MSc Program

Renewable Energy in Central & Eastern Europe

FUTURE TRENDS IN PHOTOVOLTAICS

A Master Thesis submitted for the degree of

"Master of Science"

supervised by

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Gyor, Hungary, 01/03/2008

Affidavit

I, **Peter Krupanszky** hereby declare

1. that I am the sole author of the present Master Thesis, FUTURE TRENDS IN PHOTOVOLTAICS",
   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 Thesis as an examination paper in any form in Austria or abroad.

Vienna, March 26, 2008

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EXECUTIVE SUMMARY

Oil prices over $ 100 per barrel have already become a reality and the electricity prices all over the world are continuously rising. The more abundant fossil energy resources like gas and coal are also not able to give the necessary security to the energy sector. The *Gas Crisis* at the beginning of 2006 has demonstrated that Europe is still highly vulnerable with respect to its total energy supply. A possible solution is the diversification of energy sources including renewable energies and photovoltaics.

In March 2007 the European Council endorsed the binding target of a 20% share of renewable energies in the overall EU energy consumption by 2020. The motivation behind the Council Decision is the need to stabilize atmospheric greenhouse gases in the 450 to 550 ppmv range which leads to the necessity to decarbonize our energy supply.

Photovoltaics are a key technology option to realize such a shift. The solar resources in Europe and worldwide are abundant and can't be monopolized by one country. Regardless for what reasons and how fast the oil price and energy prices will increase in the future, Photovoltaics and other renewable energies are the only ones to offer a reduction of prices rather than an increase in the future.

In 2006, the photovoltaic industry production again grew by over 40% reaching a world-wide production volume of 2,520 MWp of photovoltaic modules and has become a € 12 billion business. Yearly growth rates over the last five years were in average more than 40%, which makes photovoltaics one of the fastest growing industries at present. Business analysts predict the market volume to increase to € 40 billion in 2010 and expect lower prices for consumers. 2006 was also the year when thin film photovoltaics started to grow faster than the overall PV market and this trend continued in 2007.

Table of Contents

List of Figures:

1. INTRODUCTION

The PV industry, as a high technology industry, has the fear that somewhere in the world, in a laboratory a new technology can disappear. In relatively short time this technology could be in a volume production and producing electricity under the magic point of $1 per Watt peak. In this case all the present technologies loose their validity on the market and a lot of investors lose their investments.

I believe that the probability of this happening in the short to medium term is not zero but very close to it as the solar PV industry is exceptionally well served by its research community and in particular technical information is flowing efficiently around the market.

The real uncertainties for the industry are less to do with a solar PV "technological advantage" but how those ideas find their way to market, on what time scale, who is driving them and the scale of resources somebody is prepared to risk on them.

For me, as a PV installer and designer it is very important to know, what will be, or could be the winner technology on the market, to be able to focus on. That is why I choose this topic for my Master Thesis.

2. INTRODUCTION OF PV INDUSTRY

In 2006, the production of the PV industry was 2,520 MWp of photovoltaic generators (Fig. 1). Since 2003 total PV production grew in average by almost 50%. The thin film as a newer technology starting from a very low level, grew by almost 80% and reached 196 MW or 8% of total PV production in 2006. This high growth rate and the increase of the total production share indicate that the thin film technology is becoming more and more important for the installers, mainly because of the lower price. A thin film market share of 25 to 30% in 2010 seems not to be unrealistic. [SOLARBUZZ]

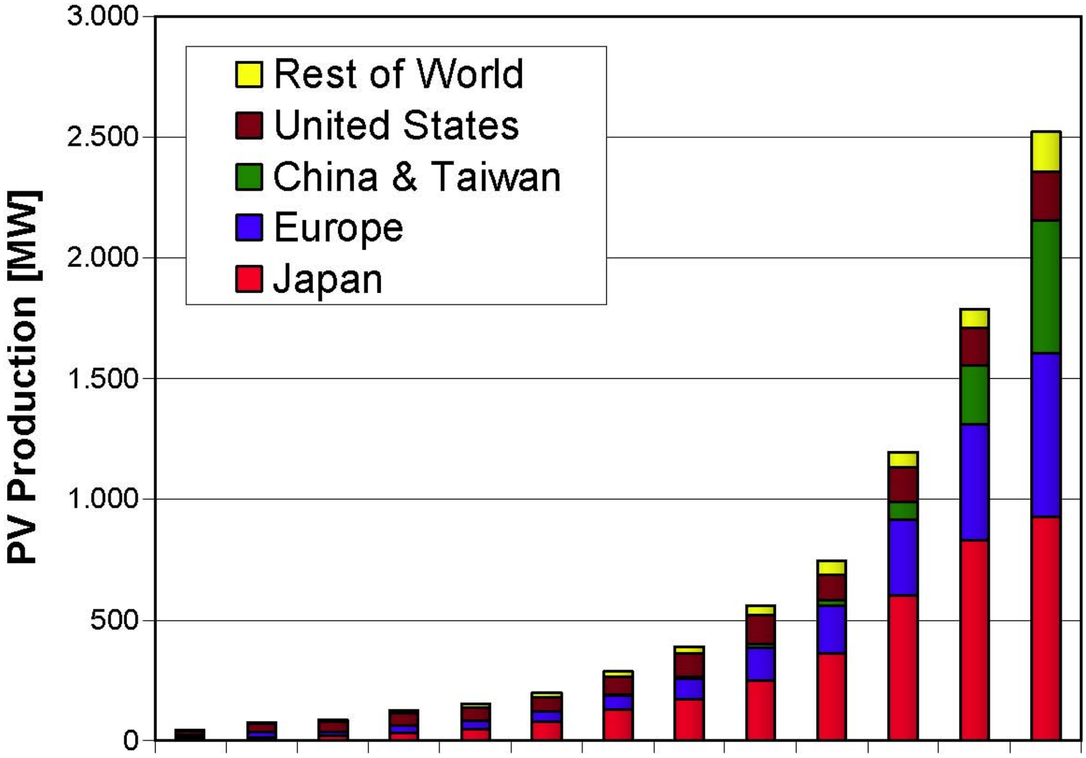


Fig 1. World PV Cell/Module Production from 1990 to 2005 (PV News 2007)

The current solar cell technologies are well-established and provide a reliable product, with sufficient efficiency and energy output for at least 20 years of lifetime. This reliability, the increasing potential of electricity interruption due to grid overloads, as well as the rise of electricity prices from conventional energy sources, add to the attractiveness of photovoltaic systems.

The growing distribution of the air condition systems, also in the Eastern European countries, increasing the electricity consumption in the summer season. In the summer of 2005 the high temperature has decreased the efficiency of the cooling systems of the coal and gas fired power plants in Germany. The overall output of these kind of power plants also decreased, but the PV power plants produced over their peak capacity. On the electricity market the price of the electricity which was produced in fossil firing power plants was higher, than the electricity which was produced by the PV power plants. This was not a usual case, but demonstrates well the importance and the raison d'être of these kind of power sources. [ZOLD]

About 90% of the current production uses wafer-based crystalline silicon technology. Up to now the main advantage of this technology was that complete production lines could be bought, installed and be up and producing within a relatively short time-frame. This predictable production start-up scenario constitutes a low-risk placement with high expectations for return on investments. However, the ongoing shortage in silicon feedstock and the market entry of companies offering turn-key production lines for thin film solar cells led to a massive expansion of investments into thin film capacities. The ongoing shortage in silicon feedstock and the relative slow response of the established silicon producers led to the market entry of new potential silicon producers. In addition, the incumbent manufacturers accelerated their build up of additional capacities. Silicon producers have now reacted and are in the process of increasing their production capacities, which will ease the pressure on the supply side within the next years. This indicates that they have recognized PV as a fully fledged industry that provides a stable business segment for the silicon industry, as opposed to being strongly dependent on the demand cycles of the microelectronics industry. New silicon producers enter the market and are in the process to finalize their business plans or are already constructing new production facilities. Meanwhile the PV companies accelerate the move to thinner silicon wafers and higher efficient solar cells in order to save on the silicon demand per W_p.

Some of the current crystalline based producers try to build up capacities for thin film manufacturing and a lot of newcomers plan to enter the market. Compared to 2005, thin film shipments increased by around 80% to 196 MW in 2006. If all currently announced thin film production capacities are realized, close to 6 GW production capacity could be reached by 2010. In addition Dye-cells are getting ready to enter the market as well. The growth of these technologies is accelerated by the positive development of the PV market as a whole. It can be concluded that in order to maintain the extremely high growth rate of the photovoltaic industry, different pathways have to be pursued at the same time:

- Drastic increase of solar grade silicon production capacities;
- Accelerated reduction of material consumption per silicon solar cell and W_p, e.g. higher efficiencies, thinner wafers, less wafering losses, etc.;
- Accelerated introduction of thin film solar cell technologies into the market and capacity growth rates above the normal trend.

Further cost reduction will depend not only on the scale-up benefits, but also on the cost of the encapsulation system, if module efficiency remains limited to below 15%, stimulating strong demand for very low area-proportional costs.

2.1 PV market

The photovoltaic world market grew again by more than 40% in 2006 to 2,520 MW. Like in the last years, Germany was the largest single market with 1,153 MW followed by Japan with 286.6 MW and the US with 140 MW The European PV production reached 657 MW, but this production cannot cover the German installations, so Europe is a net importer of PV modules. [PHOT]

The second biggest market was Japan with 286.6 MW of new installations, almost the same as the 291.1 MW of 2005 [IKK 2006]. In 2006 the Japanese solar cell production increased only by 11.3% and consequently the world market share of photovoltaic devices manufactured in Japan decreased from 47.4% to 36.9%. Nevertheless, four of the *Top Ten* companies are Japanese [IKK PV]. For 2007 the PV industry is confident that, the residential market will grow again due to the trend to fully electrified houses and the new Renewable Portfolio Standard with an increased amount of electricity generated from renewable energy sources.

The third largest market was the USA with 140 MW of PV installations, 101.5 MW grid connected. California and New Jersey account for 85% of the US grid connected PV market. There is no single market for PV in the United States, but a conglomeration of regional markets and special applications for which PV offers the most cost-effective solution. In 2005 the cumulative installed capacity of grid-connected PV systems surpassed that of off-grid systems. Since 2002 the grid-connected market has been growing much faster thanks to a wide range of "buy-down" programmes, sponsored either by States or utilities.

The rapid expansion of solar cell manufacturing capacities and production volume in China and Taiwan is not yet reflected in a significant size of the respective home markets. For 2006 the estimates of the Chinese PV market are in the order of 5 to 10 MW. As a result more than 98% of the 547 MW Chinese and Taiwanese PV production is exported. The most rapid expansion of production capacities can be observed at the moment in China and Taiwan, but other countries like India, Malaysia and South Korea are following the example to attract investment in the solar sector. [SOLSERV 74]

Europe will then be second with almost 31% and Japan third with 16% . It has to be noted that the assessment of all the capacity increases is rather difficult as it is affected by the uncertainties given below.

