

4.2 Photovoltaic power generation

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4.2.1 Introduction, PV markets

The conversion of solar radiation into electricity occurs by the photovoltaic effect which was first observed by Becquerel [1839Bec]. It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically all photovoltaic devices incorporate a pn-junction in a semiconductor across which the photovoltage is developed, but other principles are also possible as will be outlined later. The first silicon solar cell was developed at Bell Laboratories in 1954 by Chapin et al. [54Cha]. It already had an efficiency of 6% which was rapidly increased to 10%. The main application for many years was in space vehicle power supplies. Solar cell technology benefited greatly from the high standard of silicon technology developed originally for transistors and later for integrated circuits.

Terrestrial application of photovoltaics (PV) developed very slowly. Nevertheless PV fascinated not only the researchers but also the general public. Its strong points are:

- Direct conversion of solar radiation into electricity;
- No mechanical moving parts, no noise;
- No high temperatures;
- No pollution;
- Very long lifetime of PV modules;
- The energy source, the sun, is free, ubiquitous and inexhaustible.

The main problem, as will be shown later, is the high cost. Nevertheless costs are dropping continuously and a remarkable market development has taken place. The photovoltaic world market in 2005 was about 1700 MW_p (estimated). This is a remarkable market but still far away from constituting a noticeable contribution to world energy consumption. Market growth in the last decade was between 15 and 25% per year, rising to more than 40% recently as is shown in Fig. 4.2.1. The main motivation for developing solar energy is the desire to reduce dependence on depletable fossil fuels with their adverse effect on the environment. This phenomenal growth is caused by several Government support programs.

4.2.2 Principles of photovoltaic cells

A cross section through a typical solar cell is shown in Fig. 4.2.2. The semiconductor material has to be able to absorb a large part of the solar spectrum. Dependent on the absorption properties of the material the light is absorbed in a region more or less close to the surface. When light quanta are absorbed, electron hole pairs are generated, and if their recombination is prevented they can reach the junction where they are separated by an electric field. Even for weakly absorbing semiconductors like silicon most carriers are generated near the surface. This leads to the solar cell structure of Fig. 4.2.2. The pn-junction is very close to the surface in order to provide a high collection probability for free carriers. The thin layer above the junction, the emitter, has a relatively high resistance which requires a well designed contact grid also shown in the figure. Light absorption occurs mainly in the base layer. The operating principles have been described in the literature [98Goe1], [95Gre].

Silicon is by far the most important material for solar cells although from solid state physics we know that silicon is not the ideal material for photovoltaic conversion. The solar spectrum can be approximated by a black body of 5900 K. This results in a very broad spectrum ranging from the ultraviolet to the near infrared. On the other hand, a semiconductor can only convert photons with energy slightly above the band gap with good efficiency. Photons with lower energy are not absorbed and those with higher energy are reduced to gap energy by thermalization of the charge carriers. Therefore the curve of efficiency ver-

the band gap goes through a maximum (Fig. 4.2.3). It can be seen that silicon is not at the maximum but relatively close to it. A much more serious point is that silicon is an indirect semiconductor, i.e. valence band maximum and conduction band minimum are not opposite to each other in k -space. Light absorption is much weaker in an indirect semiconductor than in a direct semiconductor. This has consequences from a materials point of view: For 90% light absorption it takes only $1\text{ }\mu\text{m}$ for GaAs (a direct semiconductor) versus $100\text{ }\mu\text{m}$ for Si. The photogenerated carriers have to reach the pn-junction which is near the front surface. The diffusion length of minority carriers should be $200\text{ }\mu\text{m}$ for silicon or at least twice its thickness. Thus the material has to be of very high purity and of high crystalline perfection. In view of these physical limitations it is quite surprising that silicon has played such a dominant role in the market. The main reason is that silicon technology had already been highly developed before the advent of photovoltaics and high quality material is being produced in large quantities for the microelectronics market.

A lot of effort has been going and is still going into the search for new materials. The material used for the first solar cells were Czochralski (Cz) grown silicon single crystals. This is still a very important material for solar cells as can be seen from Fig. 4.2.4 which shows the market shares of different materials in 2001. The various forms of crystalline silicon have a share of 93% together. Single crystal and cast poly material had about equal share for a long time. Recently cast material has surpassed single crystals. Newer types of crystalline silicon like Ribbon and Si film are not very important yet. A newcomer is a-Si on crystalline silicon (see Sect. 4.2.6.2). Of the true thin film materials which are summarized as “others” amorphous silicon is dominant. Its market is mainly in consumer products. The market shares are rather stable and change only in an evolutionary manner. The dominance of the element silicon in its crystalline and amorphous form is an overwhelming 98.9%. Of all the other materials only CdTe has a market share of more than 1%.

