MSc Program
Environmental Technology & International Affairs

The Changes in the Photovoltaic Industry - Economic Analysis

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

supervised by
Em.O.Univ.Prof. Dipl.-Ing. Dr.techn. Adolf Stepan

Paul Leitner
1053815

Vienna, 20. October 2014

Affidavit

I, **PAUL LEITNER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE CHANGES IN THE PHOTOVOLTAIC INDUSTRY - ECONOMIC ANALYSIS", 60 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 20. October 2014

Signature

Abstract

The following Master Thesis is an economic analysis of the Photovoltaic production industry. In the past years this industry sector undergoes various changes and has anticipated a phenomenal growth before it was dragged inevitable into the financial crises with its huge impacts on the national budgets in the aftermath. Hence, a difficult market to survive for many companies. The analysis of the industry is based on several indicators like size, utilization-rate, the Minimum Efficient Scale, and the Herfindahl-Hirschman Index (HHI) and shall illustrate the market status and how it might develop in the long run.

Acknowledgements

First, I want to thank Em.O.Univ.Prof. Dipl.-Ing. Dr.techn. Adolf Stepan as my university supervisor, and Univ. Prof. i.R. DI Dr. Hans Puxbaum as second reader for the technical part of this Master-Thesis. Additionally, my thanks go to Dr. Elisabeth Hofer in representation of the whole Diplomatic Academy Team, to Mag. Isabelle E. Starlinger and to Karoline Rasl, B.A. for all their support during the ETIA-program.

I dedicate this work to my parents and my sister. I would like to take this opportunity to express my deepest gratitude to them for all their support, patience, and motivation throughout my studies. All of them helped me to be equipped to cope with anything life can bring.

Besides that, special thanks goes to my friends from my hometown, my friends from Alpbach and GAP, my friends in Taiwan (esp. 丁宇軒 and Po-sheng Chiang) and all the others all over the world, with whom I share endless memories of happiness, fun, talks, and sport.

Finally, I would like to express my gratitude to all my fellow ETIA friends for being on my side, supporting me and believing in me in those two years. In particular, I would like to thank my learning-partner and "roommate" Yves, my neighbors Patrick, Mareike, and Kristian.

Table of Contents

List of Abbreviations/Acronyms

AC:	Alternating current
a-Si:	Amorphous silicon
a-Si/μc-Si:	Micromorph silicon
BIPV:	Building-integrated PV systems
CdTe:	Cadmium Telluride
CIGS:	Copper-Indium-Gallium-Diselenide
CIS:	Copper-Indium-Diselenide
CPV:	Concentrating photovoltaics
c-Si:	Crystalline silicon
CSP:	Concentrating solar power
DC:	Direct current
EEG:	Renewable Energy Law (Erneuerbare Energien Gesetz)
FIT:	Feed-In Tariff
PV:	Photovoltaic
R&D:	Research and Development
USD:	United States Dollar

Units

Gt:	Gigatonnes
g/W:	Grams/watt
GW:	Gigawatt
GWh:	Gigawatt hour
KWh:	Kilowatt-hour
KW:	Kilowatt
MW:	Megawatt
MWh:	Megawatt-hour
TWh:	Terawatt-hour
W:	Watt
μm:	Micrometer

1 Introduction

1.1 Situation

In the past years the solar industry undergoes various changes and has anticipated a phenomenal growth before it was dragged inevitable into the financial crises with its huge impacts on the national budgets in the aftermath. Research and development stocked immediately, layoffs followed, companies went bankruptcy, and the innovation process of the whole industry sector came to stagnation (Timilsina et al., 2012). At the same time tragic events like the oil spill in the Gulf of Mexico or the nuclear catastrophe in Fukushima brought a fresh sense of urgency into the debate about renewable energy. With the background of political promotion and the increasing efficiency of renewable energy, it looks as if manhood progressively supports this new path. Nuclear and fossil energy loses its attractiveness, not simply because the resources are running out and the open question about storage of nuclear waste, but simply because of its failure in competitiveness and public support (Bank-Sarasin, 2011). Despite the terms "climate change" and "Energiewende" circulating in all kinds of media, it is clear that this will not be a sudden revolution, but we are in the middle of a crucial evolutionary process.

1.2 Relevance and Motivation

Searching the web for information about Photovoltaics and Solar energy in general huge amounts of papers and technical analysis can be found. Many international organizations, governments and private companies are publishing papers about the costs, technologies, country analysis and other overviews about this renewable energy source. To give a short overview Table 1.1 was insert below this paragraph in order to show the most relevant ones beforehand. It is a matter of fact that such a "new" topic gains a huge amount of popularity and many students and researchers come up with reports and papers with similar structures and which seldom contain lots of new information. I do declare that the "Background information" section follows also a similar construction and contains no new information, but this is inevitable, as the reader should be introduced to the topic and understand the following main part. The focus of this thesis is however an economic analysis of the

PV production industry itself. In the main chapter, the individual value-chain steps of Crystalline Silicone Cells and additionally the Thin-Film Cell production is analyzed, because each step shows a different picture in the world market. A size and utilization-rate analysis as well as the calculation of the Minimum Efficient Scale and the Herfindahl-Hirschman Index (HHI) show the current market situation from a very special point of view. The motivation behind this paper is to illustrate that market consolidation is inevitable and that only certain companies might survive. Hereby it is important to state that there is no ranking given, which indicates the chances of individual companies to survive or to go bankruptcy. Contrary to that, it is a scientific approach to see in which status the market is and how it might develop in the long run.

Table 1.1 List of PV related Reports

Institution	Report Name	Issue Date
EPIA (European Photovoltaic Industry Association)	Global Market Outlook 2016	May 2012
EPIA	Solar Generation 6	2011
IRENA (International Renewable Energy Agency)	Cost Analysis (Solar PV)	June 2012
European Commission	PV STATUS REPORT 2013	Aug. 2013
PWC	Die deutsche Photovoltaik-Branche am Scheideweg	Oct. 2010
IEA (International Energy Agency)	Solar Energy Perspectives	Nov. 2011
IEA	World Energy Outlook 2012	Nov. 2012
REN21	Global Future Report	Jan. 2013

1.3 Structure

This thesis is divided into five main parts. After this introduction the second chapter "Methodology and Data" shows the tools which were used in order to analyze the economic situation. The third one "Background Information" gives an overview about solar energy and photovoltaic technologies, including the production process steps, which are essential for the further chapters. In part four, the global photovoltaic market is described and in the fifth part the economic analysis for all the different value-chain-steps for the photovoltaic production is done. The conclusion that follows shows the results and indicates the end of the research.

2 Methodology and Data

The huge variety of using sun energy and their different forms of constructions and types (e.g. as additional construction on the roof of a house connected to the grid or a solar-power-plant) makes it very difficult to get an overview about all technologies. Additionally, analysis can be done in many different ways that is why the focus is drawn on following three indicators: size and utilization capacity, the Herfindahl-Hirschman Index (HHI), and the Minimum Efficient Scale.

In terms of the data used for the analysis it is important to state that company relevant figures, as for example capacities or production quantities, are nearly not available without paying for them. That is why many figures used in this paper from different reports and sources were proofed and double-checked or adapted with published figures on company-homepages or in their annual reports. Nevertheless, there are figures which could not be proofed and the two main reasons for that are following. First, some Asian companies, despite they are amongst the biggest players in the photovoltaic industry, still not have English-written websites, which made it impossible to gain any information from their homepage. Second, not all companies are listed at a stock market, which means they do not have to publish their business figures in a public annual report. In order to overcome divergences amongst different sources the source with the higher reliability was chosen and if it was necessary, especially in terms of the numbers of existing companies in an area, specific information were made in the analysis in order to show a transparent view.

2.1 Size and utilization capacity

The size of a company in terms of output-capacity per year is the first figure, which was taken into consideration for the economic analysis. The figures were necessary to establish a ranking or in other words a TOP-PLAYERS list. Specifically, it is necessary to mention, that the ranking in this paper does not always contain exactly ten companies, as it is the case in many published rankings in newspapers or magazines. The reason for example to use a “TOP 16” list for all crystalline-photovoltaic-cell production plants from all over the world is the difficulty to find the correct cut at a specific production amount. Not including companies with very similar production capacities would have drawn a deviating picture from the reality than as it is now the case with more companies taken into the focus. Next to the capacity, the actual production amounts and the capacity utilization rates are used to illustrate the current economic situation. The capacity utilization the relation between the production amount to the capacity of the individual company was calculated as percentage.

2.2 Herfindahl-Hirschman Index

The Herfindahl-Hirschman Index (HHI) measures the size of a company in relation to the whole industry. Additionally it indicates the competition amongst them. In order to calculate the HHI following formula is used:

$$H = \sum_{i=1}^{N} s_i^2$$

The values of the formula have following meaning: s_i stands for the market share of firm *i* in the market. *N* is the number of companies in the industry/market. In other words, the HHI is the sum of the squared market shares of the individual companies. Based on the results indications on the market situation can be drawn, which could be highly competitive, unconcentrated, moderate or high concentrated. (U.S. Departmetn of Justice and the Federal Trade Comission, 2010)

2.3 Minimum Efficient Scale

In the world-market, innovation is essential in order to survive among competitors in the long run. The scientific approaches in the area of innovation show not only the origination and the feasibility of innovations, but also enable to focus on certain strategies and market positioning. One concept that enables the measurement of the market is the Minimum Efficient Scale (MES). It is defined as the smallest output of a plant or company, which is necessary to be competitive viable in the long run. In other words, the determined value indicates the capacity for a production under the condition of the current prize competition, where Economies of Scale (EoS) can be generated (Stepan, 2009). The plant size at which average cost is minimized is an important barrier to enter a market, because those companies that achieve return to scale at high levels of output can successfully keep opponents outside the market (Chaaban, 2004). The determination of the capacity is based either on engineering estimations or through the "Survivor Test". Engineering estimations are done from experts based on analytical considerations of possibilities and reliability of certain facilities. The Survivor Test on the other hand is an analytical tool, which focusses on the changes of capacity in time or the current capacities amongst the competing companies, especially on the size of the market leaders also named "Survivors" (Stepan, 2009). The second method was taken into consideration for this paper in terms of using the TOP Players amongst the industry sector and setting the MES based on the analyzed figures. However, before going into the economical details the next chapter gives an insight into the technical background.

3 Background Information

In 2011 solar PV energy counts only for 0.15% of the world energy electricity generation as shown in Figure 3.1. Even among the renewable energy sources like Hydro-, Bio-, Wind-, and Geothermal-Energy, this is rather a small fraction, but the solar PV capacity has grown steadily in the recent years and rapid future growth rates are expected. But what is solar PV exactly? What kind of technologies are behind it? Which materials are necessary to produce solar PV and how efficient are those devices? This section will focus on the answer to these questions and will elaborate thoroughly all relevant background information.

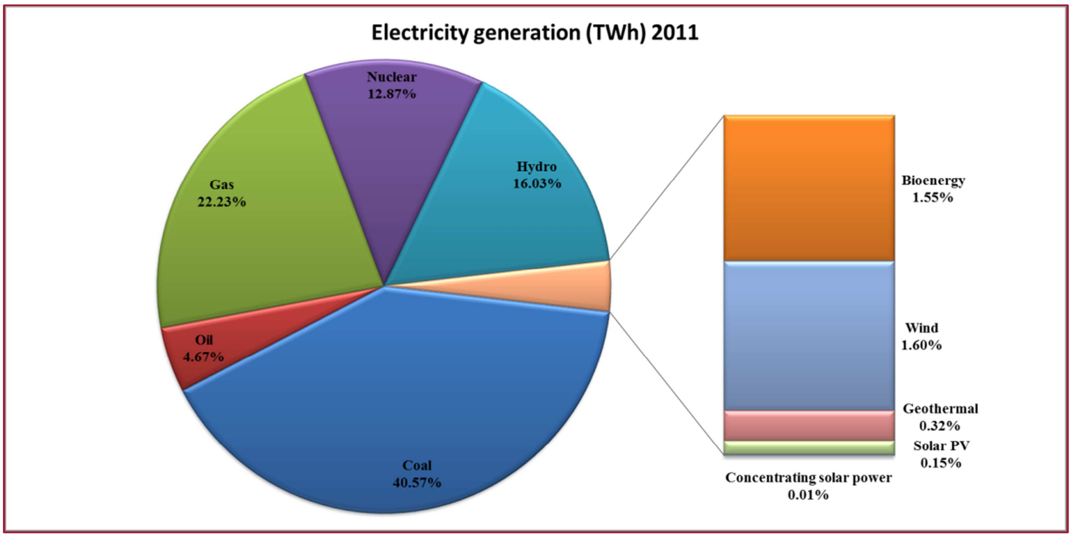


Figure 3.1 Electricity generation (TWh) 2011
Source: (IEA, 2011)

3.1 Solar Energy Technologies

Using the sunlight as energy source has already a long history. Contrary to fossil fuels solar energy is a renewable and clean source of energy, which can be directly acquired through the heat or the light of the sun. Solar energy technologies vary in their form and in their application as illustrated in following table together with the enclosed description (IRENA, 2012).

Table 3.1 Solar Energy Technologies
Data-Source: (Timilsina et al., 2012)

<table>
<tr><td colspan="5">Solar energy
Source of energy, directly attributed to the heat and the light from the sun</td></tr>
<tr><td rowspan="3">Capacity</td><td colspan="3">Active
Utilizing of energy to store it or convert it for other applications</td><td rowspan="3">Passive
Collecting energy without conversion</td></tr>
<tr><td rowspan="2">Photovoltaic (PV)
Converts radiant energy contained in light quanta into electrical energy</td><td colspan="2">Thermal
Uses the heat for either electricity production or heat as form of energy</td></tr>
<tr><td>Electric</td><td>Non-Electric</td></tr>
<tr><td>Centralized (> 200 kW)</td><td>Concentrating PV (CPV) Utility-scale PV</td><td>Concentrating Solar Power (CSP)</td><td>District water heating</td><td></td></tr>
<tr><td>Large-scale distributed (>20kW)</td><td>Commercial building PV</td><td></td><td>Commercial hot water systems</td><td></td></tr>
<tr><td>Small-scale distributed (<20 kW)</td><td>Small commercial & Residential building PV</td><td></td><td>Residential water heating/cooling systems</td><td>Heating & Cooling</td></tr>
<tr><td>Off-grid applications</td><td>Stand-alone systems for remote applications, solar home systems</td><td></td><td>Agricultural drying</td><td>Day-lighting</td></tr>
</table>

Table 3.1 shows that solar energy can be used either actively, for the generation of heat or electricity, or passively. Thermal energy generation can be divided into solar thermal non-electric technologies, like solar water heaters, solar air heaters, solar cooling systems, and solar cookers or through agricultural drying, and into solar thermal electric technologies. Secondary is also named Concentrated Solar Power (CSP) *(also known as Concentrat**ing** Solar Power),* whereby currently following four different applications are available on the market: Power Tower , Parabolic Trough, Fresnel Mirror and Solar Dish Collector (Timilsina et al., 2012) (Arvizu et al., 2011). PV is either used centralized, on large scales as for example on the roof of industry factories or whole towers. Furthermore it could be found on the roof of family houses or in the form of an off grid application, as it is commonly used in rural areas in Africa. As the title implicates, the focus of this Master-Thesis is drawn on the

production of PV Modules, which could be used on large-scale, small-scale or stand-alone systems. Before the three generations of PV cell technologies are elucidated, the following paragraph illustrates how a PV cell works.

3.2 The Photovoltaic Effect

"Photovoltaic" is combining the words "photon", which is usually known as light and "volt", which is a unit of electric potential. Knowing this it is not difficult to understand how a photovoltaic cell works. As displayed in Figure 3.2 every cell consists of two layers of semi-conducting material (n-type silicon and p-type silicon). Light falling on a solar cell generates an electric field across those layers, which creates flowing electricity. Therefore, the amount of generated electrical power from a cell depends on the intensity of the light (Masson et al., 2012).

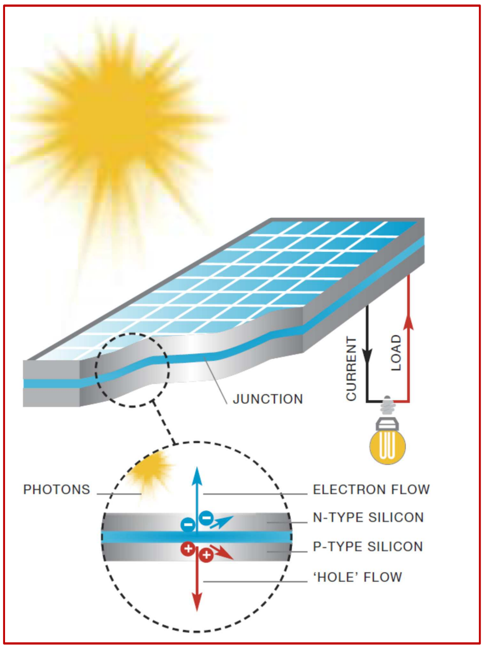


Figure 3.2 Illustration of Energy Transformation
Source: (Masson et al., 2012)

Scientists have developed already many types of cells in order to reduce costs and increase efficiency, but only few are used commercially today and play a role in the market. Based on the level of commercial maturity and the basic material used, the PV technologies are classified into three generations as shown in the following table.