The technology as well as the company distribution varies significantly from region to region. 34 companies are located in Europe, 19 in the US, 12 in China and Taiwan, 9 in Japan and 8 elsewhere. The majority of 47 companies is silicon based. The reason is probably that in the meantime there is a number of companies offering complete production lines for amorphous and/or micromorph silicon. 20 companies will use Cu(In,Ga)(Se,S)2 as absorber material for their thin-film solar modules, whereas 10 companies will use CdTe and 5 companies go for Dye & other materials. [PVEB 2007]

In the case of the more optimistic silicon feedstock expansions to 115,000 metric tons and a material consumption decrease to 8 g/Wp, about 20 GW of solar cells could theoretically then be produced annually (14.25 GW silicon based and 6 GW thin films). This would be twice as much as the current optimistic predictions forecast. Another important factor is the actual utilization rate of the production capacities. In 2006, Japan had a Capacity to announced production ratio of 77%, Europe of 61% and China of 35%.

Second, 6 companies are aiming at total production capacity in the order of 1GW or more, whereas another 12 aim at 500 MW or more. The majority of these super factories are planned in Europe (5), followed by China (4), Taiwan (3) and Japan (3).

This leads to a third observation. If the large increase in production capacity is realized in China, the share on the world market would increase from 11.9% in 2005 to about 32 % in 2010/11. This production capacity would be much more than the 500 MW of cumulative installed solar systems in the People's Republic of China by 2010, as planned in the "Eleventh Five-Year Plan" (2006 – 2010). It is obvious that the solar cell manufacturers in China intend to continue the high export rate (95% in 2006) of their production to the growing markets in Europe, the US and developing countries. [SOLARBUZZ]

3. PV MODULE TECHNOLOGIES

According to the crystalline structure amorphous, poly-crystalline and mono-crystalline solar cells are known. According to technological procedures used by production solar cells can be divided into silicon solar cells, produced from Si wafers, and thin-film solar cells produced with vacuum technologies. Solar cells are connected together and many solar cells represent a solar module with typical power range of up to 200 W or even more. For large PV system special PV modules are produced with typical power range of up to several 100 W. The solar module properties depend mainly on the solar cell type used. The most important tasks in the future are utilization of less pure silicon and increasing efficiency (monocrystalline solar cells) and increasing efficiency and life-time (amorphous solar cells).

3.1 Solar cell materials - production and features

Silicon

The most important material for solar cells production is silicon. At the time being it is almost the only material used for solar cell mass production. As the most often used semiconductor material it has some important advantages: In nature it can be easily found in large quantities. Silicon oxide forms 1/3 of the Earth's crust. It is not poisonous, and it is environment friendly, its waste does not represent any problems. It can be easily melted, handled, and it is fairly easy formed into mono-crystalline form. Its electrical properties with endurance of 125°C allow the use of silicon semiconductor devices even in the most harsh environment and applications.

In techniques, pure silicon is the only widely used chemical element produced so pure. The percentage of pure silicon in material is at least 99.9999999 %. According to density of silicon, which is $5x10^{22}$ atoms/cm^3, it means $5x10^{13}$ impure atoms/cm^3. Impure atoms values are investigated due to numerous specific physical methods like mass spectrometry and similar sophisticated measurements. Pure silicon is produced from sand (SiO_2). In production the following procedure steps are used: Pure silicon is produced from silicon by reduction in specially designed furnaces at 1800°C. The produced material contains 98-99% of pure silicon.

As a reducer carbon electrodes are used. The complete reaction is as follows:

$SiO_2 + C \rightarrow Si + CO_2$

Such silicon is used as raw material in production of pure silicon. It is also used in steel and aluminium production procedures as a supplement material. The most important producers of raw silicon are Canada, Norway and Brazil. 15 to 25 kWh of electrical energy is needed to produce one kg of silicon. We get silicon tetra-chloride (gas) by chlorination of fine ground metallurgic silicon in special reactor. Additions or impurities are eliminated in the form of chlorine salt.

$Si + 2Cl \rightarrow SiCl_4$

The following reactions result in tri-chlorine-silan gas:

$SiCl_2 + HCl \rightarrow SiHCl_3$

The gas is then additionally purified, removing any remaining tetra-chlorine-silan and other silans. The purifying is followed by reduction in hydrogen atmosphere at 950°C:

$4SiHCl_3 + H_2 \rightarrow 2Si + SiCl_4 + SiCl_2 + 6HCl$

Besides pure silicon the procedure results in a number of side products. Their origin is gaseous and they condense outside of the reactor. Tetra-chlorine-silan is one of the side products. At 1200°C, it can be converted into tri-chlorine-silan using the following reaction:

$SiCl_4 + H_2 \rightarrow SiHCl_3 + HCl$

The presented example depicts one possible way of producing pure silicon. There are other production procedures with different chemical reactions used, yet the end product is the same - pure silicon.

Gallium arsenide (GaAs)

GaAs is used for production of high efficiency solar cells. It is often utilized in concentrated PV systems and space applications. Their efficiency is up to 25%, and up to 28% at concentrated solar radiation. Special types have efficiency over 30%.

Cadmium telluride (CdTe)

Thin-film material produced by deposition or by sputtering is a promising low cost foundation for photovoltaic applications in the future. The procedure disadvantage is poisonous material used in production. Lab solar cells efficiency is up to 16%, whilst the commercial types efficiency is up to 8%.

Copper-indium-diselenide ($CuInSe_2$, or CIS)

Thin-film material with efficiency of up to 17%. The material is promising, yet not widely used due to production specific procedures.

3.1.1 Polycrystalline silicon production

The procedure of extracting pure poly-crystalline silicon from tri-chlorine-silan can be (among others) performed in special furnaces developed by Siemens. Furnaces are heated by electric current, which flows through (in most cases) silicon electrodes. 2 m long electrodes measure 8 mm in diameter. The current flowing through electrodes can reach up to 6000 A. The furnace walls are additionally cooled preventing formation of any unwanted reactions due to gas side products. The procedure results in pure poly-crystalline silicon used as a raw material for solar cell production. Poly-crystalline silicon can be extracted from silicon by heating it up to 1500°C and then cooling it down to 1412°C, which is just above solidification of the material. The cooling is accompanied by origination of an ingot of fibrous-structured poly-crystalline silicon of dimensions 40x40x30 cm. The structure of poly-crystalline silicon in part of the material is settled, yet it is not adjusted to the structure of the other part.

3.1.2 Mono-crystalline silicon production

Two different technological procedures are used to produced mono-crystalline silicon from pure silicon:

Czochralski method:

By utilization of the Czochralski method, silicon is extracted from melt in induction oven with graphite lining at the temperature of 1415°C. Silicon crystal of defined orientation is placed on a rod. In the melt, spinning the rod makes the crystal grow. The rod spinning speed comes to 10 to 40 turns per minute, whilst the movement at length comes between 1 micro-meter and 1 millimeter per second. It allows production of rods, which measure 30 cm in diameter and several meters in length. It all takes place in inert atmosphere. Possible impurities burn or eliminate in the melt.

Float zone:

Using float zone monocrystalline silicon is produced from polycrystalline silicon. The main advantage of this procedure is higher pure silicon production. The silicon rods produced Silicon rod measure 1 m in length and 10 cm in diameter. The procedure, where induction heater travels along the rod melting silicon, also takes place in inert atmosphere. Mono crystal silicon originates from the cooling. Monocrystalline or polycrystalline silicon ingots are then sawn and the wafers are worked upon until they can serve as foundation for solar cell production. By sawing approximately 50% of material is wasted.

3.1.3 Amorphous Silicon production

Amorphous silicon is produced in high frequency furnaces in partial vacuum atmosphere. At presence of high frequency electrical field, gases like silan, B_2H_6 or PH_3 are blown through the furnaces supplying silicon with boron and phosphorus.

3.1.4 Crystalline solar cells

Polycrystalline as well as monocrystalline solar cells belong into this group. The basic form for crystalline solar cells production is silicon ingot. The ingot (block of silicon), sawn with diamond saw into thin silicon wafers, is a foundation for solar cell production. Wafers of 1 mm in thickness sawn with 1/10 mm precision are placed between two plan-parallel metal plates, which rotate into opposite directions. The procedure enables wafer thickness adjustment to 1/1000 mm precisely. The subsequent solar cell production procedure consists of the following steps:

Doped wafers are first etched some micro-meters deep. The procedure removes crystal-structure irregularities caused by sawing and provides wafer cleaning. The material is doped as melt at polycrystalline silicon or adequate gas is added whilst extracting pure silicon.

The above procedure is followed by diffusion. Phosphorus, which is supplied inside the material in gaseous form, diffuses at the temperature of 800°C. N doped layer and oxide layer rich with phosphorus form on top of wafers due to oxygen reaction. Wafers are then folded to form a cube and etched in oxygen plasma, removing N layer from the edges. The following phase removes oxide layers from top of wafer by wet chemical etching. In the back, contact surface is produced from silver containing 1% aluminium. Special procedures enable silver print over mask on cell surface. Pressed cells are then sintered at high temperatures. Similar procedure is used to print contacts in the front cell surface. Anti-reflex layer is applied in a similar manner. We have titanium paste at choice, which at sintering form titanium dioxide TiO_2 or silicon nitride Si_3N_4.

3.1.5 Amorphous solar cells

Amorphous solar cells are produced with similar technological procedures than integrated circuits. Due to the procedure these modules are also known as thin-film solar cells (thin-film modules). Herein, amorphous solar cells production is described briefly:

Glass substrate is thoroughly cleaned. Lower contact layer is applied The surface is then structured - divided into bands. In vacuum, under high frequency electric field amorphous silicon layer is applied. The surface is re-banded. Upper metal electrodes are fixated.

3.1.6 Other solar cells

Among less frequently used solar cell types we find solar cells produced by EFG (Edge Defined Film fed Growth) method and Apex solar cells from silicon, cadmium telluride solar cells and copper-indium selenide (CIS) solar cells. EFG monocrystalline solar cells are produced directly from silicon melt eliminating sawing to wafers, which results in lower production costs and material saving for there is no waste due to sawing. Using EFG procedure, a silicon ribbon shaped in proper tube with eight flat sides is drawn from silicon melt. The tube length amounts to several meters. Flat sides are sawn by laser into separate solar cells. Most solar cells are proper square shaped in dimension of 100x100 mm. Consequently, the module power is greater with lesser surface compared to crystal modules of square shaped cells with truncated sides. Contacts are made in shape of copper bands. Separate cells are then combined in a similar manner than with other cell types. EFG cells are produced by Schott Solar. In contrast to EFG cells, Apex cells are poly-crystalline. Their production procedure is protected. Production procedure was developed by Astropower Inc. Cadmium telluride and copper-indium selenide (CIS) cells are thus far scarcely used, mostly in lab research. Commercial modules from above mentioned materials are still hard to find. In the table below comparison among different solar cell types with their advantages and disadvantages can be found:

Material	Thickness	Efficiency	Colour	Features
Monocrystalline Si solar cells	0,3 mm	15 - 18 %	Dark blue, black with AR coating, grey without AR coating	Lengthy production procedure, wafer sawing necessary. Best researched solar cell material - highest power/area ratio.
Polycrystalline Si solar cells	0,3 mm	13 - 15 %	Blue with AR coating, silver-grey without AR coating	Wafer sawing necessary. Most important production procedure at least for the next ten years.
Polycrystalline transparent Si solar cells	0,3 mm	10 %	Blue with AR coating, silver-grey without AR coating	Lower efficiency than monocrystalline solar cells. Attractive solar cells for different BIPV applications.
EFG	0,28 mm	14 %	Blue, with AR coating	Limited use of this production procedure Very fast crystal growth, no wafer sawing necessary
Polycrystalline ribbon Si solar cells	0,3 mm	12 %	Blue, with AR coating, silver-grey without AR	Limited use of this production procedure, no wafer sawing necessary. Decrease in production costs expected in

			coating	the future.
Apex (polycrystaline Si) solar cells	0,03 to 0,1 mm + ceramic substrate	9,5 %	Blue, with AR coating, silver-grey without AR coating	Production procedure used only by one producer, no wafer sawing, production in form of band possible. Significant decrease in production costs expected in the future.
Monocrystaline dendritic web Si solar cells	0,13 mm incl contacts	13 %	Blue, with AR coating	Limited use of this production procedure, no wafer sawing, production in form of band possible.
Amorphous silicon	0,0001 mm + 1 to 3 mm substrate	5 - 8 %	Red-blue, Black	Lower efficiency, shorter life span. No sawing necessary, possible production in the form of band.
Cadmium Telluride (CdTe)	0,008 mm + 3 mm glass substrate	6 - 9 % (module)	Dark green, Black	Poisonous raw materials, significant decrease in production costs expected in the future.
Copper-Indium-Diselenide (CIS)	0,003 mm + 3 mm glass substrate	7,5 - 9,5 % (module)	Black	Limited Indium supply in nature. Significant decrease in production costs possible in the future.
Hybrid silicon (HIT) solar cell	0,02 mm	18 %	Dark blue, black	Limited use of this production procedure, higher efficiency, better temperature coefficient and lower thickness.