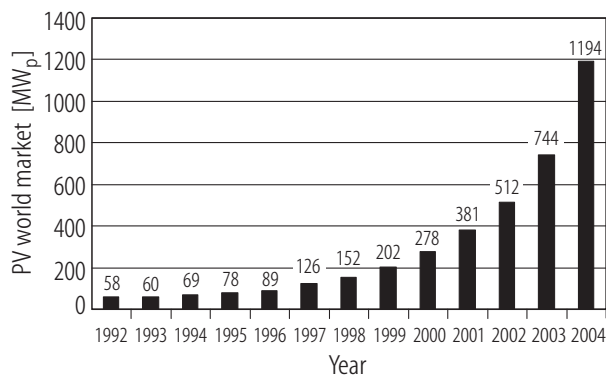


Fig. 4.2.1. Development of PV world markets (the unit W_p is defined as power under full sun, approx. 1 kW/m^2) [05PVN].

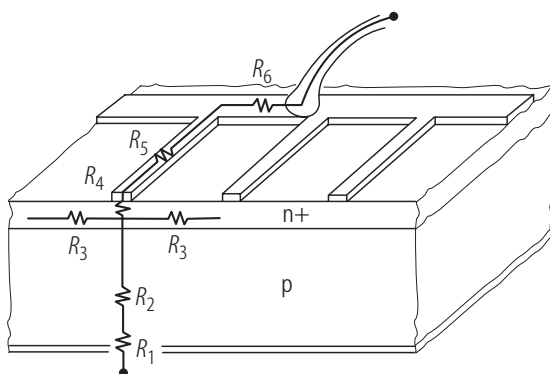


Fig. 4.2.2. Schematic diagram of a pn-junction solar cell. The resistors indicated in the drawing will be discussed in Sect. 4.2.4.2.

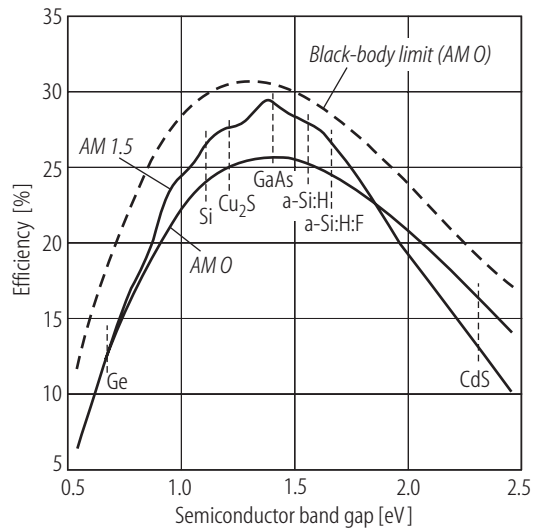


Fig. 4.2.3. Maximum conversion efficiency for different semiconductors vs. band gap for $T = 300\text{K}$. *AM 0* denotes solar radiation in space, *AM 1.5* denotes standardized terrestrial radiation. Also included is the thermodynamic black body limit.

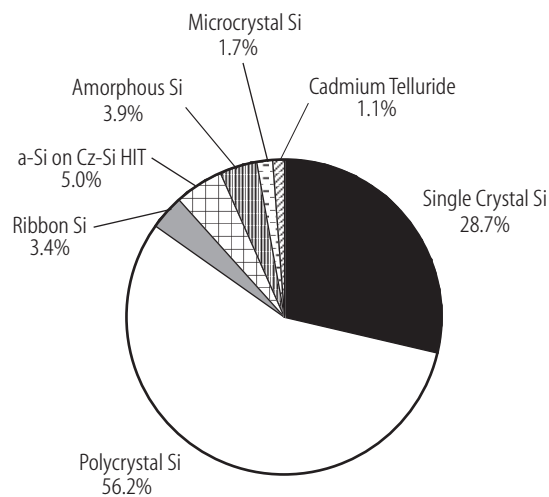


Fig. 4.2.4. PV World market shares for different technologies in 2004.

Today's photovoltaic market is characterized by the following trends:

- Slow but steady improvement of conversion efficiency;
- Slow reduction of the cost of modules and systems;
- Uncertain supply base of polycrystalline raw material.

