	Cumulated differential costs up to 2050 (in billion €)	Cumulated differential costs up to 2020 (in billion €)
A) Energy prices "moderate climate action" (15 €/t CO2 after 2010)					
MIN I		2042	422	365	133
MIN II	0,70%	> 2050		520	133
MIN III		> 2050		1.143	164
SEE I		2034	382	-574	155
SEE II	**1,10%**	**2036**	**434**	**-17**	**155**
SEE III		> 2050	1.745	201	
MAX I		2028	312	-3.462	168
MAX II	1,70%	2030	343	-2.199	168
MAX III		2046	1.683	1.623	230
B) Energy prices due to "effective climate action (15 €/t CO2 in 2010 up to 50 €/t CO2 in 2050)					
MIN I		2038	358	203	132
MIN II	0,70%	2042	401	358	132
MIN III		> 2050		982	163
SEE I		2032	331	-1.098	153
SEE II	**1,10%**	**2033**	**360**	**-540**	**153**
SEE III		2049	1.221	1.220	199
MAX I		2027	278	-4.709	166
MAX II	1,70%	2028	297	-3.447	166
MAX III		2039	1.113	376	228

Table 8-2: Cumulated differential costs, learning costs and break-even points for different PV development scenarios. Source: [Krewitt 2005]

8.1.2 Sarasin PV Sustainability Study 2005

The Swiss bank Sarasin regularly undertakes studies on solar energy to give estimates on economic developments and their influence on the financial markets.

The 2005 study focuses on the shift of **future markets.** While 43% of today's PV market is in Germany today, Sarasin estimates it to be 6% in 2020:

- In Europe Spain will gain importance as a large market for PV
- In Asia the big markets will be China and India as well as Thailand and South Korea
- The study emphasises that 2 billion people world wide still don't have access to grid-supplied electricity. Thus a high potential for PV is seen in off-grid applications

Sarasin recommends exploring markets in Africa and Asia.

Sarasin claims to give (and have given) rather conservative **market outlooks**. They confirm their previous estimates for the next two to three years (with limits mainly due to raw silicon shortage). But Sarasin has raised the prognosis for 2010 and estimates a newly installed PV capacity of 3,300 MW per year. This corresponds to a growth rate of 24% between 2004 and 2010. For 2011 to 2020 a growth rate of 18% is anticipated. [Sarasin 2005]

8.1.3 Sarasin PV Sustainability Study 2006

For the future **market development** Sarasin assumes that the raw silicon supply bottleneck will continue to slow PV growth up to the year 2008. They increased their long-term prognosis and estimate a newly installed capacity of 4.1 GWp/a globally by 2010. This corresponds to an annual growth rate of 26% between 2005 and 2010. For the time period 2011 to 2020 Sarasin estimates a market growth rate of slightly more than 21% per year.

A large share of the study deals with the silicon shortage. In return it is claimed that it is "now or never" to achieve a breakthrough for thin film PV. A large number of companies have announced the installation of new production lines. The study gives an overview of major companies' development plans. It concludes that Sarasin considers 700 MW_p of thin film production capacity in the year 2010 to be realistic.

Company	Technology	Efficiency	Capacity 2006 (MWp)	Capacity 2007 (MWp)
Antec (DE)	CdTe		10	25
Arendi (IT)	CdTe		15	
Ascent Solar (USA)	CIGS		4.5	
CSG Solar (DE)	CSG		25	
DayStarTechnologies (USA)	CIGS	10.0%		20
EPV (USA)	aSi		10	
ErSol Thin Film (DE)	aSi	10.0%		40
First Solar (USA/DE)	CdTe		20	100
Honda (JP)	CIGS		27	
Johanna Solar (DE)	CIGSSe	16.0%		30
Kaneka (JP)	aSi		20	40
Mitsubishi Heavy Industries (JP)	aSi	11.5%	10	40
Nanosolar (USA)	CIGS	10.0%		430
Odersun (DE)	CIS	10.0%		4.5
Scheuten Solar (NL)	CIS		10	
Schott Solar (DE)	aSi		30	
Sharp (JP)	aSi/Tandem		15	
Shell Solar (USA)	CIS		3	
Shell Solar/Saint-Gobain (GB/FR)	CIS	13.5%		20
Shenzen Topray Solar (CN)	aSi		10	15
Sulfurcell (DE)	CIS		5	50
United Solar Systems (USA)	aSi		25	50
Würth Solar (DE)	CIS	11.0%		15
Total			163	953

Table 8-3: Selected thin film projects (estimates given by companies) Source: [Sarasin 2006]

The study highlights furthermore the long-term risk for thin film PV of high prices for key materials, like indium. [Sarasin 2006]

8.1.4 Sarasin PV Sustainability Study 2007

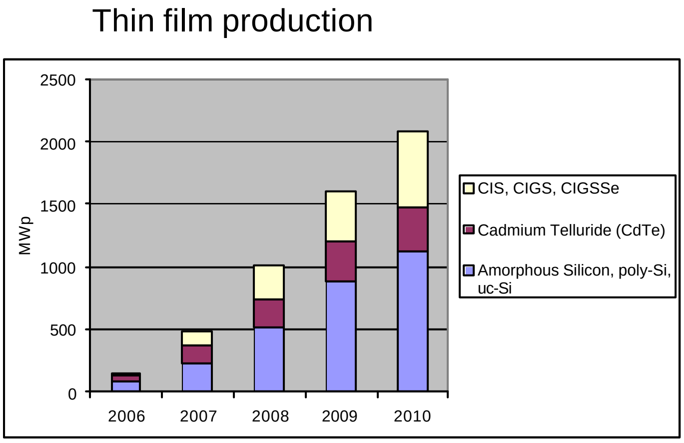
Sarasin has again increased their prognosis and now estimates a newly installed global capacity of **8.25 GWp/a by 2010** (This is twice the estimate given in [Sarasin 2006]!). This corresponds to an annual growth rate of roughly 50% between 2006 and 2010. For the time period 2011 to 2020 Sarasin estimates a market growth rate of slightly more than 22% per year. Thus the Sarasin prognosis exceeds the optimistic MAX scenario of [Krewitt 2005].

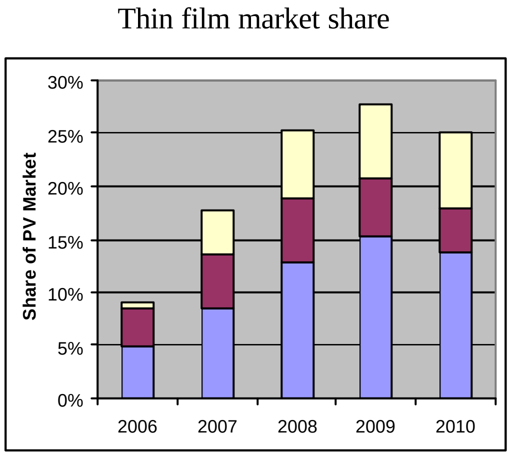
Sarasin assumes that the **raw silicon** situation will improve after 2009. However silicon prices will go down only gradually as silicon from new production sites will be sold in long-term contracts.