Fig 2. Overview of solar cell materials

Solar cells are in fact large area semiconductor diodes. Due to photovoltaic effect energy of light (energy of photons) converts into electrical current. At p-n junction, an electric field is built up which leads to the separation of the charge carriers (electrons and holes). At incidence of photon stream onto semiconductor material the electrons are released, if the energy of photons is sufficient. Contact to a solar cell is realized due to metal contacts. If the circuit is closed, meaning an electrical load is connected, then direct current flows. The energy of photons comes in "packages" which are called quants. The energy of each quantum depends on the wavelength of the visible light or electromagnetic waves. The electrons are released, however, the electric current flows only if the energy of each quantum is greater than WL - WV (boundaries of valence and conductive bands). The relation between frequency and incident photon energy is as follows:

$$W = h*w$$

Where there is: h - Planck constant ($6.626 \cdot 10^{-34}$ Ws^2), v - frequency (Hz)

3.2 Solar cell features

3.2.1 Crystalline Silicon Solar Cells

Among all kinds of solar cells we describe silicon solar cells only, for they are the most widely used. Their efficiency is limited due to several factors. The energy of photons decreases at higher wavelengths. The highest wavelength when the energy of photon is still big enough to produce free electrons is 1.15 µm (valid for silicon only). Radiation with higher wavelength causes only heating up of solar cell and does not produce any electrical current. Each photon can cause only production of one electron-hole pair. So even at lower wavelengths many photons do not produce any electron-hole pairs, yet they effect on increasing solar cell temperature. The highest efficiency of silicon solar cell is around 23 %, by some other semi-conductor materials up to 30 %, which is dependent on wavelength and semiconductor material. Self loses are caused by metal contacts on the upper side of a solar cell, solar cell resistance and due to solar radiation reflectance on the upper side (glass) of a solar cell. Crystalline solar cells are usually wafers, about 0.3 mm thick, sawn from Si ingot with diameter of 10 to 15 cm. They generate approximately 35 mA of current per cm^2 area (together up to 2 A/cell) at voltage of 550 mV at full illumination. Lab solar cells have the efficiency of up to 20 %, and classically produced solar cells up to 15 %. [SOLSERV PV]

3.2.2 Amorphous Silicon Solar Cells

The efficiency of amorphous solar cells is typically between 6 and 8%. The Lifetime of amorphous cells is shorter than the lifetime of crystalline cells. Amorphous cells have current density of up to 15 mA/cm2, and the voltage of the cell without connected load of 0.8 V, which is more compared to crystalline cells. Their spectral response reaches maximum at the wavelengths of blue light therefore, the ideal light source for amorphous solar cells is fluorescent lamp. [SOLSERV PV]

The simplest solar cell model consists of diode and current source connected parallel. Current source current is directly proportional to the solar radiation. Diode represents PN junction of a solar cell. Equation of ideal solar cell, which represents the ideal solar cell model, is:

$$I = I_{Ph} - I_s\left(e^{\frac{V}{m \cdot V_T}} - 1\right)$$

Where is: I_{Ph} - photocurrent (A), I_S - reverse saturation current (A) (approximately range $10^{-8}/m^2$), V - diode voltage (V), V_T - thermal voltage (see equation below), V_T = 25.7 mV at 25°C, m - diode ideality factor = 1...5 x V_T (-) (m = 1 for ideal diode)

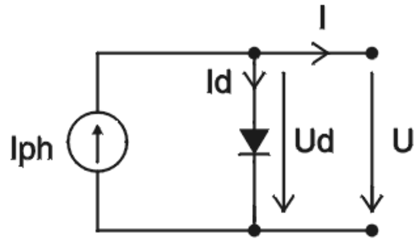


Fig 3. Ideal solar cell model

Thermal voltage / V_T / (V) can be calculated with the following equation:

$$V_T = \frac{k \cdot T}{q}$$

Where is: k - Boltzmann constant = 1.38 x 10^{-23} J/K, T - temperature (K), q - charge of electron = 1.6 x 10^{-19} As

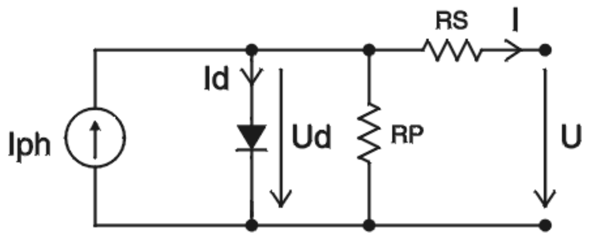


Fig 4. Real Solar cell model with serial and parallel resistance R_s and R_p, the consequences of resistances are voltage drop and parasitic currents

The working point of the solar cell depends on load and solar insulation. In the picture, I-U characteristics at short circuit and open circuit conditions can be seen. Very important point in IU characteristics is Maximal Power Point - MPP. In practice we can seldom reach this point, because at higher solar insulation even the cell temperature increases, and consequently decreasing the output power. As a measure for solar cell quality fill-factor - FF is used. It can be calculated with the following equation:

$$FF = \frac{I_{mpp} \cdot V_{mpp}}{I_{sc} \cdot V_{oc}}$$

Where is: I_{mpp} - MPP current (A), V_{mpp} - MPP voltage (V), I_{sc} - short circuit current (A), V_{oc} - open circuit voltage (V)

In the case of ideal solar cell fill-factor is a function of open circuit parameters and can be calculated as follows (Stone, see literature below):

$$FF \approx \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1}$$

Where is: v_{oc} - voltage calculated with equation below (V)

$$v_{oc} = V_{oc} \frac{q}{m \cdot k \cdot T}$$

Where is: k - Boltzmann constant = 1.38 x 10^{-23} J/K, T - temperature (K), q - charge of electron = 1.6 x 10^{-19} As, m - diode ideality factor (-), V_{oc} - open circuit voltage (V)

3.3 Module technologies

In this chapter the different module technologies will be introduced in technological point of view and from economical point of view. Each technology will be represented with a very developed product, which can be the future of the given technology.

In the economical analysis I compare the developed product prices with the factory average prices. For an installer the most important thing is the price level and the reliability of the product. For the comparison I used the prices of the pvxchange.de prices. The pvxchange.de is a marketplace for module and inverter wholesalers and buyers and represents well the price level of the products. Only those panels were taken into account which have the IEC 61215 certification and the power guarantee for 25 years.

The average price for European, Japanese, US top brand modules is 3,15 Eur/W (SolarWorld, Conergy, Sharp, Kyocera). The average price for Chinese, Taiwanesee, Indian quality modules is 2,8 Eur/W (Chaori, Yingli, Sesee). The average price for thin-film modules is 2,2 Eur/W for Kaneka and 2,45 Eur/W for First Solar.

3.3.1 Monocrystalline modules

Technical

The trends in PV production technology development can be easily summarized: the objective has been and is significant cost reduction for the whole value chain. Niches for special applications will play a limited role. Thus new technologies and structures, e.g. like the upcoming back contact cells will have to be developed following the main goals: an increase of efficiency, reduction of silicon material cost and simplified module production. At least until the end of this decade there is a high number of different technologies to be investigated in order to reach the envisaged cost reduction goals. Therefore 20% efficiency for mono-crystalline silicon and 18% efficiency for multi-crystalline silicon solar cells from wafers of 150 µm thickness and a size of at least 156x156 mm2 using high throughput and yield technologies should be addressed. The solar cell production technology developments approach at Fraunhofer ISE is followed to meet these goals. Several new technologies which have been developed at Fraunhofer ISE are already or currently in the stage of being transferred to industrial production of crystalline silicon solar cells, as there are:

- Sputtering of silicon nitride anti-reflection layers

- Laser-edge isolation using a scanning head

- Inline diffusion using dopants based on phosphorus acid and a walking string furnace

- Plasma etching of phosphorus glass

- Light-induced electro-plating

- Hot-melt paste front contact printing

- Laser-fired contacts

A typical present-day PV module is depicted in Figure 5. It consists of a string of solar cells encapsulated between a glass front cover and a backsheet protecting the module from moisture. The cells are made from square 220 µm thick Si wafers, either multicrystalline or single crystalline. They feature Ag contacts in an H-pattern at the front and a full Al-BSF at the rear. The fact that the negative contacts are at the front while the positive contacts are at the back results in a rather complicated interconnection scheme where the front of each cell is connected to the back of the next. As a result, there is a minimum spacing between each cell, which limits the achievable packing density. The current generated over a large area is carried to and by wide metallic ribbons, which contribute to substantial shadow losses and yet give excessive resistive losses for very large cells. Typical module efficiencies are in the 13-14 % range. [SHARP]

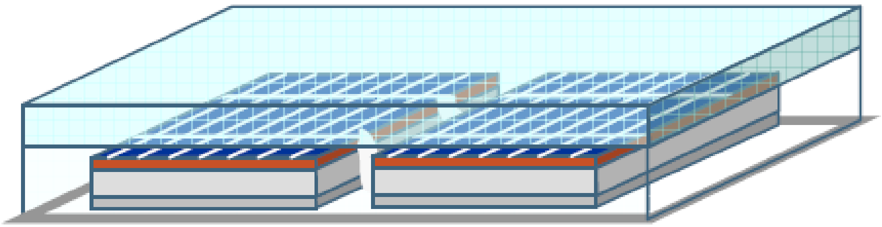


Fig 5. Schematic of a 2007 module [WAGNER]

In Figure 6, a schematic, of a typical module in 2020 shown, which will be geared towards minimal material cost. This is a crystalline Si module, with a 5 µm thick Si layer formed on the glass front cover that simultaneously acts as mechanical carrier for the film. To ensure high currents in spite of the extreme thinness of the layer, an efficient light trapping scheme is implemented resulting in a path length enhancement approaching the theoretical limit of 50. The individual cells are narrow but long, almost as long as the module width. The cells, which feature excellent surface passivation, are closely packed next to each other, with a narrow isolation region in between, consisting of a groove with an isolation material. Both contact polarities are at the rear, in an interdigitated pattern. Each finger crosses an isolation region to contact the opposite polarity of an adjacent cell, ensuring the series connection. There is no large collecting contact (except two at the ends of the module) because the current of each cell is carried over the full width of the module.

