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PV solar electricity industry: Market growth and perspective

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Abstract

The photovoltaic (PV) solar electricity market has shown an impressive 33% growth per year since 1997 until today with market support programs as the main driving force. The rationales for this development and the future projections towards a 100 billion € industry in the 2020s, by then only driven by serving cost-competitively customer needs are described.

The PV market, likely to have reached about 600 MW in the year 2003, is discussed according to its four major segments: consumer applications, remote industrial electrification, developing countries, and grid-connected systems. While in the past, consumer products and remote industrial applications used to be the main cause for turnover in PV, in recent years the driving forces are more pronounced in the grid-connected systems and by installations in developing countries. Examples illustrating the clear advantage of systems using PV over conventional systems based, e.g., on diesel generators in the rural and remote electrification sector are discussed. For the promotion of rural electrification combined with the creation of local business and employment, suitable measures are proposed in the context of the PV product value chain.

The competitiveness of grid-connected systems is addressed, where electricity generating costs for PV are projected to start to compete with conventional utility peak power quite early between 2010 and 2020 if time-dependent electricity tariffs different for bulk and peak power are assumed. The most effective current-pulling force for grid-connected systems is found to be the German Renewable Energy (EEG) Feed-in Law where the customers are focusing on yield, performance, and long-life availability.

The future growth in the above-defined four market segments are discussed and the importance of industry political actions in order to stimulate the markets either in grid-connected systems by feed-in tariff programs as well as for off-grid rural developing country applications by long-term financing schemes are pointed out.

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A technology roadmap is presented with special emphasis on the fact that different customer needs are best served with best-adopted technologies and not vice versa. The need for the third generation PV technologies, implying that so called first (c-Si-wafer)- and second (thin-film)- generation PV technologies will be overcome in a short to medium time scale, is obsolete; in contrast, the excellent scientific ideas developed within 'Third generation' concepts—like utilization of hot electrons, quantum wells and nanostructures—are shown to be part of 'New Technologies' opening new product ideas and additional market segments. The rationale for decreasing cost by increasing productivity for all technologies as well as the interpretation of price learning curves is presented.

The role of PV in the future global energy supply chain is lined out. Due to a fast growing market driven by increasing widespread acceptance of PV, a substantial PV business and creation of employment in coming decades is expected. This in turn can provide solutions for nowadays global issues, such as a global energy justice by providing environmentally benign power to billions of people, who otherwise will lack energy solutions severely.

Keywords: PV market growth; Solar electricity industry

1. Introduction

Photovoltaic (PV) solar electricity is the most elegant method to produce electricity without moving parts, emissions or noise—and all this by converting abundant sunlight without practical limitations. Consequently, in the public discussions there is quite a range of differing opinions as to when and how much this energy converter will be able to contribute to the world's future energy scenarios. This paper aims to give some answers in the form of a puzzle where at the end it will be clearly seen that PV solar industry indeed will contribute significantly in the coming decades to the global electricity supply needs. In Fig. 1 the puzzle elements which will be described in more detail in this paper are shown individually. Starting with the historic market development the fulfillment of a variety of customer needs within four main market segments is described. The rational for a future market growth of 30% and 25% until and after 2010, respectively, is given by analyzing in

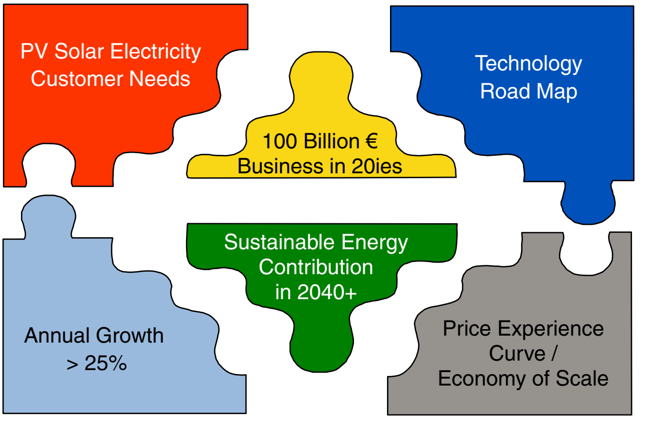


Fig. 1. The PV solar electricity jigsaw puzzle.

more detail the various applications within the four market segments. For the historic price development one may extrapolate within a price experience curve the future price level of PV components. This qualitative prediction has to be paralleled by a technology roadmap which should demonstrate on a technical level how production cost can follow this price decrease. Emphasis is made on the fact that the customer needs as described before are demanding for the most suitable technology. Hence a variety of co-existing technologies like crystalline silicon, thin film, III–V and new technologies will be present for the coming decade with no need for one so called third generation concepts—the ideas for the latter may, however, well contribute to the above-described four main technology directions. Putting together these four puzzle elements gives good evidence that within the next two or three decades the global PV module market will reach an annual turnover of 100–200 billion €, comparable to nowadays semiconductor industry. Further development will then be able to contribute more and more to the global electricity demand and thereby adding significantly to the reduction of CO_2 by replacing fossil power plants in this longer time horizon.

2. The global PV solar electricity market

2.1. Historical growth and the PV market segments

The global PV market has grown ca. 33%/year in the period 1998–2002 and has reached ca. 450 MWp in 2002, likely to have reached 600 MWp in 2003.

For explanation: the unit Wp displayed in Fig. 2 is by definition the power which a solar module yields at a "peak" irradiation of 1000 W/m^2 at standard test conditions (25 °C and spectrum of irradiation AM1.5).

The PV market for terrestrial applications may be divided into four major segments,

- Consumer
- Off-grid
  - Remote industrial
  - Developing countries (rural electrification)
- On-grid.

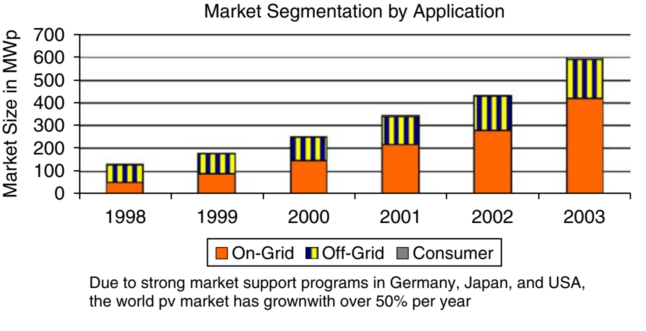


Fig. 2. Historical market growth of the solar electricity industry by application.

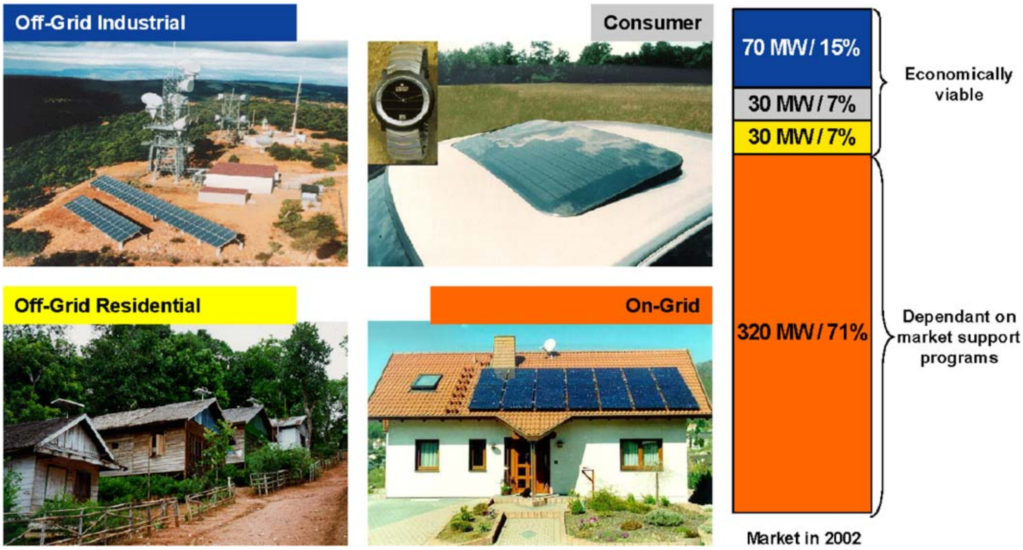


Fig. 3. Main terrestrial solar electricity market segments.

Whereas the market in the past developed basically from consumer products and remote industrial applications, the contributions of the market segments have shifted towards grid-connected systems, followed by installations in developing countries.

The various shares of the four PV market segments are shown in Figs. 2 and 3, the first three market segments are applications, where PV solar electricity is either the most cost-effective solution (as usually in most of the remote industrial and in the rural applications) or the only solution for the need of the customer.

Grid-connected systems today are only economic for the customer in connection with market support programs.

These market support programs have been implemented as tools for industrial policy in Japan, Germany, and the USA for the development of the manufacturing industry in these countries.

