MSc Program
Renewable Energy in Central & Eastern Europe

Post grid-parity scenarios for the European photovoltaic market

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

supervised by
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Affidavit

I, **Stefan Schönegger**, hereby declare

that I am the sole author of the present Master Thesis, Post grid-parity scenarios for the European photovoltaic market, 56 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Global well known energy agencies around the world have continuously underestimated and talked down the growth rates of photovoltaic throughout the last decade. On the other hand is photovoltaic often praised by green activists and populist speeches of all political parties as the “hope” for fighting against climate change.

This thesis provides information on the actual limits of large scale photovoltaic roll out in the times of grid parity. It identifies industrial bottlenecks for further PV growth in the era of a general economic viability that doesn`t anymore rely on governmental support schemes.

An introduction and evaluation of the complete supply chain from silicon feedstock to module production is followed by a scenario considering the pure demand without any restriction to identify the absolute theoretical maximum. In the next step these maximum scenarios are matched with the limits given by industrial production capacity, raw material feedstock, grid infrastructure and overall energy demand in Europe until 2020.

Results show that neither the silicon feedstock, nor the production output or the widely expected grid capacity will be the limit. The share of PV in the European energy mix is limited only by the overall peak energy demand for day time and in terms of operating hours by the non-availability of storage options for daily, weekly and seasonal fluctuations in production through PV systems. For 2020, an estimated installed capacity of 183 GW is expected by the final scenario developed within this thesis. This is more than four times higher than forecasted by the World Energy Outlook 2010, published by the International Energy Agency.

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List of acronyms

BIPV	Building integrated photovoltaic
BOS	Balance of system (cost)
CAGR	Compound annual growth rate
CAGR	Compound annual growth rate
CdTE	Cadmium Telluride
ct	Cent (Euro)
DSO	Distribution System Operator
EBT	Energy Payback Time
EEG	German Erneuerbare Energie Gesetz
ENTSOE	European Network of Transmission System Operators for Electricity
GDP	Gross Domestic Product
kW	Kilowatt
kWh	Kilowatt hours
LCA	Life Cycle Analysis
LCOE	Levelised costs of Energy
MSc	Master of Science
O&M	Operation and maintenance
OEM	Original Equipment Manufacturer
PV	Photovoltaic
ROI	Return on Investment
TCO	Total Cost of Ownership
TSO	Transmission System Operator

1 Introduction

The Italian physician Mr Volt (1745 – 1827), well known for the invention of batteries in the beginning of the 19th century, would probably be very proud to find out that his name has been mixed with the Greek expression for "light" to make up the name for one of the most astonishing scientific discoveries, the "photovoltaic effect". This effect is still the baseline for all modern photovoltaic (PV) products and technologies.

1.1 Motivation

No other renewable energy source is facing similar deviations on the statements about the ecological and economical potential than the photovoltaic technology, including current status updates as well as mid and long term perspectives. While market developments have been driven exclusively by governmental support schemes it is unquestioned that the solar radiation is by far our largest theoretical source of energy available. But are we able to make use of it? In an ecologically and economically sustainable way? Still in the first half of the 21st century?
My motivation for this thesis was to look behind the curtain of the PV industry and to evaluate the long-term prospects, independent of all current statements coming from industry, green activists or local politicians.

1.2 What is the core objective?

The objective of this thesis is to work out the key growth-limiting factors of the PV energy production in Europe for the *post grid-parity epoch*. The results will provide an inside view on the large scale „industrial bottlenecks" of the PV roll out and should be an early indicator, on which factors politics will have to stimulate investments or consider pushing for other options. Furthermore, it should also give an indication on the mid-term viability of the European PV industry. Specific questions that will be answered are:

- Is our grid infrastructure, as it is today, sufficient for a large-scale PV roll out?
- Will we see, after 2008, another poly-silicon shortage before 2020?
- Will the grid operators potentially start refusing the integration of PV energy into their grid?

- Will the PV industry be able to continue the current growth rate if no break-through in storage technology will come up?
- Will the PV technology take a significant role in the energy system within this decade?
- Will the PV industry be able to continue driving down the system costs as expected by political long-term targets?

Questions that will explicitly not be answered by this work:

- Precise quantitative answers on all above listed questions

1.3 Main literature

In order to get the key data for solar industries and the overall trends on energy markets, the main sources used for this thesis include the World Energy Outlook 2010, published by the International Energy Agency, and all the scientific papers presented during the 25th European Photovoltaic Solar Energy Conference that took place in September 2010 in Valencia, Spain. More than 6000 papers have been published during this conference, mainly on PV markets, PV technologies and PV production facilities. Furthermore the issues of the bi-weekly German renewable energy magazine “Sonne, Wind und Wärme” released between April 2010 and July 2011 helped to gain knowledge about current trends in production technologies and the “big picture” of global PV trends and scenarios.
Further important sources have been annual reports of stock listed companies within the supply chain of the photovoltaic market. These annual reports and derived material are legally obliged to follow international transparency rules and are therefore considered trustworthy sources of information.

1.4 Structure of work

The structure of this work is clearly split into three, and strictly separated, parts.
First, the supply side of photovoltaic is evaluated on their viability based on current market dynamics.
Second, the demand for PV is projected and forecasted for the post grid-parity era, specifically considering no limit on the supply side.
The third part should then bring demand and supply together to derive results and gain an early inside view on possible upcoming industrial “bottlenecks”, focussing especially on production capacity, raw material availability and grid parameters.

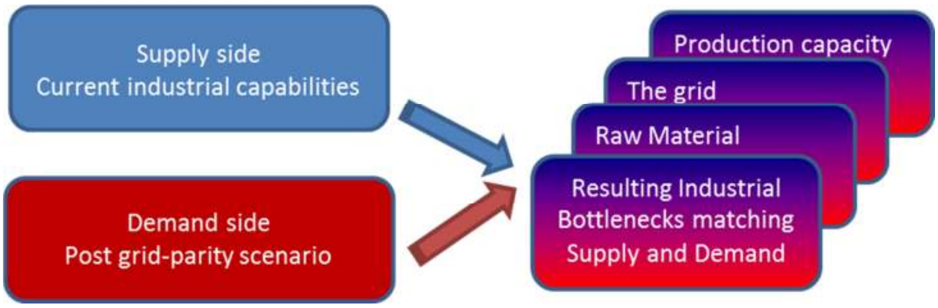

Figure 1 Structure of Work

The conclusion is based on the resulting scenario based on the identified limitations.

2 Overview on current PV market

2.1 Definition of grid parity

Grid parity in the common sense is associated with the convergence of the production costs for PV and the average household tariff for electricity.

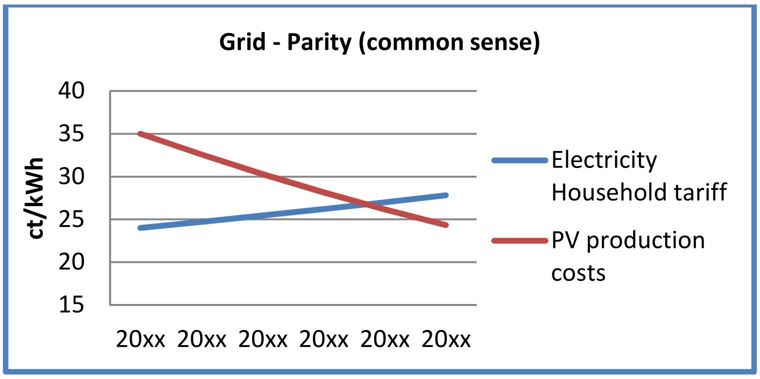

Figure 2 Grid parity

Technically this definition is not correct, as it does not consider the highly appreciated attribute "availability on demand" which is already included in the standard household tariff. To include this attribute, the PV production costs would need to include an all year balancing of energy supply using mechanical or chemical storage methods. Considering the strong difference in irradiation between winter and summer in all European regions and the resulting high storage demand, the total production costs for a PV system to match "grid parity" would be significantly higher.

This thesis solely considers grid parity in the form that the production cost for PV with an average annual irradiation matches the standard household electricity tariff.

2.2 Grid parity overview

To forecast when grid parity will be reached is only very limited covered in this thesis and as it is not within the main scope of work. Many other major scientific studies are dealing with this topic. Heilscher et al 2010 and Breyer et al 2010 are two very recent papers dealing with this topic.

Grid parity studies need to deal with a wide range of influencing factors, among others including capital costs, solar irradiation, PV system costs, maintenance costs, insurance costs and most important, regional household energy tariffs. Looking at the table below, it can be seen that in January 2011 the final electricity household price per kWh varies within the EU-27 countries nearly at a factor of three. Bulgaria offers the lowest price with 9,7 cent/kWh while Denmark marked highest with 26,3 cents.

– ELECTRICITY RATES FOR HOUSEHOLDS–

- Average price per one kilowatt-hour.
- Incl. energy taxes & VAT.
- Prices based on a consumption of 3,500 kWh per year
- Effective: January, 2011

Austria	€ 0.2038	Latvia	€ 0.1207
Belgium	€ 0.1921	Lithuania	€ 0.1061
Bulgaria	€ 0.0970	Luxembourg	€ 0.2011
Cyprus	€ 0.1764	Malta	€ 0.1580
Czech Rep.	€ 0.1557	Netherlands	€ 0.1952
Denmark	€ 0.2632	Poland	€ 0.1457
Estonia	€ 0.1010	Portugal	€ 0.1779
Finland	€ 0.1401	Romania	€ 0.1084
France	€ 0.1305	Slovakia	€ 0.1630
Germany	€ 0.2455	Slovenia	€ 0.1363
Greece	€ 0.1139	Spain	€ 0.1855
Hungary	€ 0.1798	Sweden	€ 0.1536
Ireland	€ 0.1855	United Kingdom	€ 0.1447
Italy	€ 0.2085		

Figure 3 European Electricity rates for households (Zwanenburg 2011).

The solar irradiation is another factor with a high regional difference within Europe. Irradiation in the northern part of Finland is as low as 800 – 900 kWh/m²year while in the south-western part of Spain or in Sicilia it is reaching nearly 2000kWh/m²year. Another factor of 2 that strongly influences the point of time when grid parity can be reached. Other factors like capital costs, system costs or insurance costs are less influenced by the geographical location as they can be sourced on any other European market in the same way. Resulting transport cost don`t have any significance in the overall cost calculation.

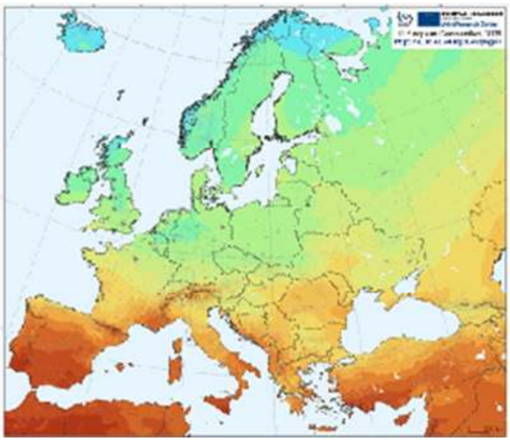

Figure 4 Solar irradiation map Europe (Sùri 2006)

Apart of "waiting" until the electricity prices will raise to an adequate level, the reduction on the specific investment cost for PV is the main driver to meet grid party. To forecast the pricing level for several years or even up to decades, using learning curves or learning rates is the most applied way. A learning rate of 20% would indicate a 20% price reduction every doubling of cumulative installations. Each technology and industry segment has some specific learning rates that can be observed and for PV the long term learning rate is in the range of 20% (Nemet 2005, Swanson 2006), possibly slowing down to 15% after 2020. Given an annual growth rate of 45% in the last decade (Breyer 2010) leaded to an average annual price reduction of 9%. The forecasted compound annual growth rate (CAGR) is expected to slow down to approximately 25-30% (Despotou 2010), which would result in further price reductions of approx. 7-9% per year. This matches the objectives of the feed in tariff of the German Erneuerbare Energie Gesetz (EEG) which targets an annual price reduction of 9% (based on an annual installation volume of 3 GW peak).