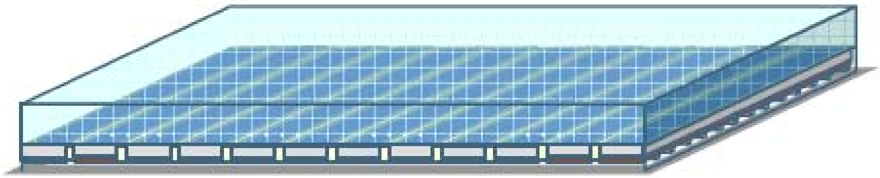


Fig 6. Schematic for a 2020 module [WAGNER]

The Si consumption of such a module is a small fraction of what is needed today. In combination with a reduced amount of module components (less encapsulant, less interconnection material), the material cost of such module would be very low, solving one of the major problems of crystalline Si technology. Cell and module manufacturing is based on process steps applied to whole panels instead of individual cells, allowing for further reduction of the manufacturing costs. The back-contact structure (either Emitter-Wrap-Through or Interdigitated Rear Junction) is anticipated because it is expected to result in the best performance (minimal shadow losses) while enabling convenient interconnection. Some of the features shown here are reminiscent of the module concept put forward by CSG Solar, which is a thin-film crystalline Si module already designed for minimal cost. There is however a major difference : the PV module described above has an efficiency of at least 15 %. In comparison, CSG Solar's targeted efficiency for large area module efficiencies in 2006 is 7 %. CSG Solar's approach is to establish a low cost concept with initially low efficiency, and to gradually improve the device (particularly on the level of material quality) to reach higher efficiencies over the years. It implies a sudden change in technology, and the acceptance that module efficiencies will be much lower than conventional products for a number of years. For the general PV industry, this strategy, which basically focuses on lowering the cost per watt at the expense of performance, has some disadvantages. Apart from the risk linked to a sudden and complete change of technology, it is unlikely that, at any point in time, the market will be satisfied with standard modules with efficiency substantially lower than that of present day modules. It is in our eyes necessary to develop intermediate technologies that will provide a continuous reduction in cost/watt while maintaining or increasing module performance.

Crystallization process developed for large size silicon ingot preparation permitted an exceptional productivity gain of more than 85% compared to standard for 260 kg ingot production. A cutting process with a significant reduction of the kerf-loss has been developed for large size and very thin wafer production. The cell process has been modified to become more suitable for large size and very thin wafers. The solar cells of the efficiency over 15% with low bow have been realized on 150 mm x 150 mm x 0,15 mm wafers cut from 450 kg multicrystalline silicon ingots. It has been shows that the 450kg large process strongly improves the productivity of multicrystalline silicon ingot production with an equivalent quality in regard to the best 260 kg ingot process. A gain of 86% on productivity has been reached. An exceptional gain of more than 85% compared to reference is obtained and still about 50% compared to "260kg new" configuration. The production of large size 450 kg ingots also allows to reduce significantly the consumption of electricity per every produced kg of silicon material. A good knowledge of the phenomena involved in the cutting of large size (150/156mmx150/156mm) and very thin multicrystalline silicon wafers (150Lm thickness) has been established and served to improve the wafer surface quality and obtain an important gain on the number of wafers cut from the same quantity of silicon bricks. The solar cell have been fabricated on 150Lm thick multicrystalline silicon wafers 150Lm with an industrial low bow screen-printing process applying a new rear side aluminium paste. A conversion efficiency of 15,2% with a bow lower than 1,5mm has been demonstrated on 150mmx150mmx135Lm cells. The feasibility of large size and very thin cell fabrication with high cost reduction potential has been demonstrated.

SANYO HIT

At the end of 2002, Sanyo announced the start of module production outside Japan. The company now has a HIT PV module production (12 MW/a) at SANYO Energy S.A. de C.V.'s Monterrey, Mexico and it joined Sharp and Kyocera to set up module manufacturing plants in Europe. 2005 opened its module manufacturing plant in Dorog, Hungary. Production capacity was planned to grow to 100MW in 2006. [SANYO PRESS]

Sanyo has set a world record for the efficiency of the HIT solar cell with 22% under laboratory conditions. The HIT structure offers the possibility to produce double-sided solar cells, which offer the advantage to collect scattered light on the rear side of the solar cell and can therefore increase the performance by up to 30% compared to one-sided HIT modules in the case of vertical installation. This application is interesting for sound barriers, rooftop fences or horizontal installation as car-ports, etc. Since FY 2003, Sanyo has been marketing its latest version of the HIT module with 19 % cell efficiency and 17 % module efficiency. [SANYO]

Overview of the elemental technology enabling the high energy conversion efficiency:

The structure of the HIT solar cell is such that it has a feature that can reduce recombination loss of the electrical element (charged carrier) by surrounding the energy generation layer of single thin crystalline silicon (c-Si) with high quality ultra-thin amorphous silicon (a-Si) layers. This time SANYO developed two special technologies, one for cleaning the c-Si surface and the other for protecting the c-Si surface from damage during construction of the a-Si layer. The result was an increase in the open circuit voltage (Voc) from 0.718V to 0.722V.

Sunlight that hits the solar cell surface is guided in through the texture of the micron order on the surface of the cell. This time, the size and the shape of the texture was optimized and the short circuit current (Isc) was improved from 38.37mA/cm^2 to 38.64mA/cm^2.

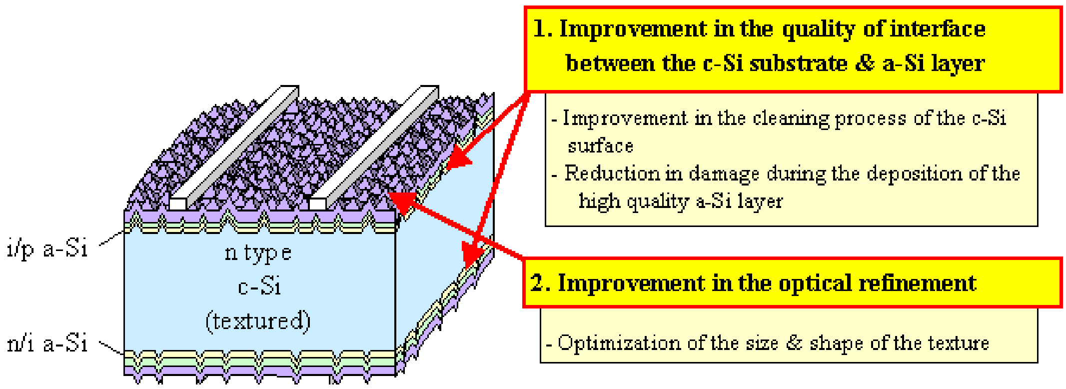


Fig 7. Diagram of the elemental technology. [SANYO]

HIT solar cells improve boundary characteristics and reduce power generation losses by forming impurity-free i-type amorphous silicon layers between the crystalline base and p- and n-type

amorphous silicon layers.

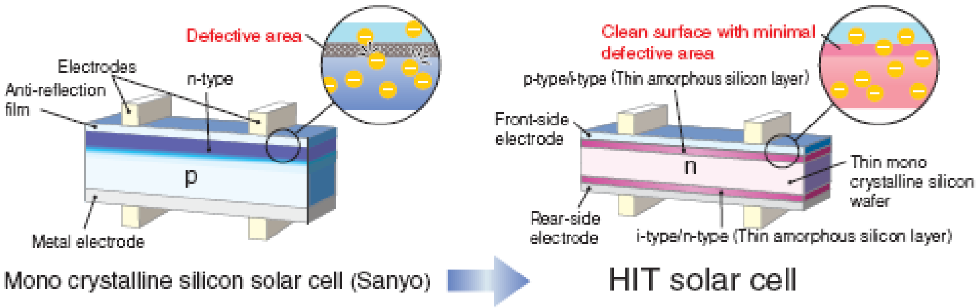


Fig 8. Conventional Sanyo cell vs. HIT cell [SANYO]

The development of the HIT technology is the HIT Double, a bifacial solar panel.

SANYO HIT bifacial solar cells are hybrids of single crystalline silicon surrounded by ultra-thin amorphous silicon layers.

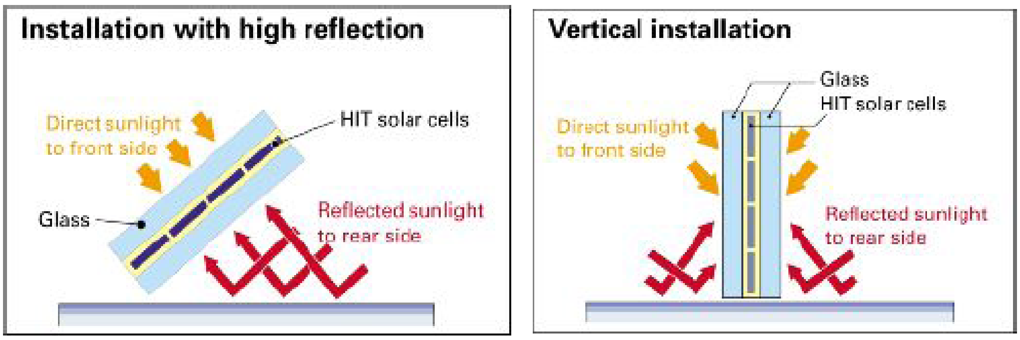


Fig 9. Double sided panel installation [SANYO]

Power from Both Sides Simultaneously

Increased power generation compared to our conventional single-sided HIT panels at any angle and any direction. In vertical installations, faced south, power generation is increased 34%. The back side of the panel generates electricity (kWh) from ambient light that has passed through the panel or is reflected off surrounding surfaces.

High Efficiency - SANYO HIT Double solar panels are a leader in cell and module efficiency. With models up to 190 Watts (18.8% cell efficiency) user can obtain maximum power within a fixed amount of space. And, depending on the installation design and location albedo, HIT Double panels can capture additional back side ambient light, and can increase the system performance by an additional 10% (or more). It can save costs using fewer support materials, wiring, and spend less time installing.

.**Unique Structure -** SANYO HIT Double solar panels are a double-glass structure with aesthetics that allow brilliant light and shadows to shine thru the panels. The panels have a silver anodized double-wall 60mm depth aluminum frame. The panels come pre-equipped with a touch-safe junction box, lead wires, MCTM plug-n-play connectors, and a unique mounting lip, all of which help to minimize support structure materials, installation time and costs.

