Environment Protection Engineering

Vol. 32 2006 No. 1

H.J. MÖLLER*

PHOTOVOLTAICS – CURRENT STATUS AND PERSPECTIVES

Photovoltaics is one of the renewable energy technologies with enormous potential for further growth. Due to favourable political frame conditions in some countries the worldwide photovoltaic industry is currently seeing an expansion with very high growth rates. The driving forces and the market development will be briefly analyzed. The industrial production is mainly based on the crystalline silicon technology. After a review of the current status of the photovoltaic technology the main research and development issues are presented. Furthermore a short outlook of some of the future developments will be given.

1. INTRODUCTION

The solar contribution to the worldwide electrical power production is still very low. In the last five years the production of photovoltaic modules increased, however, annually by about 20–40% and reached in 2004 more than 1 GW/year. Assuming the same growth rate for the next years a production of 10 GW/year will be reached around 2015 [1]. New political frame conditions in different countries, in particular in Japan and Germany, but also in the USA, China and Spain, lead to long lasting planning security and increased the readiness of the industry for investments. One can expect that under these conditions the share of solar power in the energy mix will become substantial.

An impact on the worldwide electric power infrastructure requires however continuous growth of the same order of magnitude for more than 20–30 years. To reach this ambitious goal not only reliable political conditions in many other countries but also a continuous improvement of the solar cell and system technology are necessary. The main issue is to reduce the price for solar power until it will become competitive at least with peak consumer prices.

The production cost of solar energy is determined by the cost of the solar system and the conversion efficiency of the solar modules. Figure 1 shows the system cost of

---

* Institute for Experimental Physics, TU Bergakademie Freiberg, Leipzigerstr. 23, D-09599 Freiberg, Germany.

a photovoltaic plant (in Euro/W_p) as a function of the area cost (in Euro/m^2) and the efficiency. Estimations for Germany show that system costs of about 1.0–1.5 Euro/W_p yield production prices for electrical power of about 0.05–0.1 €/kWh, which is comparable to current consumer prices [2]. In countries with higher solar irradiation the production costs are lower.

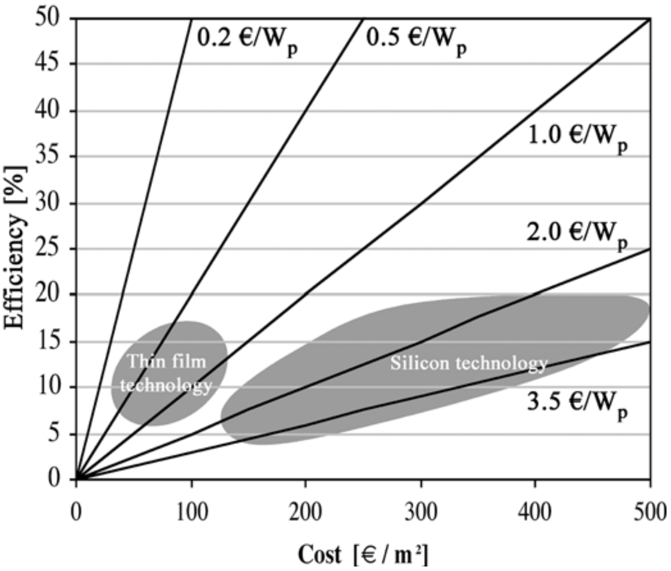

Fig. 1. Photovoltaic system cost as a function of cost per unit area and efficiency for two different technologies: silicon technology and thin film technology. System cost of about 1 Euro/W_p yields electricity cost of about 0.1 Euro/kWh

The diagram in figure 2 shows that the photovoltaic technology is mainly based on the use of crystalline silicon solar cells. It is generally believed that this technology will dominate the market for the next 10–15 years. On the other hand, one can see from figure 1 that the technology does not reach the 1 Euro/W_p line yet and the question arises whether the crystalline technology has enough potential in the long run to reach the desired goal of a comprehensive power supply. About 2/3 of the total solar module cost consist of the fabrication cost of the silicon wafer. It is thus necessary to reduce the material contribution and the cost of silicon. There is consensus today that new developments based on other concepts and the use of new materials have to be added. Promising new technologies are based on the use of thinner solar cells or even thin films on foreign substrates [3].

The development of thinner cells and the efficient use of silicon are currently accelerated by a temporary shortage of raw silicon of solar grade quality, of which about 10 000 tons are needed annually. One can estimate that with further growth at the same rate the demand on silicon for the photovoltaic industry will by far surpass the demand in the microelectronic industry, where high purity silicon has mainly been used up to now. Independent production facilities for solar silicon and the exploration of alternatives are therefore developed and will make the photovoltaic industry more self-sustaining and mature in the next few years.