3.3 Photovoltaic Technologies

In the PV industry silicon is the prevailing semiconductor, whereby monocrystalline (mono-Si) and multicrystalline (mc-Si) are predominantly used. These crystalline silicon cells achieve the highest efficiency and are categorized as First Generation cells. However, the production of high-purity silicon requires large amounts of energy, which also affects the price negatively. The Second Generation, Thin-Film technologies, requires significantly less material with the aim to overcome this drawback. Third Generation encompasses new technologies, which have not reached a commercial stage at the moment. That is why the focus of this paper is drawn on the production of First and Second Generation of PV-Technologies, as those are the ones playing a major role in the market.

Table 3.2 PV-Technology Generations
Data-Source: (IRENA, 2012) (Solarpraxis AG, 2012)

First Generation (Crystalline Silicone Cells)	Second Generation (Thin-Film Cells)	Third Generation (pre-commercial stage)
Mono c-Si (Monocrystalline) also called **sc-Si** (single crystalline)	**a-Si** (Amorphous silicon)	**CPV** (Concentrating PV)
Poly c-SI Polycrystalline also called **mc-Si** (multi crystalline)	**a-Si/µc-Si** (Multi-junction thin-film silicon)	**DSSC** (Dye-sensitized solar cells)
EFG ribbon silicon	**Cd-Te** (Cadmium Telluride)	Organic solar cells
	CIS (Copper-Indium-Selenide) **CIGS** (Copper-Indium-Gallium-Diselenide)	Novel and emerging solar cell concepts

3.3.1 First Generation: Crystalline silicon cells (c-Si)

As the title of this paragraph already states the production of the First Generation cells is based on silicon, which is one of the most abundant elements in the lithosphere. As semiconductor material it is suitable for PV applications, with an energy band gap of 1.1 eV., which measures the energy needed to produce electron excitation in order to activate the PV process. Modules produced with crystalline silicon are currently dominating the world market as the technology is already mature and mass production has started all over the world. The production rates increased in the last years tremendously and some companies already producing more than one Gigawatt (GW) a year. The manufacturing process also known as wafer-based silicon PV module supply chain comprises four steps:

Table 3.3 PV module supply chain process
Data-Source: (Masson et al., 2012) (de la Tour et al., 2011)
Picture Source: (SolarWorld AG, 2013)

	Step	Process-Description
	Raw Material	Silicia (SiO_2) found in quartz sand.
	**Step 1:** Silicon production	Through heavy and highly energy-consuming chemical processes silicia is purified to silicon, whereby a purity of >99,999% is required for the PV industry.
 	**Step 2:** Ingot and Wafer production	In this step the silicium is melted with a temperature of 1410 degree Celsius and formed to ingots (blocks/cylinder). Specific amounts of dopant impurity atoms (e.g. boron or phosphorus) are added to form n-type or p-type silicon. After cooling the blocks are cut down to filmy slices named wafers
	**Step 3:** Cell production	Two differently doped wafers are combined together in order to form a p-n junction which leads to the PV effect. (as described in Figure 3.2) Additionally the top and rear metal contacts are applied, which finally makes the cell capable to produce co-current flow through sunlight.
	**Step 4:** Module assembly	In the final production step the cells are assembled to bigger entities named modules. Therefore, the cells are encapsulated in glass sheets and laminated. The modules are framed, weatherproof, and ready for the installation on the house.

Based on the way the Silicium wafers are produced, the silicon cells are additionally divided into three main types as it was also shown in Table 3.2:

- Monocrystalline (Mono c-Si) also called single crystalline (sc-Si)
- Polycrystalline (Poly c-Si) also called multi-crystalline (mc-Si)
- EFG ribbon silicon and silicon sheet-defined film growth (EFG ribbon-sheet c-Si)

The difference between Mono c-Si and Poly c-Si is already determined in the Ingot production. The conversion to monosilicon needs more energy and is therefore more expensive than the polysilicon process, but leads to an increase of efficiency. Regarding the efficiency of crystalline silicon modules research results range in the area of 20% to 28% as demonstrated in Figure 3.3, whereas the efficiency of produced modules ranges from 14% to 19% as it also can be seen in Table 3.5. Therefore, cost reductions and improvements are still possible in the future due to reductions of materials and manufacturing costs. Additionally, economics of scales gains more and more important as this industry is fiercely competitive (IRENA, 2012).

3.3.2 Second Generation: Thin-Film Technologies

Thin-Film modules are constructed by depositing photosensitive material with a thickness of 1 to 4 µm on a low-cost backing such as stainless steel, glass or polymer. After the deposition of the thin layer on the backing, it is cut with a laser into multiple thin cells. Normally the Thin-Film modules are frameless and enclosed between two layers of glass, whereby Table 3.4 gives a step-by-step introduction into the production process.

Table 3.4 Thin-Film PV Production Process
Data-Source: (EPIA, 2011)

Steps	Description
Step 1: Front Cover	Production of a sheet of substrate typically made out of glass. Other materials could be plastic, aluminum, flexible steel.
Step 2: TCO	The substrate is coated with a transparent conducting layer (TCO).
Step 3: Absorber	Several different techniques - commonly chemical and physical vapor - are used to deposit the semiconductor material (absorber) onto the substrate or superstrate.
Step 4: Back Contact	In order to connect the modules metallic contact stripes on the back are fixed through laser scribing or traditional screen-printing techniques.
Step 5: Back Cover	Finally, the entire module is enclosed in a glass-polymer casing

The deposition of the photosensitive material on plastic film makes the usage of solar power generation much more flexible and allows the integration into the fabric of buildings (building-integrated PV - “BIPV”) or end-consumer applications. The reduction of materials leads to lower production costs and therefore to lower electricity costs for one Thin-Film cell than for a c-Si wafer based solar cell. However, the efficiency levels of First Generation cells are not reached and the c-Si module costs are also decreasing steadily (EPIA, 2011) (IRENA, 2012). Four types of Thin-Film modules that have been commercially developed:

Amorphous silicon (a-Si) solar cells have a layer with a thickness of only about 1 µm, that’s why companies used and developed it for flexible, light a-Si modules which perfectly suit for flat and curved surfaces, as for example roofs and facades. The amorphous silicon can be deposited on very large and cheap substrates (up to 5.7 m^2 glass) so that manufacturing costs can be reduced. Additionally, to the current efficiency, which is in the range between 4% to 8%, the performance of a-Si cells decreases over time per 15% to 35% (EPIA, 2011).

Multi-junction thin silicon film (a-Si/µc-Si) cells are based on amorphous silicon, but with an additional microcrystalline silicone (µc-Si) - a-Si layer. The advantage of this additional layer is that the µc-Si layer absorbs more light from the red and near infrared part of the light spectrum. This makes not only the cells thicker and stable but also increases the efficiency by up to 10%. The current deposition techniques enable the substration of multi-junction films on up to 1.4 m^2 large areas (EPIA, 2011).

Cadmium Telluride (CdTe) thin-film PV solar cells are currently the most economical ones. The manufacturing costs are lower and the cell efficiencies are higher compared to other thin-film technologies. As the name states the main materials are cadmium, which is a by-product of zinc mining and tellurium, which is a product of copper processing. Both materials entail problems that need to be tackled. First, tellurium is produced in lower quantities than cadmium. Second, the availability of tellurium in the long run is dependent on extraction optimizations, refining and recycling yields in the copper industry. Third, cadmium is toxic, which might limit its use as well (EPIA, 2011).

Copper-Indium-Selenide (CIS) and copper-Indium-Gallium-Diselenide (CIGS) PV cells are leading the list of thin-film PV technologies in terms of efficiency. The current module efficiencies range in the area between 7% and 16%, but in the laboratory, the efficiencies of up to 20.3% come close to that of c-Si cells. As this efficiency should be achieved with commercial modules, the less complex manufacturing process has to be improved in order to decrease the costs. Contrary to the mentioned shortages of tellurium, there are no issues for selenium and gallium. Indium is found in tungsten and tin ores and is available in limited quantities without shortages, but the individual extraction would be very costly and would lead to higher prices. Furthermore, other industry sectors as for example the liquid crystal display (LCD) production also compete for the resource, which also has an impact on the price (EPIA, 2011).

3.3.3 Third Generation of PV Technologies

New concepts for PV technologies are still under research and slowly start to be commercialized. Their success to take away market shares from existing technologies will be seen in the future, which will highly depend on their cost-efficiency ratio. Four types of third-generation PV technologies are introduced in the following as they are part of "The Changes in the Photovoltaic Industry" but will not be analyzed in terms of economic aspects, as they are still in the pre-commercial stage (EPIA, 2011).

Concentrating PV (CPV) uses optical devices, such as mirrors or lenses, to focus sunlight onto very small, highly efficient solar cells. The systems are differentiated based on the sunlight concentration factor, whereby 2 to 100 suns are classified as low- to medium-concentration and up to 1000 suns as high concentration. As CPV systems use only direct irradiation, their highest efficiency can be generated only in very sunny areas. Additionally a single- or double-axis tracking system for low and respectively high concentration is necessary as well as an active or passive cooling system, which is also needed for some CPV designs (EPIA, 2011).

Low- to medium-concentration systems with up to 100 suns can be combined with c-Si cells, but higher temperatures will reduce their efficiency. High concentration systems with more than 500 suns are usually focusing the light onto multi-junction solar cells made by semiconductor materials from groups III and V of the periodic table as for example gallium arsenide, which allow a very high PV conversion effect. Multi-junction cells are either 'tandem' or 'triple' junctions, which describes the structure of several layered p-n junctions, each made by different semiconductor sets with different spectral absorption and band gap in order to achieve the highest absorption rate of the solar spectrum as possible. Theoretical efficiency rates are up to 59% for triple-junction cells, but because of their costs and complexity, they are only applied for small-area cells in regions with clear skies and high direct solar irradiation or in space applications in order to generate maximum performance (Nature Photonics, 2010).

Nevertheless, efficiency rates of commercial CPV module cells are rather high compared to co conventional single-junction c-Si solar cells. Silicon-based CPV module cells have a rate of 20% to 25%, multi-junction devices manufactured by Sharp, Azur, Spectrolab and Emcore have efficiencies around 35% and further research and development forecasts CPV efficiencies up to 45% and even 50% (Cotal et al., 2009).

Dye-sensitized solar cells (DSSC) are using low-cost materials and are simple in their production. Unfortunately, the performance can decline over time with exposure to UV light and the usage of a liquid electrolyte can be problematic in the situation of freezing temperatures. The used photochemical solar cells for this technology are based on semiconductor structures formed between a photosensitized anode and an electrolyte. Typically, the semiconductor nanocrystals serve as antennae that harvest the sunlight (photons) and the dye molecule acts as charge separator (photocurrent). Despite laboratory efficiencies of 12% were achieved, the commercial efficiency rate is between 4% and 5%. The problem behind this are that there are only very few dyes that can absorb a broad spectral range. Current research is focusing on nanocrystalline semiconductors that allow DSSCs a broad spectral coverage (Grätzel and O'Regan, 1991).

Organic solar cells (OSC) are as well as the before described DSSC inexpensive, but not very efficient. Composed of organic or polymer materials, such as organic polymers or small organic molecules, their efficiency ranges now from 4% to 5% for commercial systems and from 6% to 8% in the laboratory. Additionally to the low efficiency rate, their instability is a major challenge. The production costs Nevertheless, organic cell producers plan to increase production capacities and commercialization should increase as manufacturing costs are expected to decline furthermore. For the production high-speed and low temperature roll-to-roll processes are used as well as standard printing technologies. A major advantage of organic cells is their flexibility, which makes them ideal for mobile applications and applicable for a variety of uneven surfaces. This potential includes the use as battery charger for laptops, mobile phones, flashlights, toys and almost any hand-held device that uses an accumulator. Another advantage is that they can be fixed almost anywhere, storage is easy as they could be folded or rolled up when not in use. Those possibilities make organic cells very attractive for building-integrated applications additionally to the fact, that this technology uses non-toxic, abundant materials, which could be processed highly flexible.

The development of new solar cell technologies using quantum wells, quantum wires/dots, or super lattice technologies is going on until their commercial usage is approved (Nozik et al., 2010). Research also focuses on the usage of these technologies for concentrating PV technologies in order to achieve higher efficiency by overcoming the thermodynamic limitations of c-Si cells. These ideas are still in the fledgling stages of fundamental material research as well as nanotechnology, which aim for a higher usage of the solar spectrum (Leung et al., 2011).

In the end, the technologies of the 2nd and 3rd Generation have to prove that the production is commercially feasible and that each type has a unique selling proposition (SUP), be it efficiency, applicability, or prize compared to those technologies, which are already on the market. The next paragraph illustrates the current facts of the 1st and 2nd Generation in a table and furthermore a graphic of the efficiency developments of research cells.

3.4 Efficiencies Comparison

The varieties among the different generations in terms of efficiency, price and commercialization state are enormous. To give a clear picture about the status Table 3.5 shows the differences between the 1st Generation of Photovoltaic technologies and the 2nd Generation, whereby major findings are described below. The efficiencies are measured under the condition of AM 1.5, which defines the Standard Testing Conditions: Temperature 25°C, light intensity 1000W/m^2, and an air mass of 1.5 (IRENA, 2012).

Table 3.5 Comparison between First- and Second Generation
Data-Source: (IRENA, 2012)

		1st Generation PV		2nd Generation PV			
Technology	**Units**	**sc-Si**	**pc-Si**	**a-Si**	**a-Si/ μc-Si**	**CdTe**	**CIS/CIGS**
Best research solar cell efficiency at AM1.5	%	24,7		10,4	13,2	16,5	20,3
Confirmed solar cell efficiency at AM1.5	%	20-24	14-18	6-8		8-10	10-12
Commercial PV Module efficiency at AM1.5	%	15-19	13-15	5-8		8-11	7-11
Confirmed maximum PV Module efficiency	%	23	16	7.1	10.0	11.2	12.1
Current PV module cost	USD/W	< 1.4	< 1.4	~ 0.8		~ 0.9	~ 0.9
Maximum PV module output power	W		320	300		120	120
PV module size	m^2	2.0	1.3-2.5	1.4		0.72	0.6-1.0
Area needed per KW	m^2	7	8	15		11	10
State of commercialization		Mature with large-scale production	Mature with large-scale production	Early deployment phase, medium-scale production		Early deployment phase, small scale production	Early deployment phase, medium scale production

First, the efficiency rates of commercialist PV modules for sc-Si Cells reach 15% to 19% and for pc-Si Cells also more than 14%, whereas CIS/CIGS cells reach a maximum of 12% as the best one from the 2nd Generation. Second, it can be seen that the fully developed technologies need a much smaller area - less than $8m^{2}$ -to produce one KW, whereas the new ones need more than $10m^2$. Third, contrary to those points which speak for sc-SI and pc-Si Cells, there are also positive aspects for the new generation as for example their price. While the cost of one Watt of a 1st Generation module is just below 1.40 USD, the price of Cd/TE and CIS/CIGS Modules per Watt amounts around 0.90 USD. The fourth fact, also a positive one for the newer technologies, is the module size, because this enables enormous potential in the usability of those cells (EPIA, 2011) (NREL, 2013). To sum up, both generations have advantages and disadvantages. Price and efficiency will play a major role for the usage of a technology in the future, but what can be expected?

The following graphic shows it. The work, published by NREL, the National Renewable Energy Laboratory, which operates for the U.S. Department of Energy by the Alliance for Sustainable Energy, LLC. compares record levels of reached efficiencies of different technologies.

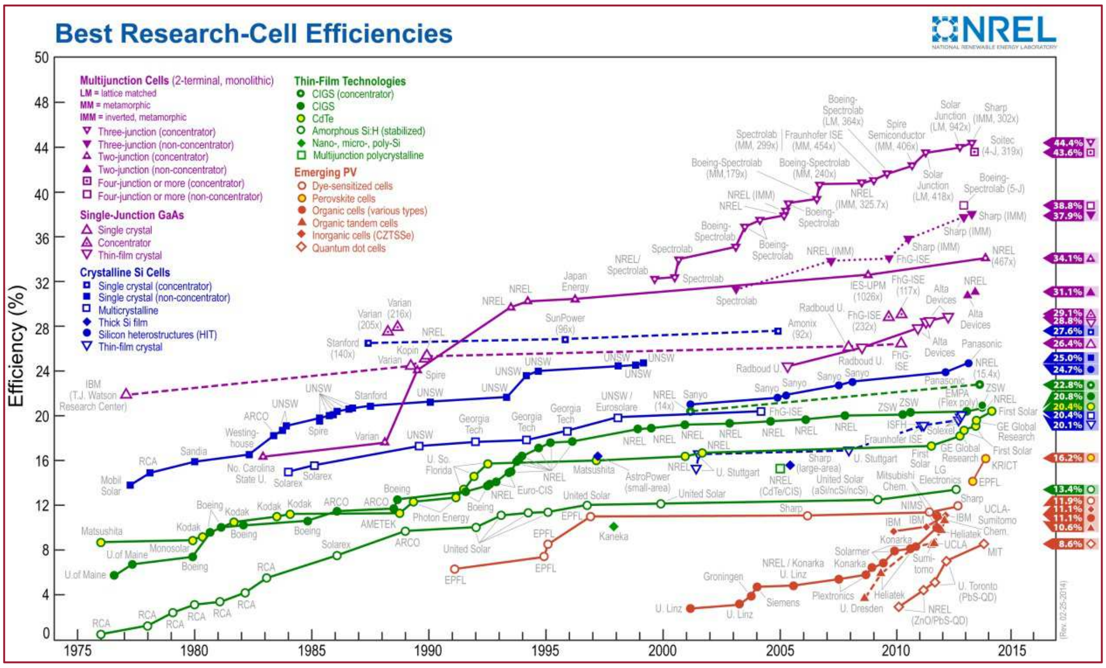


Figure 3.3 Best Research-Cell Efficiencies
Source: (NREL, 2013)

The differentiation is divided among four main colors. The blue lines show sc-Si (Single Crystalline Cell) technologies as well as mc-Si (Multi Crystalline Cells also known as Poly Crystalline Cell) technologies. Both are 1st Generation technologies and their efficiency rates are between 20.1% and 27.6% depending on the specific technology. The green lines illustrate 2nd Generation Technologies and reach according to NREL efficiencies from 13.4% to 22.8%. The 3rd Generation is summarized under “Emerging PV” and is visualized with red chart-lines.