2.3 Approaching grid parity in Europe

Obviously countries with high electricity household tariffs and high irradiation levels will be the regions to achieve grid parity first. In Europe, the residential area of Italy and Cypress will be the most promising countries in this aspect.

Brayer 2010 has outlined in his study presented during the solar energy conference 2010 that by 2016 already 70% of the residential and 30% of the industrial consumers will have exceeded grid parity level. By 2020 already 80% of the private sector and 75% of the industrial segments will be within grid parity zones.

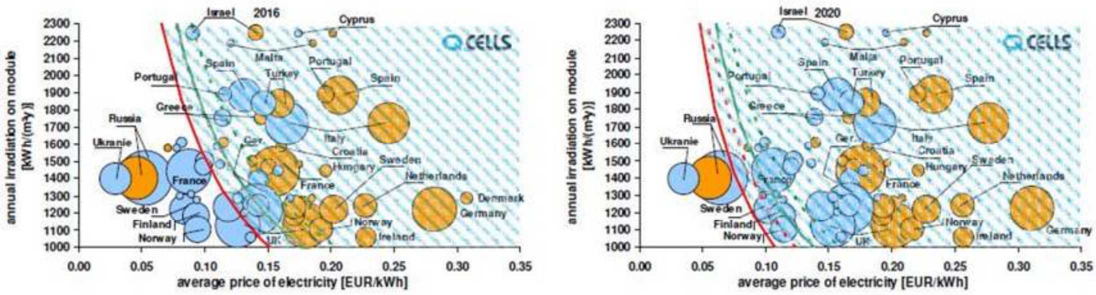

Figure 5 Grid parity in Europe 2016 and 2020 (Breyer 2010)

This figure clearly shows that dealing with “post grid parity topics” is not a topic that can be postponed to future tasks, but is much more a hot topic regarding required actions, as 2016 is in some countries already within the current political setup.

2.4 PV Industry

PV systems are small scale power plants consisting of the main PV module, installation facilities and the inverter required for the grid connection. Looking at the cost structure, module costs still make up the highest costs of turnkey solutions (Solarbuzz 2011) though a significant shift towards balance of system costs (BOS) is visible. BOS include factors like installation, cabling, grid connection and therefore a high level of human workforce. According to Kochan 2003, in 2002 module costs still made up 83% of the system costs while analysts of Solarbuzz 2011 are expecting for 2012 BOS costs to reach 50% of the TCO, while the learning rate remaining low.

Nevertheless, modules and inverters (partially included in the BOS) still further drive technology and pricing evolution through the enormous effects of the economy of scale, therefore also the manufacturers of the various components of one module are the significant industry representatives on this market.

Willeke 2011 used in his report data of company Centrotherm from 2008 to show the following split of module production costs.

Kristalline Si-Module werden in sechs Schritten hergestellt: Dabei gliedern sich die Kosten (in etwa) folgendermaßen (Centrotherm 2008)

Herstellungsschritt	Verfahren	Kosten (€/Wp)
(1) Silizium-Herstellung (mg-Si)	carbothermische Reduktion von Quarzgestein zu metallurgischem Silizium im Elektroschmelzofen	0,01 €/Wp
(2) Silizium-Reinigung (sog-Si)	Aufreinigung zu solar-grade-Silizium im Siemens-Verfahren mittels Chlorsilanen	0,20 €/Wp, (Siemens-Prozess)
(3) Kristallwachstum	p-Typ (Bor) Kristallwachstum durch Blockkristallisation (poly) und Czochralski-Verfahren (mono)	0,14 €/Wp
(4) Waferherstellung	Wafer-Herstellung durch multi-wire slurry saw MWSS	0,18 €/Wp
(5) Zellherstellung	Zellherstellung mittels Siebdruckmetallisierung	0,28 €/Wp
(6) Modulherstellung	Modulherstellung durch String-Fertigung und Glass/EVA/Tedlar-Laminierung	0,45 €/Wp
Gesamtkosten		1,26 €/Wp

Figure 6 Crystalline Si-Module production costs - data from Centrotherm 2008.

The absolute highest share of costs was resulting from module production with 45 €cent from 1,26 € total module total costs.

Also Interestingly to note that Kochan 2003 has in 2003 very well predicted the system costs for 2010 which have reached values close to 2.000 Euro per KWpeak.

This chapter is essential for a better understanding of global photovoltaic event dynamics and deriving scenarios for PV growth rates.

2.4.1 Silicon

Silicon is the main feedstock for the global PV market as still an estimated 75% of produced modules are based on mono- or polycrystalline technology in comparison to the remaining 25% thin film based solution (EPIA 2010). Outlooks to 2014 and beyond don`t show any significant changes on this ratio, as subsidy programs continue focussing on BIPV and roof-top installations where the much higher efficiencies and therefore possible power outputs of silicon based solutions will remain the differentiation factor. In my point of view, lower production costs of thin film solutions can`t compensate the efficiency advantage and the higher costs for ground space, especially taking effect for city roofs or any other form of energy production close to inhabited areas. Considering further more the required grid investment for centralized solar powered large scale plants (Hofer 2010), a significant break though of Thin Film technology is not very likely.

Polysilicon supply faced a strong outage in 2007 with prices reaching as high as 500 US$ per kg compared to the current market price of roughly 50 US$ (iSupply 2011).

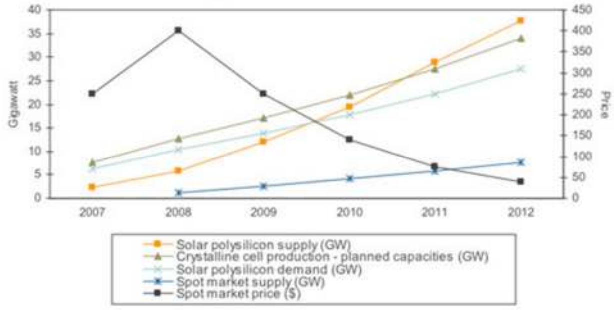

Figure 7 Correlation of polysilicon supply/demand and resulting spot market prices (iSupply 2011.

Aulich 2010 pointed on the correlation of Wafer thickness and polysilicon spot market prices. This shows a remarkable period of increasing wafer thickness, starting shortly after the breakdown of silicon prices starting in 2008.

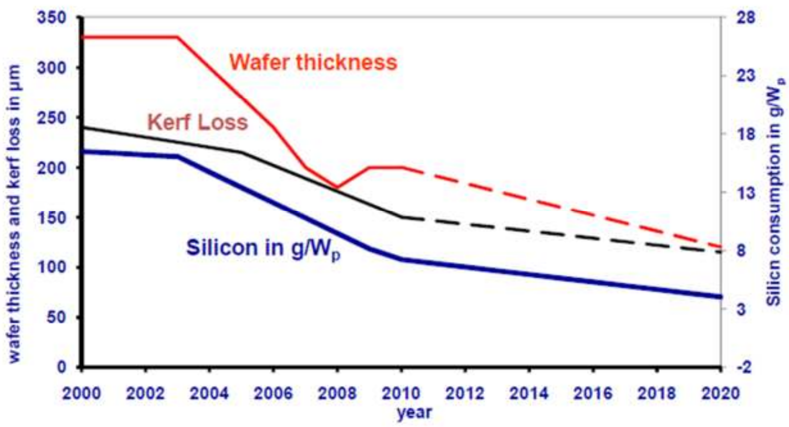

Figure 8 Wafer thickness evolution (Aulich et al 2010)

This could be an early indicator that industry is able to very quickly adopt on the feedstock price for polysilicon and applying new standards for production if required through economic reasons. As a result the feedstock demand per Wp could be reduced from 8g down to 4g/Wp by 2020 as predicted by Aulich et al 2010.

The supply market for silicon could be considered an oligopolies market, as the very high barrier to entry (factory investment) and the very low market price expected for the next decade will probably not see any new players in the market. The market is very much comparable to the energy market, with the difference of unregulated pricing structures.

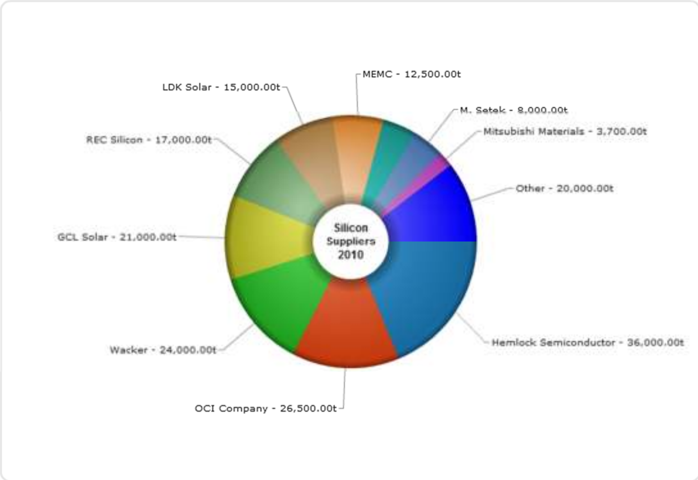

Figure 9 Polysilicon market overview (Greenrhinoenergy 2011).

A very interesting detail showing the saving potential on silicon is also the EBIT (earnings before income and tax) margin of the German manufacturer of Polysilicon Wacker AG, which achieved the value of 42,9% (Wacker 2010). Wacker expects production of approximately 33ktons in 2011 of polysilicon which should cover an annual demand of 5 GWpeak of Modules.

Also interesting to note, that polysilicon for PV has already outnumbered the quantity used for the semiconductor industry by a factor of 10. This means that PV is not anymore competing with Microprocessors or flash storage devices but much more vice versa.

2.4.2 Wafers

The production of wafers is typically not anymore manufactured by the producers of polysilicons. Vertically integrated companies like Solarworld produce most of their wafer demand themselves. The process of producing Wafers already mainly determines the final efficiency of the module. A key factor is the wasted raw material (kerf) while cutting the silicon blocks into wafers. A typical loss rate is still at 50% while taking an overall silicon cost factor of 28% (Kochan 2003).

Apart of the strong tendency to reduce the wafer thickness, increasing the efficiency related to the material input, automation (reduction of man power) and throughput of production lines are the main drivers of innovation of the wafer productions.

Dominating manufacturers of wafer production lines are Swiss based company MeyerBurger and German based Centrotherm. Also in these highly automated processes, the economic value added is mainly generated by the central European OEM machinery market.

2.4.3 Cells

Solar cells are the “finalized” silicon products ready to convert solar energy into electricity with an already defined efficiency grading. Cells are often delivered in the standardized format of 156mm x 156mm. Solar cell already provide the required characteristics of complete modules (or solar systems) on a small scale.

Class	Pmpp [Wp]	Efficiency [%]	Vmpp* [mV]	Impp* [mA]	Voc* [mV]	Isc* [mA]
4.39	4.39-4.44	18.22-18.43	526	8354	623	8878
4.34	4.34-4.39	18.01-18.22	524	8302	617	8808
4.29	4.29-4.34	17.81-18.01	521	8286	615	8795
4.24	4.24-4.29	17.60-17.81	519	8249	614	8764
4.19	4.19-4.24	17.39-17.60	517	8179	613	8763
4.14	4.14-4.19	17.18-17.39	514	8116	613	8753
4.09	4.09-4.14	17.98-17.18	513	8060	613	8750
4.04	4.04-4.09	16.77-16.98	513	7926	612	8744

The electrical data applies for standard test conditions (STC): 1 000 W/m², 25 °C, AM 1.5 (IEC 60904-3 ed.2 2008); Tolerance P: ±1.5 % rel. **

Temperature coefficients: α (I_{sc}): +0.02%/K β (V_{oc}): −0.36%/K γ (P_{mpp}): −0.47%/K

Figure 10 Example Solar Cell characteristics of Bosch M3BB cell

Cell manufacturers are competing based on pricing and efficiency parameters of the cell but also in the technology on how the electrical bus lines are placed or which connecting methods the cells would use.

Cell production is often directly included in the Wafer production process therefore also the same OEM machine builders are providing the equipment to the actual producers of cells located all around the world.

The highest production volume of cells is generated in China, followed by USA (mainly Thin film) and Japan. Interesting to note, Germany does not have any significant share in cell production even though it is by far the biggest end customer market.