Despite the dramatic increase of PV cells made in **China**, Sarasin predicts that the new and inexperienced Chinese producers may face problems with quality and tuning production processes. Securing the supply side (silicon) is another big challenge which might slow down the output of PV plants in China.

As for **thin film PV** Sarasin estimates a more than proportional growth with a market share of more than 20% by 2010. The study gives forecasts of expected output of 29 companies analysed. The cumulated global thin film production is displayed in Graph 8-1. Graph 8-2 shows the market share of different thin film technologies. It is noteworthy, that Sarasin expects the thin film market share to rise dramatically from less than 10% today, up to more than 25% in 2009, when it will saturate again.

However, Sarasin states that prognosis on future thin film is very difficult due to the immaturity of the technology and unpredictable challenges which might arise in the upscaling of production.[26]



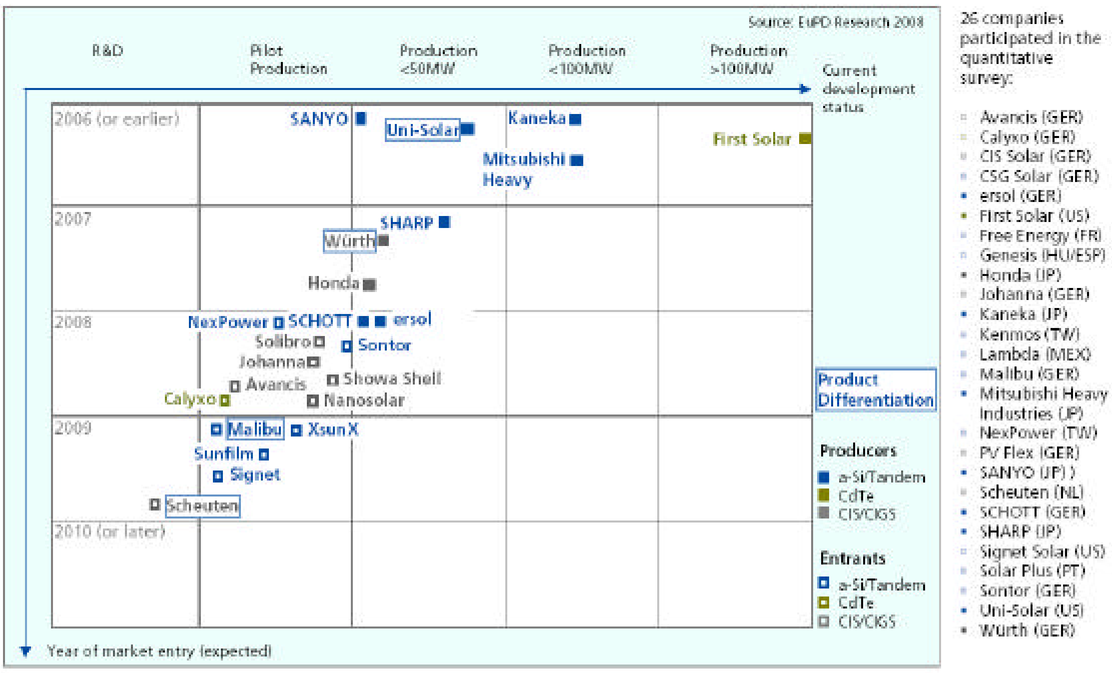


Graph 8-1: Forecast of thin film production (note differences to production capacity as given in Table 8-3). Data source: [Sarasin 2007]

Graph 8-2: Forecast of thin film market share of overall PV market. Data derived from Sarasin 2007.

8.1.5 EuPD Research: PV Thin film Industry Analysis (2008)

EuPD Research, an international consultancy, focusing on B2B market research, published an industry analysis on thin film PV markets and industry prospects [EuPD 2008]. The database stems from a survey among thin film PV producers based on interviews with the 10 active producers and 16 market entrants.



Graph 8-3: Current production status of most important thin film players [EuPD 2008].

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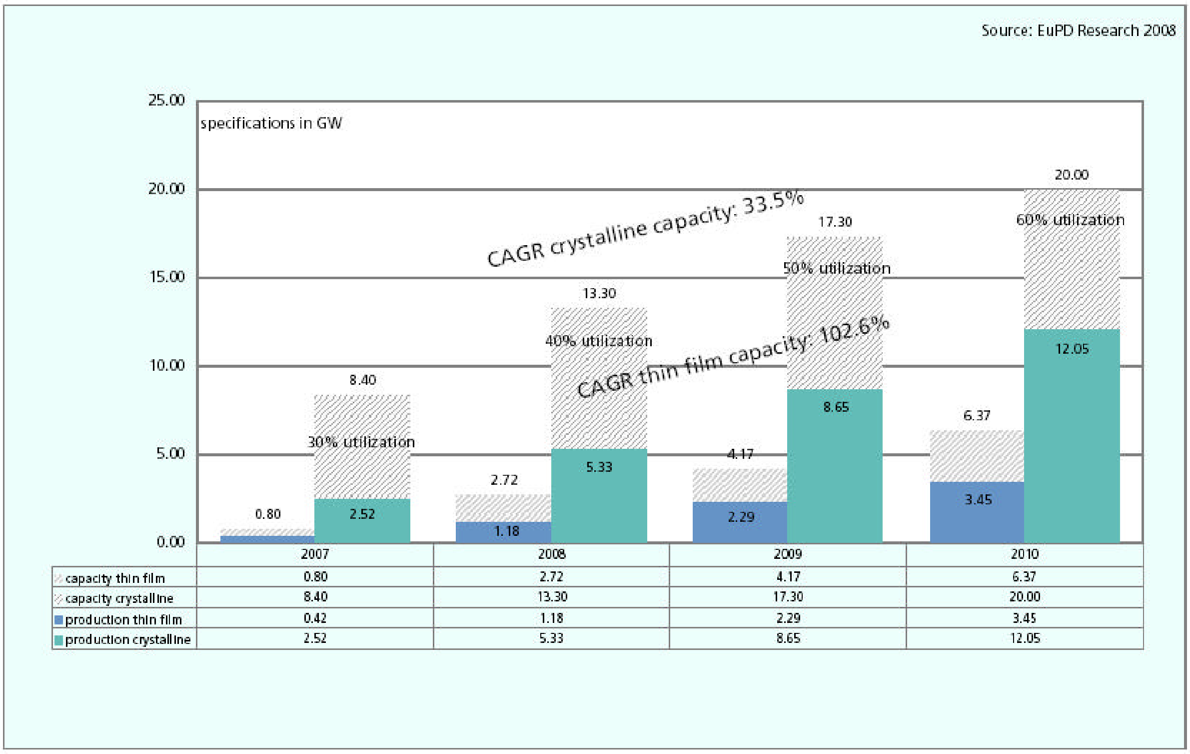
26 Furthermore, the data provided by Sarasin shows very ambitious growth plans for the near future and rather modest growth for 2010 – companies might have been reluctant to give "long-term" prognosis. Recent upscaling plans, e.g. of Sharp's 1GW plant plan in Sakai [Press Sharp 03.09.2007] may not have been included adequately.