For the future of solar energy materials three scenarios can be envisioned:

- Continued dominance of the present single crystal or cast polycrystal technology;
- New crystalline film Si materials of medium thickness either as ribbons or on foreign substrates;
- Breakthrough of true thin film materials like a-Si, CIS or CdTe.

In the long term new concepts or new classes of materials like organic solar cells also are a possibility. They will be addressed in [Sect. 4.2.6.2](#). At this point the above scenarios have about equal probability. Even more likely is that two or three of them will coexist for a considerable period and that each technology will find its own market. From an overall point of view it can be considered an advantage that so many avenues exist that potentially lead to a low cost solar cell, which greatly increases the likelihood of achieving this goal.

In this context the importance of conversion efficiency has to be discussed. It could be argued that efficiency is not important, provided the cells are very cheap, but reality has demonstrated that solar cells should have a minimum efficiency of at least 10% in order to be useful. This has to do with area related cost which is a large part of systems cost. The solar cells have to be hermetically encapsulated in modules which are held in support structures and require electric wiring. All these factors depend on area and have strong influence on the cost of photovoltaic electricity. Therefore improvement of efficiency is a high priority both in research laboratories and in manufacturing. Today, the best laboratory efficiency for single crystal silicon is 24.5% [[99Gre](#)], an efficiency that can only be realized with very elaborate technology. Experience has shown that progress in laboratory efficiency leads to improvement in production with a certain time delay. The best production cells now have an efficiency of 15 to 16%.

4.2.3 Potential and relevance of photovoltaic solar energy

Although the theoretical potential of PV worldwide is very high, it is difficult to quote a single figure for this potential. Of the total solar radiation reaching the earth's surface each year only a minute part (about 0.003%) is equivalent to global electricity demand today. The potential of PV is part of the potential of all kinds of utilization of solar radiation energy. In this respect there is no realistic limitation for this potential. Compared to wind energy which is another and presently more economical source of renewable electricity, PV has the advantage that it is not limited to certain geographic locations. Even today, PV is in use practically everywhere. On the other hand, the amount of radiation depends on geography, particularly on latitude. There is a difference of about a factor of 2.5 in radiative energy between the most arid desert regions and Central Europe. A serious problem in most locations is the intermittent nature of solar energy.

Examples of the daily and seasonal fluctuations of radiation are shown in [Fig. 4.2.5](#) and [Fig. 4.2.6](#). [Figure 4.2.5](#) demonstrates the case of Freiburg in southern Germany where we see a large but strongly fluctuating solar input in summer and very low availability in winter. [Figure 4.2.6](#) in contrast gives an example of a very sunny desert climate in Khartoum, Sudan. Solar input is much more uniform on a daily and yearly scale. In the first case seasonal storage is required for an all-solar system, while in Khartoum daily storage is sufficient.

Even in Central Europe which is not blessed with an abundance of sunshine, a large part of electricity demand (more than 50%) could be supplied by solar electricity in theory. In reality, many obstacles will have to be overcome before even a small percentage will be reached. In more northern countries a big problem is the seasonal mismatch of supply and demand. Significant contributions can only be expected from grid-connected systems. Until an economic way of seasonal energy storage becomes available, the practical limit may be about 20% of generating capacity dependent of the elasticity of the grid. This is still a large amount of energy and very far from today's contribution. It should also be kept in mind that a combination of renewable energy sources with different stochastics like wind and PV provide a more even generating capacity.

The potential for Germany has been evaluated in several studies [[93Kal](#)], [[00Nit](#)]. In very approximate terms the result is that by using all suitable roof areas about 20% of the capacity could be reached. When comparing capacities, it should be noted that the continuous average power of a PV system is only about one tenth of the peak power. Beyond roofs, other areas like roads and rails could also be used which could add the same amount. A still much bigger potential lies in unused agricultural areas. Further, it can be shown that by optimized mounting of PV generators land areas can be used for PV and crop cultivation simultaneously [[98Goe2](#)]. The reason is that PV arrays have to be spaced apart in order to avoid mutual shading. If this is done correctly and the array is mounted at some distance above ground, enough light

will penetrate during the growing season to permit growth of most common crops. Such high levels of PV generation, however, are not very likely in the foreseeable future as seasonal storage would be required.