It can be clearly seen that the efficiency rates of those technologies are still very low. For example, Organic or Dye-sensitized Cells reach a level of around 11%. The technologies that reach the highest rates are in purple and were described in the section “Concentrating PV” in this paper. Research figures for this technologies reach to amounts of 44.4%. Comparing the values of those Multijunction Cells with efficiency rates of 1st Generation Cells in the reality, the efficiency rate is twice as high. Fact is anyhow, that in the end efficiency rates have to be proofed outside of laboratories in order to get figures that are more accurate. Before further analysis on the different production steps are done, a short overview about the global PV market is given.

4 The global PV market in a Nutshell

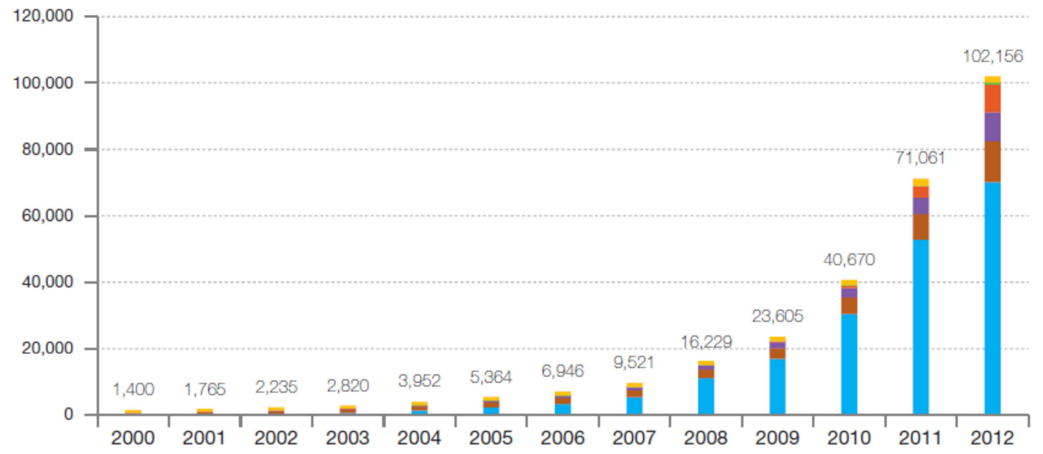
The reasons for the transforming changes of the PV market over the last years are various. As it was stated already in the introduction the solar PV world market was and still is shaped by political ideas and decisions, global economy movements, disastrous environmental destructions based on unsustainable energy sources, and not to forget by technological changes and innovations. At the beginning the subsidy-system is introduced, thereafter an overview about the booming years is given. In the third part, the burst of the solar energy bubble is analyzed and in the fourth and last part information about the situation beyond those events are narrated.

4.1 The subsidies as source for a bubble

Political involvements into market proceedings very often end up in other ways as they were planned. Currently the “Energiewende” in Germany is again one of the big topics, because the higher bills for the support of renewable energy reaches unexpected levels. However, before focusing on the resent events a dip into the past shall help to understand the whole situation better. The first Feed-In Tariffs (FIT) were introduced in the USA already in the year 1978, but the more important implementation of this subsidy scheme for the renewable energy sector started twenty years later in Germany. Despite there were federal programs to support the research of sustainable energy production, there was no tool or regular financial backup to overtake the higher costs for the new technologies to enable them to survive in the market. After the Bundestag election in 1998 the SPD (Sozialdemokratische Partei Deutschland – Germany’s Socialist Party) and the party “Bündnis 90/Die Grünen” (The Green Party) formed a coalition and proclaimed to follow a more sustainable way. That is why two years later the law for the electricity feed in act (Stromeinspeisegesetz) entered into force per January 1st, 1991. Within this law the FIT was born, which obliged the grid operator to purchase the electricity delivered by the power plant operators, for whom this security was essential for further investment and development. The topic “renewable energy” was also brought into the discussions within the EU-entities and in 1997 the European Commissions expressed its intention to double renewable energy sources until 2010. Both, the SPD and the Green Party in Germany realized that their current program is not enough to reach those goals, wherefore a new law for renewable energy was drafted (Erneuerbare-Energie-Gesetz – EEG), which came into force April 1st, 2000. This law states that renewable energy shall have priority in comparison to fossil- and atomic energy. More specifically, it outlined that for every solar-power produced kilowatt-hour (kWh) a price of 45.7 Cent should be paid to the producer. Additionally payments are made if the construction is placed on a building or on a noise protection wall (juris, 2003). Many other countries followed this way as for example Switzerland 1991, Italy 1992, and Spain and Greece adopted a Feed-In Tariff in 1994. Also not EU-members like China, Turkey, India and South Africa established subsidies, but not before 2005 (Johnson Controls, 2010). Next to the installation of several thousand solar panels on houses, the Feed-In Tariffs lead to an enormous demand for renewable energy and conducted the success for the PV industry in the following years (International Energy Agency, 2012).

4.2 The rise of the Solar PV bubble

The century after the enforcement of laws fostering renewable energy marked the booming years of the photovoltaic industry. As it can be seen in the next graphic photovoltaic technology has shown its potential with a continuous and robust growth over the last decade. It became a major source for energy generation for the world even during times of economic and financial crisis. The last three years turned out to be the most successful ones. The world-wide cumulative installed capacity increased from 2009 to 2011 each year more than 72% and from 2011 to 2012 around 44%, which are remarkable growth rates among all renewable technologies. Europe is with 70% of total installed photovoltaic capacity the world leader. China follows the ranking with 8.3 GW, the USA has installed 7.8 GW, and Japan reached 6.9 GW. Focusing back on Europe the installed capacities nearly increased thirteen fold from 5.3 GW at the end of 2007 to 70.0 GW at the end of 2012. In the same year, the world cumulative installed photovoltaic capacity reached more than 102.2 GW, which is sufficient to cover the annual power supply needs of over 30 million European households (Masson et al., 2013).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	71	192	601
China	19	24	42	52	62	70	80	100	140	300	800	3,300	8,300
Americas	146	178	225	290	394	501	650	863	1,209	1,752	2,780	4,959	8,717
APAC	355	495	686	916	1,198	1,500	1,825	2,096	2,631	3,373	4,956	7,628	12,397
Europe	129	262	396	598	1,305	2,289	3,281	5,310	11,020	16,850	30,472	52,884	70,043
Total	**1,400**	**1,765**	**2,235**	**2,820**	**3,952**	**5,364**	**6,946**	**9,521**	**16,229**	**23,605**	**40,670**	**71,061**	**102,156**

Figure 4.1 Evolution of global cumulative installed capacity in MW
Source: (Masson et al., 2013)

Below the bar-chart, the geographical distribution of the cumulative installments is shown in figures. The shortcut "MEA" stands for Middle East and Africa and it can be seen that until 2009 there were no considerable developments with PV at all. Contrary is the development in Asia Pacific countries (APAC), where 12,397 MW have been installed. "ROW" stands for "Rest of the world" and the figures exhibit a duplication within the years 2005 to 2011 (Masson et al., 2013).

4.3 The burst of the Solar PV bubble

4.3.1 Imbalance of supply and demand & falling prices

In response to the booming global demand the solar Photovoltaic cell manufacturing capacity has grown rapidly in recent years. The boom started with increasing demand in OECD-countries and spread over to China, which expanded manufacturing capacity massively in order to support exports, which altogether leads to a massive overproduction as the supply expanded much more quickly than the actual demand for solar PV panels. As for example in the year 2011, the solar module capacity had reached an amount of 46,139 MW (37,834 MW c-Si modules and 8,305 MW non c-Si modules) which outreaches the demand of 30,391 MW by far. Additionally to that, the costs for purified silicon, the essential key input for the production of c-Si modules, felt sharply since 2008. Both factors and reductions due to technological learning have driven the PV system costs down sharply. Along the value chain of the c-Si PV production the price for modules plunged from 2.00 USD/W in the 3rd quarter 2010 down to 0.68 USD/W in the 2nd quarter 2013. Figure 4.2 show the price development of polysilicon, wafers, cells and modules.

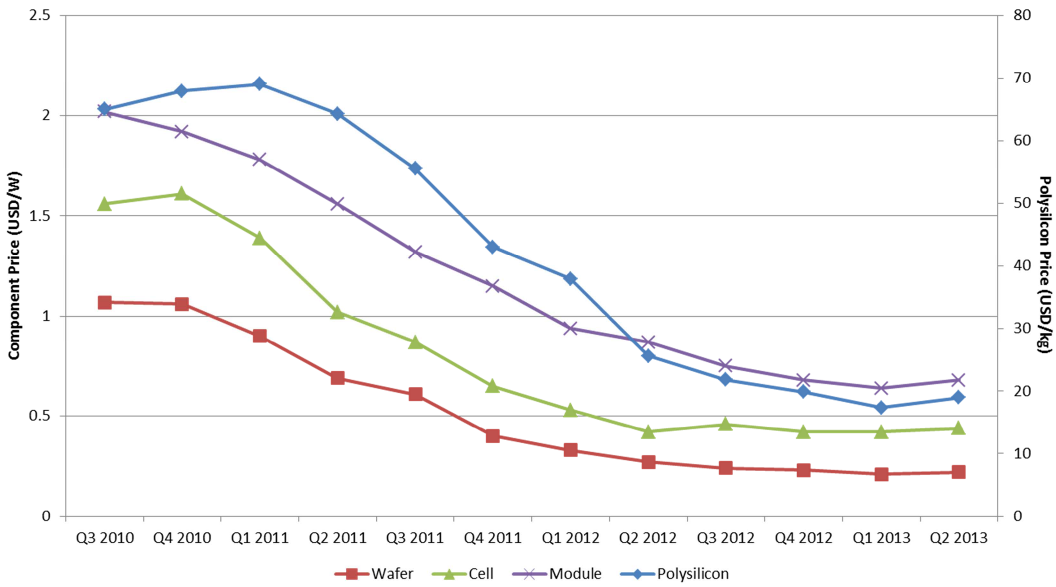


Figure 4.2 Price Development of Polysilicon, Wafers, Cells and Modules
Data-Source: (Kann et al., 2013)

4.3.2 Economic developments and the shortages for subsidies

Another factor that leads to the burst of the solar PV bubble is the global economy. Due to the national debt crisis many European countries were forced to cut the FITs down in order to reduce their financial expenditures. Because with the government-financed subsidy programs a stimulation for photovoltaic installations over the past ten years was generated, but on the other side the costs had torn a hole into the national budget, if the burden was not rolled over to the tax-payers directly with the energy bill. Already before 2010, but especially in the year 2011 many governments adopted or introduced modifications to national photovoltaic subsidy programs in order to reduce their yearly increasing national debts.

One of the first examples is Italy, where the government started to reduce the tariffs in a four-month rhythm. In France, the remuneration rates were capped by up to 67% and in the United Kingdom, a tariff reduction came into force in August 2011. An even more drastic measure was done by the government of the Czech Republic, which stopped all remunerations except for plants below 30 kW. With November 2012, the subsidy program changed as well in Germany, where the supported money now depends on the capacity installed in the previous year. Additionally to that, the FITs were decreased monthly for a certain period of time (Krannich, 2012). Thus, there were many negative trends within the European market, which affected the complete photovoltaic industry.

4.3.3 The results of this two factors

To make the recent events visible a chart-analysis seems to be the best tool to show the development of a market. In the case of the solar PV market it makes sense to consider a whole index, namely the PPVX (Photon Photovoltaic Companies Index), which is calculated and published by Bloomberg and comprises the world’s 30 biggest solar companies, listed on the stock exchange. As it makes sense to compare the development from December 2010 until February 2012, the MSCI World Index was chosen. This index contains the biggest companies of the world and therefore represents the average movement of the worldwide stock market.

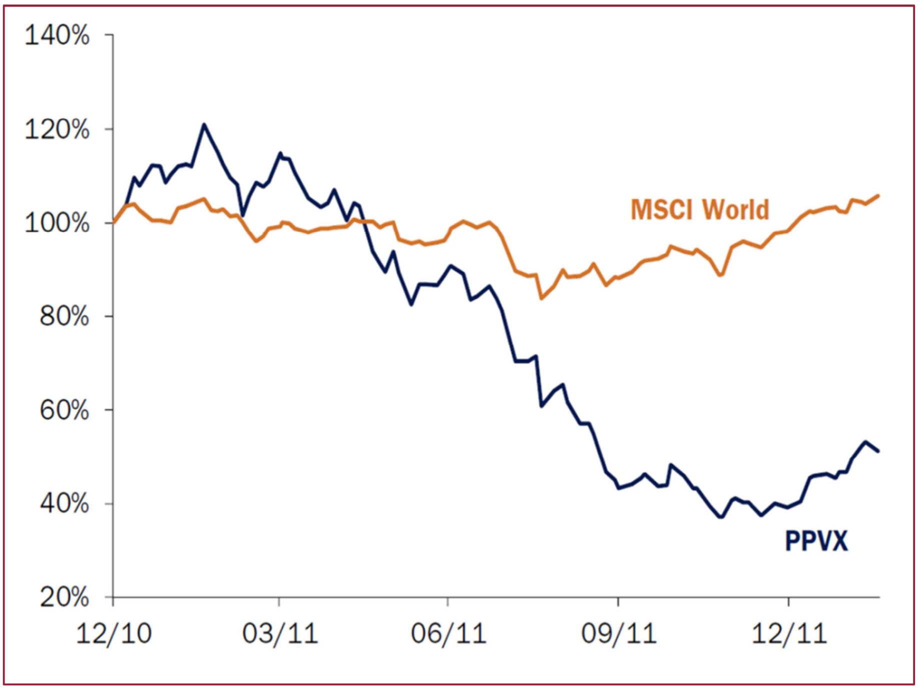


Figure 4.3 Comparison between PPVX and MSCI World Index
Source: (Fawer, 2012)

The tragic nuclear disaster in Japan in March 2011 marks a short up rise before the PV bubble bursts. As it can be seen in the chart, the PPVX headed south and plunged much more steeply than the general stock market trend of the MSCI World Index. Until the end of October, the PPVX solar index has dropped down more than 60% compared with minor losses on the global stock market, represented by the MSCI World Index. The extreme volatility in the solar stock index reflects the high dependency on the mentioned factors. Unfortunately, the change in the future energy policy in Germany, Italy, and Switzerland after the Fukushima disaster did not lead to a sudden boost for photovoltaic modules (Bank-Sarasin, 2011). A light on the end of the tunnel however are the developing countries, which came up with goals and subsidies in order to attract the market. For example, China adopted a first national photovoltaic policy in August 2011 with an FIT of 0.12 EUR/KWh (Liu, 2011). India plans to produce 20 GW in 2022 through photovoltaic and concentrating solar power and South Africa plans to establish 8.4 GW by 2030 (Bank-Sarasin, 2011).

4.4 Beyond the Solar PV bubble

The biggest profiteers from this development are the consumers together with the installers of solar PV systems. Contrary the solar PV manufacturers, especially those with manufacturing facilities in Europe or in the USA, suffered large financial losses. A former big company like Q-Cells from Germany has gone bankruptcy in April 2012 (International Energy Agency, 2012). Suntech, the world's largest producer of solar panels in the year 2011, faces enormous financial troubles and is on the way for its first bankruptcy hearing in front of a Chinese court (Hornby, 2013). Between Europe, USA, and China trade tensions have arisen which resulted in the imposition of import tariffs on panels from China. In the short term, such difficulties are likely to be on the daily agenda, while the imbalance between demand and supply endures. However, the period, which is necessary for restoring this balance, will be mainly driven by the demand growth rate for PV and China will play again a major role, as it represents one of the biggest potential markets (International Energy Agency, 2012).

5 Solar Photovoltaic Industry

The global PV industry exceeds 2011 the aggregate size of USD 100 billion per year. As mentioned in the previous chapter the installers and consumers had a good year, while the different players along the production value chain struggled to make profits and survive amidst falling prices and excess inventory. Those were the polysilicon producers, wafer, cell and module manufacturers as well as the Thin-Film module producers, which were also influenced despite they are working within a special market niche. The market growth slowed down, government support declined, and a significant industry consolidation started in the aftermath of the financial crises (REN21, 2012). However, analyzing a whole industry is a difficult task, because it is neither clear where to start nor is it easy to find an end. The best start is an overall view about the different value chain sectors as mentioned above.