2.2. *Future growth, customer use and competitiveness*

The future market growth in the coming three decades until 2030 is shown in Fig. 4.

In order to get a feeling for these anticipated high annual outputs in future years, we take a look at some specific examples for each of the main market segments.

2.2.1. *Consumer applications of PV*

Solar calculators were among the first applications of this category. Today solar watches, battery chargers, and various products of the leisure industry are equipped with small integrated PV modules. The main reason for choosing PV supplies is less cost by powering with PV compared to battery supplies, and thus more comfort without necessary replacement and proper disposal of used batteries. In the consumer market the module price is governed by the total price of the particular item, i.e. by price/piece. For all other PV market segments, comfort and also prestige may play a role, but mainly quantitative

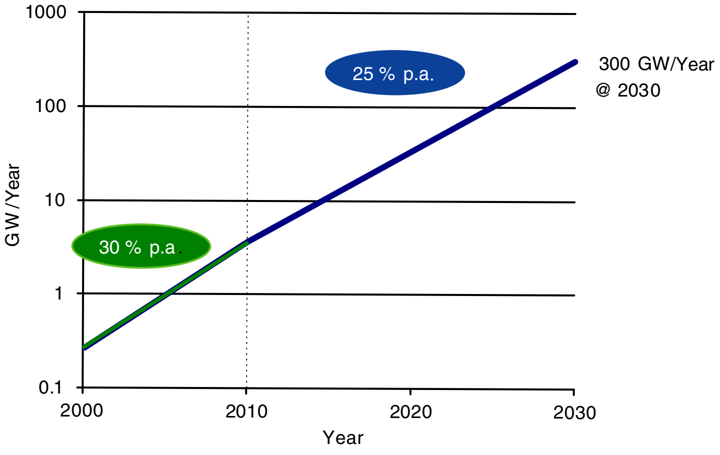


Fig. 4. Future PV growth: semi-logarithmic plot with annual rates 30%/year and 25%/year before and after 2010, respectively.

cost comparisons hold. In recent years solar modules are more and need to power the electricity needs in smaller boats and yachts. Since about 10 years solar sunroofs could be ordered as an option from the German car manufacturer Audi. In the meantime the manufacturer Mercedes has also the sunroof as an option. This integration of solar cells in the car body should serve as one example how just one product can contribute quite significantly to overall market.

In the future, more and more automobiles may be equipped with PV solar roofs to power car ventilation of parked cars for cooling and to decrease fuel consumption by supplying the increasing power demand for car electronics. Once the car manufacturers realize that by including a solar panel their total production cost is reduced by serving a customer need even better, more and more car manufacturers will take advantage of this new technology (e.g. by decreasing the peak power of the air-conditioning system and thus saving cost, while offering a much more comfortable—because cooler—environment to the driver when he enters the car after parking in the sun). It seems reasonable that like every car today has a battery, each car in 20–30 years might have solar cells incorporated into the car body. Assuming 60–80 million cars/year (from today 60 million sold per year) each to be equipped with solar cells of about 50 W, this consumer application alone will require around 3–4 GW/year.

2.2.2. Remote industrial applications

For remote industrial applications, hybrid PV–diesel systems are customary, where a PV generator is backed by batteries, and possibly by an additional diesel generator. The conventional alternative is a diesel generator alone, backed by batteries. These systems provide electric power to systems far from the main grid, such as telecommunication, traffic signals, and geographical-position systems.

For more than 15 years, a variety of these remote industrial applications for PV solar electricity have demonstrated reliable and most cost-effective means for electricity,—100% electricity supply for off-grid systems. Just to illustrate how new technologies can influence the further growth on one specific example: e.g., mobile telephones.

The worldwide spread of mobile telephones is well known. In order to cover not only the more densely populated rural areas but the urban less densely populated areas as well—even in industrial countries—a global demand of up to a million repeater and transmitter stations annually, seems realistic. With a 0.5–1 kWp-sized PV solar generator for each system this will result in 0.5–1 GWp, only for this market.

2.2.2.1. Developing countries and rural electrification. Currently there are about 2–3 billion people in the world, still without electric light and other amenities of the industrial world, and this figure is not likely to change until 2030, also due to the continuing growth of population.

Off-grid PV electricity supplies, such as PV-driven water pumping systems, small solar home systems (SHS), and small village grids are suited to greatly alleviate this situation Fig. 5.

For SHS in developing countries both cost and service are important. The average monthly cost has been estimated [1]: for nonequipped homes, batteries, candles, and kerosene amount of 6–8 US$/month. A 50 Wp PV system with battery and charge controller represents an investment of about 500 US$, that together with batteries results in about 7 US$/month over a time period of 6–8 years, under the assumption of a low-interest loan (World Bank, national institutions, or banks supporting developing countries such as KfW). In the case of SHS, the performance, the operational lifetime, and the price per service are more important than any PV module or cell efficiency considerations.

Fig. 5. Variety of benefits by rural electrification.

2.2.2.1.1. Profitability increase by adding PV to a diesel battery system. The conventional power supply in the majority of remote power supplies in the world is a diesel generator alone backed up with batteries. This conventional combination turns out to have higher production costs for electricity per kWh due to the substantial maintenance costs for the diesel and the limited lifetime of diesel gensets as well of batteries. A typical diesel lifetime is 1500 h of operation.

As a specific example for PV–diesel hybrid systems, the cost of electricity generation is compared between an 5 kVA diesel/battery system and a 1.8 kWp PV/ 5 kVA diesel/battery system, as displayed in Fig. 6.

2.2.2.1.2. Local industry and the distribution of the value chain in rural electrification. For developing countries and rural electrification, the amount of local content and the chances for developing local industry are of high importance as seen in the distribution of the value chain for rural electrification in Fig. 7.

Almost 50% of the cost are balance of system (BOS) cost whereas only 50% are attributed to solar cells and modules. The subsequent steps as shown in Fig. 7 are best suited for local content.

Electricity generating cost [€ / kWh]	Standard lifetime of Diesel and battery	Reduced lifetime of battery to 1 year
Diesel (5 kVA) @ 100% Battery	3.0 € / kWh	5.3 € / kWh
Diesel (5 kVA) @ 25% Battery PV (1.8 kWp) (@ 5 kWh / m² x d)	2.2 € / kWh	3.1 € / kWh

Fig. 6. Profitability increase by adding PV to a diesel-battery system [15].

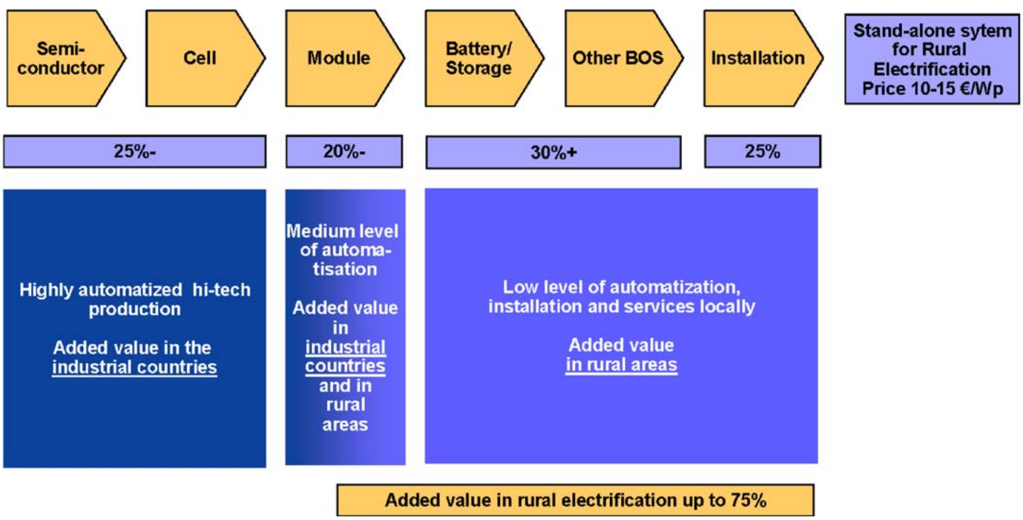


Fig. 7. Value chain in rural electrification projects.

In order to develop the infrastructure in countries suited for rural electrification it is very useful to have exchange with German universities, specialized in modular system technology. A good example is the Institute for Solar Energy Technology (ISET) near the University of Kassel in Germany which cooperate closely with the Naresuan University and the Energy Park Phirtsanalok in Thailand (Fig. 8).

2.2.2.1.3. Promotion of rural electrification—suitable measures as seen from the industry. Starting from the above picture of the value chain for rural electrification projects, it is strongly necessary to create projects in the various countries under the following boundary conditions:

- Identify confirmed regions of rural electrification.
- Infrastructure existing locally to be extended in order to install and service large numbers of systems.
- Choose suitable project size, according to the example:

○ 100,000 SHS	ca. 130Mio €
○ Schools, hospitals	ca. 50Mio €
○ Water pumps	ca. 20Mio €
Total	ca. 200Mio €

This can be made subject of a national subsidy and promotion program for the creation of local business and employment.