In climatic zones with a higher and seasonally less variable solar radiation higher contributions of PV-electricity are possible. It is obvious that the same solar cell, if mounted in a desert area close to the equator would generate 2.0 to 2.5 times more electricity at correspondingly lower cost than in Europe. Arguments against this are the problem of intercontinental electricity transport and of security of supply. Nevertheless it is conceivable that in a distant future PV farms will be set up in desert areas and the energy will be transported to the consumers by long distance grids or in the form of hydrogen.

PV today is economical only if it does not have to compete with grid electricity. Nevertheless the technology is only at the beginning of its development and hopes are high for further large cost reductions. At present, however, it is not obvious whether the cost of PV can reach present levels of the cost of grid electricity, but this is not necessary because distributed PV only has to compete with electricity cost at the consumer's site. Besides development of technology, market expansion is a proven way of bringing cost down. In several countries which take their obligation to reduce greenhouse gases seriously, comprehensive support programs for distributed PV installations have been legislated. One example is the German renewable energy law which stipulates that utilities have to pay about 0.5 €/kWh for PV electricity fed into the grid for 20 years. This reimbursement is reduced by 5% each year for new installations in order to stimulate cost reduction. The expected cost trends for the future are described in [Sect. 4.2.8](#).

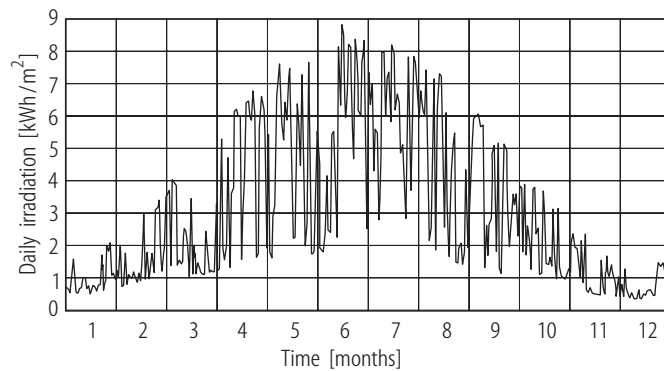


Fig. 4.2.5. Daily global radiation for one year in Freiburg, southern Germany.

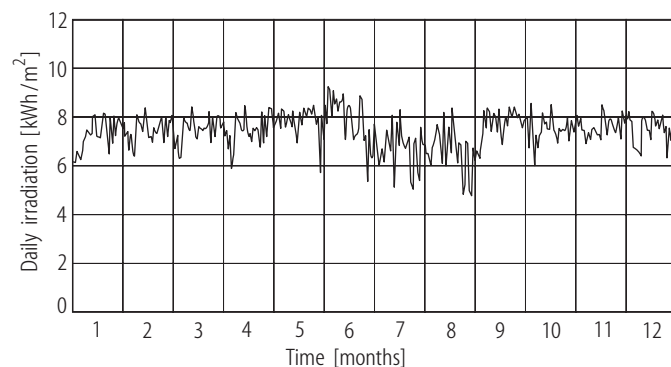


Fig. 4.2.6. Daily global radiation for one year in Khartoum, Sudan.

4.2.4 Physics of solar cells

4.2.4.1 I/V characteristic

The physics of solar cells is most straightforward for crystalline silicon cells. A typical such solar cell according to Fig. 4.2.2 consists of a pn-junction which has a diode characteristic. This characteristic can be derived from standard solid state physics [49Sho] and is

$$I = I_0 \cdot (e^{V_A/V_T} - 1), \quad (4.2.1)$$

where I is the current through the diode at an applied voltage V_A . V_T is a constant, so called thermal voltage. I_0 is the diode saturation current which depends on the type, doping density and quality of the semiconductor material and the quality of the pn-junction. If this junction is illuminated, an additional current, the light generated current I_L is added:

$$I = I_0 \cdot (e^{V_A/V_T} - 1) - I_L. \quad (4.2.2)$$

The negative sign in (4.2.2) results from polarity conventions. Now the current I is no longer zero at zero voltage but shifted to I_L , which means that power can be delivered to an electric load. The I/V characteristic with and without illumination is shown in Fig. 4.2.7. This figure also defines three important quantities: the open circuit voltage V_{oc} , the short circuit current I_{sc} which is identical to I_L and the maximum power point P_m at which the product of V and I is at a maximum. This is the optimal operating point of the solar cell. Voltage and current at P_m are V_m and I_m . It is obvious that the ideal solar cell has a characteristic which approaches a rectangle. The fill factor