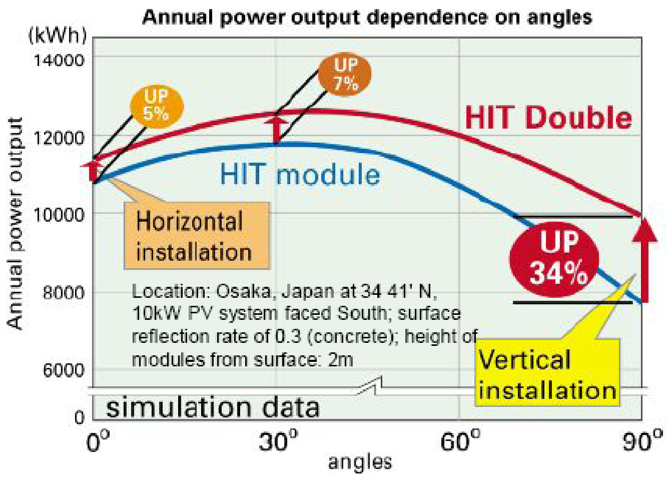


Fig 10. Annual power output dependence on angels [SANYO]

Other module manufacturers also developing their bifacial products. These developments are in different stages and only a few installation can be found with these technology.

Maker	Type of Cell	Cell Size	Cell Efficiency	Production
Gamma Solar	CZ- n+pp+ Boron BSF	125mm x 125mm t: 200 µm	16%(F) /14% (R)	Phase 1: Production starting from Sep 2008
	CZ p+nn+ Phos. BSF	156mm x 156mm T: 180 µm	17%(F) / 17%(R)	Phase 2: Production starting from Sep 2009
Hitachi (Japan)	CZ- n^+pp^+ Boron BSF	125mm x 125mm t : 210 µm	15.5%(F)/13% (R)	About 5 MW/year
Solar Wind (Russia)	CZ- n^+pp^+ Boron BSF	103mm x 103mm t: 350 µm	12.7 -16.1% (F) 7.6-9.8% (R)	Less tahn 5 MW/year
	CZ- p^+nn^+ Phos. BSF	125mm x 125mm t: 250µm	14.5% (F)/ 13% (R)	New Product: < 2 MW/yr
Sanyo (Japan)	CZ-HIT Double Amorphous +n Silicon bulk + Amorphous	125mm x 125mm t: 200µm	18.5% (F)/ 13% (R) (estimated)	Estimated only and not guaranteed because of unstable performance & reliability

Fig 11. Double sided PV module manufacturers

Economical

Unfortunately the high development of the SANYO HIT technology costs more. The price level (W_p/Eur) is 32 % more than the best priced monocrystalline modules (3,72 Eur/W for Sanyo and 2,8 Eur/W for best priced modules). This technology is mainly used on that kind of installations, where the space is limited. The economical calculations shows that it is not worth to use HIT modules for big PV power plants.

The bifacial panels are quite new on the market, only a few manufacturer offer modules in industrial amount. The offer of the Solar Wind company shows the price at level of 3,25 Eur/W_p . This price is 0,45 Eur/W_p more than a conventional monocrystalline module. The bifacial module can produce approximately 10% more electricity in case of 30^0 angle, but it is very dependent on the albedo of the surrounding surface. The industrial size power plant used to be installed on former agricultural plots where the color of the ground is dark and the albedo is low. The 10% more yield advantage is less than the 16% higher price.

Wafer-Based Silicon Solar Cells Projects

The EU continuously funds research and development in the field of PV. The following projects run:

- CRYSTAL CLEAR (**Integrated Project)**: Development of Crystalline Silicon PV technologies for low-cost high-efficiency and reliable modules EU funding: € 16 million – Co-ordinator: ECN, Petten, The Netherlands
- BITHINK (**STREP)**: Bi-facial thin industrial multi-crystalline Silicon Solar cells EU funding: € 2 million – Co-ordinator: CENER-CIEMAT, Madrid, Spain
- FOXY (**STREP)**: Development of solar-grade silicon feedstock for crystalline wafers and cells by purification and crystallization EU funding: € 2.7 million – Co-ordinator: SINTEF, Trondheim, Norway
- SISI (**SMEs-Co-operative Research)**: Silicon for solar cells at low costs on an intermediate scale EU funding: € 0.99 million – Co-ordinator: ECN, Petten, The Netherlands
- UPSSIM (**SMEs-Co-operative Research)**: Upgrading Semiconductor Silicon Wafers to Manufacture cheap *solar* cells EU funding: € 0.92 million – Co-ordinator: IMEC, Leuven, Belgium
- SOLSIC Demonstrator **(STREP)**: Validation of a direct route for production of solar-grade silicon feedstock for crystalline wafers and cells EU funding: € 1.5 million – Co-ordinator:
- LAB2LINE **(STREP):** From the Laboratory to the production Line EU funding: € 1.27 million – Co-ordinator: NaRec, Blyth, United Kingdom

3.3.2 Polycrystalline - String Ribbon

ADVANTAGES

- Nearly attains the efficiency of silicon wafer cells
- Eliminates the waste of silicon from the sawing process

DISADVANTAGES

- String wafers are not as flat as conventional sliced polysilicon wafers and this can impact yield
- Granular silicon preferred but this has been in short supply (crushed chunk material is a less ideal alternative)
- Harvesting six-foot strips of String Ribbons still a manual process (although an automated system is under development)
- Its efficiency penalty

Evergreen Solar and EverQ is the two market player company which is using this technology.

Cell and Module Efficiency

Historically String Ribbon efficiency has somewhat lagged other polysilicon efficiency, but the gap is closing. As of early 2007, both Evergreen Solar and EverQ are commercially averaging 14-14.5% cell efficiency.

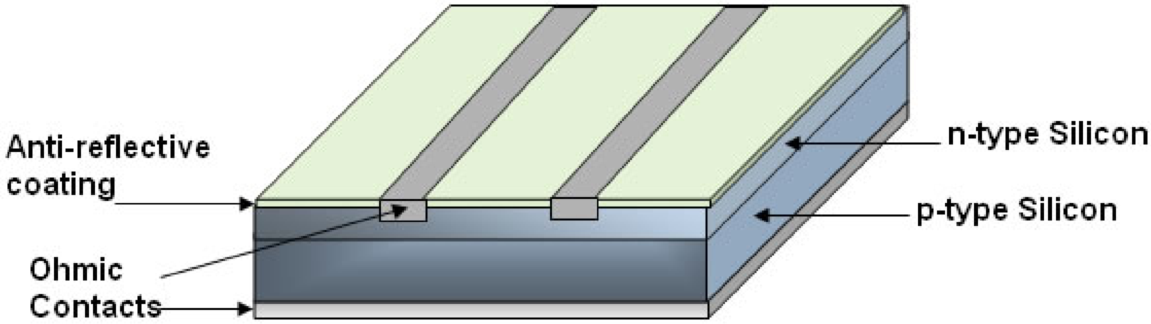


Fig 12. String ribbon cell

Raw Materials

String Ribbon requires around 35% less polysilicon than conventional solar cells but it needs specialty small granular polysilicon that has in the past only been produced in substantial volume by just one supplier, MEMC (WFR).

Renewable Energy Corporation of Norway will supply EverQ with a total of 7,400 metric tons of granular polysilicon over seven years beginning in 2008. Shipments of approximately 400 metric tons are expected to begin in the second half of 2008 and increase to 1,200 metric tons annually by 2010, continuing through 2014. This is in addition to the 190 metric tons REC is supplying EverQ annually under an existing arrangement.

(The String Ribbon process also does not need the stainless steel blades/wire, slurry, and caustic chemicals (acid) to polish or etch the wafer).

Manufacturing Process

In the String Ribbon technique, two high temperature strings are pulled vertically through a shallow silicon melt, and the molten silicon spans between the two strings through surface tension and freezes between them.

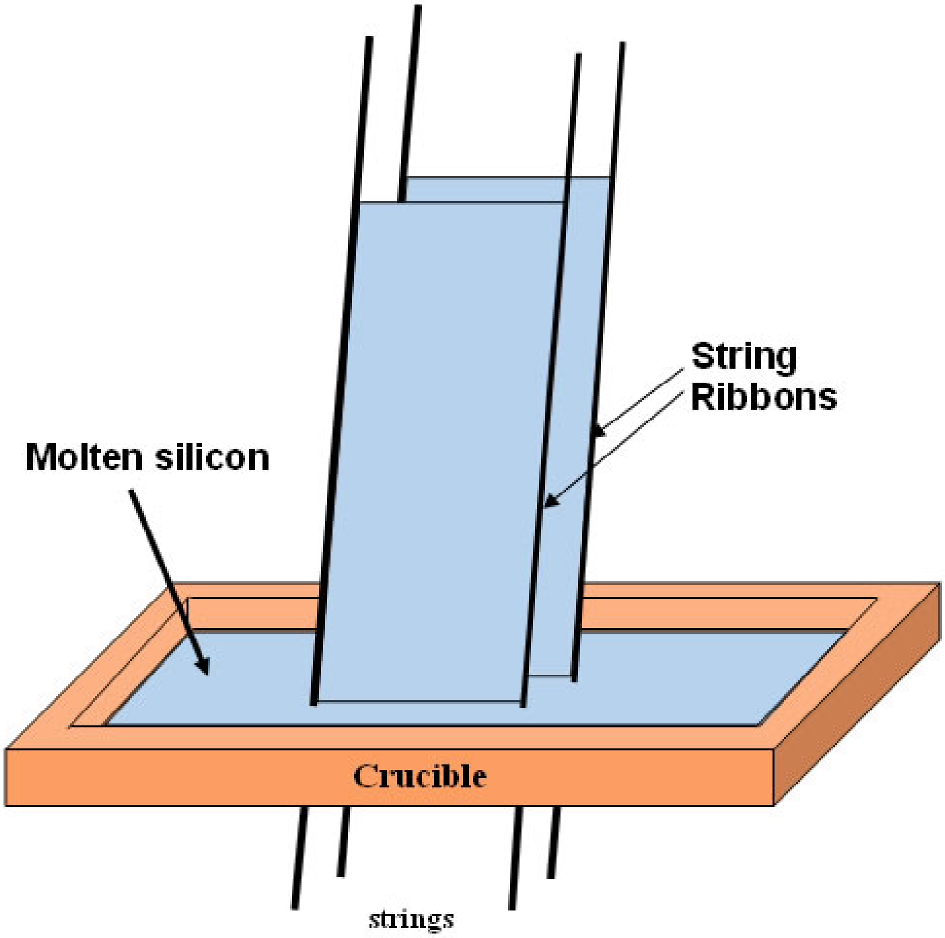


Fig 13. String ribbon production method

The process is continuous: long strings are unwound from spools; the melt is replenished; and the silicon ribbon is cut to length for further processing, without interrupting growth.

The first generation String Ribbon technology grew a single 2.2-inch-wide (5.5 cm) ribbon of silicon of 300μm thickness and used 35% less silicon than traditional wafer manufacturing. In 2006 Evergreen wafers were down to 190 and achieving 5g of silicon per watt of peak power.

Second generation furnaces grew 3.2-inch-wide (8cm) ribbon (also 300μm thickness), at a 33% faster pulling speed, for a doubling of furnace productivity. [EVS]

Third generation furnaces grew two 3.2-inch-wide ribbons at an additional 12% faster speed.