Thin film market up to 2010

EuPD estimates a thin film PV production capacity of 6.4 GW globally in 2010 (see also Graph 8-4). This capacity would be distributed among the different technologies as follows: 3.6 GW a-Si, 1.3 GW CIS and 1.5 GW CdTe. The amount of actually produced modules in 2010 is estimated to sum up to 3.45 GW. This corresponds to a market share of roughly 22% of thin film PV in the overall PV market.

New players – new competition

Currently 60% of the thin film market (2007: 420 MW) is produced by one company – First Solar. The remaining shares are almost evenly split between the nine other producers (2 to 8% of thin film market each).



Graph 8-4: Crystalline silicon PV and thin film PV production predictions up to 2010 [EuPD 2008].

EuPD predicts that the power of new market entrants will grow in the future. The rivalry among existing producers (which is low today) is foreseen to grow strongly in the future. Bargaining power is expected to shift from the producers (today) to the purchasers (in the future).

Breakeven points of different technologies

EuPD applies a learning curve approach (20% cost decrease whenever the cumulated production output doubles) to estimates of today's module costs for different technologies and compares these with (an average) of EU 15 costumer prices for electricity:

PV Technology	Costs 2008	Break-even
c-Si	1.55 € / W	2015
a-Si	1.20 € / W	2013
CIS	1.80 € / W	2013
CdTe	~ 1 € / W	2012

Table 8-4: Production costs (2008) and break-even points (competitive with costumer electricity prices) for various PV technologies [EuPD 2008a]

According to this projection, thin film technologies could reach grid parity slightly before crystalline Silicon PV does.

8.1.6 FORRES 2020: "Analysis of the RES Evolution up to 2020"

The FORRES 2020 study was initiated and financed by the European Commission, Directorate General for Energy and Transport. International consortiums of research and consultancy partners conducted the study. The Final Report was published in April 2005. The objectives of the study were to produce an independent analysis and assessment of the implementation of renewable energy sources in the Member States of the European Union and the Candidate Countries since the publication of the White Paper on renewable energy sources in 1997 and to propose a perspective for the period up to 2020.

Model calculations and analyses are based on two different scenarios; each with a different mix of promotion schemes and assumptions:

- The first scenario is the business-as-usual scenario (BAU). This scenario models the future development based on present policies under currently existing barriers and restrictions, e.g. administrative and regulative barriers. Future policies, which have already been decided on but have not yet been implemented, have also been considered. Policy instruments have been updated until December 2004. The level of social and administrative barriers as well as of the relevant grid restrictions have been estimated using stakeholder surveys as well as interviews with country experts.
- The second scenario is the policy scenario (PS). This scenario models the future evolution based on the currently available best practice strategies of individual EU Member States. Strategies that have proven to be most effective in the past for implementing a maximum share of RES have been assumed for all countries. In the case of PV it is assumed that strategies are undertaken related to the German Renewable Act (2004) – adapted for Southern European countries according to country specific insolation.
  Furthermore, the policy scenario is based on the assumption of a stable planning horizon as well as the assumption that currently existing social and technical barriers can be overcome. Both scenarios include the effect of technology learning and economies of scale.

The overall Result of the FORRES Study concerning the PV-Sector is shown in the following table:

Photovoltaic in the EU15	**2010**	**2020**
BAU scenario	3.3 TWhe	9 TWh_e
PS scenario	4.9 TWhe	17 TWh_e

Table 8-5: Electricity production of P V in the EU 15 under different scenarios until 2020

FORRES 2005]

8.1.7 Global Energy [R] Evolution - A Sustainable World Energy Outlook (2007)

The Sustainable World Energy Outlook (2007), funded by Greenpeace and EREC and carried out by DLR and Ecofys. It is a target oriented scenario approach with a main focus on the feasibility of the promoted target.

The study is divided into a reference scenario and a so-called energy [r]evolution scenario as an alternative scenario.

- The reference scenario is based on the reference scenario published by the International Energy Agency in World Energy Outlook 2004.This only takes existing policies into account. The assumptions include, for example, continuing progress in electricity and gas market reforms, the liberalisation of cross border energy trade and recent policies designed to combat environmental pollution. The reference scenario does not include additional policies to reduce greenhouse gas emissions. As the IEA scenario only covers a time horizon up to 2030, it has been extended by extrapolating its key macroeconomic indicators. This provides a baseline for comparison with the energy [r]evolution scenario.
- The alternative scenario has a key target for the reduction of worldwide carbon dioxide emissions down to a level of around 11 Gigatonnes per year by 2050 in order for the increase in global temperature to remain under +2°C. A second objective is to show that this is possible even with the global phasing out of nuclear energy.
  To achieve these targets, the scenario is characterised by significant efforts to fully exploit the large potential for energy efficiency. At the same time, cost-effective renewable energy sources are accessed for both heat and electricity generation as well as the production of biofuels. The general framework parameters for population and GDP growth remain unchanged from the reference scenario.

The main scenario assumptions are:

- Population growth rates for the regions of the world are taken from WEO 2004 up to the end of its projection period in 2030. From 2030 to 2050, data is taken from the 2004 revision of the United Nations World Population Prospects.
- Economic growth rates are also taken from WEO 2004. Beyond 2030 the rates are taken from the 2000 IPCC Emission Scenarios B2.
- Fossil fuel prices: The price of oil reaches $85/bbl by 2030 and $100/bbl in 2050. Gas prices are assumed to increase to $9-$10 per GJ by 2050.
- It is expected that a CO_2 emissions trading system will be established. For the scenarios CO_2 costs of $50/t$CO_2$ in 2050 are assumed.
- To identify long-term cost developments of RES technologies, specific learning curves have been applied. The learning factor for PV solar modules has been assumed fairly constant at 0.8 over 30 years.
- The expected costs of electricity generation from PV are assumed to be around 20 ct$/kWh in 2020 and decrease to 10 ct$/kWh in 2050.The investment costs for PV are assumed to 2000 $/kW in 2020 and decrease to around 1200 $/kW in 2020

The main results of the two quite different outlooks can be seen in the following table:

	Electricity generation in TWh/a	2003	2010	2020	2030	2040	2050
Reference Scenario	Total Generation	16,662	20,030	25,617	31,589	38,245	46,501
	PV	1	9	30	73	108	139
	PV Share	0,0%	0,0%	0,1%	0,2%	0,3%	0,3%
	Total RES	3,007	3,821	4,864	5,981	6,875	7,564
	RES share	18%	19%	19%	19%	18%	16%
	Installed capacity in GW	**2003**	**2010**	**2020**	**2030**	**2040**	**2050**
	Total Generation	3,733	4,485	5,724	7,029	8,303	9,872
	PV	1	6	22	55	81	104
	PV Share	0,0%	0,1%	0,4%	0,8%	1,0%	1,1%
	Total RES	817	1,054	1,347	1,683	1,910	2,105
	RES share	22%	24%	24%	24%	23%	21%
Alternative Scenario	**Electricity generation in TWh/a**	**2003**	**2010**	**2020**	**2030**	**2040**	**2050**
	Total Generation	16,662	17,308	20,234	23,292	27,018	30,935
	PV	1	28	269	1,003	1,835	2,835
	PV Share	0%	0%	1%	4%	7%	9%
	Total RES	3007	4104	7688	12603	17015	21444
	RES share	18%	24%	38%	54%	63%	69%
	Installed capacity in GW	**2003**	**2010**	**2020**	**2030**	**2040**	**2050**
	Total Generation	3,733	4,018	5,235	6,778	8,064	9,537
	PV	1	23	199	728	1,330	2,033
	PV Share	0%	1%	4%	11%	16%	21%
	Total RES	817	1169	2438	4196	5584	7135
	RES share	22%	29%	47%	62%	69%	75%