$$FF := \frac{I_m V_m}{I_{sc} V_{oc}} \quad (4.2.3)$$

should be close to one. For very good crystalline silicon solar cells the fill factors are above 80%. From (4.2.2) we can also recognize the importance of the saturation current I_0 . The open circuit voltage V_{oc} is obtained when no current is drawn from the cell. Then

$$V_{oc} = V_T \cdot \ln(I_L / I_0 + 1). \quad (4.2.4)$$

Even at low current densities the term I_L / I_0 is large compared to 1, so we find that

$$V_{oc} \approx V_T \ln(I_{sc} / I_0), \quad (4.2.5)$$

i.e. the open circuit voltage is proportional to the logarithm of the ratio of I_{sc} to I_0 . This means that although I_0 is a very small quantity compared to I_{sc} lowering the saturation current is very crucial for increasing efficiency. From solar cell physics it can be derived that there are three sources for I_0 :

- Minority carrier leakage current from the emitter region;
- Minority carrier leakage current from the base region;
- Space charge recombination current.

With these components, an equivalent circuit of a solar cell can be constructed. Fig. 4.2.8 contains all relevant components: a current source $h\nu$ due to the light induced current I_L , two diode saturation currents I_{D1} and I_{D2} (The saturation current has to be represented by two diodes because the space charge recombination current has a different dependence on voltage than the other two currents) and components of resistive nature, such as a parallel (shunt) resistance R_P and a series resistance R_S . Evidently R_P should be as high and R_S as low as possible.

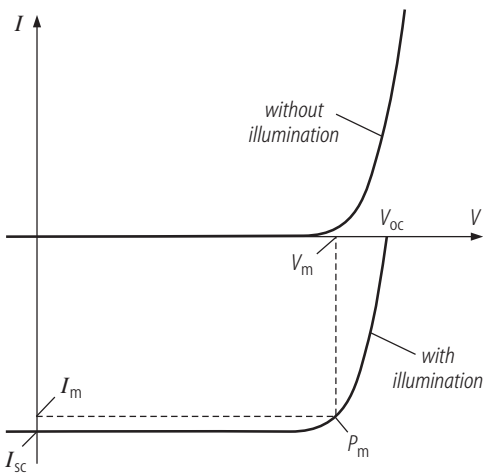


Fig. 4.2.7. I/V characteristic of a solar cell without (top) and with illumination. V_m , I_m and P_m are values at maximum power.

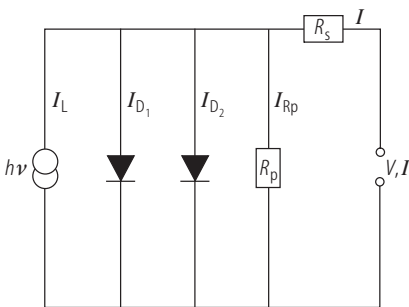


Fig. 4.2.8. Equivalent circuit of a solar cell with two diode model.

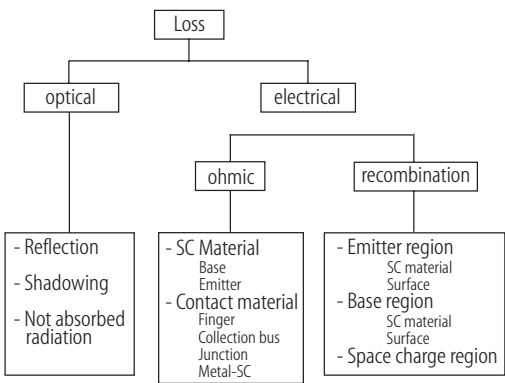


Fig. 4.2.9. Survey of loss mechanisms in solar cells.

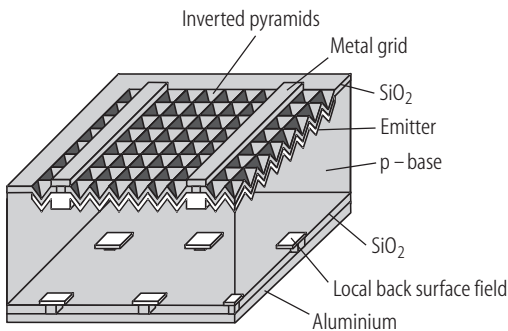


Fig. 4.2.10. Example of a very high efficiency solar cell, the LBSF cell.