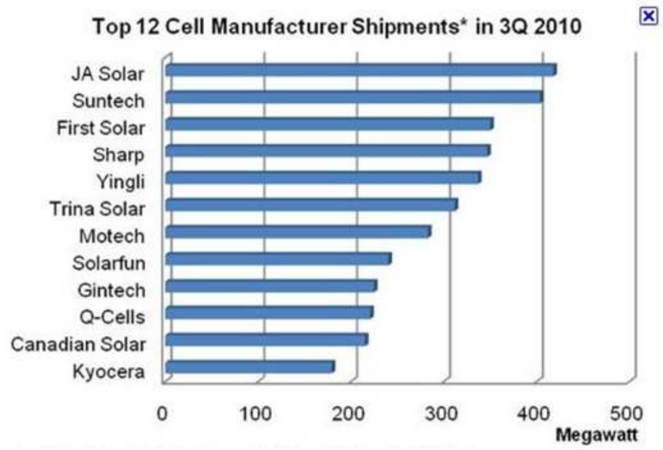

Figure 11: Top 12 Cell Manufacturers Q3/2010 (Solarbuzz 2011)

Looking at the annual report of Cell producers, operating margins are comparable low. Chinese Yingli presented the 2010 net profit margin with a rate of 11%, even though the turnover was nearly doubled within this year. German Q-Cells could present a 6% EBIT after 2 years of negative profit.

To summarize, Cell production already shows signs of a very mature, but still significantly growing market. Entry into this market is basically possible for every player in the semi-conductor industry as the handling is comparable to microcontroller manufacturing and equipment is sold as turn-key solutions. It can be assumed that companies like Samsung, LG or Panasonic will even stronger enter this market and further reduce the costs by benefitting quickly from economy of scale factors and most modern production facilities.

Return on Invest needs to be realized within less than 2 years of purchasing new equipment. Transport of cells to end customer markets does not involve any significant costs, as the volume for cells (150-250µm thickness and 156x156mm) is negligible and there is no time constraint requiring air-transport.

2.4.4 Modules

Module production in 2011 is mainly characterized by two major aspects. First, modules have a very high space demand measured in m³/kWpeak. As a rough estimate using containers with 30m³ capacity (20' container) and a space demand of approx. 0,1 m³ for each module (including packaging), an estimated 300 modules can be shipped with one container resulting in significant additional transport cost. On the other hand module production is still a process with a high share of manual workforce which puts low cost production countries like China into a favourable position.

A highly automated module production process will be required in order to gain a significant cost reduction. Robot manufacturers like German Kuka (www.kuka-systems.com) are already providing turn-key fully automated production lines. Interestingly to note, that first orders have been announced by Chinese manufactures rather than German module producers as would be expected.

Figure 12 Kuka module robot (Kuka 2011)

The status today (Kaizuka 2010) stills shows dominantly local producers rather than centralized Chinese production centres as with the cell production.

Figure 13 Cell (left) and module production (right) production [MW] (Kaizuka 2010)

2.4.5 Inverters

Inverters are required to transform the DC current produced by the PV modules into AC current required for grid connection. Burger 2007 has shown the efficiency evolution from an average of 90% in 1991 reaching 98% in 2007. Pricing of Inverters in this period has been reduced proportionally higher than the total system prices of PV. Looking at today's datasheets of inverters produced by the leading manufacturers like SMA, Fronius or Kaco, the efficiency is still indicated with values between 95% and 98.5%. Obviously the limit of efficiency evolution for inverters has already been reached and further pricing reductions are mainly achievable through economy of scale effects.

PV inverter business in the last years was very much dominated by few global players, especially focussing on this business. SMA, with an estimated market share of 45% (SMA 2011) is leading the field, followed by Austrian Fronius and KACO.

Inverter technologies are long established technologies and used in enormous quantities in industry applications. Several of these companies are now entering the market of PV which will put additional pressure on the existing pricing structure.

Figure 14 Market overview PV inverters: New players are coming (GTM 2010)

2.4.6 Balance of System

Balance of system costs (BOS) would typically include all components of a PV system except the modules. Because of their major contribution, inverters have been introduced in a dedicated section. BOS components are of extraordinary relevance for small household PV systems, as the manual labour for installation (cabling) and mounting of modules is a fixed part of the price structure. Even though industry has put efforts to produce “plug and use” mounting constructions, the annual increase of labour costs plus the cost for the infrastructure which are very much depending on raw material costs of copper and aluminium, keep the total BOS costs very much constant. Though through the decrease of retail pricing for complete systems, the sum of BOS costs become the dominant part of the package.

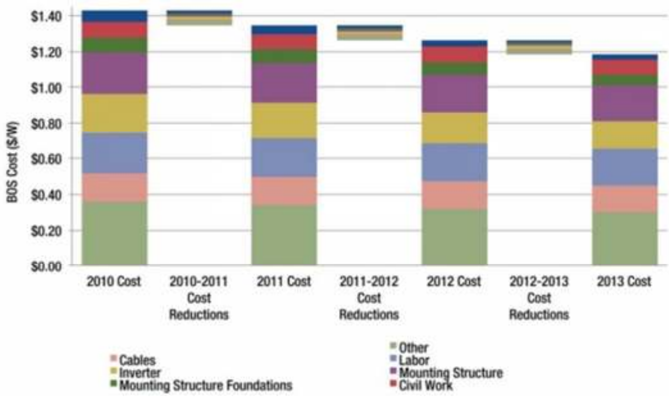

Figure 15 GMT 2010 forecast on BOS costs 2013

Even more alerting for politics and PV end users should be the analysis done by GMT 2011. The cost reduction forecast until 2013 only outlines an absolute reduction of 22 cents (USD) which relates to just about 15% of the total system costs of today (Solarbuzz 2011, values of 2010).

BOS costs will clearly become a major discussion and research topic of the next couple of years – in the mind of investors and system suppliers alike.

Very positive is of course the effect of labour work for the local value added and might therefore from political point of view be of most interest.

3 Scenario development

This scenario is taking into consideration demand side only and does not consider current limiting factors.

3.1 The precision of PV scenarios

“Never trust a statistic or chart that you haven`t done yourself” – This famous saying shouldn`t indicate that all statistics are purpose made, tuned or modified to follow certain interest or manipulate the readers opinion. Nevertheless, every data dealing with future scenarios depends on factors that can`t be described with mathematical models in its entirety. Even more, scenarios are working with probabilities and only the result with the highest probability based on given data is typically shown. Some scenarios include a bandwidth of possible results by assuming pessimistic, regular and optimistic values. But if scenarios would also include the full bandwidth of options (also those will least probability rate) the result would basically be something like “everything is possible” and therefore of no use for anyone. Another uncertainty for scenarios are influencing factors that can´t be (easily) put into models like human behaviour, climate conditions or changes in politics.
The following chart shows the forecasted production capacity of PV in the European Union (EU-25) for the year 2015 given by various professional editors and research group. Most data has been taken from the World Energy Outlook series (2006-2010). The most recent number was taken from the European Photovoltaic Industry Association which again references latest data from the World Energy Outlook.

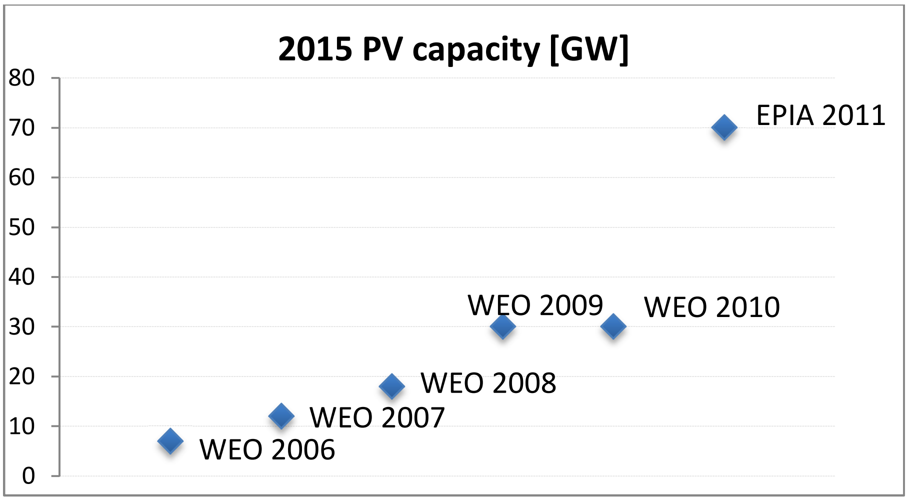

Figure 16 2015 PV capacity (WEO 2006, WEO 2007, WEO 2008, WEO 2009, WEO 2010, EPIA 2011)

For 2007 no capacity in GW was provided by WEO 2007 but only the estimated annual production of 15 TWh. For calculating the installed capacity for 2007, the productivity index was taken from WEO 2008 of 1.28 TWh for each GW of installed capacity (23 TWh production with 18 GW capacity).

World Energy Outlook 2010 was very much influenced by the world economic crisis and therefore expecting strong subsidy cuts of governmental support schemes.

The numbers of EPIA are the most recent ones, as this publication was published in May 2011 with a surely much less preparation lead time compared to WEO 2010 which was published in November 2010. According to EPIA 2011, by end of 2010 the installed capacity in the European Union already exceeded 29 GW.

Overall, the forecast for PV capacity in 2015 was revised from 2006 to 2011 by a factor of 9 and the 2015 forecast from 2009 was already achieved by end of 2010.

All numbers have been taken from the reference scenarios given in the respective sources.

3.2 Definition of main influencing factors

The concept of the scenario development is to forecast the annual growth rates of PV in Europe considering the grid-parity era and, in a first-step, only reflecting the possible growth rates of the demand side.

3.2.1 Types of PV installation

Depending on the type of installation also the influencing factors differ. As of today no standard EU wide classification of PV system types exists but most literature and also governmental support schemes differentiate between residential, commercial/industrial and ground mounted types.

Residential typically refers to small scale roof-top installations with capacities of up to 10kW peak. Germany is even considering up to 30kW for the highest feed-in tariff. Industrial/Commercial installations are typically considered PV systems built on top of industry building with system sizes of 10 – 100 kWpeak. Ground mounted systems are frequently supplied for tracker systems and can reach system sizes of up to 100 MW. Apart of the system size, the biggest difference is in the ownership structure as residential installations are owned by private persons and the other two forms are always in possession of industry companies, utilities or investors.

3.2.2 Profit and risk

Investing into corporate bonds, going to a casino, buying speculative penny stocks, bringing the savings to your home bank of trust or funding a new apartment for the children in their favourite university town? The way of dealing with savings in Europe has always been dominated by conservative, less speculative, methods (Leetmaa et al 2009). Savings on classical bank accounts is still the dominate form. It is also obvious, that this is not driven through the interest rates offered by banks (as it`s effective value is often lower than the inflation rate) but by its reputation of lowest possible risk.

Reflecting the last economic crisis and the involvement of banks in highest risk loans, it's going to be a philosophical question if our banking system (and therefore our savings) or the irradiation of sun (and therefore the output of electricity through our PV modules) is the investment of less risk.

Nevertheless, with the era of grid parity and assuming ROI times of less than 10 years while benefiting from 25 years performance guarantee of many module manufacturers, PV is offering superior attributes for classical "savings" oriented clients. The potential of shifting investments from classical forms to "photovoltaic investments" can also be derived from Leetmaa 2009. In the European Union (EU27) the saving rate in 2007 reached 10.8% of the gross disposable household income of 19.200 Euro per capita and year. This would correspond to an available investment volume of approximately 1.08 Billion Euro per year from private savings. Taking the current system costs for household (< 30KWp) plants of 2.5€/Wpeak, an annual capacity of 432 GWpeak could be installed per year.

The available amount finally going into PV investment will depend on the expected ROI. As for the competition with corporate bonds or stocks, the targeted ROI to be expected by the investors (private or corporate is likely) will be close to the 10% range based on historic experience. For example the US Dow Jones index between 1900 and 2010 was growing at an average of 9.1% per year, including a very high volatility for example in 1929, 2001 or in 2008 and therefore including a high risk for this form of saving option.