5.1 Technology Overview

The PV technology is divided between crystalline solar cells (c-si), whereby the basic material is silicium, and Thin-Film technologies as described before. The graphic below (Figure 5.1) from the "Global Market Outlook for Photovoltaics 2013-2017" Report published by the European Photovoltaic Industry Association shows the dominance of c-si modules in terms of production capacity. The total capacity in the year 2011 amounts 46,139 MW based on the calculation that non c-Si PV production capacities amount 8,305 MW and has a share of 18%. As it can be seen in the graphic below the c-Si PV production totals 82% (blue line), which is 37,834 MW. Furthermore, the ongoing increase over all the years for c-Si PV capacities is easily visible, while the non c-Si PV capacities and especially the Thin-Film modules (colored in black) will stagnate at the same level from the year 2011 onwards (Masson et al., 2013).

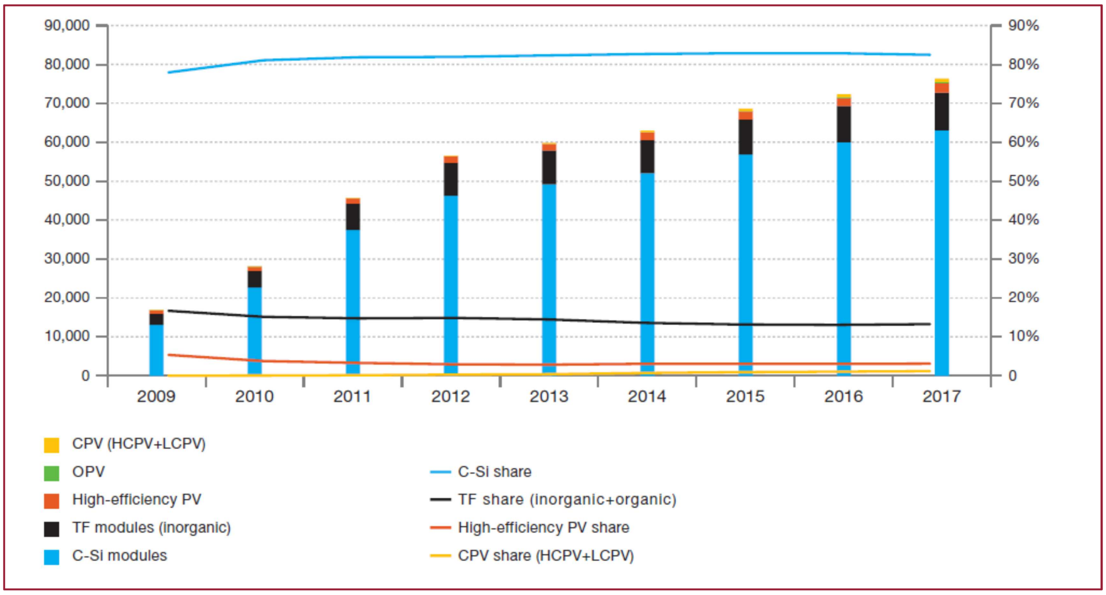
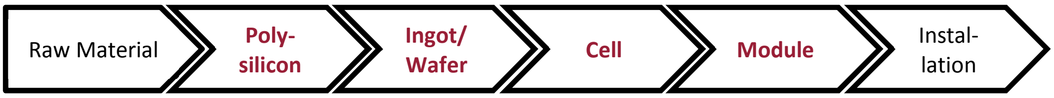


Figure 5.1 Development of PV-Technologies
Source: (Masson et al., 2013)

The industry sector for c-Si PV modules itself is a huge one. This comes along with the fact that the production is preceded within four steps, which are illustrated within this arrow-bar and described afterwards.



From the raw material Silicia, which is found in quartz sand, high concentrated silicon could be processed which is done within the first step. In the second one, the silicon is melted and formed into ingots, which are sliced into wafers. The assembling of a cell follows in the next step and is completed with the fixation into a module, which are than ready for the installation. Comparing those four steps graphically resulted in Figure 5.2. It shows the total amount in MW of each of the four value chain steps. Furthermore the bars are subdivided into different colors, each of them stand for an individual company, which ranks amongst the top players within their sector. The dark blue area marks the amount of “other” companies, which comprises small companies with a low production amount and based on this fact there is no data available and that is why they were not listed individually.

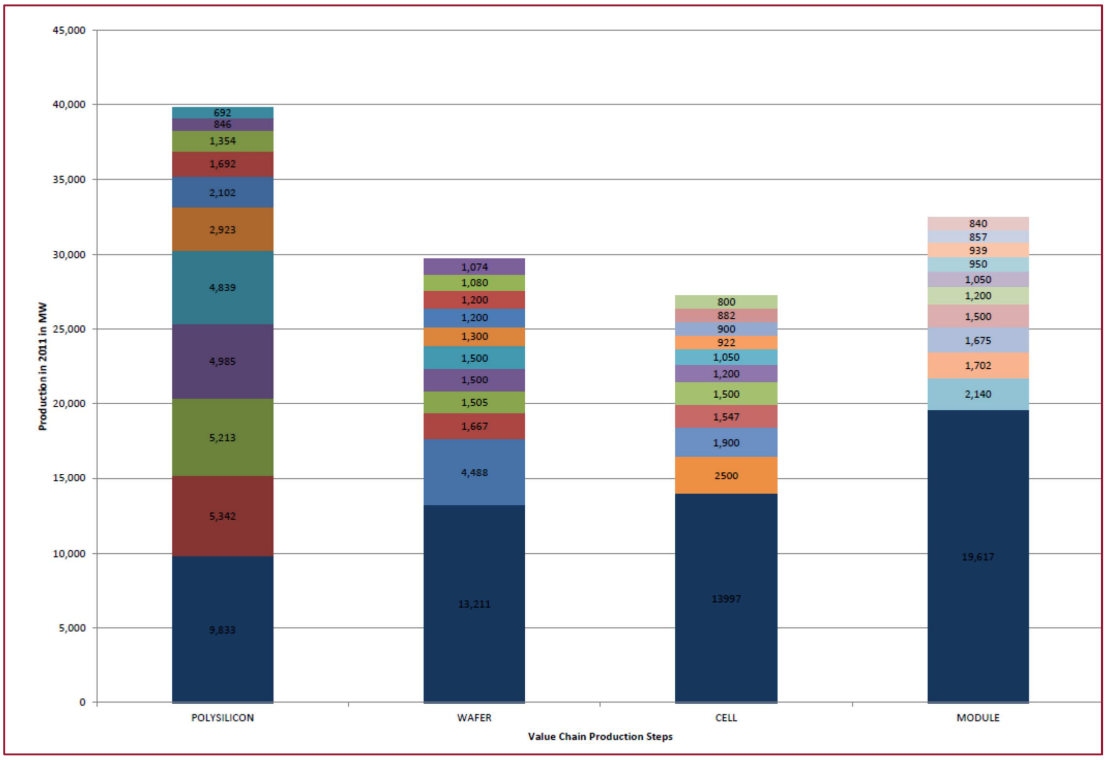


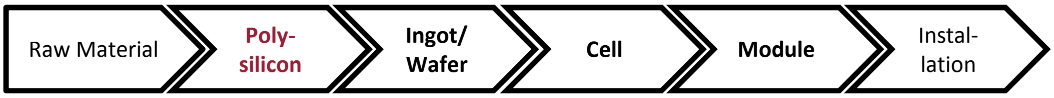
Figure 5.2 Value Chain steps - total amount in MW
Source: (Jäger-Waldau, 2012)

The total amount of polysilicon produced in the year 2011 was 39,821 MW. However, before going into detail with utilization capacity and details about size it is important to know that there are two ways to express the production or capacity values. Either they are given in MT (= metric tons) or in MW (Megawatt). In the graphic above the values are given in MW in order to compare them easily with the other steps while later the more common usage of MT was applied. A division of the collected figures of the total amount in MT through the amount in MW results in an average material need of 7.23 g/Wp.

Table 5.1 Calculation of Polysilicon Material need
Data-Source: (Prior and Campbell, 2012) (Herman, 2012)

Basic formula	Polysilicon Material need = MT / MW
Calculation	Data = Total amount of Polysilicon produced in the year 2011 287,835 MT / 39,821 MW Material need = 287,835 / 39,821 Material need = 7.23 g/Wp

5.2 Polysilicon Production



5.2.1 Introduction

The production of polysilicon is the first step in the value chain of crystalline cell production and is thereby heavily influenced from the whole industry sector. The impact of the PV industry on the polysilicon market can be clearly seen in Figure 5.3, which shows the polysilicon spot market price from the year 2002 to 2012 in USD/kg.

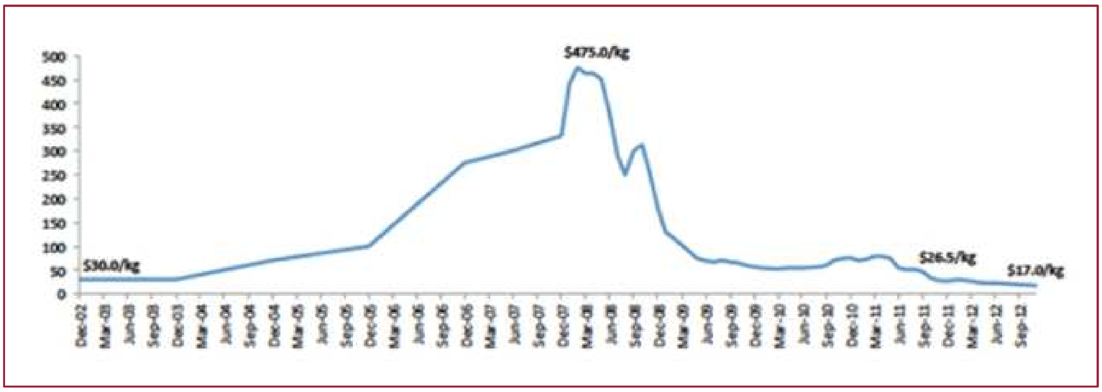


Figure 5.3 Solar Polysilicon Spot Market Price (USD/kg, 2002-2012)
Source: (The Smart Cube, 2013)

Back in 2006, the solar industry boomed and led to a run for polysilicon, which lead to an enormous increase of the price. At that time, more than the half of all polysilicon went into the production for solar panels and the price kept rising along with the demand. The supply shortages pushed the price to a peak around 475 USD/kg in 2008 and margins for the producers had risen to 70%. Such high margins enhanced the attractiveness for capacity-expansion and brought new players into the market. Because of diminishing demand during the economic crisis and the overcapacities, the price dropped to 50 to 55 USD/kg until the end of 2009. The slight upward tendency in 2010 and in the first months of 2011 remained not long and prices plunged towards 17 USD/kg in September 2012 (Jäger-Waldau, 2012) (Bank-Sarasin, 2011).

5.2.2 Size and utilization capacity

The total produced amount of solar grade silicon reaches 287,835 MT (metric tons) in the year 2011, whereby the number of companies producing polysilicon is not specified. The company "SolarPVInverstor", which publishes the capacities of top companies on its homepage, lists 33 companies with capacities of more than 1,000 MT in the year 2011 (SolarPVInvestor, 2013). Another figure, taken from the PV Status Report 2012, published by the European Commission, stated that the worldwide market is spread amongst more than 100 companies (Jäger-Waldau, 2012). The pie chart below shows the market shares of the TOP 10 polysilicon producers based on their produced amounts of polysilicon. Together they account for a market share of 67.0% of the worldwide market.

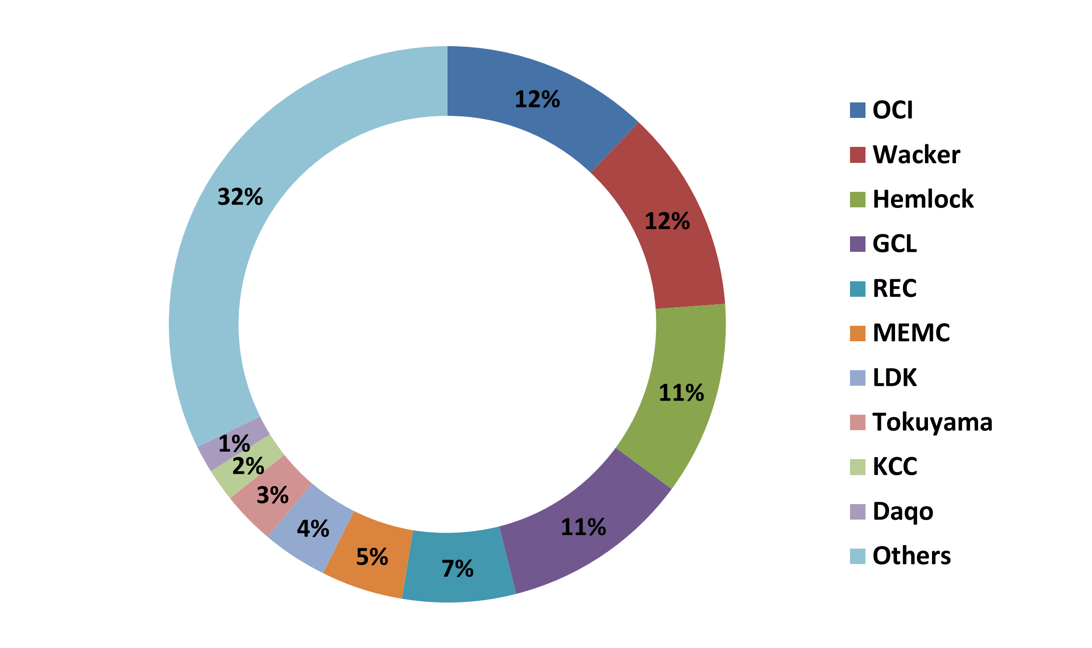


Figure 5.4 Pie chart - TOP 10 Polysilicon producers
Data-Source: (Prior and Campbell, 2012) (Jäger-Waldau, 2012)

An interesting fact to consider is however, the capacities of those companies, which would show a total different picture, as it can be seen in Table 5.2. The Chinese company GCL-Poly Energy Holdings Ltd. leads the list with a capacity of 65,000 MT but reported a production of 29,414 MT. This low capacity utilization rate of less than 50% can be attributed to the technological upgrades and capacity expansions during the year itself, because the capacity marks the amount of polysilicon in MT at the end of the year (GCL-Poly Energy Holdings Limited, 2012).

Similar explanation counts for the low rate of LDK Solar Co., Ltd., which completed its third process train in their Mahong Plant in the third quarter (LDK Solar Co., Ltd., 2012). Based on the production location and on the capacity amounts in percent following country diversification can be seen: China 23.3%, USA 21.9%, South Korea 13.0% followed by Germany with 10.8% and Japan with 2.5%. Compared to the supply chain steps of cell production and module assembling, which will both be described and analyzed later in this document, the stake of the Chinese companies is rather low. The reason for this is the high technical knowledge, which is necessary for silicon purification. The ability to produce silicon at a competitive price requires a very specific know-how to control all parameters of the chemical reaction, which enables Hemlock the production in the USA and Wacker Chemie the production expansion in Germany itself (Wacker Chemie AG, 2013) (de la Tour et al., 2011).

Table 5.2 TOP 10 Polysilicon producers list
Data-Source: (SolarPVInvestor, 2013) (Prior and Campbell, 2012) (Ciesielska et al., 2011)

Rank	Company	Capacity (MT) end of 2011	Market share based on capacity in %	Company production in MT (2011)	Capacity utilization in %	Country
1	GCL	65,000	17.57	29,414	45.25	(CHN)
2	Hemlock	46,000	12.43	32,400	70.43	(USA)
3	OCI	42,000	11.35	34,725	82.68	(KOR)
4	Wacker	40,000	10.81	33,885	84.71	(GER)
5	LDK (Liouxin Group)	17,000	4.59	11,000	64.71	(CHN)
6	REC Silicon	20,000	5.41	19,050	95.25	(USA)
7	MEMC	15,000	4.05	13,661	91.07	(USA)
8	Tokuyama	9,200	2.49	8,800	95.65	(JPN)
9	KCC	6,000	1.62	5,500	91.67	(KOR)
10	Daqo New Energy	4,300	1.16	4,524	105.21	(CHN)
	Others	105,500	28.51	94,876	89.93	
	Total Amount	**370,000**	**100.00**	**287,835**	**77.79**	

To conclude this part, the utilization capacity is calculated for the whole polysilicon industry. According to the information presented in the "Global Market Outlook for Photovoltaics until 2015" from the European Photovoltaic Industry Association the capacity amounts 370,000 MT in the year 2011 (Ciesielska et al., 2011). Compared to the produced 287,859 MT produced this is a utilization capacity of around 78%.

5.2.3 Herfindahl-Hirschman Index (HHI)

The calculation of the HHI is based on the market shares of the TOP 10 polysilicon manufacturers. Contrary to the figures in Table 5.2, the production in MT was used for the calculation of the market shares and not the capacity. The result for these companies, who have a market share of 67.0%, is a HHI of 0.0612. This indicates an unconcentrated index, which describes a competitive market.