Table 8-6: PV related main results of the reference and alternative scenario

In a back-casting approach the study concluded that the following general assumptions need to be implemented to make the alternative scenario become true:

- The phasing out of all subsidies for fossil fuels and nuclear energy
- The internalisation of external costs
- The setting out of legally binding targets for renewable energy
- The provision of defined and stable returns for investors
- Guaranteed priority access to the grid for renewable generators
- Strict efficiency standards for all energy consuming appliances, buildings and vehicles

[GREENPEACE 2007]

8.1.8 The Renewable Energy Scenario of EREC

This EREC Scenario was published in 2003 and carried out by the European Renewable Energy Council, an umbrella association of the leading European renewable energy industry.

The EREC Scenario follows a normative scenario approach. The major aim is to give proof to the feasibility to provide half of the global energy supply with renewables in 2040. Furthermore the study aims to determine which actions have to be taken to reach this target. The EREC Scenario, unlike other predictions, only concentrates on RES development and does not investigate the development of conventional energy sources.

Two scenarios have been considered.

- Advanced international policies scenario (AIP)
  The assumptions in the AIP-scenario are based on ambitious growth rates for renewable energy sources that need additional support measures in order to be reached. It is assumed that regions already active in the promotion of renewables will increase their efforts and that other regions will follow these examples. Higher prices for conventional energy supply are anticipated as well as growing support for electrification of the less and least developed regions by renewables. Implementation of the Kyoto protocol as well as additional measures on the international level for climate protection and for the promotion of renewables is also needed to reach the assumed growth rates. International cooperation on all levels has to be strengthened. The assumptions for total energy consumption are based on a scenario from the IIASA (International Institute for Applied Systems Analysis). It is optimistic about technology and geopolitics, it assumes unprecedented progressive international cooperation focused explicitly on environmental protection and international equity. It includes substantial resource transfers from industrialized to developing countries, spurring growth in the South. Nuclear power proves a transient technology that is eventually phased out entirely by the end of the 21st century.
- Dynamic current policies scenario (DCP)
  This scenario does not mean "business as usual" because the authors think that this is impossible. The model is based on less international cooperation than in the AIP-scenario in the field of RES, but expects ambitious policy measures on a national level at least in the industrialised part of the world. The assumptions are based on policy measures that are similar to what already happens in some countries of the world. During recent years some regions have given increased attention to the promotion of renewable energy sources, some have given less. It is assumed that the commitment to renewables development in the very proactive countries, such as Germany, continues to strengthen and will be adopted also by others at least in the industrialized part of the world as national policies, and additionally that, especially in the least developed countries and areas without existing networks for electricity, renewables will be a competitive alternative to conventional sources in the near future, even without special promotion.

Both scenarios are based on the total energy consumption from a scenario from IIASA, but the DCP-scenario assumes a higher total consumption because it considers this is more appropriate if no major international action is taken. The DCP-scenario incorporates more modest estimates of economic growth and technological development, and the demise of trade barriers and expansion of new arrangements facilitating international exchange.

The following table shows the main results concerning the PV sector under the two different scenarios

		2001	2010	2020	2030	2040
DCP-Scenario	World Primary Energy Consumption in Mtoe	10,038	11,752	13,553	15,547	17,690
	PV in Mtoe	0	1	15	110	445
	PV-Contribution	0%	0%	0%	1%	3%
AIP-Scenario	World Primary Energy Consumption in Mtoe	10,038	10,549	11,425	12,352	13,310
	PV in Mtoe	22	2	24	221	784
	PV-Contribution	0%	0%	0%	2%	6%
	Total Consumption in TWh	15,578	19,973	25,818	30,855	36,346
	PV in TWh	2	20	276	2,570	9,113
	PV Contribution	0%	0%	1%	8%	25%

Table 8-7: Worldwide PV Contribution to the Primary Energy and Electricity Consumption

With a view to an economically attractive growth of renewable energy sources, a balanced and timely mobilisation of all renewable technologies is considered of great importance. As core factors, technical potentials, actual costs, cost reduction potentials and technological maturity are named.

[EREC 2003]

8.1.9 Very Long Term Energy-Environment Model (VLEEM)

The aim of the VLEEM-Project was to establish a methodology and to develop tools for energy system modelling over one century. The VLEEM project has combined two methodological innovations which are imposed by the very long time-frame:

- a back-casting approach, which starts from basic needs and general descriptions of a world in 2100. From this suitable RTD- strategies are elaborated in the context of sustainability.
- a re-foundation of the energy-environment modelling structures, in order to properly assess very long term modification of social and cultural preferences and technology evolution dynamics in relation to them.

The final report of the VLEEM study was published in August 2002. Furthermore the VLEEM study carried out Monographs about important future energy carriers and conversion technologies. One of them was about „Learning and diffusion for wind and solar power technologies." However, it was not the goal of the project to produce data about the potential capacity of PV in 2100.

The global scenario for PV in the VLEEM-Study is based on data published by EPIA and IASA. The potential of PV in the world is estimated at 274 TWh in 2020, 7,368 TWh in 2040 (EPIA) and 20,880 TWh in 2100. This projection has been used for an analysis of the possible cost reduction of PV and the assumed learning curves of the PV technologies. As a result of this analysis the main challenges to reach the prospective future of PV could be derived.

The crucial challenge is to make PV an economically viable option. The efficiency of solar cells may be increased substantially. Also, the lifetime may be prolonged by prevention of significant degradation. Furthermore, consumption of materials – high-grade silicon, precious metals – may be reduced to low and 'sustainable' levels. Finally, advanced large-scale production processes will make PV more and more competitive in the long term.

Application of a progress ratio of 0.827 for modules (based on past experience), and more modest ones for other components (inverter, cabling) and installation, to the EPIA-scenario suggests that the specific investment cost of grid connected PV systems may come down by a factor 5 to 7 from € 5,400/kW in 2000 to € 950/kW (default) or possibly € 790/kW ('low') in 2035.

Learning effects for various well-known energy technologies confirm a cost reduction of this order of magnitude. Furthermore the scenario presumes a co-ordinated policy from governments and industry. The scenario implies more than 10 doublings of the cumulative installed capacity compared to 2000. The growth of PV capacity after 2035 is limited by economic factors and by the intermittent nature of a renewable option like PV, rather than by its technical potential.

[VLEEM 2002]

8.1.10 Renewables in Global Energy Supply - An IEA Fact Sheet

The study was carried out by the International Energy Agency (IEA) and was published in 2007. It presents the main elements of the renewable energy situation in the year 2004.