2.2.2.1.4. Convincing example of diesel-based local grid in remote area—Mae Hong Son, Thailand. A new convincing example for the PV supply to remote areas is the Mae Hong Son 0.5 MWp power plant built by the Energy Generating Authority of Thailand (EGAT). The local grid in this remote area in the North West of Thailand is very limited in its capacity and cannot be enlarged by the long and limited transmission line through a mountainous and ecologically worth-to-conserve area. In this respect, the Mae Hong Son plant is an intermediate between off-grid and grid-connected systems.

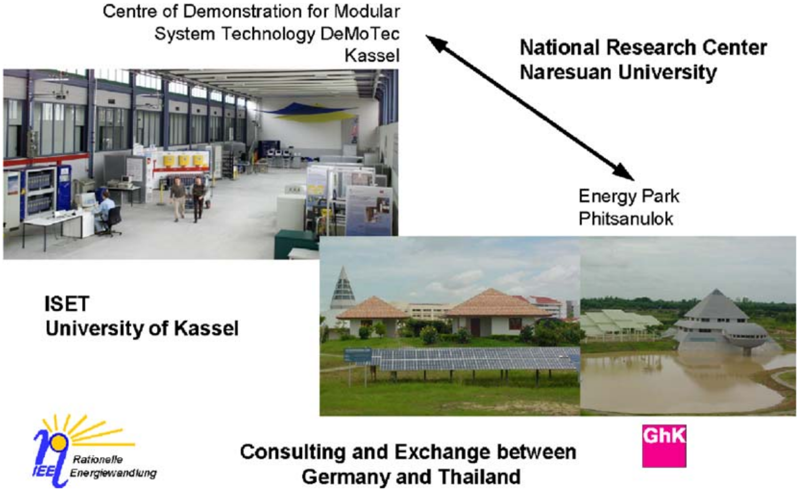


Fig. 8. Consulting and exchange between Germany and Thailand.

Fig. 9. Mae Hong Son 500 kWp schematic view (courtesy of EGAT).

A still schematic but soon (put into operation in April 2004) real view of the Mae Hong Son plat is shown in Fig. 9, equipped with double-glass ASE-300-DG-FT modules from RWE SCHOTT Solar.

Summarizing, the main reasons for the erection of the Mae Hong Son 500 kWp power plant for EGAT [2], are the following:

- Mae Hong Son only connected to 350 km distant Chiang Mai by a 22 kV line.
- Small local grid with 5 MW hydro and 6 MW diesel generators.
- Rising electricity demand and search for stabilization of the grid without further dependence on diesel by long-life and low maintenance PV installation (30 years projected) based on stable double-glass PV modules.
- Saving of 199,000 l of fuel per year and of 483 tons CO_2.
- Expected yield of 650,000 kWh/year.
- Commitment of National Policy and Planning Office (EPPO) to renewable energies.

2.2.2.1.5. Future growth of the developing countries segment. Assuming annual installations of 20–40 million SHS at 50 W each, 2–5 million water pumping and 0.2–0.5 million village grids at 50 W each, and 0.5–1 million hybrid systems at 10 kWp each, add up to 30 GWp/year in coming years.

It is interesting to note that in countries with large areas which are today without energy infrastructure from individual power supply—e.g., SHS—to village power supply—parallel operations of different sources—towards integration into the extension of the normal grid needs basically the same technology compared to grid-connected PV systems in Europe, Japan and the USA. This is shown in the lower part of Fig. 10 which has been developed by the German institute ISET in Kassel. The upper part describes, how a multitude of modular roof-top systems can serve as a means of power quality improvement, especially when installed in areas of weak grid. Together with storage batteries it is possible for the individual household to add supply safety in times of possible black outs.

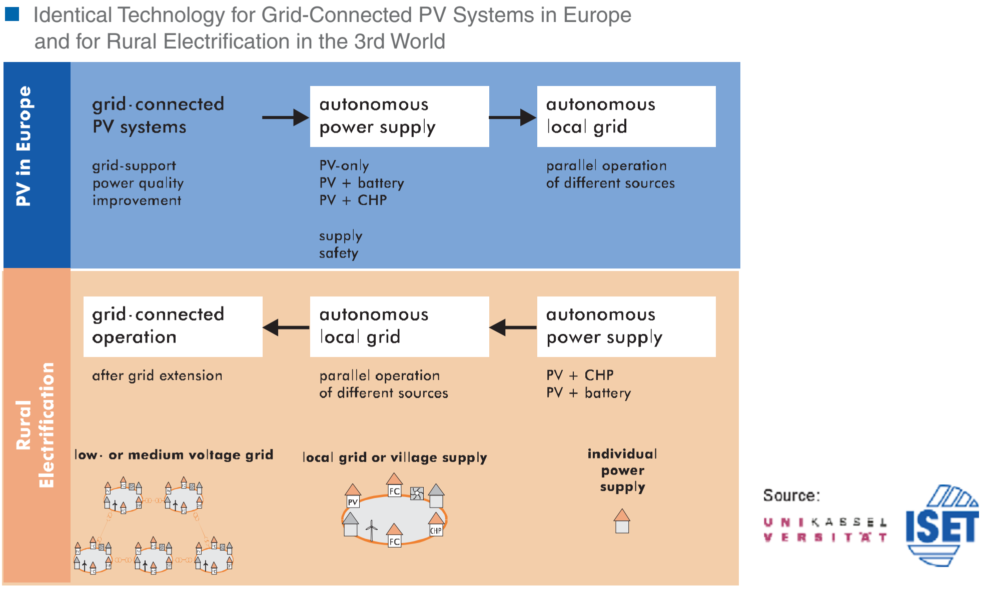


Fig. 10. Similarity of systems technology in Europe/US and areas of rural electrification.

2.2.3. *Grid-connected systems*

Today, typically roof top, building integrated roof or façade PV systems are embedded in industry—political programs like the 100,000-roof program of Germany, the 70,000-roof program of Japan, and the million solar roofs initiative of the United States. The potential for more roofs, by orders of magnitude, available for peak grid support will be demonstrated later. Other examples of this market segment are other large potentials of vast building-related areas, such as sound-barrier walls along highways, shading of parking lots, and many more, (Fig. 11).

Except for certain building-integrated applications, where the aesthetic value and the price per area €/m^2 count, such as in facades and glazing structures of representative buildings, the electricity-generating costs of grid-connected roof PV systems have to compete directly with electricity costs charged for supply by the power utilities. Most importantly, the latter distinguish more and more between bulk power and peak power, as discussed further below.

For solar electricity, an additional parameter, the geographical location of the PV installation, directly influences the generating costs, due to the corresponding insulation. In Germany, e.g., 1-sun insulation amounts to 900 h/year, while in Southern Europe it is 1800 h/year. In Fig. 12, reference is made to turnkey prices for PV solar electricity systems during the past 10 years in Germany. Starting from the early 1000-roof program in Germany in 1990 customers had to pay about 13 €/Wp installed system which in 2000 is decreased to 8 €/Wp. This corresponds to an annual price decrease of about 5%. Taking the latter price and using a formula to calculate the PV solar electricity generating cost for a kWh, the result is 0.60 and 0.30 € in Northern and Southern locations, respectively [3], without any subsidy taken into account. With the assumed growth, it can be assumed that a similar cost reduction of 5%/year will occur in the future as will be

Fig. 11. Grid-connected systems.

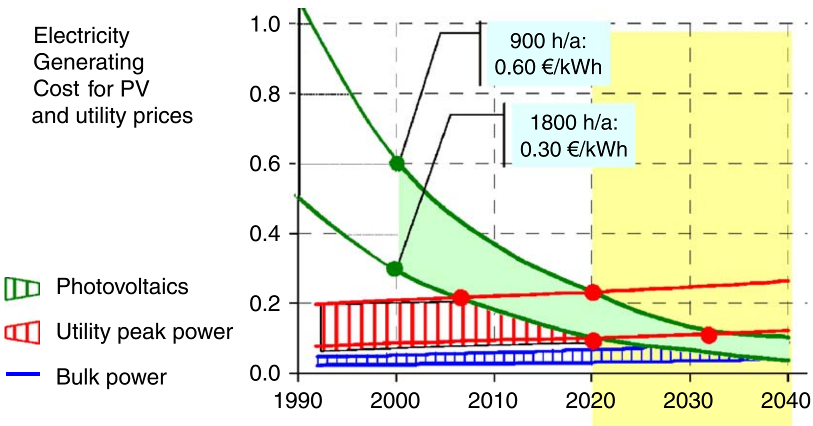


Fig. 12. PV competitiveness: electricity generating costs for PV and utility prices.

shown later by a price experience curve for the most cost-contributing item, the solar module.