4.2.4.2 Loss mechanisms

A real solar cell has a number of loss mechanisms all of which can be minimized. The record efficiencies that have been achieved in the past have mainly been accomplished by careful attention to loss mechanisms. A survey of loss mechanisms can be seen in Fig. 4.2.9. Optical losses arise from reflection losses at the semiconductor surface. These can be reduced by antireflection coatings and surface texturing. The electrical losses can be subdivided into ohmic and recombination losses. The ohmic losses arise in the semiconductor material, particularly in the thin emitter layer. In order to reduce these losses the emitter is covered by a grid of metal fingers which also contribute to losses. The junction between metal contacts and the semiconductor both at the front and rear can represent a contact resistance, particularly if the contact leads to a region of lower doping. Recombination losses occur because photogenerated minority carriers can recombine before reaching the pn-junction and are thus lost for a current flow. All three regions of a solar cell, the emitter layer, the base and the space charge region between emitter and base, contribute to recombination and have to be designed accordingly.

Optimal design principles are incorporated in modern high efficiency cells like the LBSF (local back surface field) [89Kno] cell shown in Fig. 4.2.10. The following details are important for the very good efficiency of the cell which is of the order of 23-24%:

- 200 μm thick base layer of float zone silicon;
- Textured front side with inverted pyramids and antireflection coating to reduce reflection;
- Narrow metal contacts from fingers to local highly doped emitter regions to minimize recombination losses at the emitter surface. For good surface passivation low doping at the surface is required. On the other hand, good ohmic contact can only be made to highly doped regions which also cause a high surface recombination velocity. This leads to very restricted, locally doped contact regions;
- The base contacts at the lower side are also restricted for the same reason;
- All unmetallized surfaces are covered with silicon dioxide which assures good surface passivation;
- The back surface contact has reflective properties and reflects any light which penetrates to the back of the cell.

4.2.5 Solar cell technology

4.2.5.1 Silicon

4.2.5.1.1 Silicon material

Apart from oxygen, silicon is the most abundant element in the surface of the earth. It almost always occurs in oxidized form as silicon dioxide as in quartz or sand. In the refining process SiO_2 is heated to about 1800°C together with carbon. The metallurgic grade silicon which results from this process is used in large quantities in the iron and aluminum industries. Since it is only about 98% pure, it is not suitable as a semiconductor material and has to be further refined. This is done by transferring it into trichlorosilane (SiHCl_3) which is a volatile liquid. This liquid is distilled and subsequently reduced when reacting with the hot silicon surface. Those two processes require considerable input of energy and are the major contribution to the energy content of silicon solar cells.

The fine grained polysilicon is further processed either into monocrystalline form or into cast polycrystalline material with larger crystallites. Only then the high perfection of the material necessary for solar cells can be obtained. The principle of Czochralski growth can be seen in Fig 4.2.11. Polycrystalline material in the form of fragments obtained from the previous purification process is placed in a quartz crucible, which itself is located in a graphite crucible, and melted under inert gases by induction heating.

A seed crystal is immersed and slowly withdrawn under rotation. Today crystals with diameters of 30 cm and more are grown routinely for the semiconductor market. For solar cells, crystals with a smaller diameter are grown because the usual solar cell dimensions are 10 by 10 cm. The round crystals are usually shaped into squares with rounded corners in order to obtain a better usage of the module area. For solar cells, as well as for all other devices, the crystal rods are separated into wafers of 0.2 to 0.5 mm thickness by sawing. This is a costly process because silicon is a very hard material which can only be cut with diamond tools. The standard process was the ID (inner diameter) saw where diamond particles are imbedded around a hole in the saw blade. Especially for solar cell wafers a new process, the multi wire saw, was developed. A wire of several kilometers in length is moved across the crystal in an abrasive suspension whilst being wound from one coil to another. In this manner thinner wafers can be produced and sawing losses are reduced by about 30%.

Another technology dating back to the seventies is block casting [81Die] which avoids the costly pulling process. Silicon is melted and poured into a square graphite crucible (Fig. 4.2.12). Controlled cooling produces a polycrystalline silicon block with a large crystal grain structure. The grain size is some millimeters to centimeters and the silicon blocks are sawn into wafers by wire sawing as previously mentioned. Cast silicon is cheaper than single crystal material but yields solar cells with a somewhat lower efficiency. An advantage is that the blocks can be manufactured easily into square solar cells in contrast to pulled crystals which are round. It is much easier to assemble multicrystalline wafers into modules with nearly complete utilization of the module area. Thus the lower efficiency of cast material tends to disappear at the module level.