Shares of renewables to total energy supply

The fuel share of RES[28] to the World Total Primary Energy Supply (TPES) is determined based on the physical energy content. Renewables have an overall share of 13.1% with a share of solar of 0.039%. The following table gives a brief overview of the results of this calculation.

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[27] A progress ratio (PR) of 0.8 is tantamount to a cost reduction of 20% for each doubling of the cumulative capacity.

[28] Here the used RES Definition of the IEA includes combustibles renewables and renewable waste and exclude the combustion of non- renewable waste.

Combustibles renewables and renewable waste	1170 Mtoe	10.6000%
Hydro	240 Mtoe	2.2000%
Tide	0.04 Mtoe	0.0004%
Wind	7.1 Mtoe	0.0640%
Solar	4.3 Mtoe	0.0390%
Geothermal	45 Mtoe	0.4140%
Total	1470 Mtoe	13.3174%
Total primary energy supply (TPES)	11000 Mtoe	100.0000%

Table 8-8: Fuel shares of RES to the World Total Primary Energy Supply 2004

Market shares

In total, renewables supply experienced an annual growth rate of 2.3% from 1973 to 2004, marginally higher than the annual growth of 2.2% in TPES. However, the so called "new" renewables (including geothermal, solar, wind, etc.) recorded a much higher annual growth of 8.2%. The growth rate of solar is calculated to be 28.1 %.

Looking at electricity production, the picture changes. There, renewables are the third largest contributor to global electricity production. They accounted for almost 18% of production in 2004, after coal (40%) and natural gas (close to 20%), but ahead of nuclear (16%), and oil (7%) and non-renewable waste.

Key success factors for renewable energies

Looking at the past market and policy trends on renewables the study gives several statements:

- The biggest challenge facing renewable energy technologies might be that they have to advance the state-of-the-art to the point where more renewable options can generate energy at costs that are competitive with conventional sources.
- Significant market growth in renewable technologies results from a combination of policies that address specific barriers and/or complement existing policies. For example, in Japan, photovoltaic (PV) technology was supported by extensive RD&D investments to increase the competitiveness of the technology, through demonstration projects (to increase public awareness and acceptance), financial incentives (to reduce the purchase price of PV systems) and by requiring utilities to accept, through net metering, excess power generated by PV systems at the retail price of electricity.
- Longevity and predictability of policy support are important to overall market success. In most cases, feed-in tariffs for renewable energy sources have an eight- to twenty-year time frame. The long-term support offered to biomass district heating plants in Austria provides an example. Conversely a 'stop–and-go' policy environment does not provide a sound basis to encourage the much-needed private sector involvement.
- With the trend towards market liberalisation, early support policies for emerging renewable energy technologies must be tailored carefully to insure against the impact of a significant drop in overall energy prices.

PV market analysis

Concerning PV, the study points out that the PV market has grown extensively since 1992. RD&D efforts, together with market deployment policies, have effectively produced impressive cost reductions: every doubling of the volume produced prompted a cost decrease of about 20%. But market deployment is concentrated: Japan, Germany and the United States account for over 85% of total installed capacity. PV still requires substantial RD&D investments, as well as deployment support, to gain market learning. In the near term, RD&D efforts will focus on improving the balance-of-system components for both grid connected and stand-alone applications. Even with these supports, PV is not expected to be generally competitive until after 2020 – although it will continue to compete well in a growing range of market niches in which the cost of deployment support is moderate.

World Energy Outlook - Alternative Policy Scenario

Furthermore the study presents the results of energy scenarios based on the latest World Energy Outlook.

The first scenario called “Alternative Policy Scenario“ shows how the global energy market could evolve if countries around the world were to adopt a set of policies and measures that they are now considering and might be expected to implement over the projection period up to 2030. In this scenario, the share of renewables in global energy consumption will remain largely unchanged at 14%. The shares of the so-called „new“ renewables (including geothermal, solar and wind) will increase most rapidly at 6.2% per year but because they start from a very low base (0.5% share in 2003) they will still be the smallest component of renewable energy in 2030 with a share of only 1.7% of global energy demand.

The following table gives a brief overview concerning the role of PV in this scenario

Electricity Generation (TWh)	**2030**
Total	29,904 TWh
PV	238 TWh
RES	7,775 TWh
Share RES	26%

Table 8-9: Global contribution of RES to the electricity generation by 2030

The projected increase is the result of new policies currently under discussion - on the assumption that these policies will be implemented- as well as the result of the extension and strengthening of policies currently in place. Most OECD countries and an increasing number of countries outside the OECD are considering policies to increase the contribution of renewables. For the countries of the European Union, the Alternative Policy Scenario assumes that additional policies will be put in place to meet the target of the directive on the promotion of electricity from renewable energy sources. The study noted no targets for renewables beyond 2010 at the EU level, although some countries have set national ones. The intention, however, is to continue the shift to renewables beyond this period. In the United States, about half of the states have plans to increase the share of renewables through renewables portfolio standards. China’s Renewable Energy Law, which came into effect in January 2006, could have a large impact on electricity generation from renewable energy sources.

In the Alternative Policy Scenario, the share of renewables increases by ten percentage points above current levels in the OECD, by four points in developing countries, and by four points in the transition economies. In the OECD, the most dramatic increase is projected for OECD Europe, where 38% of electricity is based on renewables in 2030.

Key drivers for PV development

Furthermore the Study developed several other scenarios but without explicit statements in regard to PV. However, they made assumptions and the nominated key drivers are worth mentioning.

The main aim of the scenario called “Beyond the Alternative Policy Scenario” is to ensure that global energy related CO_2 emissions in 2030 are not higher than in 2040 and to illustrate the potential of additional emissions reductions. The suggested political and technical options are

- CCS in power generation
- RES based generation
- Nuclear power-plants
- Efficiency of power plants
- Bio fuels and hybrid
- Efficiency and CCS in Industry

- Efficiency of electricity use.

Different Accelerated Technology scenarios are derived for the last five. The main key drivers with different assumption for each of these scenarios are:

- Renewables
- Nuclear
- CCS
- H_2/Fuel cells
- Advanced Biofuels
- End-use Efficiency

[IEA2007]

8.1.11 The German energy economic reference prognosis - Energiereport IV

The Study “Energiereport IV” was carried out by EWI/PROGOS and funded by the German Federal Ministry of Economics. It is the most common reference prognosis in Germany covering a time frame up to 2020. In contrast to the reference scenarios published by the German Ministry for Environment the Energiereport is considered a rather conservative energy economic study.

Underlying assumptions

Beside assumptions about the global megatrends and specific developments in the main sectors of energy demand, the study is based on the scenarios of the world energy consumption from EIA, EU-Commission and the IEA.

Prospects of PV technologies

Concerning the PV sector, the study argues that photovoltaic is not competitive without extensive public funding and therefore will play no significant role in the future generation of electricity. An entrance in the competitive market is only possible in off-grid situations and for mobile devices where PV is in competition with battery and small diesel generators.