A mixture of base-, ''medium''- and peak power electricity has to be provided by the power utilities worldwide to serve the varying load requirements from the customers. In the past when a regulated market existed worldwide, it was common practice to allow for a certain over-capacity in base power stations. If peak power had to be delivered there was usually a competing situation to supply these needs at equal or cheaper prices compared to bulk electricity utilizing the existing over-capacity. Only specific demands for peak power have been sold at prices adequate to the actual peak power generating cost. Due to the worldwide deregulation of the utilities a new situation has already arisen and will develop over the next few years.

Accordingly, utilities will increasingly be going to charge higher rates for periods of peak demand and in addition proportional to the load. As a consequence, the tariff situation will, around 2010, be more and more such that a PV system will be competitive with otherwise purchased peak kWh from the utility, as seen in Fig. 12. In Southern Europe PV generation starts to compete with utility peak power around 2010, whereas in Germany around 2020. The competition with bulk power occurs much later, projected to around 2030 for Southern Europe.

Considering facility management of buildings, particularly in southern regions in Europe, US and Asia, the peak demand for electricity occurs during midday as well as during the summer (Fig. 13). Plotted is the typical load profile during the course of the day for an office building in Spain.

The electricity demand shown in Fig. 13 in the office building exhibits a pronounced peak between 9 and 16 h which is significantly higher in summer than in winter. Synchronously in phase to this demand, PV energy is produced by the solar modules.

This is in contrast to the use of wind energy, which can economically best be used in the future in central power stations (multi-GW off-shore) where by the stochastic yield of wind a temporal assignment is not possible. With solar radiation a clear temporal and seasonal assignment is possible.

Due to this reason, for the assessment of electric energy prices from different energy sources, the cost calculation of these prices will strongly depend on the temporal availability of the energy sources. This temporal dependence of electricity prices is displayed in Figs. 14 and 15. The higher figure of merit of PV solar electricity production in summer and at noon time is illustrated in Fig. 14, in this case at a site in Australia.

Similar functional relationships regarding the higher value of solar PV electricity, in future to be taken into account for time-dependent electricity tariffs, can be found in Southern Europe, in the South of the USA, Japan and will probably be found increasingly among Asian countries, with advanced electricity tariff structures.

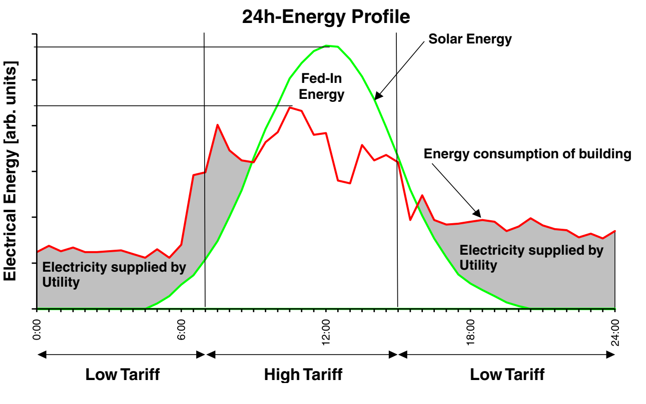


Fig. 13. Daily profile of solar-energy production and energy consumption of an office building.

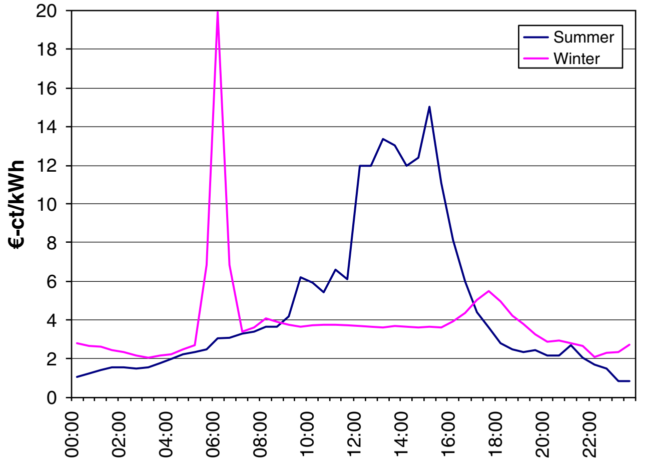


Fig. 14. Electricity prices in 2000 depending on bulk and peak power in Victoria, Australia.

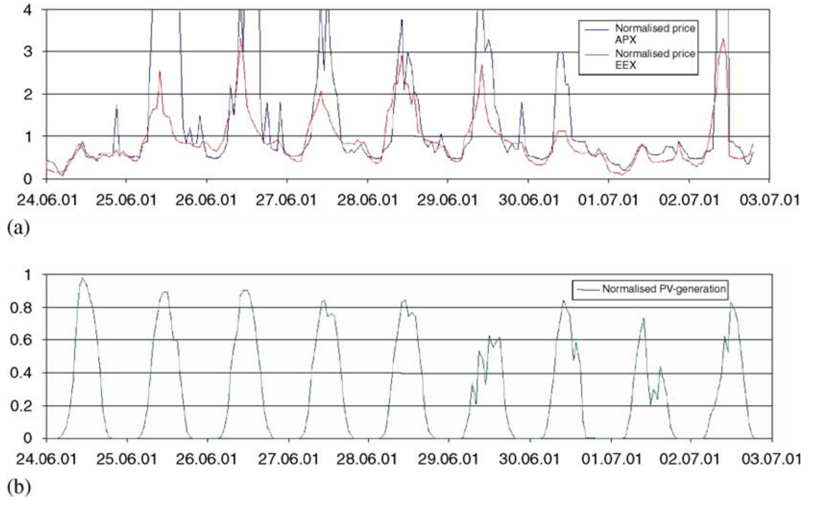


Fig. 15. Spot market prices in correlation with PV electricity generation (source: FhG-ISE).

An impressive correlation between spot market prices at the Amsterdam (APX) as well as European (EEX) Power Exchanges and the power output of PV roof top systems installed in Germany has been worked out by the Fraunhofer institute ISE in Freiburg [4] and is shown in Fig. 15 for the last week of June in 2001. The value for PV electricity is low on Sundays due to low energy demand as reflected in low spot prices (24.6.2001 and 1.7.2001). During the week, however, there is a remarkable increase in spot market price following closely the output of the PV sytsem as seen in the time period 25th to 30th of June 2001. It has been demonstrated in the Fraunhofer paper [4] that the correlation increases when the output of 16 PV systems dispersed over a larger area in Germany compared to a single PV system is taken into account.

Accordingly, grid-connected PV installations will compete with new peak power stations required in the future, particularly if time dependence of energy consumption and electricity tariffs are considered as in the above considerations. A study by Lahmeyer International [5] concluded that in addition to the existing 4000 GW power stations worldwide there will be an increasing new power per year installed of about 100 GW in 2000 growing to 250 GW in 2030.

Consequently, at a replacement period of 30 years for the existing electric power, there will be an additional need of about 130 GW/year for replacement. Part of this power requirements will be satisfied by grid-connected cost-competitive PV installations, starting around 2010 and reaching about 25–100 GW/year by 2030, depending on the price development for peak and bulk utility power (see Fig. 12) as well as the electricity as a function of time.

2.2.3.1. German Feed-in Law EEG—the most effective program worldwide to stimulate the renewable energy market. For the moment and in order to bridge the period when grid-connected systems can compete with utility power as described above, the big driving forces causing this large market segment are coming from national stimulation programs in Japan, the US, and in Germany, such as the German Feed-in Law EEG. According to this law, PV solar electricity fed into the public grid by owners of installations has to be purchased by the utility companies at an enhanced price (in the order of magnitude of PV production price around 0.5 €/kWh).

This German feed-in law EEG, which is not an investment subsidy, has shown up to pull the PV market substantially as illustrated in Fig. 16.

As seen in Fig. 16, the 1000 PV-roof program in Germany was implemented in the period 1990–1992. It was acknowledged as the first widespread program for the successful demonstration of the performance of PV solar installations. Rather small in size (ca. 2 MWp/year), this program had, however, no sizeable impact on the market volume as displayed in the figure.

The prominent rise of the market volume in Germany since 1999 is first due to the 100,000 roof program (low interest rate by KfW bank) and second, more pronounced so, after the year 2000, due to the Renewable Energy Feed-in Law (EEG): In only 4 years the market has been multiplied by a factor of 10.

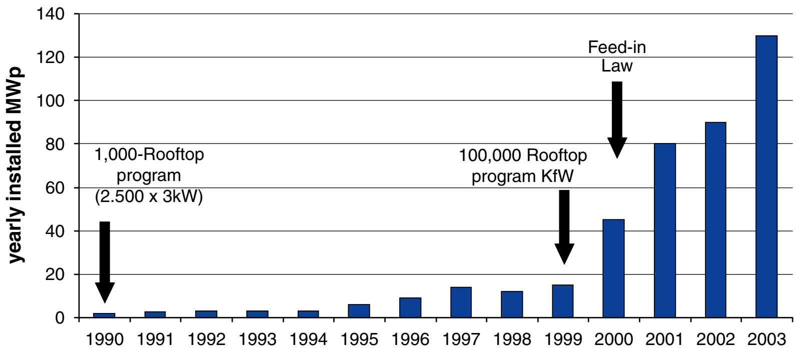


Fig. 16. Market pull by EEG and 100,000 rooftop program in Germany.