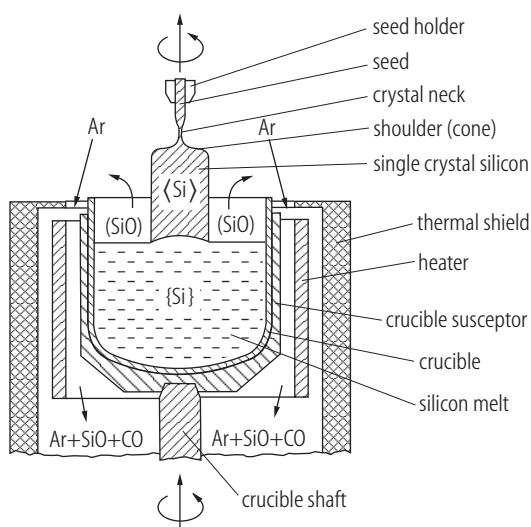


Fig. 4.2.11. Cross section of a Czochralski single crystal puller.

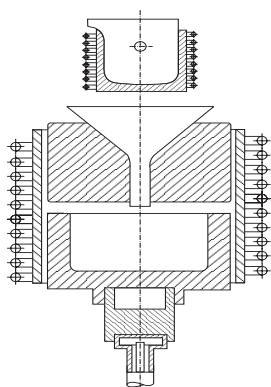


Fig. 4.2.12. Apparatus for polycrystal block casting. Molten silicon is poured into a crucible, and a large block containing large crystallites is produced by slow cooling.

4.2.5.1.2 Cell and module technology

Cell technology converts the silicon wafers into solar cells. In general p-type silicon is used in the photovoltaic industry, but in principle n-type can also be used. For this processing the following steps are important.

4.2.5.1.2.1 Production of pn- and pp-junctions

The active junction (Emitter) is very close to the front surface. At the rear of the device a high p-doping is introduced to reduce the contact resistance and surface recombination. These junctions are realized by thermal diffusion. In the diffusion process, an electrically heated tube furnace with a quartz tube is used. Diffusion temperatures vary between 800 and 1200°C. Diffusion sources are phosphorus for the emitter junction and boron for the so-called back surface field. The doping elements are introduced as liquid or gaseous compounds, e.g. phosphine (PH₃) or phosphorus oxychloride (POCl₃) for n-doping and boron bromide (BBr₃) for p-doping. In industry the back contact is often only accomplished by sintering of the aluminum contact. Since Al is a group III element, it will also generate p-type doping. This procedure, however, cannot be used for very high efficiency solar cells.

4.2.5.1.2.2 Oxidation process

Oxidation of the silicon surfaces is an important step in solar cell manufacture. It is carried out in quartz tube furnaces like the diffusion process. The oxidation atmosphere can either be dry or wet oxygen, the latter meaning oxygen plus water vapor. SiO₂ surface layers have several functions. They passivate the surface by reducing surface states which act as recombination centers. They act as diffusion barriers in selected locations and they provide mechanical and chemical protection of the sensitive surface against further processing and module manufacturing. On air they also provide some antireflection property, but in encapsulated cells other materials with higher index of refraction have to be used. For well passivated surfaces oxidation has to be done under very clean and carefully controlled conditions.

4.2.5.1.2.3 Electrical contacts

In the laboratory electrical contacts are mainly made by vacuum evaporation which is a very controllable technique. In industry screen printing of thick films which is more amenable to automation, is used. For the front contacts a paste consisting of 70% Ag, an organic binder and sintered glass is applied. After deposition the layer is sintered at approximately 600°C and a good electrical contact results. Screen printing has several disadvantages. Its lateral resolution is limited and it only makes good contact to highly doped surfaces. For the back contact a paste containing aluminum is also screen printed over the entire surface and then sintered. These and other simplifications explain why industrial solar cells have significantly lower efficiency than the best laboratory cells.

4.2.5.1.2.4 Antireflection technologies

Two measures which can be combined are instrumental in reducing surface reflection. The first is surface texturing which bends incoming rays into a more horizontal direction and thus increases its path length inside the silicon (see Fig. 4.2.10). Surface texturing only works on monocrystalline silicon of <100> orientation. For texturing the silicon wafers are immersed in a weak solution of KOH or NaOH at 70°C. In this way the <111> orientations are exposed as random pyramids. Chemical texturing cannot be applied to cast multicrystalline silicon because it consists of crystal grains of different orientations.