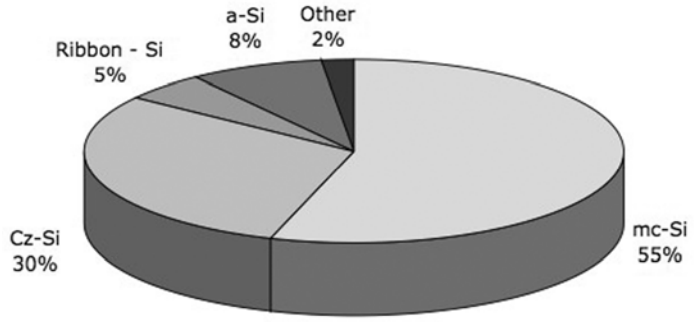

Fig. 2. Market shares of the different solar cell materials in industrial production today

In this paper, the present status of the photovoltaic technology will be reviewed and some of the technical and scientific problems connected with the growing photovoltaic industry are addressed. The issues cover a broad range of topics, such as feedstock supply, crystal growth and wafering, solar cell and module processing, and efficiency and material improvement. Alternative concepts are still mainly at the laboratory stage. Some of the more promising solutions and their further perspectives will be discussed.

2. SILICON SOLAR CELL TECHNOLOGIES

Both mono- and multicrystalline silicon (mc-silicon) is used with an increasing share of mc-silicon because of the higher potential for cost reduction. The solar conversion efficiencies of commercial mc-cells are typically in the range of 14 to 15% and up to about 17% have been obtained by sophisticated solar cell designs. In theory, the potential of mc-silicon is even higher, possibly up to 20% [4], [5]. Such an improvement of the efficiency would greatly increase the commercial viability.

Crystalline silicon is produced by crystal growth technologies. Various growth techniques are used, which yield either mono- or multicrystalline ingots. Crystals with weights up to 300 kg are already grown today and the development goes towards even larger crystals. The performance of crystalline solar cells is mainly limited by the loss of charge carriers due to minority carrier recombination. Depending on the crystallization process the materials develop different defect structures, which determine and limit their efficiency. In general, crystal defects such as dislocations, impurities and small clusters of atoms or precipitates are mainly responsible for the recombination processes.

More than 80% of the current solar cell production requires the cutting of large silicon crystals. While in the last years the cost of solar cell processing and module fabrication could be reduced considerably, the sawing costs remain high, about 30% of the total wafer production (see figure 3) [6].

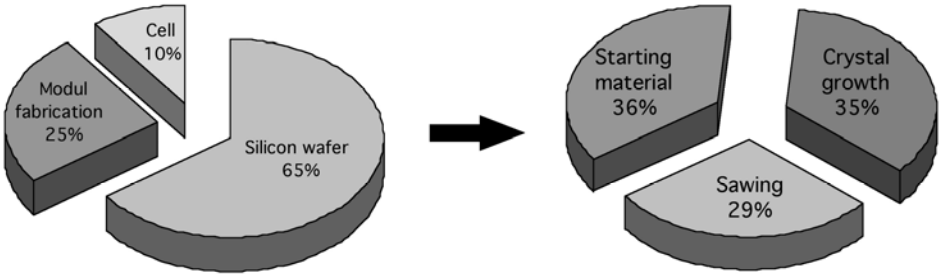

Fig. 3. Cost distribution for a solar module made from silicon solar cells

The incentive to optimize the sawing technique for further cost reduction in mass production is thus high. At present the large crystals are cut using the multi-wire slicing technology into wafers with a thickness between 200 and 300 μm, but a wafer thickness down to about 100 μm can be achieved by the technique.

The sawing process damages the wafer locally across the surface and at the edges by the formation of cracks in the micrometer range. These microcracks reduce the fracture strength of the wafers considerably. In mass production fragile wafers can break which reduces the production yield. The mechanical properties of wafers and solar cells have thus become an important research area recently. In particular, it has been recognized that basic knowledge about the microscopic details of the sawing process is required in order to slice crystals in a controlled way.

A further reduction of the costs is expected from technologies that avoid the slicing step altogether by growing the silicon directly in the final shape in form of sheets or ribbons. A number of continuous ribbon growth techniques have been developed, among which the EFG process is most important. EFG solar cells reach efficiencies up to 15.5% and have already been introduced into the market [7]. Ribbons show different material properties compared to multicrystalline silicon grown by ingot techniques. Consequently, the material properties and the key defects which determine the essential material features are different. Each material thus requires individual research and development efforts to improve the material and solar cell performance.