Table 5.3 Calculation HHI Polysilicon-Manufacturers
Data-Source: (Prior and Campbell, 2012) (Jäger-Waldau, 2012)

Basic formula	HHI = (company 1-s_i)^2 + (company 2-s_i)^2 + (company 4-s_i)^2 … + (company N-s_i)^2	
Calculation (TOP 10)	Data =	Market share of the TOP 10 companies based on produced MT (Company1 = 12.06%; Company2 = 11.77%; Company3 = 11.26%; ….)
	s_i =	Company1: 0.1206; Company2: 0.1177; Company3: 0.1126; ….)
	HHI =	$(0.1206)^2 + (0.1177)^2 + (0.1126)^2 + \ldots$
	HHI =	0.0612

5.2.4 Minimum Efficient Scale

Referring to chapter 3, where the Minimum Efficient Scale is defined as minimum capacity in terms of quantity and quality of a company to be competitive viable in the long run, following reflections can be done. The four main players, Hemlock, the German producer Wacker, OCI, and GCL-Poly, increased their capacities to around 50,000 tons per year, which is a remarkable difference to the other companies ranked in Table 5.2. Additionally, according to Bank Sarasin, those four players are also leading in terms of quality and because of their size, they will be able to increase their market share to 70% in the next years (Bank-Sarasin, 2011). On the already mentioned Website of SolarPVInvestor, the lowest capacity of a company for the year 2012 states 600 metric tons for a Japanese company.

Additionally, several Chinese companies are listed, where an additional comment states, that those companies reported a shutdown. However, those companies had capacities of at least 1,500 tons up to 7,200 tons (SolarPVInvestor, 2013). A in depth research showed that MEMC, which was renamed to SunEdison in May 2013 and sixth largest polysilicon producer in 2011 also closed down its facility in Merano, Italy with a production capacity of 6,000 tons by the end of the year 2011, because of the significant downturns in the industry (MEMC Electronic Materials, Inc., 2012). Contrary to Table 5.2 following figure shows the top ten silicon producers based on their production. Furthermore, the authors of the report "engineering the solar age" considered ReneSola as top ten producer, whereas other sources - as used before - took KCC into the list.

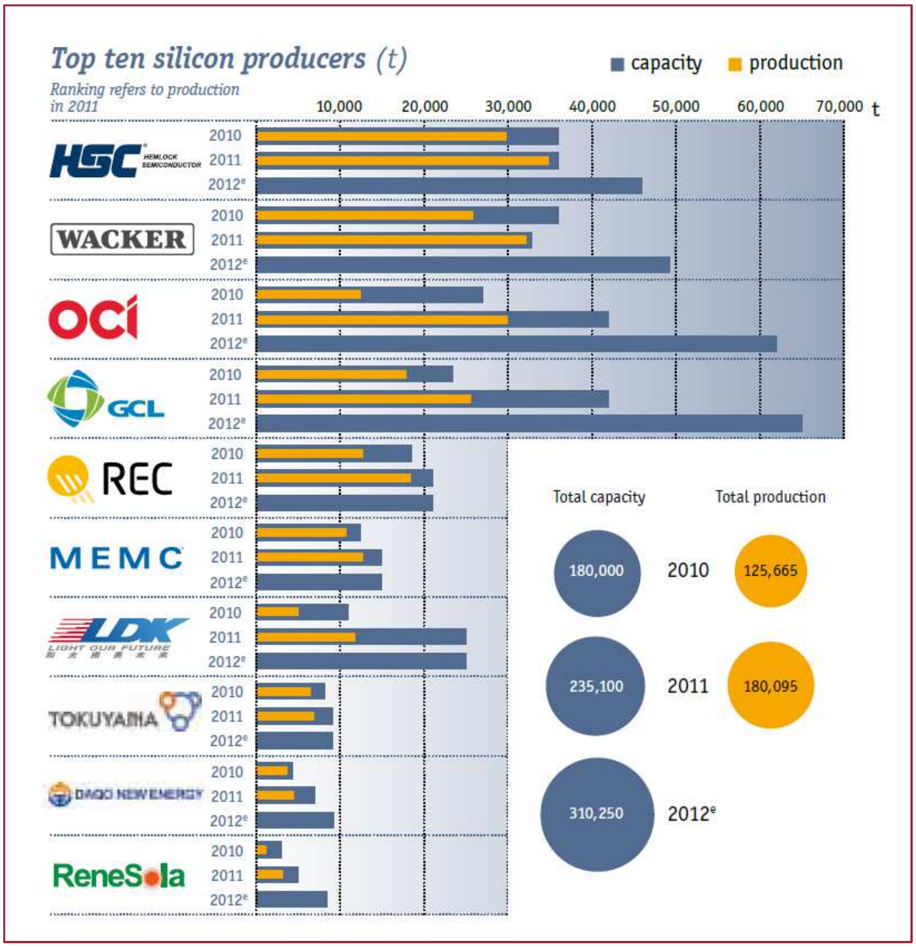
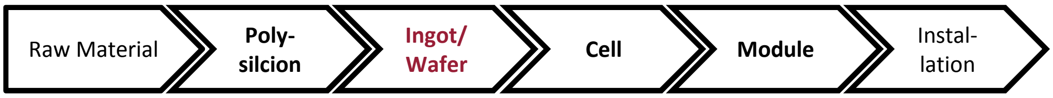


Figure 5.5 Bar diagram - TOP 10 silicon producers 2011
Source: (Solarpraxis AG, 2012)

Going a step further, the webpage “pv-magazine” classified all polysilicon producers into Tier 1 to Tier 3 suppliers, whereby the biggest four are Tier 1. Among the Tier 2 suppliers, the analyst Henning Wicht predicted at least one to go bankruptcy, whereby the rest will be able to hold their production level in 2012 and 2013. The article, which was published Nov. 15th 2012, named REC, MEMC, LDK, Tokuyama, Daqo New Energy, and ReneSola. The last group, Tier 3 suppliers, is defined as those companies producing less than 15,000 tons per year of silicon. Setting this as Minimum Efficient Scale based on the explanation of the photovoltaic analyst, only those companies will survive if they have an internal market to purchase their polysilicon or if they are able to invest into new technology in order to lower cost (Hall, 2012).

5.3 *Ingot and Wafer Production*



5.3.1 *Introduction*

Before starting with the second step within the value chain a short notice on the differences between ingot and wafer. Ingots are whole blocs of silicon, whereas a wafer is the cropped slice from this silicon bloc. The market pressure for wafer producers is attributable to two main factors. First, the dramatic plunge of cell and module prices forces the manufacturers to lower their prices as well. Second, many companies, which were not vertically integrated and produce their polysilicon within its structures, stuck in long term contracts with fixed prices with their silicon suppliers. Therefore, when wafer price in US-Dollar per Watt plunged from 1.07 USD/W in the third quarter 2010 down to 0.22 USD/W in the first quarter 2013 many wafer producers struggled to get out of their long term contracts and to survive in the fierce competition.

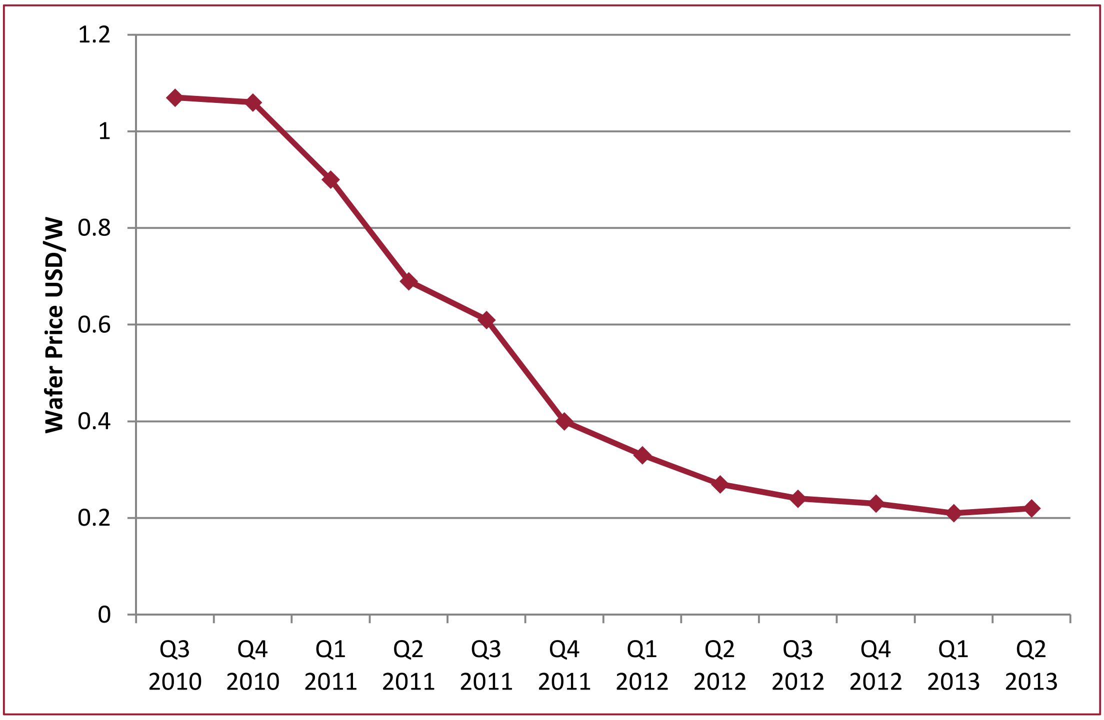


Figure 5.6: U.S. Wafer Price USD/W
Data-Source: (Kann et al., 2012) (Kann et al., 2013)

5.3.2 *Size and utilization capacity*

According to Mr. Masson and his research team from EPIA the market for wafer production is divided amongst 250 manufacturers, whereby Chinese companies leading the market (Masson et al., 2013). Amongst the top twelve producers shown in the graphic below there are nine companies which have their headquarter in China and also the main production facilities are located there. Taking only the produced wafers in MW of the TOP 12 for the year 2011 into consideration, their domination reaches a significant value of 81%.

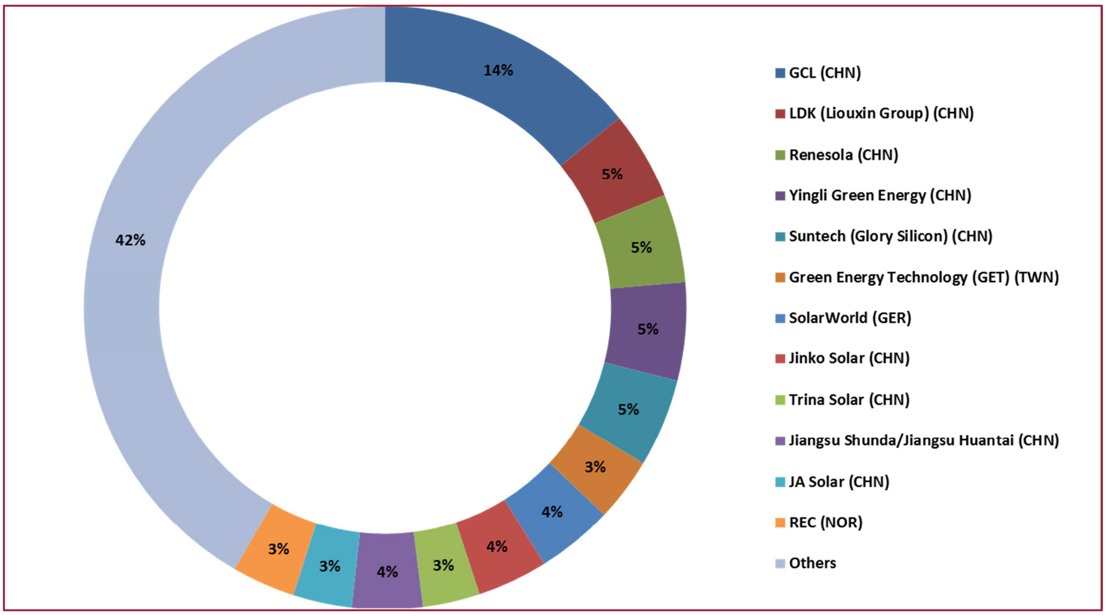


Figure 5.7 Pie chart - TOP 12 Wafer-Manufacturers
Data-Source: (Solarpraxis AG, 2012)

To bring it down onto numbers the total amount of wafers produced reaches 31,696 MW, whereby the twelve top players produced 18,845 MW. Those are 58.32% from the total market from companies with a production of a minimum of at least 970 MW (= Trina Solar) as it can be seen in the following table. Looking at the capacities all TOP 12 players start with nearly 1,000 MW, whereby the smallest of the three non-Chinese companies, namely REC from Norway, reaches only 950 MW. The capacities of the other two companies located outside from China, SolarWorld from Germany and Green Energy Technology from Taiwan, are in the middle of the ranking. The clear market leader is the company GCL, which was already mentioned as top player in the silicon production, with a capacity of 8,000 MW. The utilization rate of the company is rather low and according to the annual report, this fact can be explained with the enormous step-ups and capacity increasing development of subsidiaries, which took place during the year (GCL-Poly Energy Holdings Limited, 2012). The average utilization capacity amounts 86.10% which is similar to the one calculated for those companies summarized under others.

Table 5.4 TOP 12 Wafer-Manufacturers list
Data-Source: (SolarPVInvestor, 2013) (Prior and Campbell, 2012) (Ciesielska et al., 2011)

Rank	Company	Capacity (MW) end of 2011	Market share based on capacity in %	Company production in MW (2011)	Capacity utilization in %	Country
1	GCL	8,000	19.28	4,488	56.10	(CHN)
2	LDK (Liouxin Group)	4,300	10.36	1,500	34.88	(CHN)
3	ReneSola	2,400	5.78	1,505	62.71	(CHN)
4	Yingli Green Energy	1,700	4.10	1,667	98.06	(CHN)
5	Suntech (Glory Silicon)	1,600	3.86	1,500	93.75	(CHN)
6	Green Energy Technology	1,550	3.73	1,080	69.68	(TWN)
7	SolarWorld	1,250	3.01	1,300	104.00	(GER)
8	Jinko Solar	1,200	2.89	1,200	100.00	(CHN)
9	Trina Solar	1,200	2.89	971	80.92	(CHN)
10	Jiangsu Huantai	1,000	2.41	1,200	120.00	(CHN)
11	JA Solar	1,000	2.41	1,000	100.00	(CHN)
12	REC	950	2.29	1,074	113.05	(NOR)
	Others	15,350	36.99	13,211	86.07	(CHN)
	Total Amount	41,500	100	31,696		

5.3.3 Herfindahl-Hirschman Index (HHI)

Similar to the calculation of the HHI in the chapter before the considered data is the individual production per company in the year 2011. Based on those figures, which can be seen in Table 5.4 the market shares and in the second step the HHI was calculated.

In this section of the c-Si solar module value chain the HHI amounts 0.0383. The low value compared to the calculated HHI for polysilicon companies indicates a higher competition within this market. Nevertheless, the index is not below 0.01, which would represent a highly competitive index.

Table 5.5 Calculation HHI Wafer-Manufacturers
Data-Source: (Prior and Campbell, 2012) (Jäger-Waldau, 2012)

Basic formula	HHI = (company 1-s_i)^2 + (company 2-s_i)^2 + (company 4-s_i)^2 … + (company N-s_i)^2	
Calculation (TOP 12)	Data =	Market share of the TOP 12 companies based on produced MW (Company1 = 14.16%; Company2 = 5.26%; Company3 = 4.75%; ….)
	s_i =	Company1: 0.1416; Company2: 0.0526; Company3: 0.0475; ….)
	HHI =	$(0.1416)^2 + (0.0526)^2 + (0.0475)^2 + ...$
	HHI =	0.0383

5.3.4 Minimum Efficient Scale

Concerning the minimum Efficient Scale three important hurdles can be seen. First, the entry barrier, which is a minimum production capacity of 1,000 MW. Focusing on the TOP 12 companies REC with 950 MW is quiet close to this and was therefore taken into the ranking, but companies with a lower amount will definitely face difficulties in the long run as this value is below the MES. Defining groups leads to the classification of Tier 2 companies with a production capacity between 1,001 MW and 2,000 MW. Starting with Trina Solar and Jinko Solar with 1,200 MW and including Yingli Green Energy with 1,700 MW this would count six companies within this category. Tier 1 or Top companies would be ReneSola, LDK, and GCL - all with capacities above 2,000 MW.