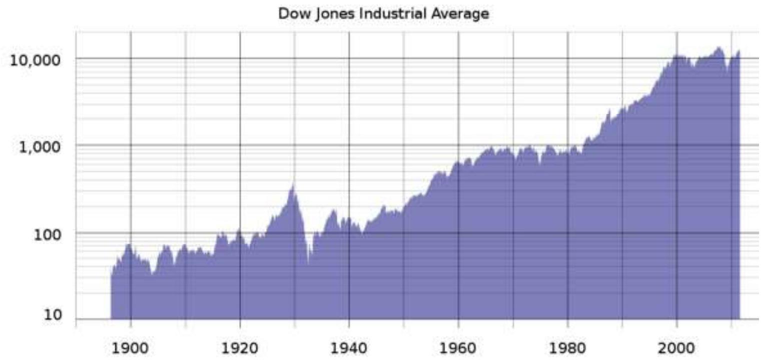

Figure 17: History of Dow Jones Industrial Stock market (New York Stock Exchange 2011)

Through the expected learning rate for PV in the range of 20%, the gap between household electricity price and production costs of PV generated electricity will be increasing and therefore improving the achievable ROI. This in return will again accelerate the annual installation capacity and further bringing down costs. A self-accelerating energy and finance eco-system.

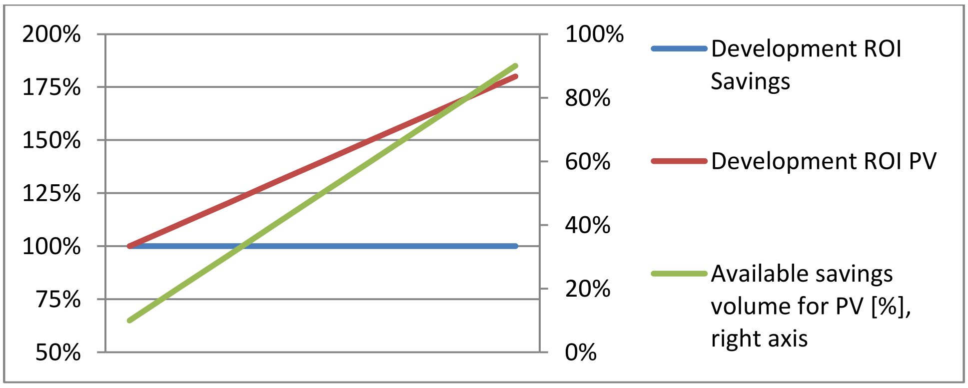

Figure 18 Potential savings volume moving into PV as a function of ROI ratios – schematic presentation

Figure 18 should visualize how much of the savings volume could be invested in PV. The ROI for classical savings is expected to be constant (levelling at 100%) whereas the PV ROI will be increasing as prices further drop and energy prices at least remain constant. The result will be a more attractive investment into PV rather than other forms of savings used so far. The numbers in the graph are not fundamentally investigated, but should rather illustrate the expected trend for the next years.

The post grid parity growth rate α for the profit and risk factor will be dynamic as with increased capacity and the resulting learning curve, the benefit over classical savings will increase, which again further accelerates the demand.

The resulting factor is assumed with

$$\alpha\,[\%] = 10\% + \frac{2\%}{doubling\ of\ cumulative\ capacity}$$

3.2.3 Green mind set – positive image

"I will buy a PV because it is beneficial for our environment to buy one". Certainly there is a number of potential PV users that might simply be attracted by the positive image of PV installation and therefore decide to invest. Nevertheless, the main reason not to invest is clearly the factor of cost and therefore the topic of "image" or green mind set is in my point of view negligible in the large scale sense of PV today. A high quality statistic about the PV investment reasons (economic reason, environmental reasons) could not be found. It would be different if the cost for environmental threats (CO2 certificate, nuclear waste storage) would be fully considered, but then this factor would be taken into consideration in the profit and risk section and again not part of the "green mind set".
This factor is not considered for any further work of this thesis.

3.2.4 Available physical space

This factor is a limiting factor and not required for the demand analysis.

3.2.5 Public awareness

The potential of photovoltaic in the public is widely unknown and many people still would consider PV systems only of interest for off grid installations for remote areas or a special hobby of "eco-fundamentalists".
Without public awareness, on industry (large scale PV) and residential (roof top PV) level alike, demand (through basic awareness) will be generated only very slowly through neighbourhood success stories.
This thesis does not deal with possible measures on how to generate public awareness, but nevertheless will be an important factor for all PV scenarios.
Basically by just spreading information on the most recent ROI calculations via newspaper, magazines and especially websites will help strongly to push the usage of PV. As an example 29 cent per kWh feed-in tariff compared with purchasing 5kWpeak PV system for 14.500 Euro isn`t a very easy baseline for discussion. But saying that it has paid off after 9 years with an expected lifetime of more than 20 years (plus any additionally referring to the pension system) could put a very different view on the decision maker.
On the main European markets (Germany, Italy, France) so far the public awareness is working well – especially in Germany the confidence to invest in PV systems is extremely high and this is very much further driving the roll out. On the

contrary in Czech Republic the changes in legislation for the PV market will generate uncertainty about the long-term availability of grid-connection and therefore financial compensation for generated electricity.

The growth rate factor β for the public awareness will be less influential than the factor α. For this thesis it is considered constant with

$$\beta = 5\%$$

which would relate to an increase of the CAGR of 5% through potential investors, looking at examples of already installed systems.

3.2.6 Longing for energy autonomy

This factor should basically reflect the need for most human beings to feel independent and self-determining. Similar to what we have seen during the economic crisis starting in 2008, that even though the risk of unemployment rose or income dropped, demand for own property increased significantly. This request for own independence already approached the energy supply significantly in the last decades. In the 70s the oil crisis affected the daily life of Europe in its entire and more recently, the gas crisis at the end of 2008 also affected our (especially Slovakian industries) daily activities. And this just because Ukraine and Russia were not clear about the amount of money Ukraine still owes to Russia. The central European countries affected most, where not even involved in the conflict itself. Though the longing for independence is a very human factor, also companies start introducing risk mitigation strategies for the energy supply as with a cut in energy supply, even just for some days, companies will struggle more than with a constant decrease of sales prices that can be compensated with other measures.

The tsunami disaster in Japan from March 2011 also showed the vulnerability of industries and cities to centralized large scale power plants.

Growth factor γ representing the longing for independence will have very little impact, as history has shown a very reliable energy supply so far and is considered with

$$\gamma = 2\%$$

3.2.7 Historic data

Even though this work deals with a new “post grid-parity epoch”, historic data are still the only hard facts that can be used for the scenario development.

Clearly one of the most important factors is the average Compound Annual Growth Rate (CAGR) which is shown below. It basically reflects all other historic data like annual installations, changes in PV subsidies and system costs. The numbers for the CAGR have been calculated from the historic values of the annual installed capacities given in EPIA 2011. The strong variance from 40% to more than 110% nevertheless shows a strong uncertainty of this value. The CAGR from 2001 until 2010 was 67%

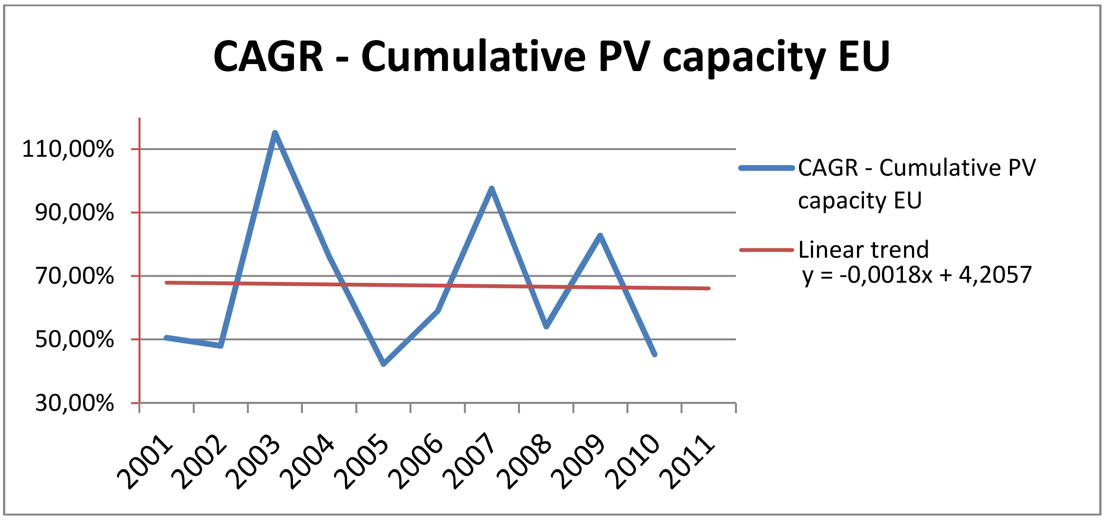

Figure 19 CAGR cumulative PV capacity EU (EPIA 2011)

The growth rate considering the historic PV deployment is referenced δ where

$$\delta = 67\%$$

3.3 The scenarios – Demand side

3.3.1 Mathematical baseline for the scenarios

$$system\ cost = function\ (module\ cost, BOS\ cost)$$

$$LCOE = function\ (system\ cost, O\&M, fuel\ cost, capital\ cost)$$

$$Grid\ parity\ \rightarrow LCOE\ \left[\frac{€}{kWh}\right] < Electricity\ consumer\ costs\ \left[\frac{€}{kWh}\right]$$

As grid parity is the basic assumption for the entire thesis, the LCOE for PV and the electricity consumer costs are not any more relevant for the development of the scenarios.

$$Post\ grid\ parity\ growth\ rate = function\ (current\ annual\ installation, \alpha, \beta, \gamma, \delta)$$

All growth parameters will be accumulated to a new adopted CAGR [%] and applied to the latest available figure of installed capacity.

3.3.2 As-Is Scenario

The As-Is scenario only considers the historic growth rate δ and does not consider any other growth rate parameter.

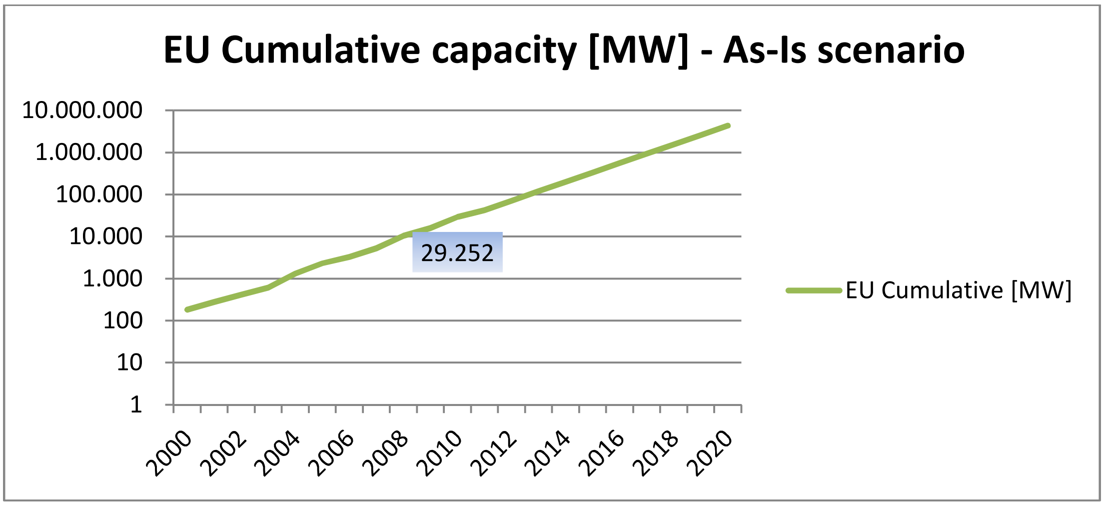

Figure 20 Cumulative capacity 2020 - As-Is growth scenario

Figure 20 considers the actual capacity values from 2001 until 2010 and forecasts the period of 2011 until 2020. 29.252 GW is the official number provided by EPIA 2011 for the capacity available by end of 2010.

Already with an annual increase based on the historic CAGR, the scenario (attention – logarithmic scale!) would result in a 2020 cumulative PV capacity of 4.300 GW.