Assuming a lifetime of 20 years, full load hours of 850 a year, interest of 6% on the loan and a specific investment cost of 5,800 Euro per kW, the electricity generation costs are estimated to be around 70ct per kWh. In large scale plant, this cost is able to decrease to 62 to 48 ct per kWh . Considering a learning rate of 18 to 20% based on the experience in Japan (1981-1995) and in the USA (1976-1992), this cost can be decreased further to 20-25ct per kWh by 2020. Based on these assumptions the installed capacity of PV in Germany is estimated. Results are shown in the table below.

	2010	**2030**
Installed capacity	1.1 GWp	2.4 GWp
Power Generation	1.2 TWh	2.7 TWh
Äquivalent of primary Energy	4.4 PJ	9.5 PJ

Table 8-10: PV Capacity, Generation and Primary Energy in Germany

Because of their cost-effective, large scale and material saving manufacturing technique, the thin film technology is given a good prospect, but the wafer technology maintains their established role and, as a result of a lock-in effect, the thin film technology is not expected to reach a breakthrough in the next few years.

[PROGNOS 2005]

8.1.12 Solar Opportunity Assessment Report

The Solar Opportunity Assessment report, presented by the Solar Catalyst Group in 2003, analyses PV development paths from a US perspective. The report is mainly based on interviews with US PV experts and stakeholders. It describes three different scenarios for PV market development in the US:

Projected PV Growth Under Three Pathways

	Current Growth	Accelerated Growth	Hypergrowth
Compound annual growth rate	24%	28.5%	38%
Cumulative Installed MW in 2025	35 gigawatts	70 gigawatts	290 gigawatts
Electricity Production Equivalent in 2025	63,000 gigawatt-hours	126,000 gigawatt-hours	522,000 gigawatt-hours
% of Projected U.S. Electricity Consumption in 2025	1.2%	2.4%	10%

Assumes each kilowatt-hour installed provides an average of 1,800 kilowatt-hours a year. Source: International Energy Agency, 2001. Includes only installations greater than 40 watts.

Table 8-11: Key figures of three PV development pathways for the US.
Source: [Makower et al. 2003]

The hypergrowth scenario is linked to the existence of a societal vision and an array of well funded partnerships, which the authors named SHINE – Solar High-Impact National Energy – Project. To demonstrate the efforts needed, reference is made to the 1961 "man-on-the-moon" vision. The SHINE idea is developed in more detail in [Makower, Pernick 2005].

The major part of the report covers "levers" to promote PV development. The main focus lies on (US) policy and financing as well as cross cutting issues like education, standardization and market aggregation.

A part of the report deals with the question whether or not technological breakthroughs are necessary to trigger accelerated growth. Technological breakthroughs are defined as disruptive technology paths in contrast to incremental improvements. In this respect thin film technologies are discussed. Implicitly they are labelled "disruptive technologies". Despite their potential, they are perceived as very risky and unreliable. The report was based on interviews done in 2003 and earlier. Today a different image might evolve. However it has to be pointed out that the questioned PV experts did not believe in technological leaps but rather incremental improvements.

[Makower et al. 2003]

8.2 PV Roadmaps

8.2.1 EU White Renewable Sources of Energy

The White Paper ENERGY FOR THE FUTURE: RENEWABLE SOURCES OF ENERGY of the EU commission was published in 1997. However, it is still an important benchmark for the renewables sector. It provides the foundation of many of today's targets and milestones. Concerning PV, the white paper calls for a 100-fold increase in photovoltaic systems by the year 2010, which corresponds to a market growth rate of 30% annually.

With respect to estimates of possible PV development, the white paper forecasted the world's annual production of PV to reach 2.4 GWp by 2010. Annex III of the white paper gives an overview of Member States' plans and actions for the development of renewables. Based on this the projected share of PV is estimated to be 3 GWp in the EU15 by 2010. Major shares are expected to come from grid-connected installations either incorporated into the structure of buildings (roofs and façades) or stemming from large-scale power plants (0.5-5.0 MWp).

Comparing the white papers targets with today's achievements, it can be stated that the capacity of PV in the EU targeted for 2010 was already installed in 2006. However the corresponding average cost level of 3 Euro per W_p has not been reached yet.

[EC 1997]

8.2.2 The EREC Renewable Energy Technology Roadmap - Up to 2020

The EREC Roadmap RES Technology was produced by the European Renewable Energy Council, an umbrella association of the leading European renewable energy industry. The roadmap was published in the year 2007 and considers several RES scenarios and targets, reflecting on their feasibility and deriving the specific needs for the different RES technologies. The aim of the PV Technology Roadmap is to be an effective tool for maintaining, exploiting and strengthening European leadership in the PV sector. It addresses the PV Industry and the technological innovations.

The starting point of the study is that published baseline ("business as usual") scenarios[29] are arguing that Renewable Energies will not meet the expectations[30] by 2020 without further political and legal attention. According to the baseline scenario by Mantzos and Capros their contribution to the total primary energy demand will only be roughly 8% in 2010, slightly more than 12% in 2020 and only 12% in 2030, far away from any target set so far. Concerning that point the study advises a more ambitious, long term, mandatory and especially overall target for 2020, followed by targets for the different sectors (electricity, heating/ cooling, biofuels). Following this suggestion the roadmap makes a concrete proposal for such new targets.

As reasons for not reaching the targets, the study cites targets that are too unspecific and the absence of necessary legislation and support measures. Apart from the legislation problems, the study considers the statistics and calculation methods of the European database, and more precisely, the Eurostat methodology, compared to the substitution principle as used in a similar approach by the International Energy Agency (IEA) and other several authoritative energy statistics, such as the BP's annual "Statistical Review of World Energy", the Shell Scenarios, and the annual "Renewables Global Status Report" of the REN21 network. In the Eurostat methodology the primary energy value of the electricity produced by the different energy sources is found by assuming a conversion efficiency factor for each source.

For the electricity produced from hydro, wind, solar and ocean power the conversion efficiency factor is assumed to be 100% and so the primary energy value of these sources is assumed to be the same as

[29] E.g.: European Energy And Transport, Scenarios on energy efficiency and renewables, Dr. L. Mantzos and Prof. P. Capros, Institute of Communication and Computer Systems of National Technical University of Athens (ICCS-NTUA), E3M-Lab, Greece

[30] e.g.: Green Paper; A European Strategy for Sustainable, Competitive and Secure Energy, 8.3.2006, COM(2006) 105

the electricity they produce.

Fossil fuels are converted to their primary equivalent by applying a universal conversion efficiency factor. The usual value, which is used, is 38.5%, reflects the average efficiency of a thermal power station. This clearly favours conventional and nuclear sources in terms of the percentage share of overall primary energy use. Sources such as wind, hydro and PV are underestimated so far as the substitution principle is in force and the political discussions of RES targets are based on primary energy equivalent.

Concerning PV, the projections of the EREC roadmap about electrical installed capacity in the EU25 is estimated at 8 GW_p by 2010 and 52 GW_p by 2020.These projections mean growth rates around 45% from 2004 to 2010 and 20% from 2010 to 2020. If these projected growth rates are achieved the electricity production of PV is estimated at 7.5 TWh by 2010 and 55 TWh by 2020.