A major problem presently is the shortage of solar grade silicon, which slows down the current rapid growth (figure 4). It is, however, no principal problem since silicon as the second frequent element in the earth's crust is available in large quantities. Its use in solar cells requires, however, high purities and sophisticated purification procedures. Since high purity silicon is also used in the microelectronic industry purification plants are available. Technological development is, however, necessary to reduce the production costs for the solar market. One can expect that in about two years the first dedicated production plants for solar grade silicon will be available.

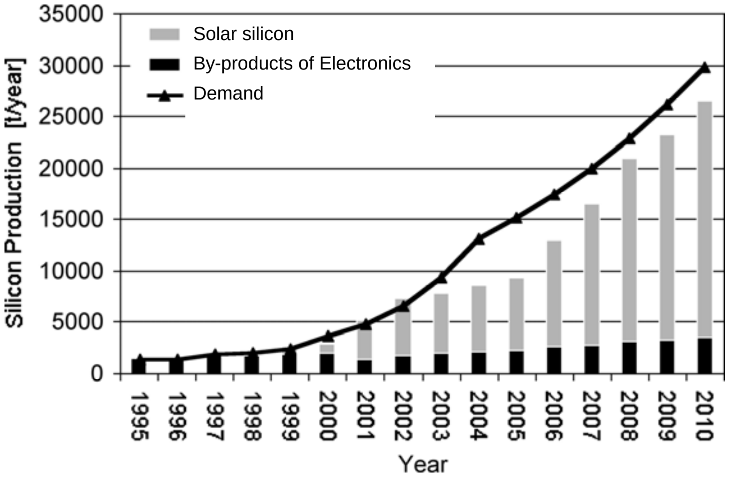

Fig. 4. Production and demand of solar grade silicon and expected future development. Comparison with the amount of by-products of the microelectronic industry

In the meantime waste material from the microelectronic industry with different specifications and recycled silicon wafers from damaged modules are also used. The use of such materials in large quantities requires automated classification and sorting machines, which are currently also under development.

3. ALTERNATIVE SOLAR CELL CONCEPTS

In general, it is assumed that further cost reduction can only be achieved if less material is used (see figure 1). This is possible if either other photovoltaic materials or much thinner light absorbing layers of silicon are used. Alternative materials that have reached an industrial production stage are cadmium telluride (CdTe), copper-indium-diselenide (CIS), gallium arsenide and amorphous silicon. Other materials such as photoconducting polymers, for instance, are still at the laboratory stage of development. It is common to these materials that only a thin layer of about 1–30 μm thickness is required for the light conversion.

The next generation of solar cells is expected to be based on what has become widely known as thin-film technology. By using very thin layers of the expensive semiconductor material, the overall costs of solar cells can be reduced. Thin-film cells are less efficient than the best crystalline silicon cells, but they are expected to become more cost effective in the future because they can benefit substantially from economies of scale in production.

The use of thin film materials leads to completely new fabrication techniques. The material has to be deposited on a substrate, for instance glass, which supports and carries the film. Although many deposition techniques are available from the semiconductor industry, it is still very difficult to fabricate large areas of many square meters in a short time, with homogeneous properties and a high conversion efficiency. The most advanced technology is available for amorphous silicon, because it is mostly used in the display technique. The efficiencies in large scale solar modules are still rather low at around 6–8%, which limits their widespread commercial use so far.

4. SOLAR CELL AND MODULE TECHNOLOGY

The most advanced solar cell concepts have been developed for silicon and gallium arsenide. High efficiency cells reach 24% and about 30%, respectively. The drawback is the high production or material costs, which prevent the commercialization so far. In general, one can say that more processing steps increase both cost and efficiency. So far the increase in efficiency does not balance the cost increase. The development of high efficiency cells may, however, yield innovative ideas, which can eventually be incorporated in standard cell processes. Another application can be the use in light concentrator system. Direct sunlight can be focused by mirrors or lenses on a small solar cell. Since less area is required, higher production cost of the cell can be tolerated. These developments are particularly suitable for countries with much direct sunlight.

A solar cell is an electronic device, the so-called pn-diode, which converts light into electrical current. It consists of differently conducting regions, which are contacted by thin metal layers to extract the current under illumination. The fabrication involves high temperature steps, which may affect the material properties. Solar materials thus require adjusted solar cell processes to yield the best efficiencies. Since even in the crystalline silicon technology differently produced materials are used, solar cell manufacturers need flexible cell lines in industrial production.