According to the World Energy Outlook 2010, the total electricity capacity in Europe for 2020 will reach 1026 GW. This would mean that the forecasted PV capacity would exceed the total EU cumulative power forecast, including nuclear, water, gas, coal and all renewables, by a factor of 4.

The overall likelihood of this scenario to become effective is very low.

3.3.3 Pure-demand scenario

The pure demand scenario considers all above mentioned factors that will potentially further increase the CAGR through some post grid parity effects.

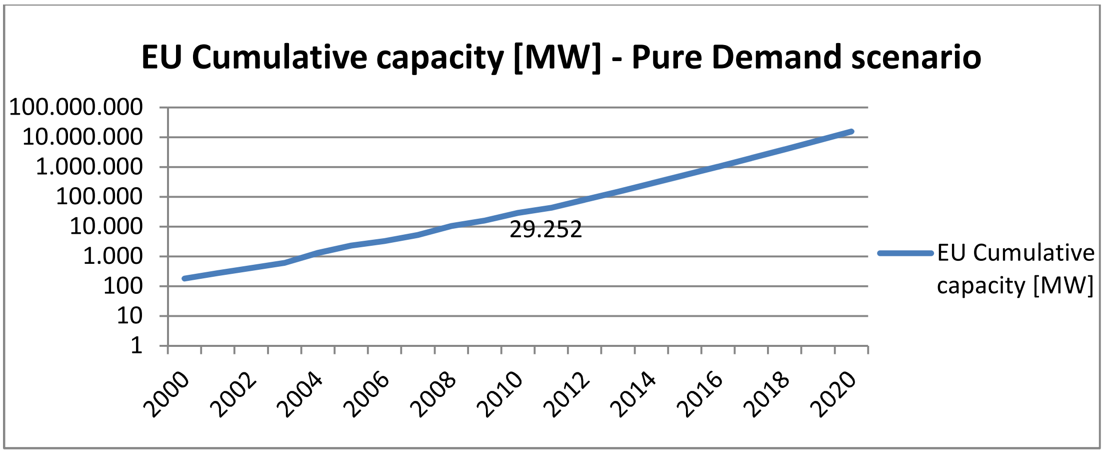

Figure 21 Cumulative capacity 2020 - Pure Demand scenario

Again the chart takes all historic values from 2001 until 2020, but instead of continuing with the historic CAGR δ, also the factors α, β and γ are included and further accelerate the PV roll out. The new CAGR from 2011 until 2020 was calculated to reach 93%. Furthermore this chart assumes that grid-parity has reached all over Europe at the end of 2011.

The resulting forecasted cumulative capacity of PV in Europe is calculated with 15.500 GW. This would correspond to an output electricity power on sunny day in Europe of approximately 15.000 nuclear power plants.

Booth scenarios clearly outnumber all most positive and optimistic forecasts of PV industry. Even though PV roll out has been considerably underestimated by many different kind of professional energy scenarios, it is highly unlikely that either of these two scenarios will be fulfilled throughout the next decade though the growth rates indicate kind of maximum numbers that all related aspects of the energy market should consider when dealing with PV roll out scenarios.

4 Evaluation of raw material requirements

Mono –and polysilicon based PV systems will be covering a major share of more than 75% of the market (EPIA 2010) as subsidies focus rather on roof-top based systems which have less available space and therefore favour high efficiency modules. Thin film technologies are not covered in detail within this thesis as it is not clear which exact technology will be of significant importance in the long term aspect. Currently Cadmium Telluride (CdTe), Amorphous Silicon (a-Si) and Copper Indium Diselenide (CiS) modules are the most common types which are in volume production today. An interesting study was conducted by Bleiwas 2010, who showed the required thin film based material for the production of 4 GWpeak photovoltaic power plants. The evaluation was done based on CIGS and CaTe based thin film technologies (see figure below).

Type of photovoltaic technology	Metals required		
	Metal	Quantity[a2] (metric tons)	Percentage of 2008 estimated world refinery production from primary sources[3]
Thin-film CIGS	Gallium	30	27
	Indium	90	16
	Selenium	180	6
	Total	XX	XX
Thin-film cadmium telluride	Cadmium	340	2
	Tellurium	390	82
	Total	XX	XX

Figure 22: Material requirement for 4 GWpeak thin film plant (Bleiwas 2010)

Bleiwas 2010 also compared the required quantity for the 4 GWpeak setup with the estimated 2008 annual refinery production. The 4 GWpeak volume for CdTe should be reached before end of 2012 which should then already require 82% of the total annual Tellurium production. It was not possible to find out if the global Tellurium production can be easily increased if demand is further increasing. Also the main supplier of CdTe based thin film modules, US based company FirstSolar (www.firstsolar.com) does neither mention in their investors report any change in material strategy nor identifies any upcoming shortage in Tellurium.

Because of the higher relevance for the global PV market, especially for the European PV market, this chapter deals only with Silicon based product.

4.1 Required raw material per year

The silicon requirement for the PV industry is determined by three key factors:

- The installed capacity [kWpeak]
- The thickness of the silicon required to achieve a certain module efficiency
- The lowest possible kerf-loss (loss through cutting of wafers)

Taking the results from Aulich 2010 (see also chapter 2.4.1) the estimated demand on PV grade silicon (purity is > 99.9999) is currently 7.2g/W. Through the optimization in terms of efficiency and reduced cutting loss, the demand should be able to be reduced significantly throughout the next years.

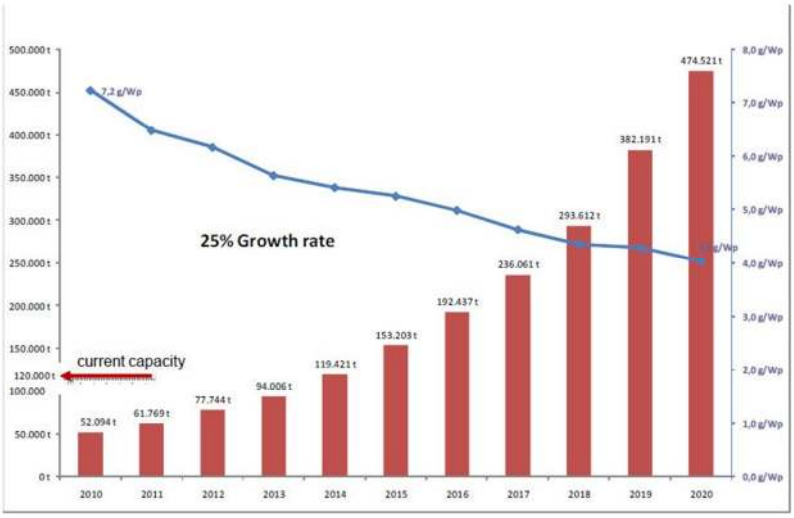

Figure 23: Expected Silicon demand / Wp for a 2020 scenario with 12% PV share of total electricity production (Aulich 2010)

For the deployment (and investment cost) of new production machines to fulfil the requirements on reduced kerf-loss, the growth rate as used by Aulich 2010 is the baseline. As our demand scenarios include a much higher PV installation base, the forecasted values can be taken as a reference.

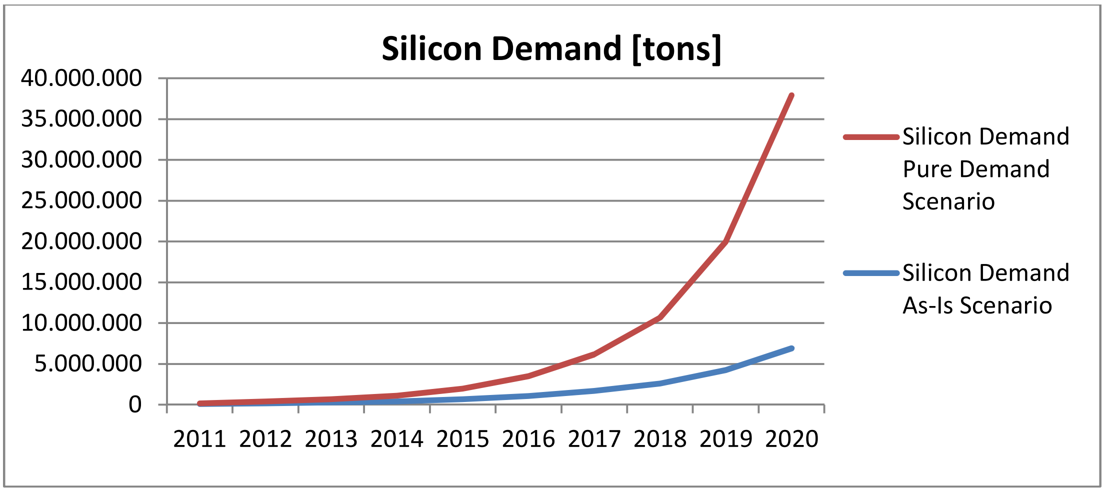

Figure 24 Silicon demand [tons] - for demand-only scenarios

Compared to the study of Aulich 2010, our scenario would require a ten folded supply of production in 2020 compared with our scenario using just historic CAGR or 30 times higher volume if compared with our pure demand scenario.

In the later scenario in 2020 a silicon feedstock of 31 Mio tons would be required to fulfil the demand of that year.

4.2 Comparison with feedstock availability

Silicon, a chemical abbreviated with Si, is one the most common elements on earth. Earth`s crust is made up of 27.7% of silicon by mass (Corathers 2009) and is therefore just behind oxygen the 2nd most available element.

Even though it would be possible to calculate the quantitative availability of silicon on earth, Corathers 2010, on the point of view of the U.S Ministry of Interior summarized in the most obvious way: “The reserves in most major producing countries are ample in relation to demand”.

There is clearly no lack of feedstock of the key element of PV modules expected.

Looking at production capacities also an optimistic picture can be shown.

With the example of Wacker Chemie, Germany`s leading and global number two polysilicon producer, provided an outlook about their production facilities (Wacker AG 2011).

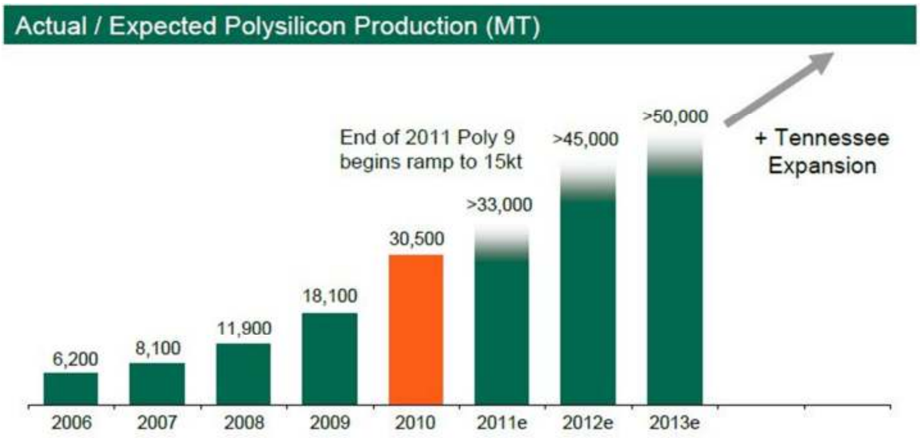

Figure 25: Polysilicon Production capacity (Wacker AG 2011)

Wacker Chemie could increase their production capacity from 2006 to the 2010 capacity by a factor of 5 and has announced further plans to increase to more than 50.000 tons by end of 2013. The CAGR that Wacker has targeted is 35%, which is still far below the more than 80% of the "Pure Demand" scenario developed within this thesis. Nevertheless, as the market is in a situation of more production output than demand, it is likely that with an increasing demand, also the production output could be ramped up faster.

Similarly OCI Company Ltd., who is also among the top producers of high purity polysilicon products, announced plans to multi-fold the production capacity.

Generation	Phase	Completion	Capacity (MT/year)
GEN1	P1	Q1, 2008	6,500
GEN2	P2	Q3, 2009	10,500
	P3	Q4, 2010	10,000
	P3.5(1)(2)	Q3, 2011	8,000
	P3.7(1)(2)	Q4, 2011	7,000
GEN3	P4(2)	Q4, 2012	20,000
GEN3	P5(2)	Q4, 2013	24,000
Total			86,000

Figure 26: OCI Co. Ltd Production capacity plans (OCI 2011)

The aimed CAGR from 2008 until 2013 is 68% and would exactly match the growth rate in the As-Is scenario.