This illustrates the strength of the market pulling forces of a rate base incentive (German feed-in law) compared to investment subsidies.

The German Renewable Energy Feed-in Law can therefore be regarded as the most effective program worldwide to stimulate the renewable energy market:

- Equal market opportunities for all the renewable energies based on specific feed-in tariffs.
- Customer focus is on product quality and performance as a result of high competition in the market.
- The long-time reliable availability (>20 years) of the system performance is the key requirement of the end-user of renewable power technologies.
- In contrast to short-term subsidy cash programs the new law offers the perfect basis to forecast annual sales volumes in the mid-run.
- Feed-in Law EEG win–win situation:
  - Stimulation of customers demand
  - Economy of scale in production (e.g. SmartSolarFab® by RWE SCHOTT Solar)
  - Defined decline of feed-in tariff rate and price level of system.

2.2.4. Development prediction of PV market segments

Future growth of the market segments, as extrapolated after Maycock [6] is shown in Fig. 17.

The grid-connected PV system market will probably rise in the future as strongly as up to now due to the support programs in the respective countries.

Using the 30 and 25% annual growth rates as in Fig. 4, the range of the respective market size in 2030 for the four main market segments is shown in Fig. 18. This results in a total of 300 GW. The individual values for the four market segments are based on estimates by Maycock [7], plausibility arguments, and the wish that PV in developing countries in particular will grow with the highest rates in the coming decades.

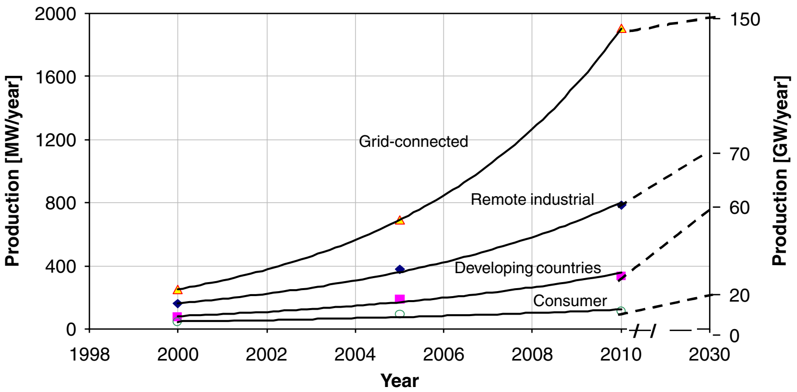


Fig. 17. Development prediction for PV market segments.

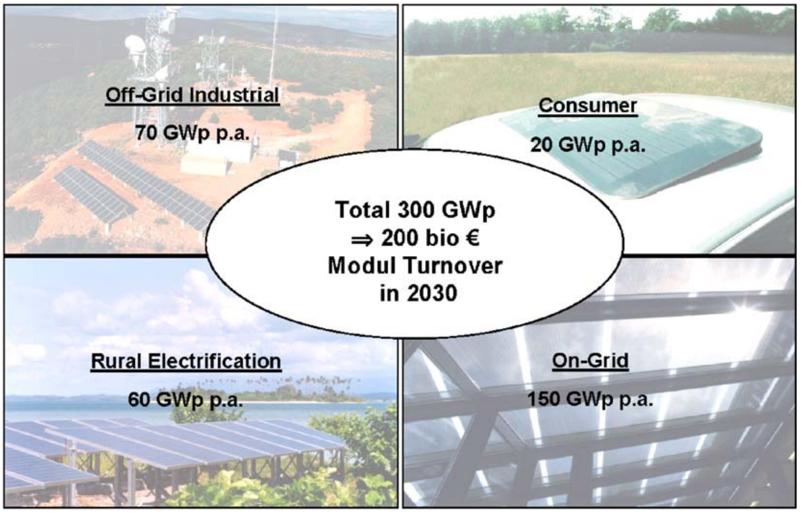


Fig. 18. Market size and global module turnover projections for 2030 for the four market segments.

2.2.5. *Price experience curve*

The projected growths of the market must be accompanied by production cost reductions. Production costs (and prices derived there from) are related to learning and experience in production, which is reflected from the level of production output. Following Boston Consult, the logarithms of the cost of a specific product and the corresponding accumulated number produced define cost learning curves. From the negative slope, typical for different technologies, the relative decrease of cost for doubling the cumulative number of produced products can be calculated and is called the learning factor. In the past years the approach of calculating learning factors has been transferred to a more complex methodology, i.e. for a whole industry. Using the same double logarithmic graph but using typical market prices for the product one obtains again a straight line, called a price experience curve.

In Fig. 19 (insert) the historic learning curve that traces world market module prices as a function of the accumulated module production is shown. This PV experience curve demonstrates a 20% price decrease by doubling the cumulative volume, equivalent that half the production cost can be anticipated upon a tenfold increase of the accumulated output. It is noted that the experience curve does not directly contain a time scale. The learning and experience is affected by various influences that range from progress in research and development, to funding in the industrial and political environment, and on to interactions with the market.

Since the already industrialized PV technologies still promise potential for further development, and "next-generation" technologies are well underway, a strong confidence is justified to postulate that the experience curve will also extend into the future.

With the increasing economy of scale, material cost contributes relatively more and more to the total cost of a module. In order to account for that the learning factor is decreased from 20% down to 18% and even pessimistically to 15%. The continued experience curve thus indicates, depending on the assumption of the learning factor between 15% and 18%, that the 1 €/Wp cost level will be reached at an accumulated

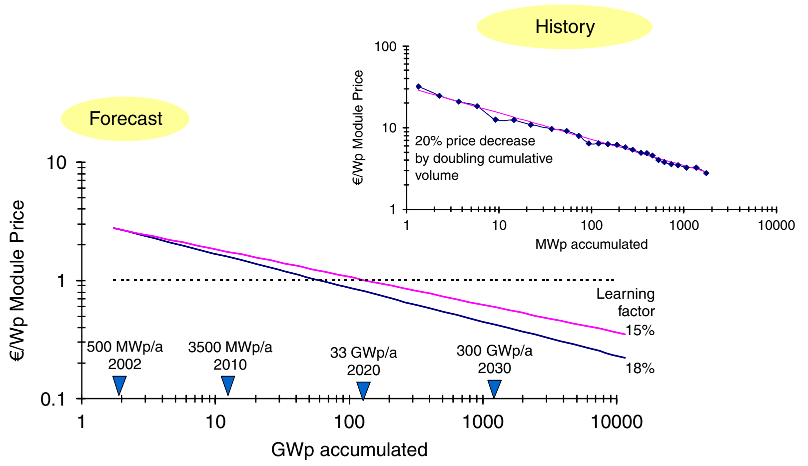


Fig. 19. Price experience curves for PV modules.

(a) **Crystalline Silicon**		(b) **Thin Film**	
Cz, Fz	High power/area @ premium price eta 16 - 25 % space, niche markets	II - VI compound (CIS, CTS) a-Si / µc-Si and thin Si films	Additional solutions for cost effective power applications eta 8 - 18 %
mc & ribbon (EFG)	Cost effective power application eta 14 - 16 % "The PV workhorse"	pin-ASI and ASI-THRU®	Low price/area @ low eta eta 4 - 6 % "Solar electricity glass"
(c) **III - V compounds (GaAs)**		(d) **New Concepts**	
Highest power/area @ very high price		dye cells	"Colour to PV" (eta 3 - 10 %)
multi bandgap	eta 25 - 40 %	organic cells	"low material cost option"
	space, concentrating systems	Scientific high eta approaches aiming for eta 30 - 60 %	utilization of hot electrons, intermediate band cells, up/down conversion, quantum wells, nanostructures etc.

Fig. 20. Four main technology routes.

production of around 100 GW, which according to the projected growth will occur around the 2020s.

3. The PV solar electricity technology

3.1. Technology routes

The main technology routes as seen today can be characterized into four main areas as summarized in Fig. 20(a)–(d). The areas crystalline Si, thin film, II–IV compounds and new concepts are shown together with their special characteristics in terms of performance, price, efficiency and contribution to market segments and applications.