Globally the EREC Roadmap considers an installed capacity of 259 GWp by 2020 delivering an estimated power of 325 TWh corresponding to approximately 1.8 % of total electricity consumption in 2020.

By 2040 the solar generation will reach 16% of worlds energy output.

To reach this projection several technological innovations have to be made.

- The price of the PV systems has to come down from 6 Euro per Wp to 3-4 Euro per Wp by 2010
- The electricity generating costs have to decrease to 10 - 20ct per kWh in 2020 and 5-10 ct per kWh in 2030.

Concerning the technological innovations, the EREC roadmap is based on a market share of 90% by crystalline silicon cells in their different forms and 10% by thin film technology for the next 10-15 years.

The following technological aims are adopted for 2010

- Material (Si) consumption for mono-crystalline silicon from 10 gram per Watt peak (g/Wp) to 7.5 g/Wp
- Ribbons from 8 g/Wp to 4 g/Wp
- Wafer thickness from 300 µm to 100 µm
- Kerf loss in the sawing process from 250 µm to 150 µm

Concerning the efficiency of crystalline silicon cells the following aims are defined up to 2020:

- Efficiency increase for mono-crystalline silicon from 16.5% to 22%
- Efficiency increase for multi-crystalline silicon from 14.5% to 20%
- Ribbon efficiency from 14% to 19%

Concerning the thin film technology the targets up to 2020 are.

- Thin film aiming at efficiencies between 10% and 15% (a-Si/mc-Si, CIS and CdTe)
- Building integrated PV (BIPV) with low cost per m^2, price reduction of 75%

Although cells based on gallium arsenide (GaAs) and other III-V-compounds have higher cost, the high conversion efficiencies of these cells measured so far make them ideally suited for concentrating systems where the area price of solar cells is of minor importance. Concentrating systems using the highest efficiency solar cells could become an interesting opportunity for medium and large installations in the MW-range in southern countries.

Furthermore the EREC Roadmap notes the improvement in the lifetime of solar modules as another step to further reducing solar electricity prices. It is expected that the lifetime will be extended from 25 years to 35 years, for example by longer lifetime encapsulation materials or new module architectures.

[EREC 2007]

8.2.3 A Strategic Research Agenda for Photovoltaic Solar Energy Technology

The Strategic Research Agenda for Photovoltaic Solar Energy Technology (SRA) has been produced by Working Group 3 “Science, Technology and Applications” of the EU PV Technology Platform and was published in June 2007.

The scope of the publication is less a scenario of PV development but rather a strategic roadmap to achieve research and development results. The target for PV development is largely based on the Report of the Photovoltaic Technology Research Advisory Council (PV-TRAC) [EC PV Vision 2005].

As a PV implementation target, the SRA defines 200 GWp of installed capacity in the EU and 1000 GWp worldwide by 2030.

The SRA argues that the cost and performance of PV technology is the main focus of research effort, but the importance of other drivers should be emphasised.

In summary, the SRA identifies and addresses the following drivers for PV development:

Electricity generation costs and value

- turn-key investment costs (price) of modules, BoS and system engineering
- operation & maintenance costs (& planned replacement if applicable) / technical lifetime
- value e.g. possibilities for supply-on-demand or at peak prices
- energy yield
- (factors out of scope of the SRA like interest rate, economic lifetime,…

Environmental quality

- energy pay-back time of the modules and the BoS (Balance of System)
- substitution of hazardous materials
- options for recycling

Integration

- method and ease of mounting, cabling, etc. (also for maintenance and repair)
- flexibility / modularity
- aesthetics and appearance
- lifetime

Socio-economic aspects

- public and political awareness
- user acceptance
- training and education
- financing

As cost targets used for all **flate-plate** PV module technologies the SRA consider 0,8 to 1,0 Euro per Wp for technology ready by 2013 and implemented in large-scale production in 2015, 0,6 to 0,75 Euro per Wp by 2020 and 0,3 to 0,4 Euro per Wp in 2030. Indicative targets for the BoS costs for roof-top systems are: 0.9-1.1 €/Wp in 2013, 0.75-0.9 €/Wp in 2020, and under 0.5 €/Wp in 2030.

For concentrator systems indicative targets for the turn-key cost (not price) of full systems have been identified as 1.2 to 1.9 Euro per Wp in 2013, 0.8 to 1.2 Euro per Wp in 2020 and 0.5-0.8 Euro per Wp in 2030.

Concerning the **thin film technology** the SRA expects the global production capacity to reach 1 GWp per year in 2010 and 2 GWp per year in 2012. Taking account of the increase in production facility sizes, improvements in module efficiency and differences in the calculation methods used by the PV industry, in 2010, the total manufacturing costs will most likely be in the range of 1 to 1.5 Euro per Wp. Further cost reduction to below 0.75 Euro per Wp in 2020 and 0.5 Euro per Wp by 2030 can be reached.

The SRA points out the following common research aspects for thin film:

- Reliable, cost-effective production equipment
- Low cost packaging solutions both for rigid and flexible modules
- More reliable modules through better quality assurance procedures (advanced module testing, and improved assessment of module performance)
- Recycling of materials and old modules
- Alternatives for scarce chemical elements such as indium and gallium

The specific research targets of the main thin film technologies are the follows:

Thin film silicon

- Processes and equipment for low-cost, large area plasma deposition of micro/nanocrystalline silicon solar cells.
- Mastery of the interplay between plasma/devices/upscaling.
- Development of high-quality low cost TCOs suitable for
- large area high performance (>12% efficiency) modules
- Demonstration of higher efficiency TFSi devices (above 15% on laboratory scale), improved understanding of interface and material properties, of light trapping, and of the fundamental limits faced by TFSi-based materials and devices

CIS

- Improvement of the throughput, yield and degree of standardisation of production equipment
- Modules with efficiencies greater than 15% (or greater than 20% at laboratory scale) through deeper understanding of the fundamental physics of these devices
- Alternative/modified material combinations and alternative approaches to processing like roll-to-roll coating and combined or non-vacuum deposition methods; highly reliable and low cost packaging to reduce material costs

CdTe

- Activation/annealing treatments to control the electronic properties of the CdTe layer

- Improved and simplified back-contacting for enhanced yield and throughput
- Concepts for high efficiency
- New device concepts for thinner CdTe layers
- Enhanced fundamental knowledge of materials and interfaces for advanced devices with high efficiencies (up to 20% at laboratory scale)

[EC PV Vision 2005]

8.2.4 PVNET European Roadmap for PV R&D

The PVNET roadmap is the outcome of an EC funded FP 5 Thematic Network, a network which brought together representatives of relevant research and development as well as production areas in photovoltaics. The Roadmap summarises the status of PV markets and technology development, it identifies bottlenecks and sets R&D priorities to overcome existing challenges. Bottlenecks and priorities are exemplified for wafer based Si-cells, thin film cells, module and system technology.