4.3 Comparison with competing industries and it`s forecasted growth

The only competing industry on the polysilicon market is the semiconductor industry. It is used for the production of all electronic equipment with the usage of polysilicon in the most pure form (higher than 99.9999%).

Until the PV market started to take off in large scale, the semiconductor market was the only consumer of these high grade silicon products.

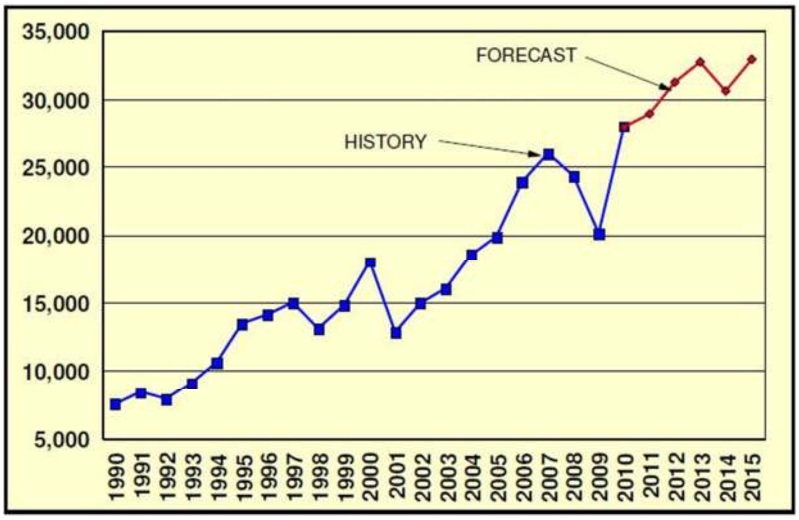

Figure 27: Polysilicon demand from Semiconductor industry in tons (Winegarner et al 2011).

Even though we saw a strong increase and a steadily growing demand in the semiconductor market between 1990 and 2010, the study done by Winegarner et al 2011 showed an increase from 7.588 to 28.028 tons, in comparison with the PV market the significance on the global total polysilicon market is constantly decreasing.

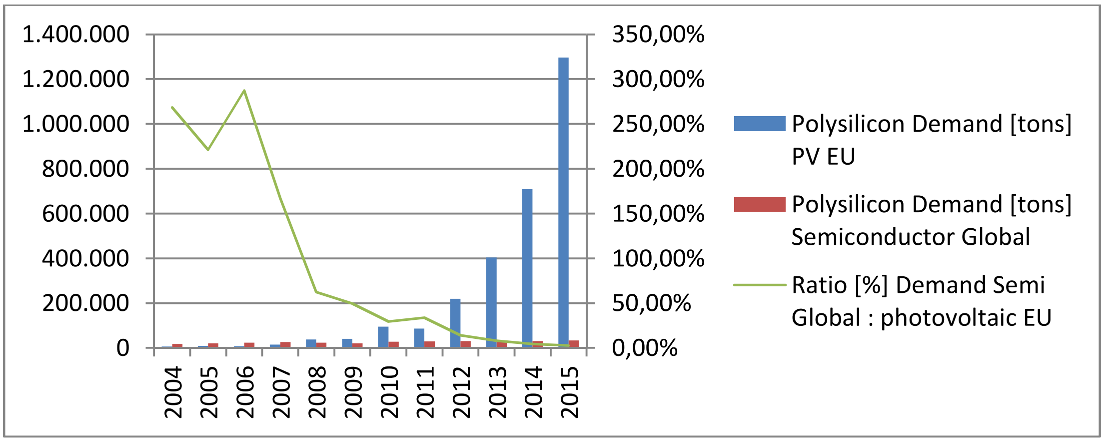

Figure 28: Relevance of Semiconductor industry for PV demand

Until 2007 the semiconductor industry was the determining industry for the global polysilicon demand, but already in 2008 the demand for the PV industry in Europe outnumbered the demand for the global semiconductor market.
By 2013 the demand for PV polysilicon in Europe will be a factor of 10 higher than the demand forecasted for the semiconductor industry by Winegarner et al 2011. As a consequence, I don`t expect any impact on the PV industry by any scenario of the semiconductor industry but rather see a strong influence of the PV market towards the semiconductor industry.

4.4 Possible influence on PV system costs

As of today, by assuming system costs of 2.000 Euro per kWpeak the polysilicon demand is 7.2 Euro per Watt and the current spot market price of 55€ per kg of polysilicon. With this aspects, polysilicon costs are 396 Euro / kWp corresponding to as much as 19.2% of the total system cost (including BOS cost).
A general market expectation (but not fundamentally confirmable), because of the general polysilicon oversupply for 2012, is a spot market price of 35€ per kg. This would result in polysilicon cost of 252 Euro and without requiring any technical advances reducing the system cost at 144 Euro (or 7%). The production process of polysilicon is a well-established, capital and energy intensive, process and did not show any strong learning rate throughout the last decade. The price was mainly determined by the correlation of supply and demand and not determined by any new upcoming technology. The interesting question would be about the lowest possible spot market price in a fully competitive market. No credible answer was found in literate but some correlating answers discussed about 25 € per kg polysilicon as the lowest possible cost to still achieve positive operational margins.
Taking the targeted polysilicon consumption of 4g for 2020 (Aulich 2010) with 25€ per kg, the resulting cost factor for the base feedstock would be exactly 100 Euro for each kWp and a total cost reduction on the system cost of roughly 15%. Of course the reduction from 7.1g to 4g also requires new generation of wafer and cell production methods and therefore a general investment in R&D along the supply chain.
In general I don`t expect a limitation on any kind of future PV scenario through the supply of polysilicon. The system price will in the future strongly depend on the supply and demand ratio of polysilicon. An increase of capacity by setting up new plants only becomes affective after 2-3 years which will potentially lead to a certain time of undersupply with polysilicon and resulting in higher silicon cost. In the long

term, in a mature and competitive market (which is possible as the feedstock is not limited to certain countries or regions), supply and demand will perfectly correlate on the economically lowest possible pricing range.

5 The grid

5.1 Objective of the electricity grid

Our electricity distribution and transmission grid (further referred to as “the grid”) is designed to transport electricity from remote power generation plants to the decentralized consumers like industry or private households. A key attribute of electricity systems is the fact that the energy has to be consumed at the same moment when it was produced. Storage always involves conversion losses or high investments compared to the low storable energy.

The European grid is divided into various transmission and distribution levels, depending on the amount of power it is able to transport. The European grid typically operates with levels of 380kV for “the backbone”, 110kV for the connection of smaller cities, mid-size power plants (e.g. large wind parks) or very big industrial consumers (steel plants) and with <50kV for regional connections.

5.2 Energy demand vs. PV electricity supply

5.2.1 Solar radiation pattern

Availability of solar electricity can be optimized by adjusting the PV systems inclination and azimuth angle, but much more depends on the general availability and distribution of solar irradiation. Season, daytime and general weather conditions strongly influence the capacity.

As an example I have taken the Germany city of Munich which is located in the centre of Europe. Conditions further south will be generally more favourable and further north will provide less output on a same installed capacity.

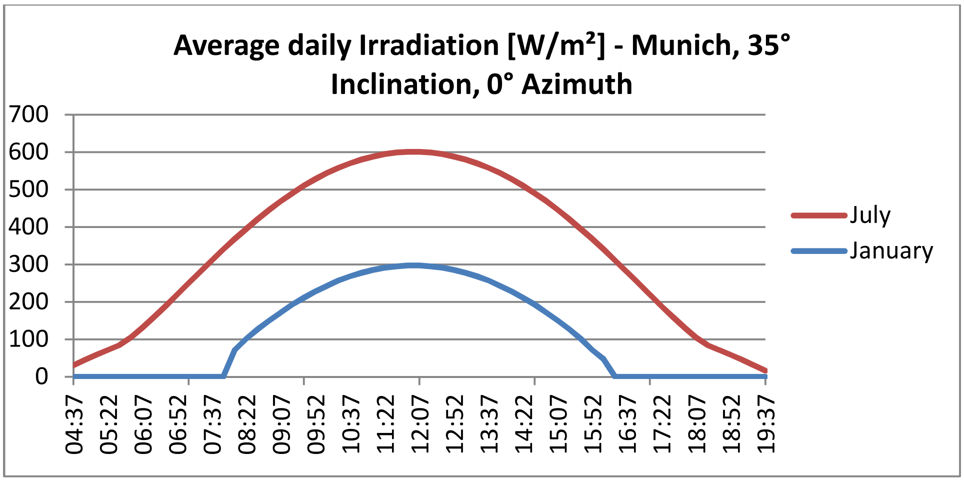

Figure 29 Average daily irradiation Munich (PVGIS 2011)

The annual irradiation [kWh/m²] for Munich is approximately 1300 kwh/m² for optimally inclined areas. What we see in the figure above is the obvious zero irradiation throughout the night time and the huge difference between summer and winter periods. The graph shows an average per day irradiation (including days with clear sky and days with 24 hours of rain) as some days, even in July, will have hardly any irradiation if the clouds are almost fully shielding the irradiation. There is no usable irradiation through the night time.

5.2.2 Electricity demand

The electricity demand on a regional basis varies strongly depending on, but not limited to,

- Household habits and household density (city or country side)
- Local industry segments
- Industry load factor (night shifts)
- Public holidays
- Weather conditions.

Generally the load curve can be very well described using historic values as household habits on a country or regional base don`t change. Also the industry follows some certain “default” load curve. To describe common load curves, so called standardized load curves are used. These data is provided by local TSOs (Vattenfall 2011) and in Germany specifically known under the abbreviation H0 (household) and G0 (small industry) load curve.

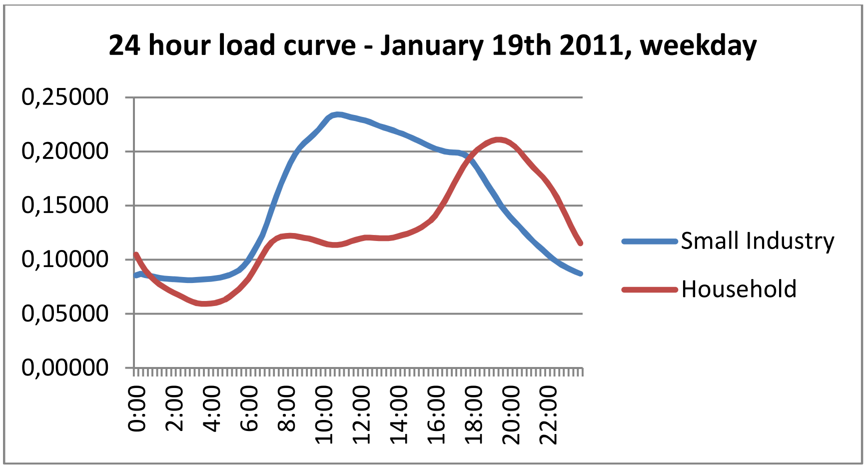

Figure 30: 24 hour standard load curve (Vattenfall 2011)

On a 24 hour base the demand curve for small industries overlaps pretty well with the supply pattern of “average” PV production. For households the demand is highest in the early evening, which, especially in wintertime, already is out of production time of PV systems. Overlapping both curves will result in a peak demand between 18:00 and 20:00 as well as just before lunch when the energy consumption of small industries is typically highest.