Fourth generation furnaces which currently constitute 100% of production at Evergreen and Ever-Q grow two 3.2-inch wide ribbons with 190µm thickness

Fifth generation furnaces, currently in R&D and pilot operation, grow four ribbons per furnace

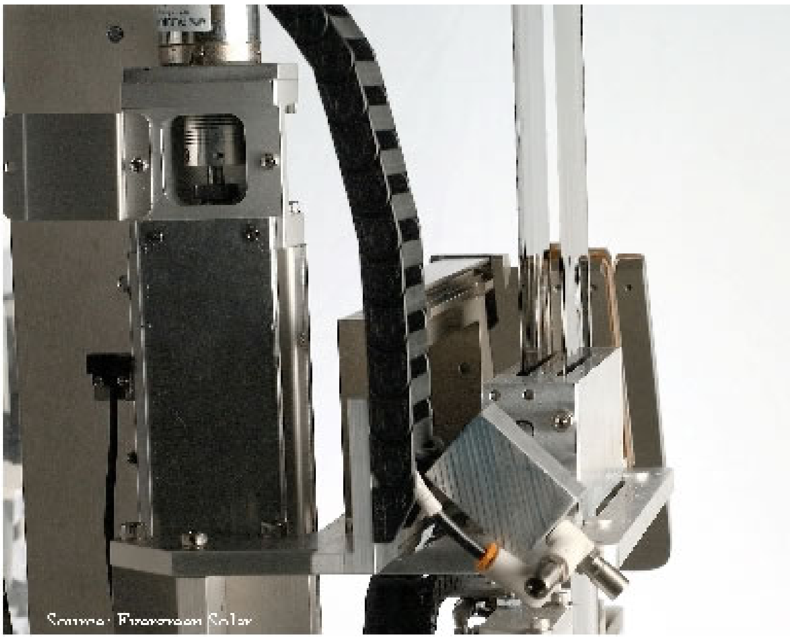


Fig 14. String ribbon manufacturing equipment [EVS]

Industrial Capacity Behind the Technology

Evergreen Solar - Their Marlboro (Massachusetts, US) factory currently has a 15 MW/year capacity.

EverQ began production in its first factory in Thalheim, Germany in Q2 2006 with 30 MW capacity. EverQ's second factory at 60 MW, also in Thalheim, is expected to begin in Q2 2007 and reach full capacity by year-end 2007.

Future R&D Directions

Reduction in material usage. The impressive progress to date in reducing the amount of polysilicon for one Watt of peak power of a solar PV cell is illustrated in the following table:

	2004	2005	2006
Industry Average	13.0 g/W	11.5 g/W	10.5 g/W
Evergreen	9.3 g/W	8.1 g/W	5.0 g/W

Fig 15. Amount of polysilicon for one Watt

Evergreen are in process of introducing four-ribbon technology in order to double wafer output and is on a road map to substantially thinner, 150µm wafers.

Georgia Institute of Technology claims to haves fabricated record high efficiency ribbon Si solar cells with screen-printed and photolithography defined contacts. String Ribbon cells achieved 15.6% and a high efficiency String Ribbon cell 16.6% with photolithography defined contacts. A two-step RTP firing process was critical in achieving high efficiency screen-printed cells.

Evergreen have R&D programs underway targeting 16% to 18% efficiency cells

Economical

The simplicity of the technology cannot be realized in the price level of the modules. The EVERGREEN EC-120 GL module costs 3,140 Eur/W (pvxchange.de), which is on the same price level as the top-brand European modules. The efficiency of the module is still lower than an average monocrystalline module, what means the cost of the substructure and the installation is higher.

3.3.3 Thin film

Technical

Lot of predictions visualize that the thin-film technology will be the future of the PV. The two largest company on the thin-film market is the KANEKA and the FIRSTSOLAR.

FIRSTSOLAR

While the theoretical benefits of CdTe and other thin film technologies have long been recognized, First Solar's successful scale up demonstrates the actual production of high performance CdTe modules in volume, transitioning the technology from the "development" to "growth" phase. Multiple years of field data are now available to demonstrate First Solar's efficiencies, high energy yields and excellent system performance ratios. CdTe module production facilities are today, even at the early stages of commercial production, achieving levels that required many years of production experience to achieve with traditional technology. Repeatable production processes have been fully demonstrated, enabling large scale expansion of CdTe module production.

This success is, to a significant extent, attributable to the unique physical properties of CdTe which make it ideal for converting solar energy into useful electricity.

CdTe is a direct bandgap semiconductor, which enables it to convert solar energy into electricity more efficiently (i.e., more watts per kg of material) than the indirect bandgap semiconductor materials used historically. The energy bandgap of CdTe, at 1.45ev, enables it to convert more energy from the solar spectrum than the lower energy bandgap materials (1.20ev) used historically. As a result, CdTe is capable of converting solar energy into electricity at an efficiency rate comparable to historical technologies with about 1% of the semiconductor material requirement. [FS]

CdTe will generally produce more electricity under real world conditions than solar modules with comparable powered ratings.

Solar cells become less efficient at converting solar energy into electricity as their cell temperatures increase. However, the efficiency of CdTe is less susceptible to cell temperature increases, enabling CdTe solar modules to generate relatively more electricity under high ambient (and therefore high cell) temperatures. CdTe also absorbs low and diffuse light and more efficiently converts it to electricity under cloudy weather and dawn and dusk conditions where conventional cells operate less efficiently. As a result, CdTe will generally produce more electricity under real world conditions than conventional solar module with similar power ratings.

CdTe permits simple device structures and processes, leading to low cost production.

The robustness of CdTe enables relatively simple device structures and production processes. High performance modules are achieved with single junction, polycrystalline devices. Automated high throughput production processes have been employed successfully with CdTe, without the need for expensive clean rooms or other expensive specialty equipment.

Abundant raw CdTe material to support high volume production and demand.

CdTe is made by transforming cadmium and tellurium into a stable, inert semiconductor. Both elemental materials are produced as byproducts of mining processes (primarily zinc mining and copper refining) and present in abundant quantities to support multi-GWs of annual production

These attributes have lead the National Renewable Energy Laboratory in Golden, Colorado to recognize CdTe's potential for achieving the lowest production costs among current thin film technologies. CdTe module costs well below $1.00/Wp have been predicted by NREL and others.

Economical

In spite of that the predictions of the CdTe technology`s price will reach the \$1.00/$W_p$ (0,71 Eur/$W_p$) the current price of the FirstSolar panels is 2,45 Eur/$W_p$. This price seems to be very attractive in comparison with a conventional monocrystalline panel, but we have to take into consideration, that the module`s efficiency is much lower. The lower efficiency leads to more expensive substructure and installation costs. The price advantage for a thin-film park in case of a turn-key contract is only 0,1-0,2 Eur/W_p. The space requirement of these kind of PV parks are much higher such as the operation costs. That means the lower installation costs can disappear due to the higher running costs.

The situation can dramatically change if the predictions come true and the price level will reach even the 1 Eur/W_p.

Thin-Film R&D Projects

- ATHLET (**Integrated Project):** Advanced Thin-Film Technologies for Cost Effective Photovoltaics EU Funding: € 11 million – Co-ordinator: Hahn-Meitner-Institut Berlin, Germany

- BIPV-CIS (**STREP)**: Improved integrated PV using thin-film CIS modules for building retrofit EU funding: € 2.3 million – Co-ordinator: ZSW, Stuttgart, Germany

- FLEXCELLENCE **(STREP)**: Roll-to-roll technology for the production of high-efficiency low-cost thin film silicon photovoltaic modules EU funding: € 3.1 million – Co-ordinator: Université de Neuchâtel, Neuchâtel, Switzerland

- LARCIS **(STREP)**: Large-Area CIS Based Thin-Film Solar Modules for Highly Productive Manufacturing EU funding: € 4.19 million – Co-ordinator: ZSW, Stuttgart, Germany

- LPAMS **(STREP)**: Production process for industrial fabrication of low price amorphous-microcrystalline silicon *solar* cells EU funding: € 0.61 million – Co-ordinator: ECN, Petten, The Netherlands

- SEPOWERFOIL **(STREP)**: Roll-to-roll manufacturing technology for high efficient multi-junction thin film silicon flexible photovoltaic modules EU funding: € 2.2 million – Co-ordinator: Helianthos b.v, The Netherlands

- HIGSPEEDCIGS **(STREP)**: High speed pilot production line for CIGS manufacturing EU funding: € 1.12 million – Co-ordinator: Midsummer AB, Bandhagen, Sweden

- SOLARPLAS (**SMEs-Co-operative Research)**: Development of Plasma-Chemical Equipment for Cost-Effective Manufacturing in Photovoltaics EU funding: € 1.1 million – Co-ordinator: Fraunhofer Insitut für Solarforschung, Freiburg, Germany

3.3.4 High concentration

The idea of the high concentration PV (HCPV) is to substitute the expensive electricity producing material with a relatively cheap concentrating material. This can be a mirror or a lens system. All over the world several companies and individuals research the best solution, but only a few companies could produce in industrial size. One of them is the USA based AMONIX and the Spanish Sol3g.

Technical

Sol3g is a company devoted to the consulting, research, development and manufacture of third generation solar systems, particularly specializing in concentration photovoltaics, nonimaging optics and advanced intelligent tracking electro-mechanical and control systems.

Sol3g`s **M40** HCPV modules include Fresnel lenses and non imaging secondary elements combined with triple-junction cells. Cells are MOCVD manufactured using III-V materials (InGaP and GaInAs) laid down over a Ge substrate. Those cells are very reliable under very high irradiance, yielding nowadays a 37% efficiency. Geometrical concentration is 476 suns, this taken together with a greater cell efficiency makes for a dramatic semiconductor material saving compared with silicon crystalline flat panel. As depicted in the introduction, to make up a 1 MWp plant made up with silicon flat panel the PV panels need a semiconductor surface around 0,75 Ha, similar to that of a soccer field, whilst to make up the same power capacity using the HCPV modules the technology just use 8 m2 of cells, more or less the surface that a car covers. Main design requirements have been: minimal cost, near 1 €/Wp at long term, maximum efficiency, acceptance half-angle more than 1 degree, less than 75 gr/Wp of weight, optimal thermal cooling in order to maximize performance under high irradiance and high ambient temperature and module assembly not requiring high capital investment in order to allow for manufacture decentralization. [SOL3G]

Cell design

Triple-junction InGaP-GaInAs-Ge cells are used, made by RWE Space Solar Power GmbH (thereafter RWE). Those cells are manufactured by MOCVD of III-V compounds over a Ge substrate.

The following drawing shows the cell structure:

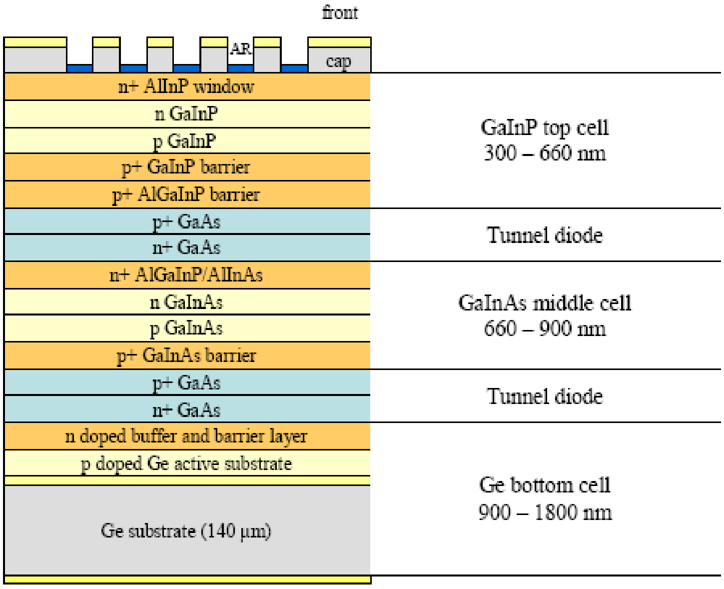


Fig 16. Cell structure of triple junction cell. [SOL3G]

The cell has been designed to work under an homogeneous 400 suns flux. Cell size is 6,5 x 5,5 mm, being the active area of 5,5 x 5,5 mm, surrounded by two bus bars 0,5 mm wide each. Thickness is around 150 microns. Thanks to the uniform cell illumination that the optical system produces it has been possible to minimize the metallization density, and this increase the active area yield.