A few years ago the standard silicon solar cell had a size of 10×10 cm^2 and a thickness of about 300 μm. Today larger and thinner cells are fabricated and this trend will continue to dimensions of 20×20 cm^2 and 100 μm thickness or even less. Because of the brittleness of silicon its handling becomes more difficult then. The increasing throughput in industry will certainly lead to more automation and the need for more standardization in production in the future. The advantage will be a further cost reduction.

The solar cell is the basic unit in a PV system. In actual usage, the cells are interconnected in certain series/parallel combinations on a flat plate to form modules. These modules are hermetically sealed for protection against corrosion, moisture, pollution and weathering. The encapsulation must be durable, because PV modules are now expected to have a lifetime of at least 20 years. A wide range of module sizes is commercially available to suit the ever growing number of application.

5. SOLAR SYSTEMS AND INSTALLATIONS

For many years the largest photovoltaic application was for mid-size, stand-alone systems, producing from a few watt-hours to a few thousand watt-hours. They are mainly used in isolated sites, where all means of power generation are expensive, and where PV offers a clean, silent and very reliable power supply. Stand-alone PV systems are used in automated applications such as highway lighting, navigational buoys, lighthouses, telecommunication repeater stations, and weather stations. These systems have proven to be reliable, maintenance-free, and cost-effective power sources. Also, tens of thousands of stand-alone homes worldwide now rely on PV systems for most or all of their electrical needs. Solar electricity provides power for water pumps, refrigerators, communications, etc.

In recent years, much greater emphasis has been placed on the development of grid connected PV generators particularly in countries which subsidize the use of photovoltaic systems. Feed-in laws that have been established in Germany and Spain have proven to be very effective to encourage investors to build large PV systems, producing from a hundred kW to a few MW. They also have enormous potential to furnish electricity to towns and villages throughout the world that are not now connected to a utility grid.

The increasing use of solar home systems, which are usually placed on roofs or on facades, leads to an awareness that the solar system has to fit into the architectural design of buildings and the neighbourhood. This is particularly the case in towns which want to preserve their former or older character. Special attention has thus been paid to combining photovoltaic systems with monument buildings. There exist now many architecturally attractive solutions, which show that PV systems can be incorporated even in these difficult cases and may also offer new design elements.

REFERENCES

[1] MÖLLER H.J., *Zukünftige Entwicklung der kristallinen Solarsiliziumtechnologie*, Tagungsband zum Workshop “Materialien und Verfahren zur Herstellung von Solarzellen”, Europäische Forschungsgesellschaft Dünne Schichten e. V., Frankfurt, 2004.
[2] *The Future for Renewable Energy 2*, EUREC Agency, James &James, 2002.

[3] PVNET Workshop Proceedings "RTD Strategy for Photovoltaics" Ispra 30/31 (2002), European Commission, DG JRC, Special Publication: S.P.I.02.117, Ispra.

[4] LAUTENSCHLAGER H., LUTZ F., SCHETTER C., SCHUBERT U., SCHINDLER R., Proc. 14th Europ. Photovolt. Solar Energy Conf., H. A. Ossenbrink, P. Helm, H. Ehmann (eds.), Stephens & Accociates, Bedford UK, 1997, 1358.

[5] GEE J.M., KING R.R., MITCHELL K.W., Proc. IEEE 25th Photovolt. Specialist Conf., P. Basore (ed.), IEEE , New York, 1996, 409.

[6] ENDRÖS A., FRANKE D., HÄßLER Ch., KALEIS J., KOCH W., MÖLLER H.J., [in:] *Handbook of Photovoltaic Engineering*, A. Luque and S. Hegedus (eds.), Wiley-VCH, Weinheim, 2002, 634.

[7] GOETZBERGER A., RÄUBER A., [in:] Techn. Digest of 9th Int. Photovolt. Solar Energy Conf., W. Palz, GT Wrixon, P. Helm (eds.), Kluwer Acad. Publ., Dordrecht, Netherlands, 1989, 4.

FOTOWOLTAIKA – STAN OBECNY I PERSPEKTYWY

Fotowoltaika jako technologia oparta na odnawialnych źródłach energii rozwija się bardzo dynamicznie. Sprzyja temu korzystna ramowa polityka prowadzona w niektórych krajach. W artykule omówiono przyczyny rozwoju rynku fotowoltaicznego, zwracając uwagę na fakt, iż produkcja przemysłowa opiera się na technologii wykorzystującej krzem krystaliczny. Przedstawiono obecny stan rozwoju fotowoltaiki z uwzględnieniem aktualnie prowadzonych badań. Wskazano również przyszłe kierunki rozwoju tej technologii.