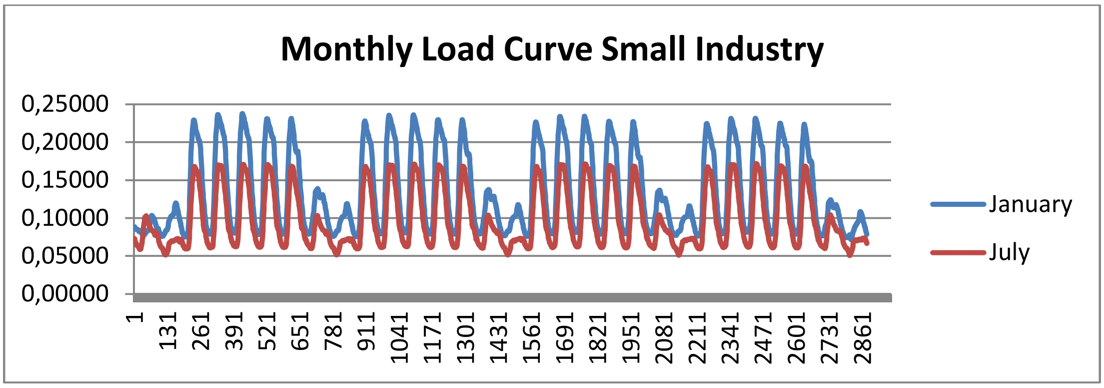

Figure 31 Monthly load curve small industry G0 (Vattenfall 2011)

As expected, when looking at monthly load curves for small industry, weekends show a much lower electricity demand than weekdays. Some industries (or shops) are working on Saturdays which is also shown in the G0 demand curve for 2011.

The consumption in January is 25% higher than the consumption in July.

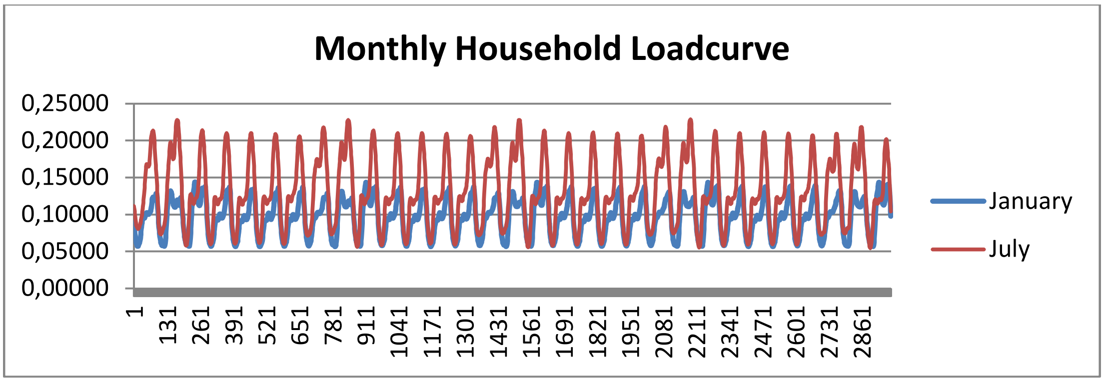

Figure 32 Monthly household load curve H0 (Vattenfall 2011)

In the household load curve the daily changes are very little. On Sundays the demand is generally highest, followed by Saturdays. Other weekdays follow a very balanced demand curve. The comparison between winter time (January) and summer time (July) shows an average difference of 26% and during day time an increase demand of plus 50% in winter time (while PV supply is generally higher in summer).

5.2.3 Demand and supply mismatch

Even not taking into consideration deviations of the statistical average of the PV supply, supply and demand curve look similar, but don`t overlap.

This is specifically related to

- Relation of winter / summer demand is reverse to supply curve
- Peak demand time of the day is in the early evening when PV production is very much limited.

Some measures or influence factors could improve the demand and supply correlation. In areas when energy demand in summer is very much increased by the usage of cooling systems, correlation of demand and supply would perfectly fit.

Another opportunity would be to extend the production period of PV systems by placing them in areas with more continuous and wider supply curve.

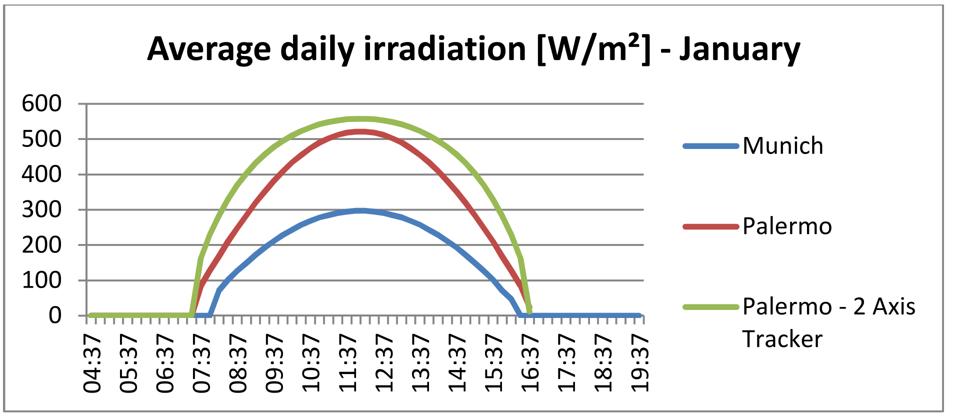

Figure 33 Irradiation comparison Munich - Palermo (PVGIS 2011).

As an example the picture above shows the irradiation per m² for a PV system in Munich and for Palermo, Sicilia. Palermo already shows about 80% higher irradiation than Munich in January and the supply curve could further be improved by using tracking systems. Of course tracking systems could also be used for systems in Munich but nevertheless even with using tracking systems, the supply curve doesn`t fully accommodate the demand.

5.3 Grid transmission capacity

Grid losses for currently installed capacities sum up to approximately 10% per 1000km (Sörensen 2004). Considering the distance of an estimated 2.000km between Munich and Palermo, the resulting loss would be in the range of 20%. This would still provide some benefit compared to the 80% additional gain from Palermo versus Munich so an energy transfer should be evaluated.

The net transfer capacity is mainly limited through the interconnection between countries. The European Network of Transmission System Operators for Electricity (ENTSOE) annually provides an overview of each interconnection capacity between all member states (currently 34 countries, including all EU-27). The map can be downloaded from ENTSOE 2011 and is updated twice per year.

Taking as an example the transfer from Italy to all neighbouring countries (Greece, Austria, France, Switzerland) the interconnection capacity is limited with 3750 MW which would only allow a very minor part of the total demand to be transported through existing network infrastructure. Looking at the connection from Italy to Austria only, it is currently limited with 285MW.

5.4 Grid applications

In order to evaluate if the European electricity grid limits the rollout of PV in Europe, first has to be defined for which type of applications the grid would be required.

For making use of electricity produced in southern areas like Sicilia for times of the day when PV systems are not anymore working in central Europe, I don`t think the current grid capacity is the limit. It is simply a question of providing more capacity in Munich than it would be required in Sicilia and as a reminder, this thesis deals with a post grid-parity era, the investment cost to install additional capacity for the early morning and late afternoon time should not affect the overall financial viability of these installations. In many cases, the gain in output will be balanced with the additional transmission losses for decentralized applications.

Grid capacity will be much more important if PV energy will be coupled with decentralized storage systems like large-scale pumped hydro plants. In this case the pumps need to be powered with PV electricity at the same time when the load anyway already is highest (during daytime). This is in contrary to the options provided by wind power plants, as they can be used also throughout the night.

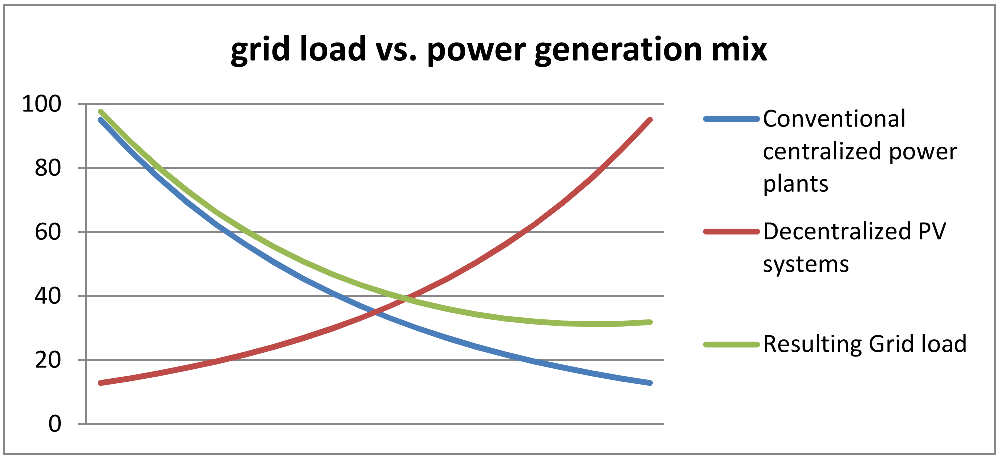

Figure 34 Grid load vs. power generation mix

Decentralized PV power generation (rooftop rather than MW size ground based solutions) generally works in favour of the grid load as the energy produced can be mainly consumed locally without putting load on the grid. Conventional centralized power plants (nuclear, coal, gas turbines, off-shore wind farms) put a very high load on the grid as all the energy has to be transmitted from the generation via the grid to the consumers. The picture above should provide a schematic picture of the resulting grid load while the energy mix is smoothly changing from 90% centralized and 10% decentralized PV to 90% PV and only 10% centralized large scale power plants. The grid load resulting through PV is estimated with 20% of the grid load.

The graph indicates that with an increased amount of PV on the market, the grid would be freed up providing spare capacity to serve large scale centralized hydro pump storage plants. These can then again be used for a night base load supply.

Essential for the stability of the grid is of course that supply matches demand. If the produced electricity through PV can neither be consumed locally (current demand) nor supplied to storage systems (central or decentralized) it is required that the grid operators (DSO/TSO) are able to take the PV inverters off the grid or reduce the amount of energy supplied.

The grid will only become the limiting factor if the required overall electricity demand exceeds the current grid capacity. What works with centralized large-scale plants, will also work with decentralized PV installations.

6 Demand of electricity in Europe

It wouldn`t make sense to produce more electricity that we can consume. This means that the overall limit for PV will be the amount if all conventional (fuel based) energy sources would have been replaced by PV. Furthermore it can be assumed that compared with today, more services will be available requiring electricity and other services will move to electricity powered forms (heat, transport).

	2008	2020	2025	2030	2008
Total generation	**3 339**	**3 572**	**3 703**	**3 832**	**100%**
Coal	940	668	590	517	28
Oil	105	42	29	24	3
Gas	786	853	893	934	24
Nuclear	937	937	922	910	28
Hydro	327	369	380	392	10
Biomass and waste	110	183	217	247	3
Wind	119	446	557	647	4
Geothermal	6	10	14	18	0
Solar PV	7	48	74	91	0
CSP	0	13	23	39	0
Marine	1	2	4	14	0

Figure 35 EU electricity generation [TWh] - New policy scenario (WEO 2010)

The International Energy Agency (WEO 2010) expects for 2020 a total electricity generation (and consumption) within the EU of 3.572 TWh. Considering a theoretical 100% share of photovoltaic (WEO 2010 expects ~1%) and an optimistic European average of 1300 kWh/kWpeak, the required installed capacity would be 2.748 GWpeak. The higher installed capacity compared with the WEO 2010 expectations is based on the much lower full load hours of PV compared with coal, nuclear or hydro power plants. This theoretical result would require sufficient storage (and resulting generation) options to cover night times, rainy weeks and seasonal effects.
Nevertheless, the required 2.748 GWpeak would not meet the “pure demand” curve with a total of 15.509 GWpeak in the 2020 scenario.
Considering further that it wouldn`t make sense at all to stop “fuel free” existing power plants (hydro, wind) the theoretical potential would further be reduced by 446 TWh resulting in 3.126 TWh of PV (2.404 GWpeak), again considering a theoretical existing equivalent storage capacity and infrastructure. The actual maximum required / produced load reached 420 GW on December 16th 2009 (ENTSOE 2009).

With an estimated increase of 10% until 2020, the maximum required load is expected to reach 462 GW peak. Subtracting again the installed capacity for Hydro in Europe (ENTSOE 2009) of 178 GW, the maximum required useful installed capacity for PV would be 284 GW. This requires that all other fossil or nuclear power plants are switched off for this point in time which of course questions the economic viability.