The optical system is composed by two elements, combining a classical imaging Fresnel lens with a non imaging secondary.

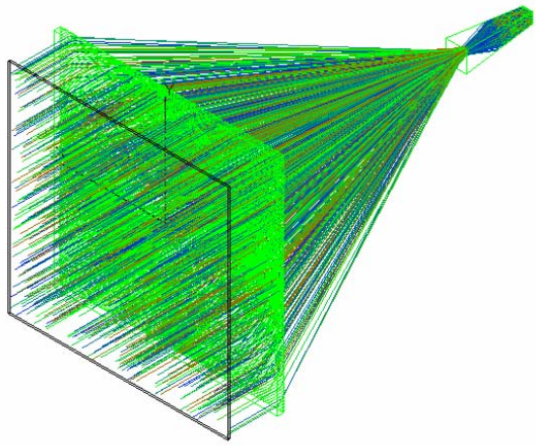


Fig 17. Fresnel lens and secondary optics [SOL3G]

The working principle is as follows: The primary lens projects a sun image within the secondary entry aperture. This image is of much smaller size than the secondary entry aperture area, and therefore it can drift within this square aperture, and this gives tolerance to the whole system, absorbing tracking deviations, assembly tolerances and thermal dimensional changes.

Dimensions, weight and solar aperture

The 40 W_p module has the following physical characteristics [SOL3G]:

Cells per module	10
Solar aperture per module	0,144 m2
Dimensions	1206x130x194 mm
Weight	2,7 Kg
Acceptance half angle	1,15 degree

Module HCPV Sol3g Vs Flat Panel:

	Flat Panel	M40 Module
Cell Efficiency	15%	31%
Module Efficiency	12%	24%
Temperature coefficient		
Voc Voltage	-0,347 %/°C	-0,159 %/°C
Pmp Power	-0,430 %/°C	-0,085 %/°C

Economics

The current price of the module is 2,4 Eur/W_p . almost the same price level as the thin/film products. The efficiency of the module is 2,5 times higher, what means lower costs on the substructures and installation. The main disadvantages of the HCPV systems, that they must be installed on 2-axis tracker substructures and can only utilize the direct radiation. Predictions show that the price level of the HCPV system can easily reach the magical 1 Eur/W_p and can compete with thin film technology.

Future PV technologies

New Concepts R&D programs

- FULL SPECTRUM (**Integrated Project)**: Development of new concepts for third-generation PV materials and techniques aiming at very high efficiency solar cells EU funding: € 8.4 million – Co-ordinator: IES-Madrid

- HICONPV (**STREP)**: High-concentration PV systemEU funding € 2.7 million – Co-ordinator: SOLUCAR Energia, Sevilla, Spain

- MOLYCELL **(STREP)**: Molecular materials and hybrid nano-crystalline/organic solar cells EU funding: € 2.5 million – Co-ordinator: CEA-GENEC, Cadarache, France

- ORGAPVNET **(Co-ordination Action)**: Co-ordination Action towards stable and low-cost organic solar cell technologies and their application EU funding € 1.2 million – Co-ordinator: IMEC, Leuven, Belgium,

- NANOPHOTO **(STREP):** Nanocrystalline silicon films for photovoltaic and opto-electronic applications EU funding: € 1.7 million – Co-ordinator: University of Milano-Bicocca, Milano, Italy

- WELLBUS **(Mobility):** Study of Efficiency Enhancement Mechanisms in Quantum Well Solar Cells for Better Utilisation of the Solar Spectrum EU funding: € 0.108 million

- FV-TR-SMS **(Mobility):** Time Resolved Single Molecule Spectroscopy Studies of Photo-induced Charge Separation and Charge Transfer in Model Photovoltaic Solar Energy Devices EU funding: € 0.271 million

3.3.5 Nanosolar

One of the most promising company, which started the production and sold the first panels few weeks ago. The yearly production capacity of the brand new plant in Palo Alto is 420 MW, but if the indicated price is valid – 1 USD/W – this amount of modules will not be enough for the US market.

Nanosolar has taken the highest-performance and most durable photovoltaic thin-film semiconductor, called CIGS (for "Copper Indium Gallium Diselenide"), and innovated on seven critical areas necessary to reach a breakthrough cost reduction in solar cells, panels, and systems.

Nanoparticles ink

Leveraging recent science advances in nanostructured materials, Nanosolar has developed a proprietary ink that makes it possible to simply print the semiconductor of a high-performance solar cell. This ink is based on Nanosolar developing various proprietary forms of nanoparticles and associated organic dispersion chemistry and processing techniques suitable for delivering a semiconductor of high electronic quality.

A key advantage of the ink is specific to an idiosyncrasy of the CIGS semiconductor: Because it consists of four elements which have to be in just the right atomic ratios to each other, the ink serves a useful purpose by effectively "locking in" a uniform distribution ("by design"). The homogeneous mix of nanoparticles in the ink in just the right overall amounts ensures that the atomic ratios of the four elements are correct wherever the ink is printed, even across large areas of deposition. This contrasts to vacuum deposition processes where, due to the four-element nature of CIGS, one effectively has to "atomically" synchronize various materials sources -- a challenge with no successful precedent in any industry on a repeatable high-yield production-scale basis. [NANO]

Semiconductor printing

Printing is by far the simplest, highest-yield, and most capital-efficient technique for depositing thin films. Printing is extremely fast; the equipment involved is easy to use and maintain; and it works in plain air (no vacuum chamber required).

Another key advantage of a printable CIGS ink is that one can print it just where one wants it to be, achieving high materials utilization of the semiconductor material.

Printing is much simpler and more robust than vacuum deposition techniques such as sputtering or evaporation which have conventionally been used to fabricate thin-film solar cells; the process cost of vacuum techniques is so high that the result is not an inexpensive cell relative to the per-square-meter economics that the solar industry requires. [NANO]

Conductive substrate

Nanosolar is the first and so far only company in the world that has managed to make efficient solar cells work on a metal foil substrate that is both low cost and highly conductive. The metal foil has a conductivity that is more than 20 times higher than that of the stainless steel used by others and thus enables major cost reduction on the solar cell's thin-film bottom electrode.

Note that a thin-film solar cell consists most fundamentally of an absorber layer (the semiconductor) sandwiched in between a top and a bottom electrode layer. If the thin films of a solar cell are deposited directly onto a highly conductive metal foil (as opposed to glass or stainless steel), then the bottom electrode gets much simpler because the substrate can do the job of carrying the current. [NANO]

Roll-to-roll processing

Roll-to-roll processing is the manufacturing implementation framework of choice for any product with very low cost required per large areas of deposition. Rolls that are meters wide and miles long can be processed efficiently with very high throughput (and thus minimal capital cost) in equipment with a very small footprint.

A key advantage of roll-to-roll processing is that after the first few meters of initializing a new roll, the whole process hits a steady state which can then be maintained for the entire rest of the roll, resulting in very uniform deposition process parameters applied to essentially the entire (foil) substrate. This is much better than processing wafers or glass plates, which have to be moved in and out of each process station individually, introducing undesirable start-up and move-out process state variability (and cycle time cost).

Edge effects are also greatly minimized in roll processing (whereas processing glass plates or wafers requires much work and capital dealing with uniformity issues at the edges of the substrate). [NANO]

Low-cost top electrode

Nanosolar has developed a fundamental innovation on its solar cells' top electrode which has two major benefits: It supports an entire order of magnitude higher current than any past or present thin-film solar product known; and it is very low cost. [NANO]

Sorted cell-assembly

With conventional silicon solar technology, individual wafer cells are sorted into performance bins before the cells are assembled into panels. This ensures that each panel produced contains cells with matched electrical characteristics.

Nanosolar's approach combines the advantages of thin films with the power of electrically matched cells, resulting in better panel efficiency distribution and yield.

Note that with conventional thin-film-on-glass solar technology, cell sorting and matching is not possible because cell transitions are created through scribing after they are already deposited on the glass substrate. But since each cell has somewhat different electrical characteristics, a thin-film-on-glass panel consists of cells that may not be well-matched.

It turns out that the effect of electrical mismatch per cell leads to exponentially greater losses per panel as a result, and panel yield and efficiency distribution suffer: A bad cell results in a bad panel with thin-film-on-glass technology; but with a cell-sorting technology, only that cell will be a loss. The value impact of that difference is staggering: If a panel contains 100 cells, sorted-cell assembly lowers the yield-loss cost of a bad cell to 1/100th compared to monolithic cell integration. [NANO]

High-current panel

Based on cell and product design innovations, Nanosolar is capable of delivering high-power solar panels with 5-10 times higher current than other thin-film solar panels on the market today.

This has enabled them to to dramatically reduce the balance-of-system cost involved in deploying solar electricity systems.

The amount of current that a panel can support is important because current capacity limitations negatively impact balance-of-system cost and thus power economics. [NANO]

4. Substructures for PV

In cost and environmental analyses the contribution of Balance-of-System (BOS) components is often given less attention because its share is smaller than that of the PV modules. However as module costs and environmental impacts decrease, the balance-of system part will become of increasing importance. Also in systems with less efficient modules the contribution of BOS will be higher. In the following a short overwiev about the systems and their future will be analysed.

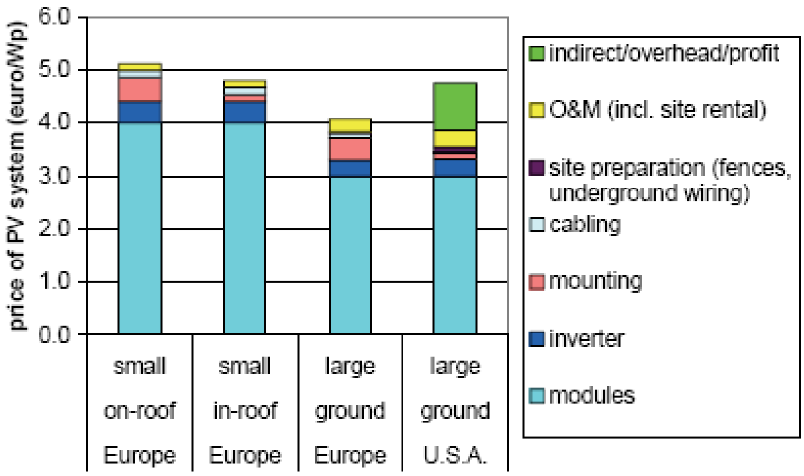


Fig 18. Price analysis of PV systems

4.1 Fixed

Fixed systems as the less difficult substructure are widely used in greenfield power plants. The main used material is the aluminium, because of the water resistance and long life, but hot-dip galvanized steel and wood can be used. The ideal angle in Europe is 29^0 – 35^0 and the modules are facing to the South direction. A typical fixed system cost is 30 Eur/m^2 , that means 210 Eur/kW_p for crystalline modules and 450 Eur/kW_p for thin film modules. Only small price reduction can be expected in the following years, because the producers have to take into consideration the valid standards and this makes possible only limited reduction of the materials.