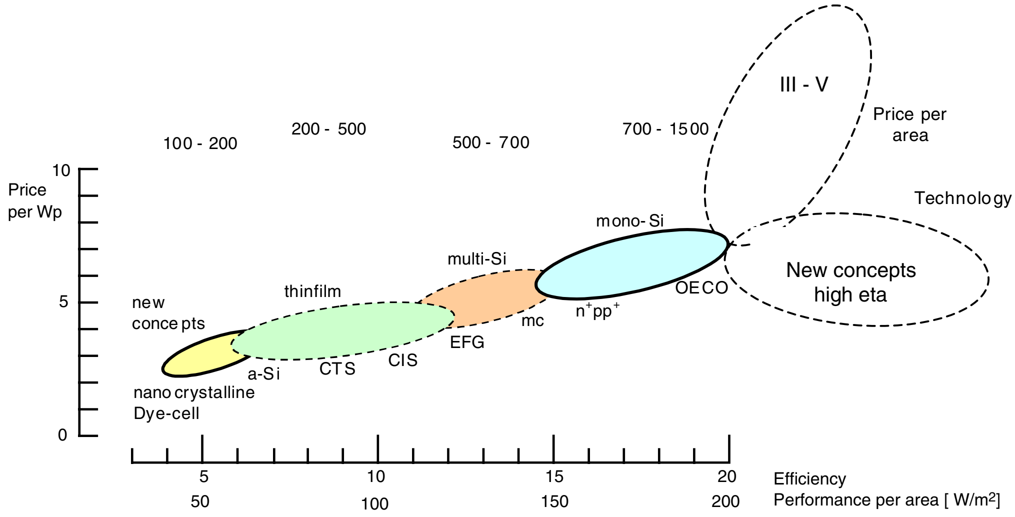


Fig. 21. Area-related price and power output for various technologies.

As described in Section 2 of this paper it is important to note that for the variety of customer needs there is also a multitude of products necessary which reflect also several technologies. This can be visualized in Fig. 21 where the various technologies are plotted in terms of performance per area, price per area and projected price per power unit (Wp).

It must be emphasized that the different technologies will coexist, even though their efficiencies may be quite different, but so may be their costs per Wp or per m^2.

This is even better recognized when plotting the various technologies in a graph like in Fig. 18. Starting from low 5% efficiency/low price/W dye cells on the left side we go up to high 20% efficiency/high price/W Cz-OECO cells on the right hand side. Other technologies (amorphous silicon—a-Si, II–VI, mc, Cz-std) are in between. Important is a look to the upper calculated value "price per area". If a customer needs high power output from a limited area (laptop, sunroof, etc.) he is proposed to pay a high price/W and the high price/area is not important. However, if for a skyscraper facade some south-oriented 10,000 m^2 could be covered by PV modules it becomes quite obious that a low price/m^2 can be offered, most efficiently with a-Si today. As a result from the APAS study [8] all different thin-film technologies show the same production cost/Wp (see Fig. 23). As the power output for CdTe and CIS are higher compared to a-Si it is clear, that there is a clear a-Si advantage for a lower price/area module. In addition, the thin layers of a-Si compared to II–VI compound semiconductors make it easier to produce semitransparent modules, which nicely fit into building-integrated PV systems (see also Fig. 15 in connection with grid-connected systems).

The dominance of silicon further extends into the thin-film technologies, particularly that based on hydrogenated a-Si [9].

Other thin-film technologies, based on copper–indium–gallium–diselenide (CIGS) and cadmium telluride (CdTe), have reached sufficient maturity to be industrialized, and, in fact, have gone, or are about to go, into production. In 2000 their output still remained at the 1 MW/year level [10]. While their module efficiencies have exceeded, or have the

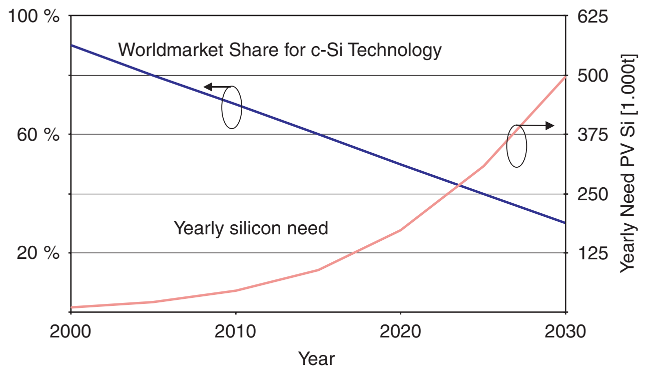


Fig. 22. Market share of c-Si technology relative to the total market and corresponding yearly silicon need.

potential to exceed, those of a-Si modules, it is not likely that these technologies may become the "work-horse" of PV solar electricity generation, since the materials availability, particularly indium and tellurium, will restrain the expansion of module production at about 20 GW/year for CdTe, and 70 GW/year for CIGS [11].

For many years to come, crystalline silicon (c-Si) based technologies will play a dominant role (see Fig. 22). Although with increasing volume, the supply of cost-effective "reject" silicon, a material not usable by the chip industry, but perfectly adequate for PV, will become scarce, the required silicon quantities will become sufficiently high to economically justify the production of a "solar-grade" silicon for the cell wafer production. Already today a number of chemical companies e.g. Wacker, Solar Grade Silicon LLC, Tokuyama, MEMC are starting the production of this feedstock Si -material.

Even at an aggressive growth of thin-film technologies there are in 2030 at least 30% of the global demand coming from c-Si. This amounts to a solar-grade silicon consumption in 2030 as high as 160,000 t in 2030 using Si feedstock consumption values from Schmidt et al. [16].

Nevertheless, several advantages of thin-film technologies, such as

- very low materials consumption/m^2,
- large-area deposition,
- automated monolithic series connection of cells (e.g. laser scribing),
- shorter energy pay-back times and
- potential for lower module manufacturing costs,

will considerably stimulate a continued development of the thin-film technologies.

Both c-Si and thin-film technologies will play major roles in the future, but their shares are likely to shift towards thin-film technologies, mainly due to cost, and hence price considerations.

In the long term, the role of silicon may further extend into film-silicon technologies. The underlying process is a high-temperature CVD of silicon to thicknesses on the order of 10 μm on temperature-resistant substrates, like ceramic materials. Further developments in this area aim at combining the high efficiencies of c-Si with advantages of thin films, like lower materials consumption, larger deposition areas, and eventually monolithic series connection of cells [11].

3.2. Technology road map

The purpose of a road map is to draft approaches, by which the goals of a certain program can be reached. In this endeavor, the choice of PV technologies not only depends on the achievable efficiencies of production modules, but, even more important, also on the maturity of the technology in terms of its degree of industrialization, module manufacturing costs and the additional area-related BOS costs, on the applicable energy pay-back times, and even raw materials reserves (Fig. 23).

Of all the modules globally sold in 2000, about 90% are made from c-Si. The silicon wafer material is monocrystalline, derived from Czochralski processes, for about 40% of all c-Si modules, and multicrystalline, derived from casting methods and ribbon technologies, like the edge-defined film-fed growth (EFG) [9], for about 60% of all c-Si modules. Pulled Cz and cast mc silicon are already well-known processes worldwide, which both still have the drawback of high raw material losses (about 50%) during the wire sawing of the wafers from the block. In contrast to this, EFG of wafers in form of ribbons pulled directly from the silicon, leads to a material efficiency of around 90%. An illustration of the EFG-prepared wafers and subsequent automated inline cell production is shown further down in the context of the large size factory SmartSolarFab® (see Fig. 25).

New concepts for solar electricity are still in the research stages. Among those closest to a transfer into a piloting stage is the dye-sensitized nanocrystalline solar-cell concept [12]. Further developments in this area are all-solid-state photoelectrochemical cells, where the liquid electrolyte of the former is replaced by a gel or solid ionic conductor. Finally, organic solar cells have been invented at efficiencies around 2% [13]. For all these concepts, it is too premature to make any prediction with regard to their role in any road map.

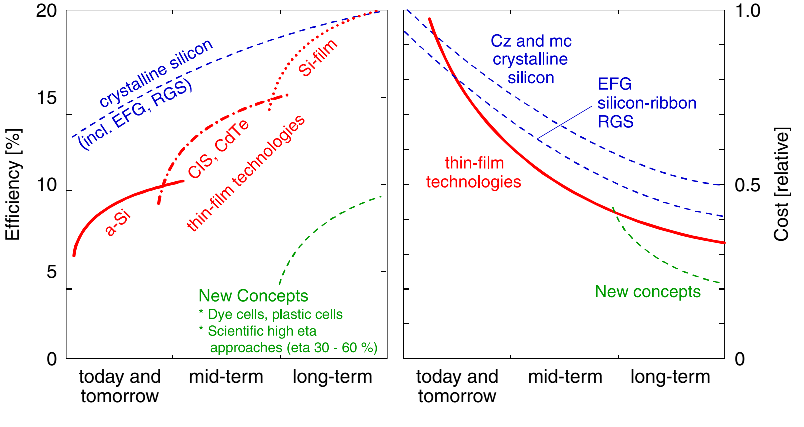
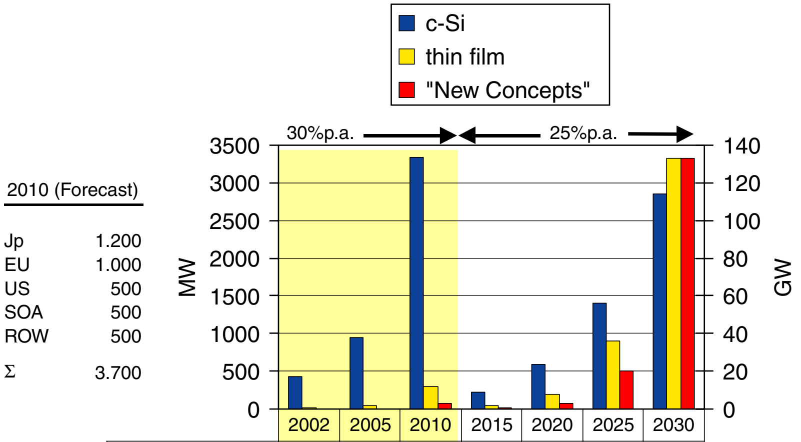


Fig. 23. Technology road map.