6.1 European centralized storage options

Hydro storage (dams or pumping systems) are the most mature, cost effective and widest used methods of storing energy (mechanical) and being able to convert it to electrical energy within seconds. This attributes together with a very high efficiency make them usable for

- Peak load supply (second and minute reserve)
- Daily load balancing
- Weekly load balancing

According to Gutschi 2010, the totalled installed capacity of pump storage hydro power plants reached 40 GW by beginning of 2010. A value of storage capacity in terms of total TWh could not be found (other scientific papers indicated the same difficulty during their research work) and exact measures of reservoir volume is not provided by all major hydro plants. Nevertheless taking the pumping capacity of 36 GW (Gutschi 2010) this would result in a generation capacity of estimated 11 hours compared to the required 13 hours of pumping. And 11 hours of generation capacity indicate **a** storage capacity of at least 396 GWh though the overall storage is estimated to be much higher. For long term, seasonal, storage hydro power plant will be clearly the path for the next decade and also the key limiting factor in terms of achieving a major (> 25%) share of PV in the overall electricity supply. Many new pump storage power plants are in preparation (e.g. in Austria Limberg II – went live on Sept 7th 2011, Reiseck II with joint capacity of 910 MW additional capacity).

6.2 Decentralized storage vs. own consumption

In order to even further avoid transmission losses and the building of new large scale centralized hydro pump storage plants, a decentralized local storage system would be also possible and is likely to be rolled out within the next two decades. Apart of storage, local battery buffer systems can also be used for grid stabilization. Possible storage possibilities, off grid and grid connected systems, are discussed in many scientific papers as part of today's PV research activities including Lippert et al 2010, Shimoo et al 2010 or Nge et al 2010. This thesis deals with the identification of limits and clearly the storage capacity, either local without investment into the grid, or centralized with adequate grid capacity is not available today, to support PV as required for the pure demand scenario. Decentralized storage options are already offered by some PV companies (e.g. Solarworld) though the increase in cost per KWh would be exceeding again the limits for grid parity. The detailed costs of installed storage capacity is still very fluctuating and no main stream technology and resulting costs have been identified as of today.

7 PV development – adjusted scenario

Considering the prior analysed limiting factors and comparing them with the artificially created pure demand scenario, clearly shows that the PV industry growth as it is today cannot be anymore continued with the 2001 – 2010 CAGR of 67%.

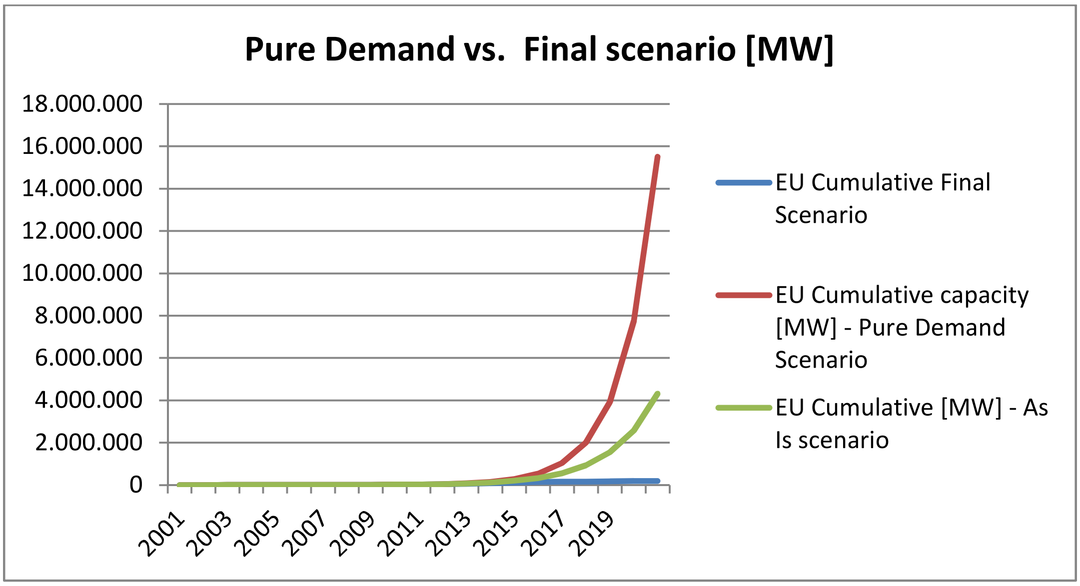

Figure 36 Comparison final scenario with pure demand scenario [MW]

Compared with the As Is scenario, the final adjusted scenario only reaches 183 GW. The As Is scenario reached more than 4 TW and the pure demand scenario 15.5 TW peak PV installed capacity.

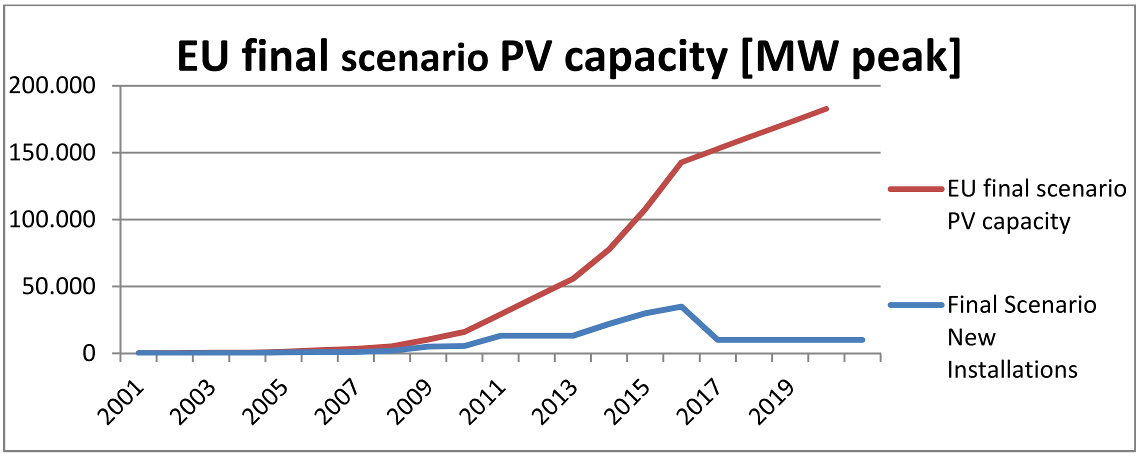

Figure 37 Final scenario PV capacity EU [MW]

The detailed developed final scenario assumes a zero growth in terms of new installed capacity until 2013 when grid parity will be reached in first areas according to Breyer et al 2010. 2013 until 2015 shows again a CAGR as it was derived from

2001 until 2010. By 2015, PV has reached a critical capacity for the European power plant infrastructure and all countries start quickly introducing caps for limiting the PV production.

7.1 Expected consequence on energy costs

An excess of PV without adequate storage capacity will not significantly influence the electricity tariffs because of unavailability on important peak demand times. As it is not expected to have large scale decentralized storage options before 2020 no further evaluation has been done on the cost forecast.

8 Conclusion

Against the wide public opinion, I expect photovoltaic to become the European energy source with the highest installed peak capacity in our energy mix, outnumbering coal, gas, nuclear and hydro before 2020. After 2014, with PV system prices reaching 1.5 €/kWh for rooftop installations, incentives will be redirected from wind towards PV and further boosting the demand. Wind will lose its attractiveness compared with PV because of missing grid capacity for large off shore parks and the general public will refuse local wind power plants in its neighbourhood area. The existing grid infrastructure is not the limiting factor for PV. Supply of silicon as well as products along the supply chain like wafers, cells or modules can be increased on the scale of the most optimistic scenario and is also not a limiting factor.

The limiting factor identified was the actual electricity demand in general, and more specifically demand through night time, cloudy days and winter time. The insufficient storage capacity (short time, weekly, seasonal) will limit an even more dominant role of PV until 2020. Until then PV can only take the share of generation that can be directly consumed. After that DSO will refuse the integration of PV energy into the grid and 100% rely on other sources for covering times with low or without solar irradiation. Caps for PV integration will be introduced as the available demand is already exceeded by PV supply during peak times. This means further that a large share of existing power plants need to be kept operational and depending on feedstock cost will serve as the main supply for night and winter times.

New generation of optimized battery systems (life time, load cycles, investment costs) will lead to a further boost of PV before 2030 and to a final replacement of conventional energy sources in Europe. In terms of viability of the PV industry, PV rollout will be widely matching demand by 2030 and afterwards there is no more need of large scale PV production apart of repowering and spare part business.

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10 Appendix

10.1 PV retail prices (Solarbuzz 2011)

Solarbuzz Retail Pricing

Date: June 2011

	unit	Mai 10	Jun 10	Jul 10	Aug 10	Sep 10	Okt 10	Nov 10	Dez 10	Jän 11	Feb 11	Mär 11	Apr 11	Mai 11	Jun 11
Module	US$/Wp (≥125 W)	3,78	3,77	3,73	3,71	3,61	3,59	3,51	3,47	3,38	3,29	3,19	3,12	3,11	3,10
	Euro€/Wp (≥125 W)	3,33	3,32	3,3	3,25	3,23	3,2	3,19	3,09	3,05	2,9	2,8	2,73	2,69	2,66
Inverter	US$/Continuous Watt	0,715	0,715	0,715	0,716	0,715	0,715	0,715	0,715	0,715	0,715	0,715	0,715	0,715	0,715
	Euro €/Continuous Watt	0,536	0,579	0,572	0,544	0,558	0,522	0,508	0,543	0,537	0,522	0,515	0,508	0,479	0,500
Battery	US$/Output Watt Hour	0,207	0,207	0,207	0,207	0,207	0,207	0,207	0,21	0,21	0,211	0,212	0,212	0,213	0,213
	Euro€/Output Watt Hour	0,155	0,168	0,166	0,157	0,161	0,151	0,147	0,16	0,16	0,154	0,153	0,151	0,143	0,149
Charge Controller	US$/Amp	5,87	5,87	5,87	5,87	5,87	5,87	5,87	5,87	5,88	5,93	5,93	5,93	5,93	5,89
	Euro€/Amp	4,4	4,75	4,7	4,46	4,58	4,29	4,17	4,46	4,41	4,33	4,27	4,21	3,97	4,12
Solar Systems*	Residential c/kWh	34,74	34,74	34,64	34,56	34,28	32,05	31,91	31,63	31,4	30,96	30,53	30,42	30,34	30,31
	Commercial c/kWh	24,71	24,71	24,65	24,57	24,32	22,31	22,19	21,9	21,69	21,28	20,87	20,74	20,71	20,67
	Industrial c/kWh	19,27	19,27	19,2	19,14	18,95	17,38	17,29	17,07	16,91	16,59	16,27	16,20	16,14	16,11

These prices reflect the lowest price quoted on each company's website for the particular component and do not include sales tax.
Solarbuzz collects pricing information from companies worldwide. The current surveys include companies located in the US, Germany, UK, South Africa,
Australia, Brazil, Bulgaria, France, Greece, Korea, Switzerland,
Canada, and Japan.
Exchange rate conversions were made on the survey date.
This information may not represent actual pricing since actual pricing may be decided by discounts on multiple unit purchases and price matching of competitors.
Additional pricing detail, including factory gate pricing, manufacturing costs and manufacturer margins can be found in these Solarbuzz reports:

Solarbuzz Quarterly

Marketbuzz

* **Solar Systems** are indexes of grid-connected solar-system cost in price per kilowatt hour (after financing). These indexes are based on the Solarbuzz solar module retail price survey and draw exclusively on module prices in the high power band exclusively (> 125 Watts). They include full system integration and installation costs.

The **Residential Index** is based upon a standard 2 kilowatt peak system, retrofit roof-mounted solar system with a battery back-up.
The **Commercial Index** is based on a 50 kilowatt ground-mounted solar system. It provides distributed energy and excludes any back-up power.
The **Industrial Index** is based on a 500 kilowatt flat roof-mounted solar system, suitable on large buildings, without back-up power.
Prices are illustrative only and indicative of global rather than specific country, grid-connect markets. Prices for individual projects vary widely according to location and type of system. Indexes were rebased in October 2010.

10.2 EU interconnection capacity [ENTSOE 2011]

All values are indicated in MW. Numbers that are agreed on both involved countries are indicated with a black coloured single number [WM]. If countries indicated different numbers, both numbers are indicated with green numbers.