A big disadvantage of the fixed substructures, that they are not able to move into flat, horizontal position in case of wind storm, or move to vertical position in case of hail storm. The structure has to withstand the strongest possible wind of the area, to protect the mounted panels, that is why the engineers have to design the system much more stronger, than needed.

4.2 Trackers

The movement of the earth and the composition of the atmosphere lead to constant fluctuations in the intensity and the angle of solar irradiation. As a consequence, the cells of rigid photovoltaic modules are only able to convert a fraction of the light energy given off by the sun into electric energy. They constantly adapt the angle of PV modules to face the sun, so that the irradiation angle and the light intensity remain constant and a maximum of electrical energy can be generated. This not only helps to exploit every minute of sunshine but also to make the best use of diffuse light – all year round. This leads to an added solar energy yield of 17 – 25% for single-axis, and 35 – 45% for dual-axis tracking systems.

4.2.1 1-axis tracker

Two main types of the 1-axis tracker system exists. The first type is close to a fixed systems in the basic structure.

East-West trackers

An East-West 1-axis system was designed to minimize the additional costs of a tracker system. The rows are follows the motion of the Sun in the East – West direction, to optimize the production of the power plant. According to the test and calculations, 18% higher yield can be reached, compared to the optimal inclined fixed system.

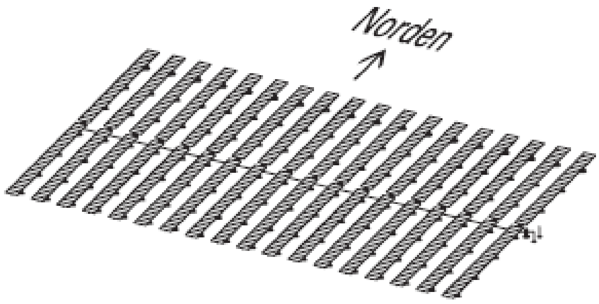


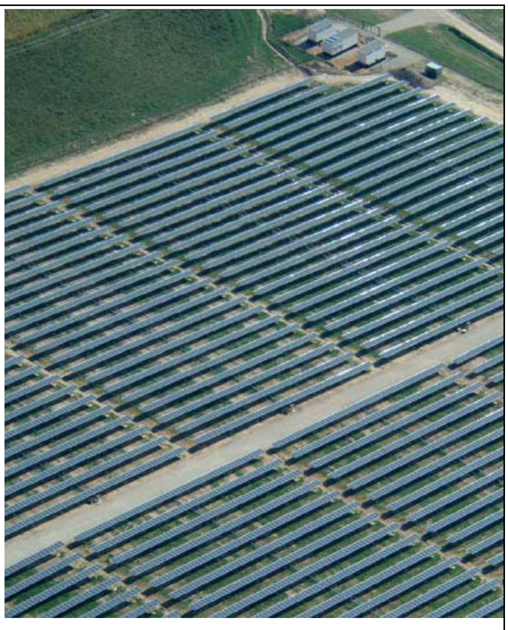
Fig 19. Module row direction in the East-West tracker

The module rows oriented to the East-West direction. The rows are linked to each other and rotated by a robust central drive. The parts of the tracker is made of aluminium, to avoid corrosion.

In the 1-axis tracker system a central drive rotates the panels. One drive is enough for rotating a 340 kW of subsystem. The drive is a very robust linear actuator, with 100 kN of dynamic trust The bearing for the rotation is made of special ZX-100 plastic. This makes the whole system maintenance free. The system is designed to withstand the highest winds. If the wind speed is more than 100 km/h, the center logics moves the panels to horizontal position, to present the lowest wind resistance. In case of ice fall the panels are able to stand in vertical position to avoid cracks on the panel surface. This protection gives higher security to the 1-axis tracker system than the fixed supporting structure and makes possible to produce lighter and cheaper supporting structure and basement.

The biggest *advantage* of the system is the 17-19% of added yield in the production, in comparison to the fixed system. The space requirements of the 1-axis tracker park is only 20% higher, than the same fixed system.

From the economical point of view, the added costs of the east-west type 1-axis tracker system are the bearing system and the mover drives. A typical east-west tracker system cost is 40 Eur/m^2 , that means 300 Eur/kW_p for crystalline modules and 600 Eur/kW_p for thin film modules. The cost of the east-west tracker is only 33% higher, than the fixed system component. For the total installation this difference is much less.

	
East-West tracker central drive [POWER]	East-West tracker PV park

Tilted 1-axis tracker

In comparison with the east-west type 1-axis tracker, the tilted 1-axis tracker has an inclination to the South direction, which can be between 30-50^0 depending on the location.

Fig 20. Tilted 1-axis tracker system [LOR]

The tilted one axis tracker is closer to the 2-axis tracker system in the structure than to the east-west tracking system. The size of the tracker usually small about 10-15 m^2 and there is no possibility to connect the trackers to each other, that means each tracker has their own drive to follow the sun movements. This solution makes this type more expensive than the east-west system and the probability of the failure is higher. In case of the east-west tracker one central drive can move 340 kW, the number of the linear actuators for the same size tilted system is more than 200.

4.2.2 2-axis tracker

The 2-axis tracker system seems to be the most developed substructure. The module surface can rotate in each direction, which allows the system to capture the light with the highest efficiency. The added yield can be 35% in comparison with the fixed system, but for this advantage we have to pay a high price. The complexity of the system is very high.

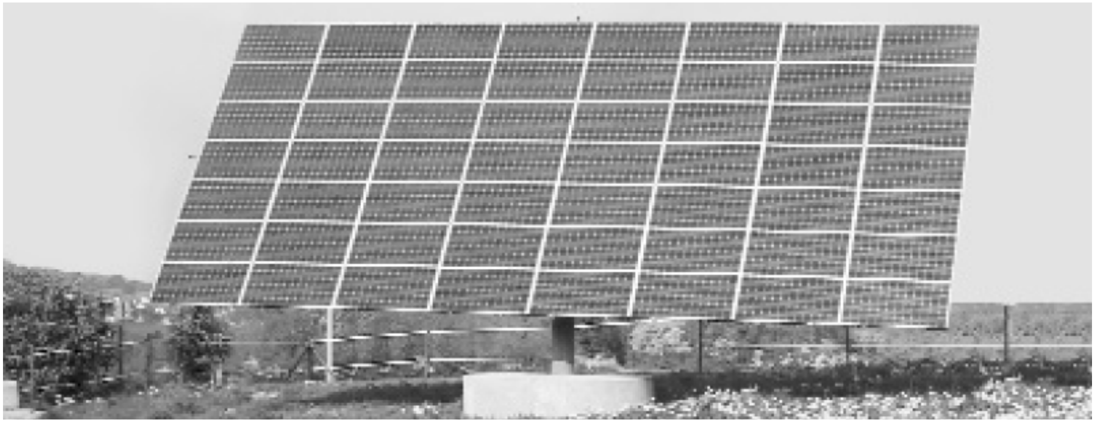


Fig 21. 2-axis tracker system with 50 m^2 PV surface [DEG]

The biggest difference in comparison to tilted 1-axis tracker, that this system cannot just change the elevation, but can turn around the azimuth angle. The most expensive part of the system is the turning drive and bearing. This type of trackers are operating with larger module area. The most common surface in large installations is between 40-60 m^2. In case of this size the weight of the modules and the steel structure is above 1500 kg. The wind load of the modules can exceed the 500 N/m^2, for the whole surface 30 000 N. These loads require robust, strong bearing and turning drive, which makes the whole system expensive.

The biggest disadvantage of this system –besides the high price – the high area requirements. To avoid the shadowing by the individual trackers, they have to be relatively far from each other. 60 m^2/kW_p is the special requirement of a solar park with these kind of technology. This value is more than the double than the fixed system and still much higher than a 1-axis tracker park.

4.3 Summary of substructures

	Fixed system	1-axis east-west	1-axis tilted	2-axis
System costs Eur/m2	30	40	60	100
System costs Eur/kW	210	275	450	750
Turn key cost Eur/kW	4300	4400	4650	5200
Added yield	-	18%	24%	30%
Added costs	-	2,40%	8%	21%
Space requirements kW/ha	360	300	250	170

Fig 22. Cost analysis of substructures

The high price and space requirements of the 2-axis tracker strongly limited the usage of the system. Few years ago, when the PV module prices were much higher, the 30% added yield of the 2-axes tracker was attractive even in the German market, where the this 30% was equal to 300 kWh/kW_p and the land prices were high. Nowadays the decreasing module prices and feed-in tariff, the importance of the 2-axis tracker systems is also decreasing. The last big market was Spain, with their huge, empty and relatively cheap land prices and high irradiation and feed in tariff. The 30% added yield was 450 kWh/kW_p and the feed-in tariff could reach the 0,44 Eur/kWh. With these conditions it was worth to take the risk and the higher investment to install PV parks with 2-axis trackers. The change of the Spanish law, with the 25% decreasing feed-in tariff will cancel the advantage.

The renaissance of the 2-axis tracker systems can be come with the development of the high concentration photovoltaics. This kind of modules requires the 2-axis tracker, because they can use the direct radiation.

The close future big PV installations can use the 1-axis tracker east-west technology. The very low added cost in comparison with the fixed systems, makes it attractive, even with the thin-film technology. The reliable central drive and the possibility to stand in horizontal position in case of high winds can convince the investors to think about this technology and not waste the 18% more electricity.

5. CONCLUSION

As it can be seen from the analysis, it is very hard to predict the future trends in the PV sector. My opinion, that in short period the crystalline technology remains the leader, especially, because the long term reliability. The investors and the banks only accepts those technologies, which have proven their reliability. The oldest crystalline PV parks are in operation since 15-20 years, without any major problems, but the newer technologies have only few years of experience.

In mid-term the thin-film technology and the HCPV have more capacity to decrease their prices and get bigger and bigger shares from the market. With the current prices, the investors (just a small percentage of them) want to take the risk of the new, not so proven technology, especially if we calculate the turn-key prices, not just the PV module per kW prices. In the mid-term strategies of those companies who produce these kind of modules, the magical 1 Eur or 1 USD / kW price is mentioned. With this price the crystalline technology cannot compete.

The two technology which can reach the magical 1 EUR, USD / kW price have their own disadvantages. The HCPV can use only the direct radiation and need the 2-axis tracker technology. For these reasons the main market in Europe is the Mediterranean countries. In these countries the high irradiation and the cheap system prices (in the future) can make the HCPV comparable alternative to the grid electricity. The thin-film with the lower efficiency, can be the solution for the Northern countries. It can use better the diffuse radiation and can be integrated into the roof.

The decreasing price of the technology will force the governments to rethink about the feed-in tariffs for the PV. The big PV parks will be preferable only the Mediterranean countries in Europe, in Africa, Middle and South America (also the southern states of the USA), Australia, and the southern parts of Asia. In these region the PV technology can compete with the other, even with the fossil power resources. The northern regions of the Earth can use the PV to decentralize the power production and use them as an individual power source for the households, connected into a large grid. In these regions the PV cannot be the solution for the whole energy supply.

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