	2002	2005	2010	2015	2020	2025	2030
c-Si	430	950	3340				
thin film	20	50	290				
"New Concepts"			70				
c-Si				8.96	23.8	56	114
thin film				1.68	7.48	36	133
"New Concepts"				0.56	2.72	20	133

Fig. 24. Production of solar modules using different technologies.

A projection concerning the growth of the main technology routes in the next two to three decades is shown in Fig. 24. While today the dominating technology is c-Si with about 95% market share and the remaining 5% is thin film, almost all a-Si.

Until 2010 there will be a slight increase towards 10% market share by thin-film technologies. The main relative growth until 2020 will then be covered by thin film whereas until 2030 new technologies will take the lead, respectively. Within new technologies reference is made to dye and organic solar cells as well as to scientific high efficiency approaches. The latter are sometimes referred to as third generation concepts and utilize hot electrons, quantum wells, intermediate band gap structures and nanostructures. While these excellent ideas from the research community are very valuable in obtaining higher efficiencies—even with nowadays materials—they will not replace by themselves the existing technologies.

3.2.1. Solar industry progress at RWE SCHOTT Solar—SmartSolarFab® inline production of EFG wafers and solar cells

An important step towards more efficient and material-saving economy of scale has been achieved in the recently built SmartSolarFab® in Alzenau near Frankfurt, Germany, by RWE SCHOTT Solar. An illustration of the EFG wafer-pulling machines and the subsequent automated inline cell production is seen in Fig. 25.

3.3. Energy pay-back time

The energy pay-back time represents that time period over which a PV module generates the amount of energy that was required to produce it. It is thus a parameter that

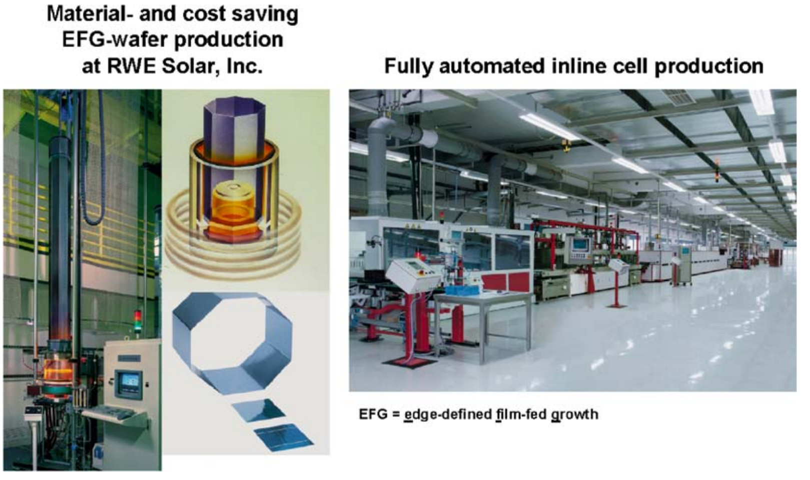


Fig. 25. RWE SCHOTT solar leadership: EFG wafer production and fully automated inline cell production.

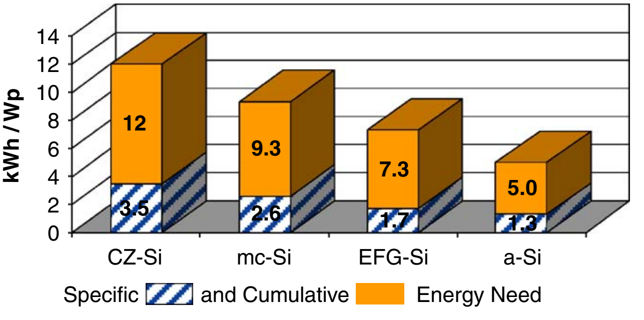


Fig. 26. Energy need for PV module production.

particularly in view of environmental considerations ought to be considered. While it is obvious that these time periods depend on the cumulated insolation and hence on the geographical location of the solar module installation (i.e. longer energy pay-back items at larger geographical latitudes), a comparison of the absolute values requires a clear definition of the energy consumptions that are to be taken into account for manufacturing the solar module. In Fig. 21 the energy requirements needed to produce a frameless solar module (based on own estimates and Ref. [14]) are compiled for two scenarios, that either take into account only the energies needed for the immediate steps to produce a module (silicon feedstock, wafers, cells, and modules), or additionally include the energy requirements to produce the raw materials needed (e.g. glass, plastics etc.). In the latter case, all electricity needs are changed into primary energy. The conversion factor electrical to primary energy typically is assumed to be 0.35. At 1 kWh/Wp year insolation, roughly Central Europe, the energy need, expressed as kWh/Wp, equals the energy pay-back time in years; for Southern Europe at about twice the insolation, the energy pay-back time corresponds to about one-half the energy needs. While these data may vary significantly depending on the accuracy of data collection, it is safe to state that the energy pay-back times are far below the anticipated service life of modules. Hence PV must be considered as an environmentally meaningful way of electricity generation (Fig. 26).

4. Industry

The local PV industry for manufacturing wafers, cells and modules has always paralleled in growth with the respective size of the local market. The co-incidence of industry development as shown in Fig. 28 and the regional market growth as summarized in Fig. 27 is striking. During the 1980s and until the mid 1990s the biggest market was in the US and the biggest manufacturers were also US companies: ARCO Solar (now Shell Solar), Solarex (now BP Solar), ASTROPOWER, Mobil Oil (now RWE SCHOTT Solar). With the start of the 70,000 roof program in Japan the goal there was and still is to be the leader in manufacturing worldwide. It is impressive to see how well the actual figures for the market as well as the manufacturing industry agree with the planned number in 1995: for 2004 the plan was a market size of 250 MW with a significant additional export from Japanese manufacturers; the actual figures for 2003 most likely are already approaching the goals. In parallel, the Japanese manufacturers Sharp and Kyocera took meanwhile the lead in manufacturing capacity and produced cells and modules with other Japanese companies (e.g. Sanyo, Mitsubishi, Kaneka) following. With the start of the German 100,000 roof top program in 1999 and the feed in tariff in 2000 the market in Germany grew 10 times in only 5 years from 13 MW in 1998 to about 130 MW in 2003 and this was again accompanied by heavy investments from manufacturing companies, e.g. RWE SCHOTT Solar , SolarWorld, Q-cells, Shell Solar ErSol, PV Crystallox, Sunways and others.

The main growth areas are:

1. Japan due to the 70,000 roof program.
2. Germany due to the 100,00 roof program (low-interest loan financing by KfW bank) and Renewable Energy Feed-in Tariff.
3. USA due to market support programs in various states.
4. Rest of World (ROW).

In the next figure, Fig. 28, are illustrated the produced quantities by the different manufacturers.

As seen from Fig. 28, the ranking changed over the years among the world leading companies. This is due to shifting priorities and enhanced activities in subsidy politics for

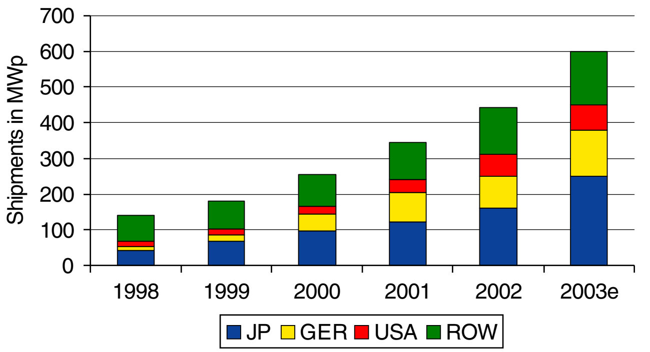


Fig. 27. Historical market growth of the solar electricity industry by region.