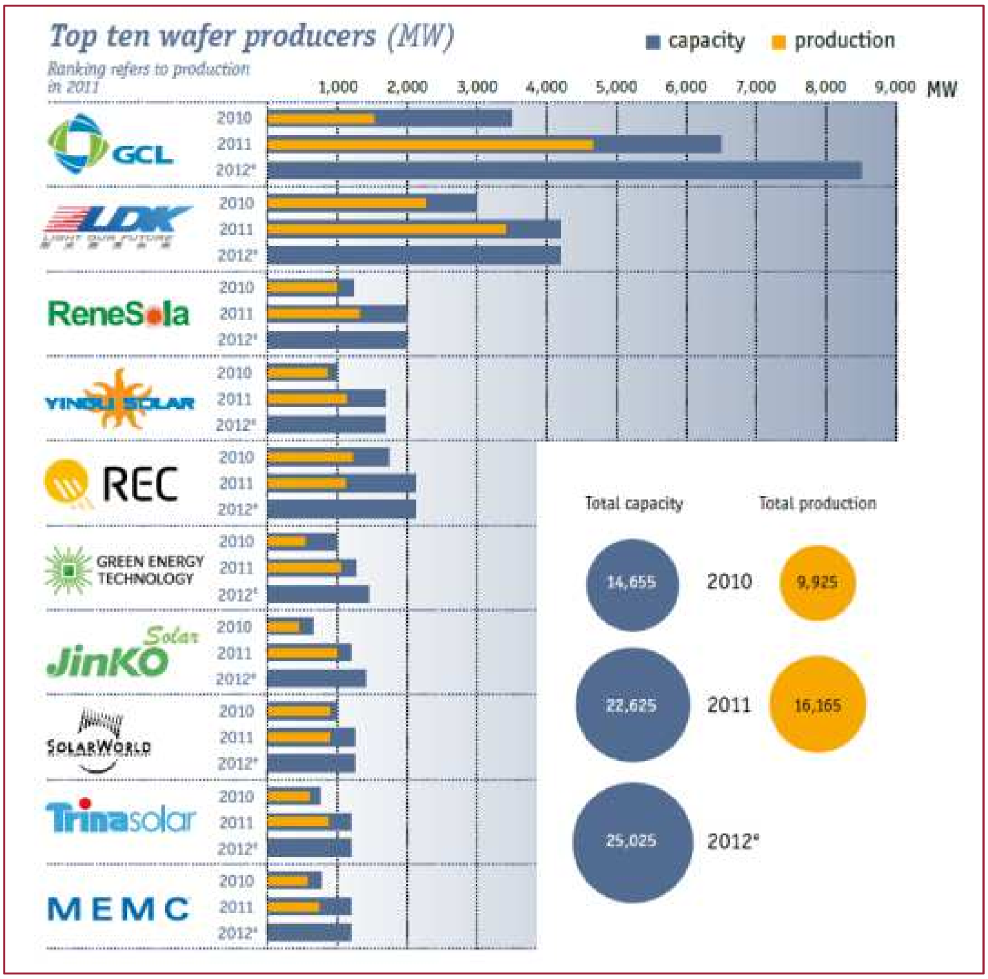
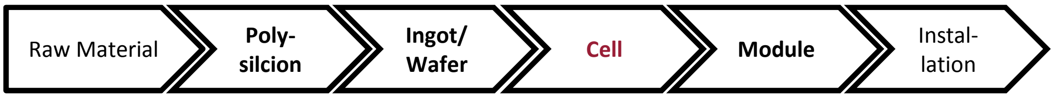


Figure 5.8 Bar diagram - TOP 10 wafer producers 2011
Source: (Solarpraxis AG, 2012)

Looking at the graphic above "Top ten wafer producers", following deviations contrary to Table 5.4 appear. Suntech, Jiangsu Huantai and JA Solar did not make it onto the list published by Solarpraxis AG, but on the other side, MEMC was considered. Checking the annual report of MEMC showed that the produced amount was clearly below 500 MW that is why it was not considered in the Top 12 list.

5.4 Solar Cell Production



5.4.1 Introduction

The solar cell industry also faced a dynamic history, whereby the changes since 2011 are the most significant ones. Worldwide, there are more than 350 solar cell producers, whereby this number is changing nearly weekly since the burst of the PV bubble. However, not necessarily downwards, because according to the PV Status Report 2012 the number of newcomers and their planned capacities outweighs the companies that filed bankruptcy, reduced their capacities or went bankruptcy (Jäger-Waldau, 2012). Figure 5.9 shows the downslope of the solar cell price, which was up to 1.61 USD/W in the fourth quarter 2010. After the plunge, the price for a cell leveled between 0.42 USD/W and 0.46 USD/W since the second quarter 2012.

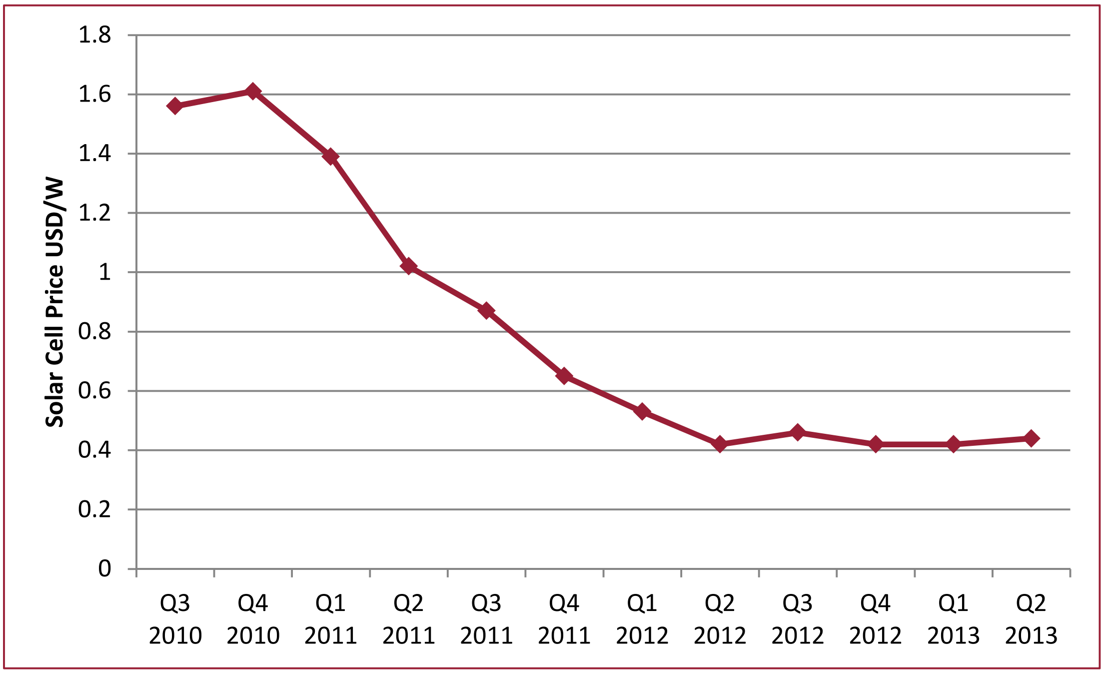


Figure 5.9 Solar Cell Price in USD/W
Data-Source: (Kann et al., 2012) (Kann et al., 2013)

5.4.2 Size and utilization capacity

Not many players can survive such a fierce price competition, hence also companies from China dominate the solar cell production. This can be seen easily in the pie chart below, which shows the TOP 16 players based on their market share calculated in terms of the MW produced in the year 2011. Eight out of the 16 companies are from China, whereby JA Solar, Suntech, Trina Solar, Yingli Green Energy, Jinko Solar, and Canadian Solar, which produced more than 1,000 MW, lead the list. All Chinese companies together hold nearly 35.0% of the world market. Other players from the Asian continent like Motech, NeoSolarPower, and Gintech are from Taiwan, Solarfun/Hanwha SolarOne from Korea, and Kyocera from Japan hold only a little bit more than 12.5%. Actually, Q-Cells could be counted in this group as well, because it was taken over one year later by the Korean Hanwha Group (Hanwha Q Cells, 2014). The stake of producers from other countries is minor. Sunpower (USA) produced 922 MW, which makes 3% out of the world production of 31,051 MW and REC from Norway produced 640 MW.

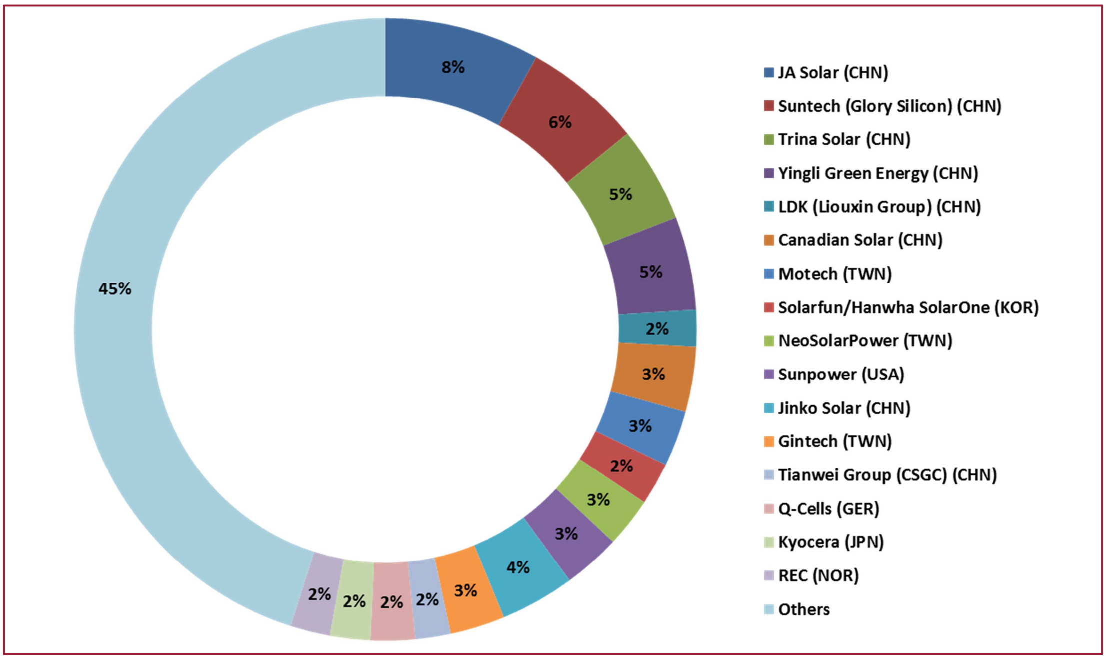


Figure 5.10 Pie chart - Top 16 Solar Cell producers
Data-Source: (Solarpraxis AG, 2012)

In terms of capacity, the following table illustrates the domination of Chinese companies even more. The average utilization rate of all 16 top manufacturers' amounts 72.5%, whereby LDK shows the lowest rate of all with 34.7%. According to the annual report, a capacity increase from 1,500 MW to 1,700 MW took place during the year 2011 but further details for the low utilization rate are not given.

Table 5.6 TOP 16 Solar Cell producers list
Data-Source: (Solarpraxis AG, 2012)

Rank	Company	Capacity (MW) end of 2011	Market share based on capacity in %	Company production in MW (2011)	Capacity utilization in %	Country
1	JA Solar	2,800	7.37	2,500	89.29	(CHN)
2	Suntech (Glory Silicon)	2,400	6.32	1,900	79.17	(CHN)
3	Trina Solar	1,900	5.00	1,547	81.42	(CHN)
4	Yingli Green Energy	1,700	4.47	1,500	88.24	(CHN)
5	LDK (Liouxin Group)	1,700	4.47	590	34.71	(CHN)
6	Canadian Solar	1,500	3.95	1,050	70.00	(CHN)
7	Motech	1,500	3.95	900	60.00	(TWN)
8	Solarfun/Hanwha SolarOne	1,350	3.55	687	50.89	(KOR)
9	NeoSolarPower	1,300	3.42	800	61.54	(TWN)
10	Sunpower	1,300	3.42	922	70.92	(USA)
11	Jinko Solar	1,200	3.16	1,200	100.00	(CHN)
12	Gintech	1,170	3.08	882	75.38	(TWN)
13	Tianwei Group (CSGC)	1,000	2.63	569	56.90	(CHN)
14	Q-Cells	950	2.50	717	75.47	(GER)
15	Kyocera	800	2.11	650	81.25	(JPN)
16	REC	750	1.97	640	85.33	(NOR)
	Others	14,680	38.63	13,997	95.35	
	Total Amount	38,000	100	31,051		

5.4.3 *Herfindahl-Hirschman Index (HHI)*

In the ranking of the TOP 16 cell manufacturers the highest market share based on produced MW in the year 2011 is JA Solar with 8.05%. In the two production steps before the wafers are assembled to cells there was at least one company with a market share of more than 10.00%, in the Polysilicon production even four companies reached such a market share. The calculated HHI of 0.0235 proofs that competition amongst the companies is even higher than in the wafer production.

Table 5.7 Calculation HHI Cell-Manufacturers
Data-Source: (Prior and Campbell, 2012) (Jäger-Waldau, 2012)

Basic formula	HHI = (company 1-s_i)^2 + (company 2-s_i)^2 + (company 4-s_i)^2 … + (company N-s_i)^2	
Calculation (TOP 12)	Data =	Market share of the TOP 12 companies based on produced MW (Company1 = 8.05%; Company2 = 6.12%; Company3 = 4.98%; ….)
	s_i =	Company1: 0.0805; Company2: 0.0612; Company3: 0.0498; ….)
	HHI =	$(0.0805)^2 + (0.0612)^2 + (0.0498)^2 + ...$
	HHI =	0.0235

5.4.4 *Minimum Efficient Scale*

The market entry barrier for companies can be classified with 1,000 MW production capacity per year. The value is taken from the company ranked on the thirteenth place - Tianwei Group, which has a production capacity of 1,000 MW by the end of the year 2011. An indicator for taking this value is Q-Cell, which went bankruptcy even though it used to be one of the world’s top manufacturers with a capacity of 950 MW. There are still other companies far below the MES and not listed in the ranking, as for example CHN Sunergy with 400 MW or ReneSola with 240 MW, both are one of those companies which have to show if they can compete amongst the bigger players in the long run. Taking 1,000 MW as MES and an upper limit of a production capacity of at least 1,350 MW forms the first category - Tier 3 producers. Cell manufacturers like Kyocera and REC are also below the MES and doubling their capacities would enhance their surviving chances on the market enormously as companies with production amounts around 1,350 MW are already among the TOP 10 producers. Within and below the Tier 3 category, all companies outside of Asia are included, showing again the dominance of Asian and especially Chinese companies as stated before. From 1,351 MW to 2,000 MW capacity, companies are categorized as Tier 2 players and here only Motech, a Taiwanese company, is not under Chinese leadership. Tier 2 consists of five companies and their individual market share amounts between 4% and 5%. The top players in the list are the two Chinese companies Suntech and JA Solar, with capacities above 2,000 MW. Contrary to Table 5.6 Suntech is listed as Number one in the graphic below, but the production quantity of more than 2,000 could not be quantified. In addition, the figure for Sharp was not stated in the annual report of the company nor could it be verified with reliable data that is why it is not under the TOP 16 solar cell manufacturers list.

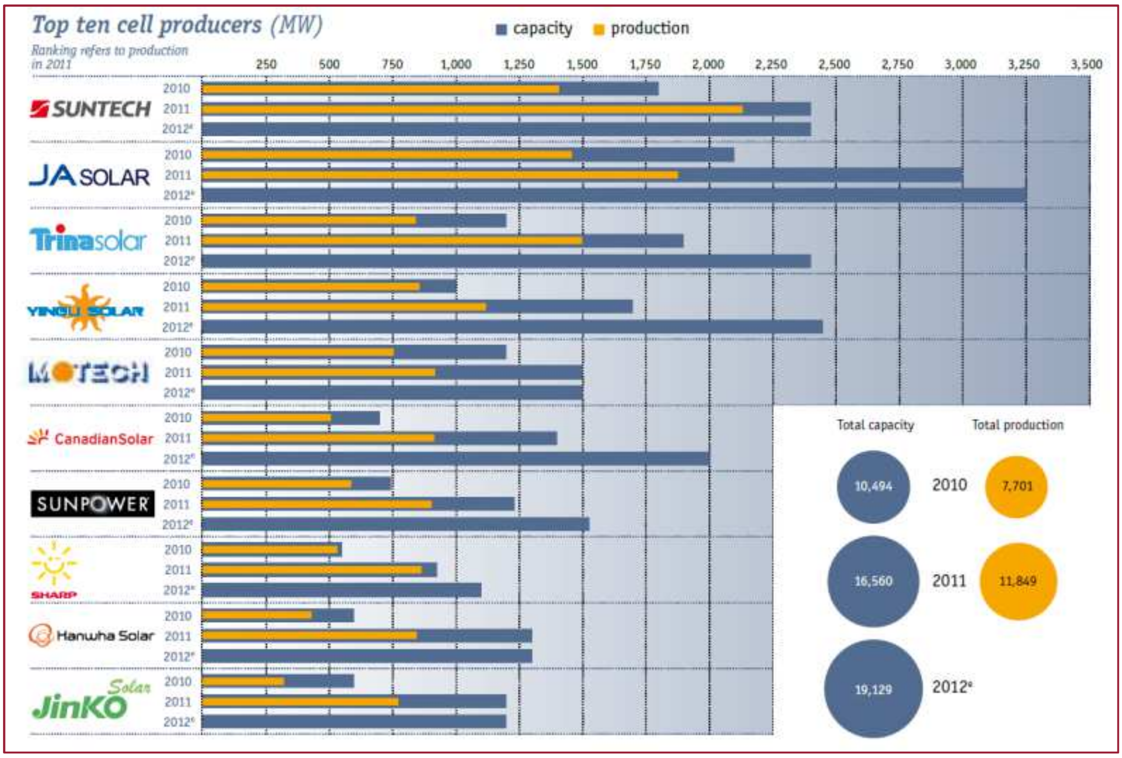
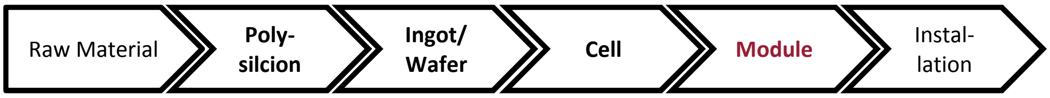


Figure 5.11 Bar diagram - TOP 10 cell producers 2011
Source: (Solarpraxis AG, 2012)

5.5 Solar PV Module Manufactory



5.5.1 Introduction

The final production step before installing the photovoltaic panels onto a roof is the assembling of several cells to a module. The technological difficulty and the added value to the product in this step is rather low, hence it is again dominated by countries in the Far East. Looking at the price development in Figure 5.12 a clear downward tendency can be seen. While in the third quarter 2010, the price used to be 2.02 USD/W it bisected until the first quarter 2012 and decreased even further to 0.68 USD/W in the second quarter 2013.