For thin film PV the following main bottlenecks are identified:

- still a relatively low efficiency for commercial modules (except maybe CIS)
- lack of standard production equipment; high costs and longer time to start-up production
- the relatively low yield in production related to the use of prototype equipment and quality control systems still in use
- expected module lifetime (poor image from the first, amorphous silicon products)
- safety requirements of some materials in production (CIS, CdTe), availability and cost of materials (Ga, Ge, In, Te)
- reduction of material purity and material yield

It is pointed out that all six problems have to be addressed simultaneously for thin film technology to take a major share of the growing market.

[PVNET 2004]

8.3 Articles

8.3.1 PV-News: "Thin film Forecast – Sunny with Clear Skiers"

The Article appeared in June 2007 in the oldest PV-industry newsletter "PV-News" published by the Prometheus Institute for sustainable development. Founded in 2003 by Travis Bradford, a former private equity and hedge fund executive, the Institute was created to fill a need for reliable data, quantitative analysis and practical information about the renewable energy industry.

The article gives a quantitative estimation about the production capacity of different thin film technologies until 2010 and points out the different factors which influence the worldwide thin film industry and the PV market in general. Until 2010 the growth rate of thin film PV solar panels is estimated to be as high as 60%.

Firstly it is pointed out that while total PV production grew at a compound annual growth (CAGR) of 49.5% since 2003, the CAGR in the thin film sub-segment was 79% during the same period. In 2006 the world wide thin film PV production was 196 MW, a 100% increase from the year before. Compared with traditional crystalline Si panels, thin film PV panels generally have a lower energy conversion efficiency and thus require a larger area to generate the same amount of power. In applications where space is not a constraint, thin film PV panels can be more economical than traditional PV panels because of their lower costs. Solar energy farms and roof-top installations (Grid-Tied commercial and Utility) are therefore ideal markets for thin film PV panels as well as the emerging applications field of building integration. Furthermore thin film PV is more aesthetically pleasing and can be deposited on flexible but durable substrates. It could be used as roofing material in residential applications as well as in a variety of consumer products such as portable electronics or power generating fabrics for structures such as tents, awnings and roofs.

The following table shows the projected and potential thin film manufacturing worldwide through 2010 differentiated by technology:

in MW	2006	2007		2008		2009		2010	
	projected	projected	potential	projected	potential	projected	potential	projected	potential
Emerging (Dyne, Nano Organic)	-	15	15	123	145	223	290	463	385
CIS	5	37	93	138	433	286	940	451	1,393
CdTe	68	140	153	233	250	283	300	286	313
a-Si	123	271	327	622	934	1,103	1,784	1,514	2,478
Total	**196**	**463**	**587**	**1,115**	**1,762**	**1,894**	**3,314**	**2,714**	**4,568**

Table 8-12: Projected and potential thin film manufacturing worldwide through 2010

[Prometheus 2007]

8.3.2 EurObserv'ER: "Photovoltaic Energy Barometer 2007"

The Photovoltaic Energy Barometer is published by EurObserv'ER in Cooperation with the Systemsolaires – le Journal des Ènergies Renouvelables. Issue no 178 from April 2007 gives an overview about the current and prospective situation of the PV market in Europe and worldwide. The current situation of the PV market in the EU 25, with growth rates of the installed capacity of about 36% from 2005 to 2006 and with a growth of 57% in the cumulative PV capacity in the same time period, is dominated by the German PV market. The German contribution of the PV market in the EU 25 in both annual installation and in cumulative capacity is estimated at about 90-93%. The growth rate of the worldwide photovoltaic cell production from 2005 to 2006 amounted to 40%. A brief overview of the underlying data of these growth rates is shown in the following table:

		2005	**2006**
Installed PV capacity	Germany	866 MWp	1,153 MW_p
	EU 25	914 MWp	1,239 MW_p
PV Cell Production	Worldwide	1,815 MWp	2,536 MW_p

Table 8-13: Installed PV capacity and Cell Production.

Furthermore the table shows that the German market continues to be the world leader for solar cells, far ahead of the Japanese market (which is expected to remain at approximately 300 MWp in 2006) and the American market (estimated at more than 120 MWp). The solidity of the German market is explained by the stability of the incentive system, essentially based on the Renewable Energies Law (EEG), which, since August 2004, obliges electricity suppliers to purchase photovoltaic electricity at a predefined tariff.[31]

The silicon shortage has put pressure on many European PV players that have had to adapt their strategies as a result. The companies are trying to sign long term contracts with silicon producers (Hemlock, Wacker, REC, etc.) or to become silicon producers themselves by creating joint ventures with these same manufacturers. Certain industrialists are even trying to be more and more autonomous by following a vertical type strategy, going from the production of the silicon up to the supply of the photovoltaic modules. They also develop ever thinner crystalline silicon cells to reduce the raw material requirement. Finally, more and more manufacturers are diversifying their activities into other technologies like thin film PV (chalcopyrites- copper indium gallium selenide, in particular), which consume less material and offer the prospect of a greater reduction of production costs than for crystalline silicon. These different strategies for ensuring procurement security and reducing production costs should permit the European industry to be able to compete with the Japanese and Chinese industrialists on the gigantic world market that is emerging on the horizon.

For the performance of the market growth in the future two main influencing factors are nominated

- The overcoming of the silicon shortage which will finally allow industrialists to fully use their production capacity and supply to fully meet demand.
- The continued decrease of the price of installation which will improve the sector´s competitiveness.

The outlook for the European PV Market is oriented to the two growth scenarios of the EPIA scenarios. The pessimistic version does not foresee reinforcement in current incentive mechanisms. The other, the policy driven scenario, foresees the introduction, the continuation and the reinforcement of incentive systems in all of the European countries. The pessimistic vision will lead to a total

[31] In 2006, the grid connected systems (around 97% of all PV Systems in Germany) benefited from a feed-in tariff varying between 51.8 c€/kWh and 48.74 c€/kWh on a duration of twenty years, with a 5% per year degression. A 5 c€/kWh bonus is added for building façade integrated systems. The possibility of a modification of the EEG law is currently under discussion, notably with regard to a possible increase of the annual degression to 10%.

European power of 7905 MWp, while the voluntarist projection will bring total European installed capacity up to 9921 MWp, i.e. very near to the symbolic benchmark of 10 GWp by 2010. But these scenarios, established at the end of the year 2005, correspond only moderately to the results of the survey that have been performed for the year 2006. The German market is largely underestimated in 2005 and 2006 and, conversely, the markets of the other EU countries are for the most part overestimated (except for that of Spain). Taking into consideration the consequent re-evaluation of the German market made by the Ministry of the Environment and the predictable acceleration in the growth of the Italian, Spanish and French markets, an installed capacity of 8713 MWp by 2010 is a realistic extrapolation of the current trend.
To reach this prospective market volume it is necessary to train more and more numerous professionals (technicians and administrative staff), to permit connection to the power grid and to build a network of distributors and installers. Furthermore the creation of riches and of qualified jobs is an opportunity for society, of which the political decision makers must be persuaded.

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Workshops

Within the scenario building process four workshops, with Athlet project partners and some selected experts were conducted. In the workshops interim results of the literature research and scenario driver identification were presented and discussed with the workshop participants.

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