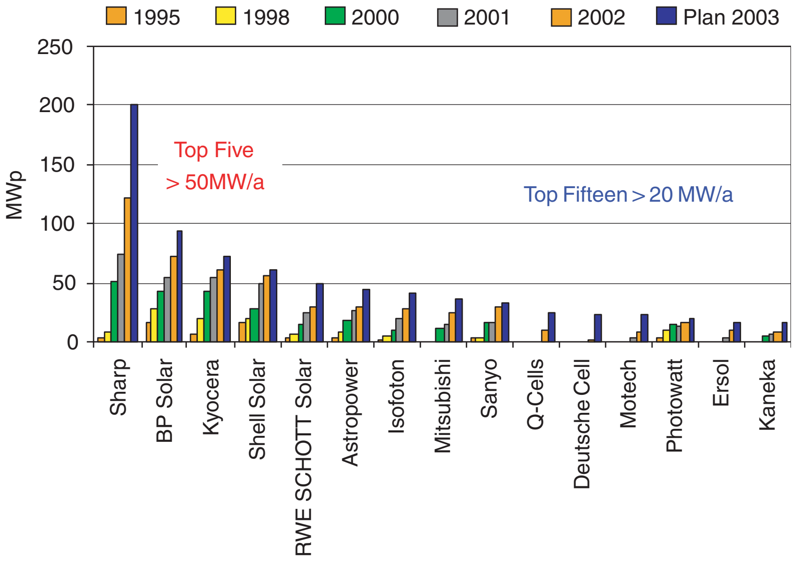


Fig. 28. PV cell and module production companies worldwide.

renewable energies in Japan, Europe, the US, and other countries with upcoming subsidy and promotion programs.

Overproportional growth is seen at the companies Sharp and Kyocera from Japan with strong growth of European manufacturers over the last 3 years.

5. PV solar electricity in the context of a future global energy supply chain

Summarizing the findings in this paper, PV Solar electricity combines the following prime features to become a new-millennium industry, namely,

- *Fast growing market*: Over the last 5 years, an average global market growth of 33%/year has occurred. As the main market segments being served today show widespread acceptance and imply a sound demand, a market pull for many years to come, with a continued annual growth between 25% and 30% may be anticipated for the future.
- *Substantial business in coming years*: The anticipated module turnover in the 2020s will be in the range of 100–200 billion €/year—a market that will support employment on the order of several million people worldwide.
- *Global energy justice*: Providing affordable power to the billions of people in developing countries.
- *Shift to service society*: The PV industry enables the industrial countries to shift from an industrially oriented employment society to a service society by mass-producing with highest productivity high-tech PV solar electricity products. To maintain or even to increase the gross national products, the service-orientated society is bound to create the corresponding employment.

- *Environmentally sound*: The impact of PV product manufacturing is the lowest when using
  (a) low electronically grade pure silicon and low primary energy consuming processes such as the above-mentioned ribbon sheet EFG c-Si process or thin-film technology.
  (b) PV module assembly such that due to their lifetime expectation (ca. 30 years and more) and during their period of operation they produce a multiple of the primary energy needed for their fabrication.

Therefore, combining these economic, social and environmental aspects, it turns out that.

5.1. PV solar electricity is one of the big future industries

So far however, in terms of global electricity contribution this new business does not yet play an important contribution for the momentary electricity production, as seen in Fig. 29, where in the development prediction at the 30% and 25% annual growth level a worldwide contribution of 1%—based on primary energy (and assuming that 5 Wp primary power corresponds to 1 W electrical power installed) is reached in the late 2020s of this century and a 10% level may be reached around 2040. These figures are based on the already mentioned 4000 GW worldwide electricity power generating capacity [4], the global electricity production in 1998 being about 14,000 TWh [17] and assuming 1.5 kWh/year generated by 1 Wp of solar modules; for comparison: the worldwide primary energy consumption in 1990 was about 100,000 TWh [18].

A future projection for primary energy consumption was published by Shell as displayed in Fig. 30.

In the global prime energy picture PV solar electricity shows visibility in 2040 and later very much in line with our projection.

At the very end remains the question as to how fluctuating renewable energy sources—like wind and solar electricity—may serve continuously the energy needs of mankind, assuming that electricity storage of huge GWh amounts daily, and even more seasonally, is economically prohibitive. In order to solve that problem two solutions exist: firstly, a global hydrogen society, and secondly, a worldwide high-tension DC grid.

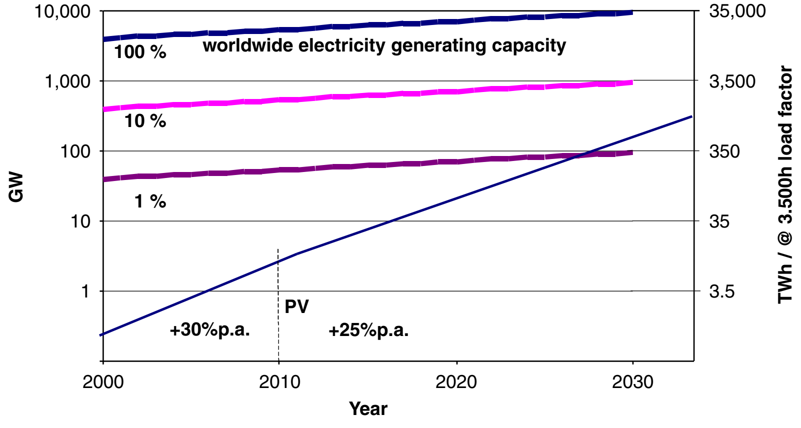


Fig. 29. Development prediction of worldwide electricity production.

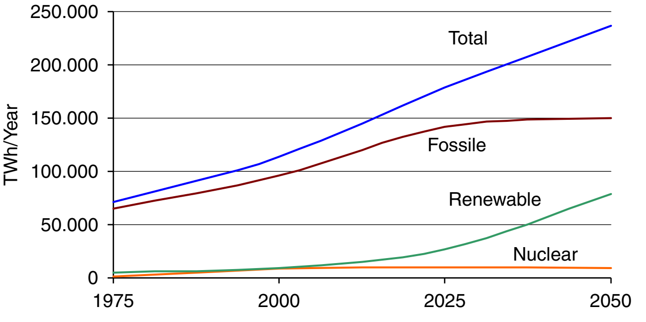


Fig. 30. Global energy consumption (sustained growth), source: Shell [18].

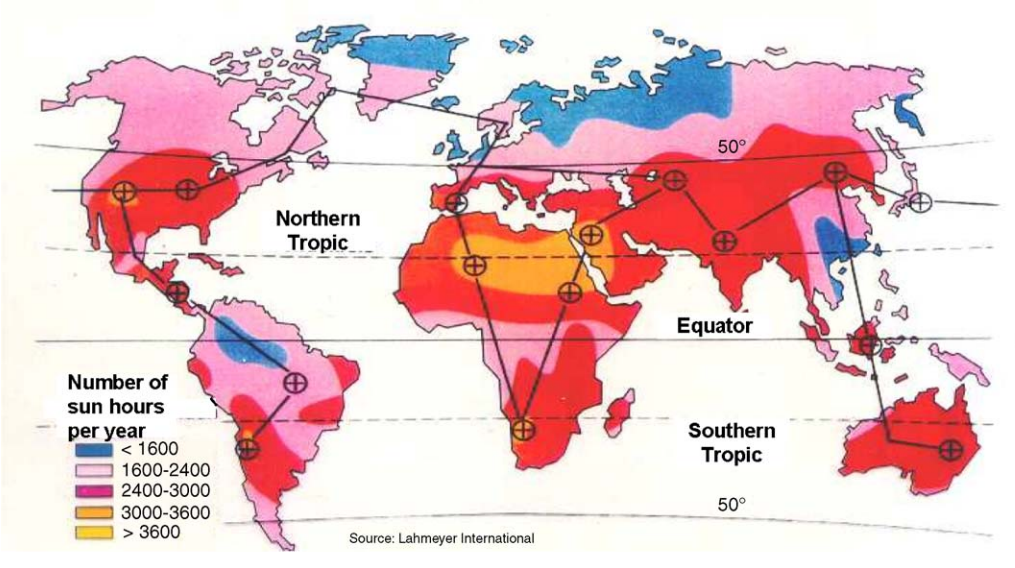


Fig. 31. Vision for a global and sustainable energy supply.

Whereas hydrogen will undoubtedly play an increasing and later dominating role in global mobility purposes by fuel cells and turbines, it remains to be seen, where the stationary energy suppliers will take their energy from. If a worldwide high-tension DC grid is able to transport GWh of electricity half around the globe at similar—even slightly higher—losses compared to a hydrogen pipeline and storage there would be a big advantage for the world electricity grid as there are not the twofold losses by first electrolysis of water to hydrogen and second by fuel cells converting hydrogen back to electricity again.

Looking at Fig. 30 and remembering that the size of one dot like the one in the Sahara desert would be sufficient to supply the worlds annual primary energy needs, it can be concluded that by combining all renewable energy sources there is a good solution available for future generations of mankind, namely to utilize the very best fusion reactor—the sun (Fig. 31).

Acknowledgments

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