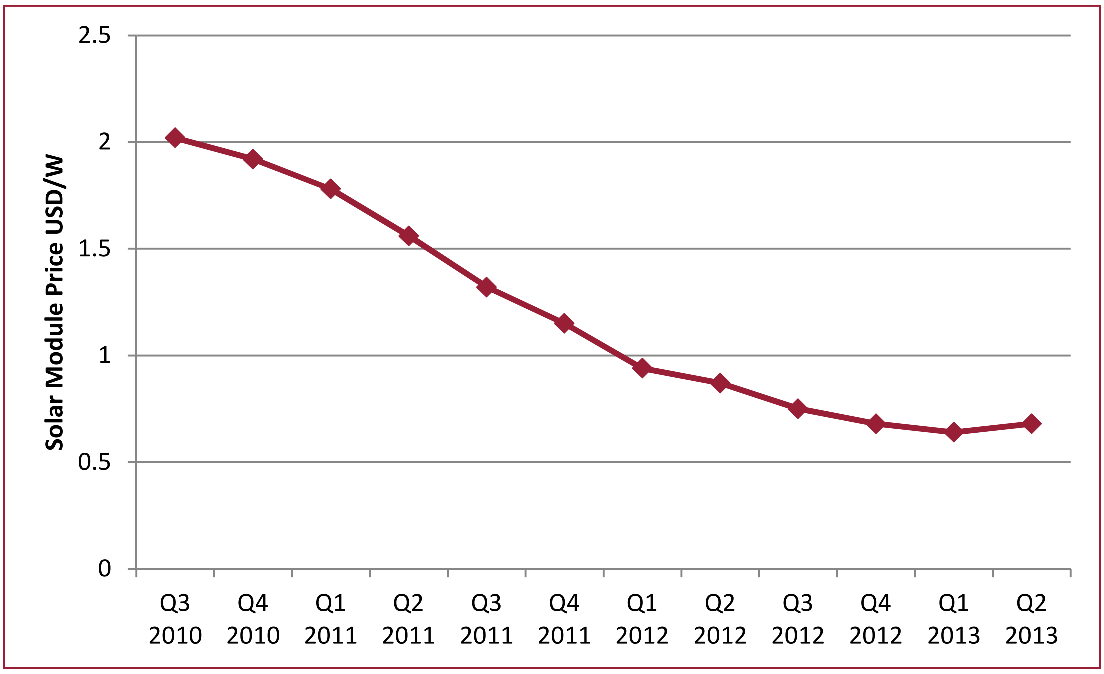


Figure 5.12 Solar Module Price in USD/W
Data-Source: (Kann et al., 2012) (Kann et al., 2013)

5.5.2 Size and utilization capacity

The total amount of produced modules reached 34,009 MW in the year 2011. In the Global Status Report an amount of more than 400 module producers is stated. Additionally, the authors indicated that China alone had around 650 producers before many of them were kicked out of the market. The consolidation process has not only brought big companies like Q-Cells and BP Solar into troubles, but also many others had to pull out the industry in 2011. Nevertheless, competition is still high and the TOP 12 companies taken into consideration for the graphic below have only a market share of 42.02% together. The market shares of the top producers are based on the produced MW in the year 2011. Suntech is leading the ranking with 2,140 MW, followed by Canadian Solar and Trina Solar both with market shares of around 5%. The domination of Chinese players is evidently. Eight out of the TOP 12, with a market share of 31.19% are under Chinese control. The other four companies, Solarfun/Hanwha SolarOne (Korea), Sharp (Japan), Solar World (Germany), and REC (Norway) play only a minor role in the ranking (REN21, 2012).

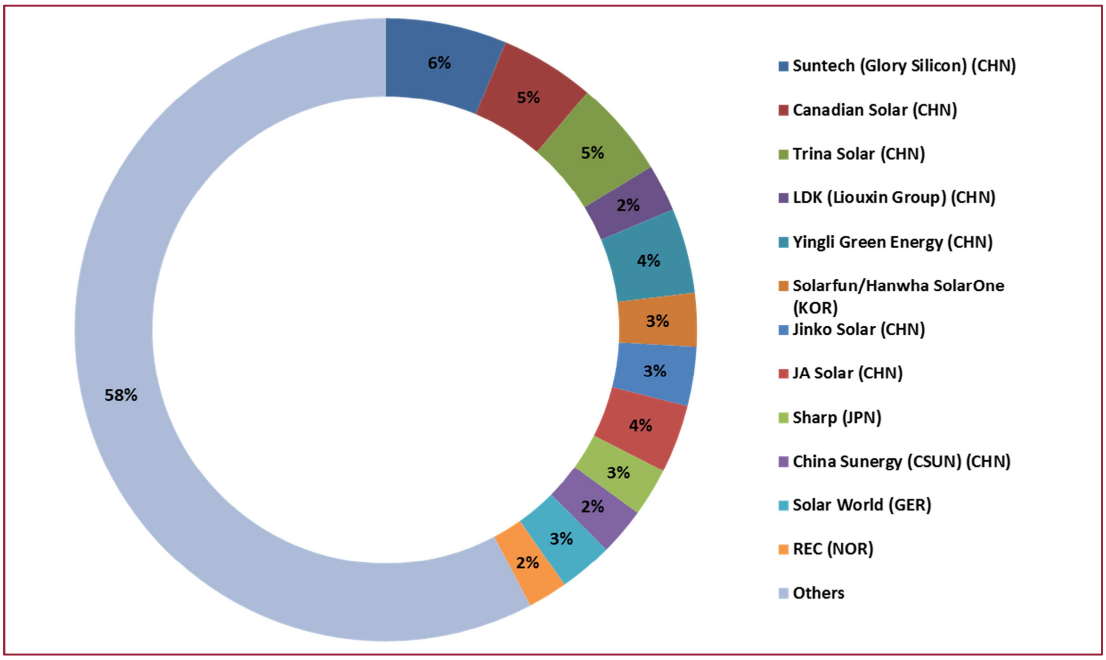


Figure 5.13 Pie chart - TOP 12 Solar-Module Producers
Data-Source: (Solarpraxis AG, 2012)

Considering the capacity utilization in the next table, again LDK shows a low rate of nearly 50%. Similar to the other value chain steps much higher capacities are in contrast to the amounts produced. According to the annual report, the reason is expansion and the clear commitment of the company to continue with its strategy in order to survive in the market (LDK Solar Co., Ltd., 2012).

The average utilization rate is around 84.00% clearly affected by the low rate of LDK as mentioned above and by Solarfun/Hanwha Solar One, which has a utilization rate of 55.89%. Unfortunately, the reason for this low rate was not stated in the annual report. Another interesting fact is that nine of the TOP cell producers can be found also in the TOP ranking of module producers. This is a clear picture for an integration of this value chain step in order to increase the value of the price. According to a report published by Bank Sarasin & Co. Ltd. vertically integration is a major asset for surviving the market. Looking at the list below and the TOP rankings before, two companies can be found on all lists: LDK (Liouxin Group) and REC from Norway. Despite REC is one of the smaller players within those rankings the company's strategy of producing everything from Polysilicon until the module enables them to survive, even having production facilities in Europe and in the USA. Five players, namely Suntech, Trina Solar, Yingly Green Energy, Jinko Solar, and JA Solar are amongst the TOP from wafer to module production. Also partly integrated and in this value steps one of the market leaders is GCL, which not only produces polysilicon, but also cuts it into wafers.

Table 5.8 TOP 12 Solar-Module producers list
Data-Source: (Solarpraxis AG, 2012)

Rank	Company	Capacity (MW) end of 2011	Market share based on capacity in %	Company production in MW (2011)	Capacity utilization in %	Country
1	Suntech (Glory Silicon)	2,400	6.20	2,140	89.17	(CHN)
2	Canadian Solar	2,100	5.43	1,675	79.76	(CHN)
3	Trina Solar	1,900	4.91	1,702	89.58	(CHN)
4	LDK (Liouxin Group)	1,700	4.39	840	49.41	(CHN)
5	Yingli Green Energy	1,700	4.39	1,500	88.24	(CHN)
6	Solarfun/Hanwha SolarOne	1,680	4.34	939	55.89	(KOR)
7	Jinko Solar	1,200	3.10	1,050	87.50	(CHN)
8	JA Solar	1,200	3.10	1,200	100.00	(CHN)
9	Sharp	1,070	2.76	857	80.09	(JPN)
10	China Sunergy (CSUN)	915	2.36	840	91.80	(CHN)
11	Solar World	850	2.20	850	100.00	(GER)
12	REC	750	1.94	699	93.20	(NOR)
	Others	21,235	54.87	19,617	93.94	
	Total Amount	38,700	100	34,009		

5.5.3 Herfindahl-Hirschman Index (HHI)

Assembling solar cells together to a module is the easiest part in the c-Si solar module value chain, hence many companies can do it and many companies entered the market. The HHI with 0.0169 is the lowest value amongst the different producing steps. Despite that this value still falls in the category of an unconcentrated index, the value is close to 0.01, which indicates a highly competitive market.

Table 5.9 Calculation HHI Module-Manufacturers

Data-Source: (Prior and Campbell, 2012) (Jäger-Waldau, 2012)

Basic formula	$HHI = (\text{company } 1\text{-}s_i)^2 + (\text{company } 2\text{-}s_i)^2 + (\text{company } 4\text{-}s_i)^2 \ldots + (\text{company } N\text{-}s_i)^2$	
Calculation (TOP 12)	Data =	Market share of the TOP 12 companies based on produced MW (Company1 = 6.29%; Company2 = 5.00%; Company3 = 4.93%; ….)
	s_i =	Company1: 0.0629; Company2: 0.0500; Company3: 0.0493; ….)
	HHI =	$(0.0629)^2 + (0.0500)^2 + (0.0493)^2 + \ldots$
	HHI =	0.0169

5.5.4 Minimum Efficient Scale

As there are big overlaps amongst the cell and module producers the same hurdles were taken into consideration. The MES of 1,000 MW per year indicates the level for being successfully in the long run. Again, REC would miss this value as it has a capacity of only 750 MW in the year 2011, but the company has the advantage of being vertically integrated as stated above. Tier 3 companies are those with capacity levels from 1,000 MW till 1,350 MW, whereby three companies fall into this category. Four companies are counted in the Tier 2 group, all with a production capacity above 1,351 MW but below 2,000 MW. Tier 1 is again limited to two companies, Suntech and Canadian Solar, both with higher capacities as 2,000 MW.

5.6 Thin-Film Production

5.6.1 Introduction

The second Generation of PV-Technologies developed itself as opponent to the dominating silicon cell technology and the niche players are analyzed in the first step as if they are in a separate market. The Thin-Film production consists of several materials and technologies as it was stated in Chapter 3.3.2. The graphic below shows the market share of the different materials used, whereby also 3rd Generation technologies are included. Looking at the year 2011, the technology with the highest market share are a-Si (Amorphous silicon) solar cells, followed by CdTe (Cadmium Telluride) and CIGS (Copper-Indium-Gallium-Diselenide). CPV (Concentrated Photovoltaic) and OPV (Organic Photovoltaic) are not big market players in the year 2011, but will play bigger roles in the future according to the graphic.

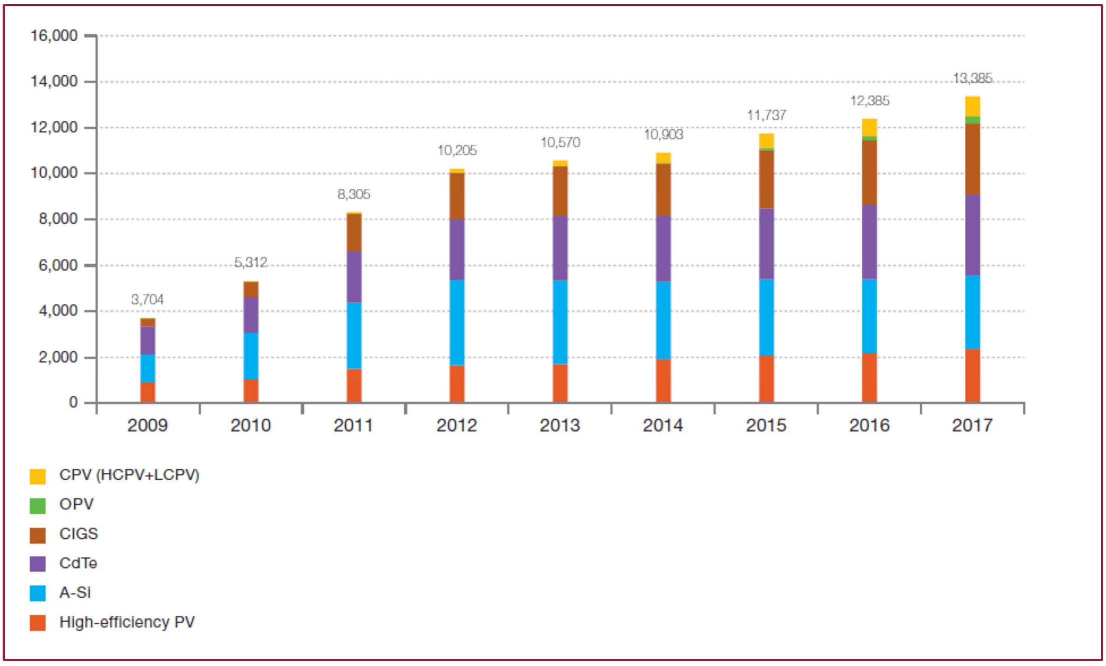


Figure 5.14 Previous and Future Development of Thin-Film-Technologies
Source: (Masson et al., 2013)

The Thin-Film industry is challenged on two fronts: first, competing the success of crystalline silicon technology, which has an advantage due to higher efficiency rates and mass production, and second, the fall in prices. Mass production enables to produce more cost effectively and so the market share in the module production is declining steadily. According to the authors of “engineering the solar age” the proportion of Thin-Film modules to the overall amount of produced modules was 19% in 2010 and 11% in 2011. This clearly illustrated in **Figure 5.1**, where Thin-Film technologies are colored in black and will not show an increase in the market share of the whole industry in the next years, while the c-Si modules can steadily increase its power on the market.

5.6.2 Size and utilization capacity

The Thin-Film industry produced in the year 2012 7,491 MW out of a capacity of 10,205 MW. This was reached by around 120 companies according to the researchers of Bank Sarasin The TOP 14 companies are shown below in Figure 5.15 in a pie chart. Contrary to all market share figures before, this one shows a clear leadership, namely the company First Solar with a market share of 23.61%. The company produces CdTE modules and is the only one, which can keep up with its 2,440 MW production capacity with the Tier 1 c-Si module producers. On place two and three two Japanese companies can be found, Solar Frontier with a market share of 7.56% and Sharp with a share of 3.53%. All other companies play a minor role as their market share is below 2.00%.

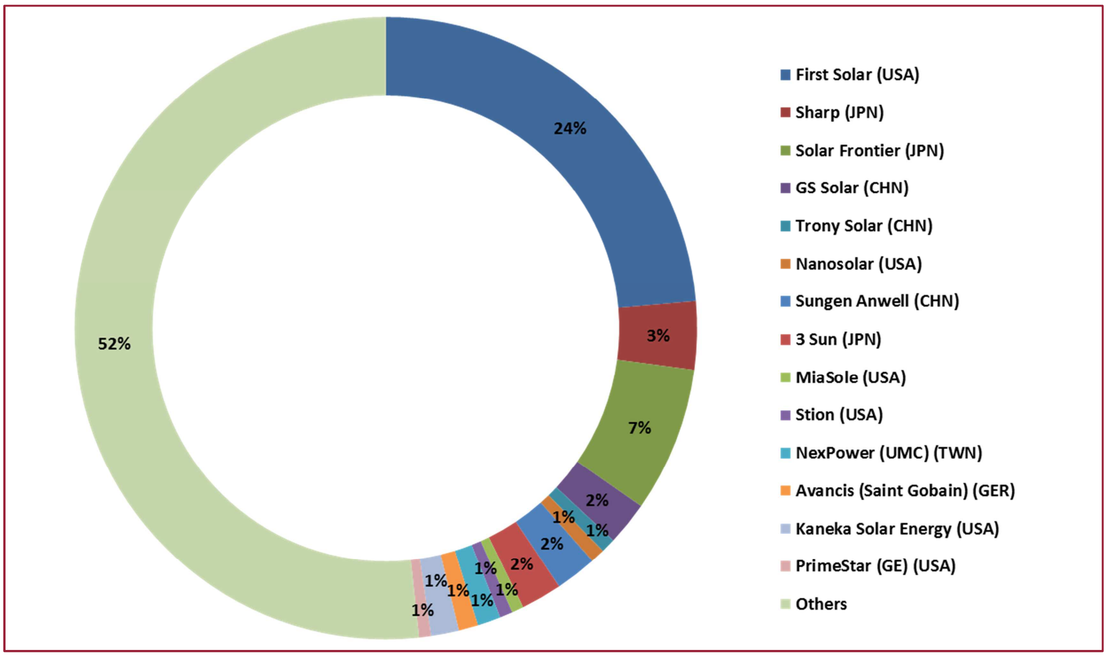


Figure 5.15 Pie chart - TOP 14 Thin-Film producers
Data-Source: (Solarpraxis AG, 2012)

Contrary to the last three value chain steps of c-Si module production, Chinese players do not dominate the Thin-Film industry. Considering the TOP 14 list, six producers are coming from the USA, three from Japan and China and NexPower is a Taiwanese company and Avancis a German one. Going into the next detail of production and capacity figures the low utilization rates are also signs of the continuously decreasing share within the PV market. The companies rather shut production lines down, than producing goods with a higher value than the market can offer. This leads to a decrease of significant investments either in increasing capacities or into research and development for efficiency improvements. Nevertheless, all companies are anxious to lower production costs and improve the throughput within the current manufacturing facilities. The following table was supplemented with a column for the technology used. The majority of the companies is producing a-Si modules, followed by CIGS. CdTe modules are not only produced by First Solar, but also by PrimeStar, which is on the last place of the ranking.

Table 5.10 TOP 14 Thin-Film producers list
Data-Source: (Solarpraxis AG, 2012)

Rank	Company	Capacity (MW) end of 2011	Market share based on capacity in %	Company production in MW (2011)	Capacity utilization in %	Country	Technology
1	First Solar	2,440	23.91	1,875	76.84	(USA)	CdTe
2	Sharp	1,000	9.80	280	28.00	(JPN)	a-Si/yc-Si
3	Solar Frontier	980	9.60	600	61.22	(JPN)	CIS
4	GS Solar	300	2.94	180	60.00	(CHN)	a-Si
5	Trony Solar	265	2.60	60	22.64	(CHN)	a-Si
6	Nanosolar	250	2.45	59	23.60	(USA)	CIGS
7	Sungen Anwell	250	2.45	170	68.00	(CHN)	a-Si
8	3 Sun	160	1.57	169	105.63	(JPN)	multi-junction
9	MiaSole	150	1.47	49	32.67	(USA)	CIGS
10	Stion	140	1.37	53	37.86	(USA)	CIGS
11	NexPower (UMC)	130	1.27	96	73.85	(TWN)	a-Si, a-Si/yc-Si
12	Avancis (Saint Gobain)	120	1.18	80	66.67	(GER)	CIS
13	Kaneka Solar Energy	120	1.18	115	95.83	(USA)	a-Si/yc-Si
14	PrimeStar (GE)	100	0.98	49	49.00	(USA)	CdTE/CIGS
	Others	3,800	37.24	4,106	108.05		
	Total Amount	10,205	100	7,941			

5.6.3 Herfindahl-Hirschman Index (HHI)

The HHI for this industry is based on the figures in Table 5.10 TOP 14 Thin-Film producers listTable 5.10, the TOP 14 Thin-Film manufacturers and amounts 0.0648. This value indicates an unconcentrated index, which describes a competitive market.

Table 5.11 Calculation HHI Thin-Film Producers
Data-Source: (Prior and Campbell, 2012) (Jäger-Waldau, 2012)

Basic formula	HHI = (company 1-s_i)^2 + (company 2-s_i)^2 + (company 4-s_i)^2 … + (company N-s_i)^2	
Calculation (TOP 12)	Data =	Market share of the TOP 12 companies based on produced MW (Company1 = 23.61%; Company2 = 7.56%; Company3 = 3.53%; ….)
	s_i =	Company1: 0.2361; Company2: 0.0756; Company3: 0.0353; ….)
	HHI =	$(0.2361)^2 + (0.0756)^2 + (0.0353)^2$ + ...
	HHI =	0.0648

5.6.4 Minimum Efficient Scale

Entry barriers for Thin-Film companies are much lower than for c-Si module producers as it can be seen by the capacities in the table above. On the one side, it could be the individual usage of the PV product for example in a special architecture or design. On the other side, a huge advantage in the price could be the reason that a company survives in the market. Nevertheless, reaching certain capacities in order to profit from economies of scales is an important success factor for surviving. Setting the MES to a level of 100 MW is rather low, considering the bankruptcy of the American CIGS firm Solyndra in the year 2011, which was placed on rank seven the year before. Categorizing the 14 TOP players into Tiers, the upper level for Tier 2 companies has to be at least 900 MW. Eleven out of the TOP players are falling into this category, whereby it is necessary to state that they will only survive if they increase capacities quickly or if they have found a way to become a niche player. The best three producers, also categorized in Tier 1 companies are: First Solar, Sharp, and Solar Frontier. All of them have already managed to produce more than 900 MW per year.

In order to conclude this chapter, it is important to mention that Thin-Film companies will only survive either if they can compete with a very low price or if they have found a market niche, where c-Si solar modules are not marketable.

6 Summary and Conclusions

After many years of tremendous innovations and growth, the PV industry is now going through a challenging period. The market dynamics have shifted and political support has changed, which are both indicators for a climate full of uncertainty. The market evolution is taking place and the following key factors will have a huge impact on the further development.

First, the political environment is the dominating stimulator for the development within a country. Governments can change and adapt to meet environmental commitments and with sustainable and smart support schemes for PV, a positive demand can stimulate the market. Second, PV is becoming competitive with other power sources and in certain areas - geographically or in terms of better usability - it is already a competitive alternative to "traditional" power solutions, like oil, gas and coal. However, market and grid integration still experience challenges that need to be overcome. As a third factor, the trade attributes have to be mentioned. Barriers and delivery bans between China and the Western Alliance USA and EU create uncertainty in the market, which cannot be predicted easily. Subsidies distort the market and normally are more harmful than successful. Last but not least, the industry consolidation, which was the major topic of this master thesis, plays an important role in the market's development.

A final calculation based on the previously established figures shall show the theoretical development of the market, without taking the above mentioned factors into consideration. First, the demand for PV is calculated based on the installments of the previous three years. In the year 2011 the installed capacity amounted to 30,133 MW, 30,035 MW in 2012 and 38,352 MW in 2013, which leads to an average demand of 32,840 MW per year. Dividing this by the MES of 1,000 MW (MES for the PV value chain steps wafer, cell, and module production) per year, which was developed within the research of this paper, theoretically 38 companies can serve the market. The second value calculated, is the inverse of the HHI which shows how many equal companies correlate to the index. Two figures were calculated, number ONE is the invers of the HHI of c-Si Module producers brought a result of 59 companies. This would indicate that even more companies can be expected to enter the market. Number TWO is the inverse calculation of the average of c-Si Module and Thin-Film Module producers together. The result showed the theoretical potential for 24 companies, which would indicate that more companies will leave the market in the long term.

However, the high competitiveness, as indicated by all HHI calculations, has a severe effect on all companies along the solar value chain, but a precise forecast into the future cannot be made, because the facts stated above cannot be suppressed as easily as it was done for the calculation. Amid these wide ranging factors, the enormous potential and undeniable benefits of solar PV remains unchanged (EPIA, 2011). As a reliable source of clean, safe and infinitely renewable energy for everybody, Solar PV will enhance the energy mix positively in the long run and will help to achieve environmental and economic goals.

Bibliography

Arvizu D., Balaya P., Cabeza L., Hollands T., Jäger-Waldau A., Kondo M., Konseibo C., Meleshko V., Stein W., Tamaura Y., Xu H., and Zilles R. (2011): Direct Solar Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, New York.

Bank-Sarasin (2011): Solar industry: Survival of the fittest in a fiercely competitive marketplace. Bank Sarasin & Co. Ltd., Basel. pp.7-45.

Chaaban J. (2004): Technical Efficiency and Technologically Independent Sub-Markets. Research Paper. Institute National de la Recherche Agronomique, Toulouse. p.44.

Ciesielska J., Concas G., Despotou E., Fontaine B., Garbe K., Montoro D.F., Latour M., Lenoir S., Masson G., Roesch A., Sweerts S., Vanbuggenhout P., and Varga S. (2011): Global Market Outlook for Photovoltaics until 2015. European Photovoltaic Industry Association, Brussels. p.44.

Cotal H., Fetzer C., Boisvert J., Kinsey G., King R., Hebert P., Yoon H., and Karam N. (2009): III–V multijunction solar cells for concentrating photovoltaics. Energy Environment Science, Sylmar. pp.174-192.

de la Tour A., Glachant M., and Ménière Y. (2011): Innovation and international technology transfer: The case of the Chinese photovoltaic industry. Energy Policy 39(2), 761-770.

de la Tour A., Glachant M., and Ménière Y. (2011): Innovation and international technology transfer:The case of the Chinese photovoltaic industry. Energy Policy 39(2), 761-770. DOI: 0301-4215.

EPIA (2011): Solar Generation 6 - Solar Photovoltaic Electricity Empowering the World. European Photovoltaic Industry Association - Greenpeace International, Brussel.

Fawer M. (2012): Solarwirtschaft: Hartes Marktumfeld - Kampf um die Spitzenplätze. 10. Nationale PV-Tagung 2012. Bank Sarasin, Baden. p.20.

Frauenhofer ISE (2012): Photovoltaics Report. Presentation Slides. Frauenhofer Institute for Solar Energy Systems ISE, Freiburg.

GCL-Poly (2013): Annual report 2012. Annual Report. GCL-Poly Energy Holdings Limited, Hong Kong. p.181.

GCL-Poly Energy Holdings Limited (2012): Annual Report 2011. Annual Report. GCL-Poly Energy Holdings Limited, Hong Kong. p.178.

Grätzel M., and O'Regan B. (1991): A Low-Cost, High-Efficiency Solar Cell Based on Dyesensitized Colloidal TiO2 Films. Nature 353, 737-740.

Hall M. (2012, November 15): pv magazine. Industry analysis: Half of tier 3 polysilicon suppliers face bankruptcy. [Online] http://www.pv-magazine.com/news/details/beitrag/industry-analysis--half-of-tier-3-polysilicon-suppliers-face-bankruptcy_100009224/#axzz2flNjtMzA - accessed: September 14, 2013.

Hanwha Q Cells (2014): Q-Cells. Q-Cells Unternehmen: Über uns. [Online] http://www.q-cells.com/unternehmen/ueber_uns.html#28167 - accessed: February 22, 2014.

Herman T. (2012, January 29): CHEAPER AND CHEAPER SUN. NewEnergyNews. [Online] http://newenergynews.blogspot.co.at/2012/01/cheaper-and-cheaper-sun.html - accessed: May 19, 2013.

Hornby L. (2013, September 26): China delays Suntech bankruptcy hearing. Financial Times. [Online] http://www.ft.com/cms/s/0/cc3d3152-2671-11e3-9dc0-00144feab7de.html#axzz2iMQ0phUn - accessed: October 1, 2013.

IEA (2011): Solar Energy Perspectives. OECD/IEA, Paris.

International Energy Agency (2012): World Energy Outlook 2012. International Energy Agency, Paris. p.690.

IRENA (2012): Renewable Energy Technologies: Cost Analysis Series - Volume 1: Power Sector Issue 4/5 - Solar Photovoltaics. International Renewable Energy Agency, Abu Dhabi.

Jäger-Waldau A. (2012): PV Status Report 2012. European Commission - Joint Research Enter, Renewable Energy Unit, Luxembourg.

Johnson Controls (2010, August): institute for building efficiency. Feed-In Tariffs: A Brief History. [Online] http://www.institutebe.com/energy-policy/feed-in-tariffs-history.aspx - accessed: September 13, 2013.

juris (2003, December 22): juris: Das Rechtsportal. juris. [Online] http://www.gesetze-im-internet.de/bundesrecht/eeg/gesamt.pdf - accessed: June 10, 2012.

Kann S., Mehta S., Shiao M., Honeyman C., Litvak N., Jones J., Baca J., Lent W., and Rumery S. (2013): U.S. Solar Market Insight_Q2 2013. Executive Summary. Solar Energie Industries Association + GTM Research, Boston. p.21.

Kann S., Mehta S., Shiao M., Krulewitz A., Campbell C., Burger S., Litvak N., Baca J., Lent W., and Rumery S. (2013): U.S.Solar Market Insight Report / 2012 Year in review. Executive Summary. GTM Research and the Solar Energy Industries Association, Boston. p.17.

Kann S., Mehta S., Shiao M., Krulewitz A., Campbell C., Kimbis T., Fenn S., Baca J., Lent W., Rumery S., and Hernandez M. (2012): U.S. Solar Marekt Insight_Q1 2012. Executive Summary. Solar Energie Industries Association + GTM Research, Boston. p.12.

Krannich C. (2012, April 1): Förderung-Photovoltaik. [Online] http://www.foerderung-photovoltaik.eu/inhalte/einspeiseverguetungen-photovoltaik-deutschland.html - accessed: June 2, 2012.

LDK Solar Co., Ltd. (2012): 2011 Annual Report. Annual Report. LDK Solar Co., Ltd., Xinyu City. p.250.

Leung S.-f., Long Y., Lin Q., and Fan Z. (2011): Engineered Optical Absorption of Nano/Micro-pillar Arrays for Efficient. 2011 MRS Spring Meeting & Exhibit Symposium B: Third-Generation and Emerging Solar-Cell Technologies. Materials Research Society, Golden.

Liu C. (2011, September 14): The New York Times. [Online] http://www.nytimes.com/cwire/2011/09/14/14climatewire-china-uses-feed-in-tariff-to-build-domestic-25559.html - accessed: June 2, 2012.

MacPhee C., and Peterson R. (1990): The Economies of Scale Revisited: Comparing Census Costs, Engineering Estimates, and the Survivor Technique. Quarterly Journal of Business and Economics 29(2), 43-67.

Masson G., Latour M., and Biancardi D. (2012): Global Market Outlook for Photovoltaics until 2016. European Photovoltaic Industry Association, Brussels. p.76.

Masson G., Latour M., Rekinger M., Theologitis I.-T., and Papoutsi M. (2013): Global Market Outlook for Photovoltaics 2013-2017. European Photovoltaic Industry Association, Brussels. p.60.

MEMC Electronic Materials, Inc. (2012): 2011 Annual Report to Stockholders. Annual Report. MEMC Electronic Materials, Inc., St. Peters. p.128.

Nature Photonics (2010): Future Perspectives of Photovoltaics, Proeceedings of the Conference. Nature Publishing Group, Nature Asia-Pacific, Tokyo.

Nozik A., Beard M., Luther J., Law M., Ellingson R., and Johnson J. (2010): Semiconductor Quantum Dots and Quantum Dot Arrays and Applications of Multiple Exciton Generation to Third-Generation Photovoltaic Solar Cells. Chemical Reviews 110(10), 6873-6890.

NREL (2013, May 14): National Renewable Energy Laboratory. NREL National Center for Photovoltaics. [Online] http://www.nrel.gov/ncpv/images/efficiency_chart.jpg - accessed: March 08, 2014.

Prior B., and Campbell C. (2012): Polysilicon 2012-2016: Supply, Demand & Implications for the Global PV Industry. Sample Analysis & Figures. GTM Research, Boston.

REN21 (2012): Renewables 2012 Global Status Report. Renewable Energy Policy Network for the 21st Century, Paris. p.176.

Solarpraxis AG (2012): engineering the solar age. Solarpraxis AG, Berlin.

SolarPVInvestor (2013, May 15): SolarPVInvestor. Polysilicon Capacity 2011-2013. [Online] http://solarpvinvestor.com/database/capacity/polysilicon-2010-2012 - accessed: May 15, 2013.

SolarWorld AG (2013): SolarWorld AG. www.solarworld.de. [Online] - accessed: May 19, 2013.

Stepan A. (2009): Corporate Entrepreneurship, Cluster und Innovationsmanagement. In: Frank H. (Ed.) Corporate Entrepreneurship, 2nd edition. Facultas, Wien, pp.168-193.

The Smart Cube (2013, January 7): The Smart Cube. www.thesmartcube.com. [Online] http://www.thesmartcube.com/insights/blog/blog-details/insights/2013/01/06/plummeting-polysilicon-prices-what-does-it-mean-for-solar- - accessed: May 15, 2013.

Timilsina G. R., Kurdgelshvili L., and Narbel P. A. (2012): Solar energy: Markets, economics and policies. Renewable and Sustainable Energy Reviews 16(1), 449-465.

U.S. Departmetn of Justice and the Federal Trade Comission (2010, August 19): Horizontal Merger Guidelines. www.justice.gov. [Online] http://www.justice.gov/atr/public/guidelines/hmg-2010.html - accessed: October 14, 2014.

Wacker Chemie AG (2013): Geschäftsbericht 2012. Annual Report. Wacker Chemie AG, München. p.266.

List of tables

List of figures