The other possibility is to deposit a transparent antireflection layer. For this purpose a material with a refractive index $n = (n_s n_s)^{1/2}$ has to be used, where n_s is the refractive index of the surrounding medium. Since in industrial production the cells are embedded into modules with a glass cover, its index has to be used. A practically applied material is titanium dioxide (TiO_2). It can also be incorporated into a screen printing paste and treated as described before.

4.2.5.1.2.5 Module technology

First of all, photovoltaic modules have the purpose to seal the solar cells against environmental influences, particularly against moisture. Another purpose is to reach higher voltages and currents than a single silicon cell can deliver. A cell usually has the dimensions of 10 by 10 cm, sometimes 15 by 15 cm. As the open circuit voltage of such solar cells is only about 0.5 to 0.6 V, a number of these cells have to be connected in series in order to obtain a usable voltage. After electrical series connection the cell assemblies are laminated into the modules by means of transparent plastic sheets. Either two panes of glass are used or only the front cover consists of glass. Selecting the right components for modules is very crucial for their lifetime. Today most manufacturers guarantee a module lifetime of 20 to 25 years. Thus one can assume that the actual lifetime is 30 years or more which makes PV modules one of the most durable industrial products manufactured today.

4.2.5.2 Thin film materials

As was pointed out in [Sect. 4.2.2](#), thin film materials are a way to reduce cost. In addition to the low materials consumption of thin film materials another advantage is that they can easily be connected in series in an integral manner on large area substrates. Thus entire modules are manufactured in the deposition process, which is advantageous economically. But it is also very demanding for the process technology because large areas have to be processed without defects. Although the market share of thin films is low today, prospects for growth are good. One problem is that a number of different materials are being pursued and it is not at all clear which one is the best choice. The most important materials and technologies will now be briefly described.

4.2.5.2.1 Amorphous silicon

Amorphous silicon is an alloy of silicon with hydrogen. The distribution of bond length and bond angles disturbs the long range of the crystalline silicon lattice order and consequently changes the optical and electronic properties. The optical gap increases from 1.12 to about 1.7 eV. The high expectations in this material have been curbed by the relatively low efficiency obtained so far and by the initial light inducing degradation for this kind of solar cells (so called Staebler-Wronski effect). Today, a-Si has its fixed place in consumer applications, mainly for indoor use. After understanding and partly solving the problems of light induced degradation, amorphous silicon begins to enter the power market. Stabilized cell efficiencies in the laboratory reach 13%. Module efficiencies are in the 6-8% range. The visual appearance of thin film modules makes them attractive for facade applications.

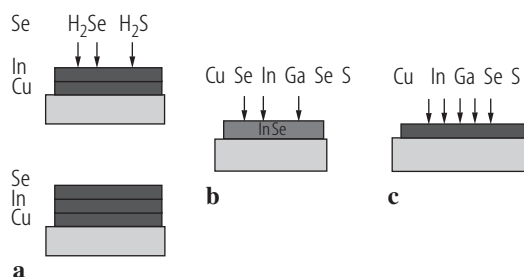


Fig. 4.2.13. Different methods for CIGS film deposition. **(a)** Reactions of metal layers with the gas phase (sequential process). **(b)** Reactions of binary compounds from the gas phase (sequential process). **(c)** Co-evaporation.

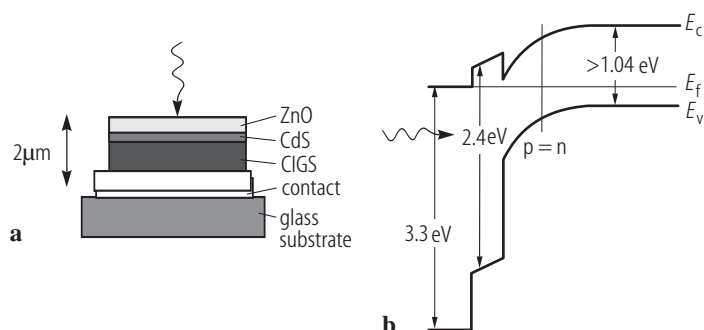


Fig. 4.2.14. (a) Schematic structure of a CIGS based solar cell. (b) Heterojunction band structure of the CIGS based solar cell.

Basis for all deposition processes is silane as precursor gas in a chemical vapor deposition (CVD process). Typical deposition temperatures are below 500°C, otherwise no hydrogen is incorporated in the film. At the low substrate temperature pre-dissociation of the SiH_4 molecule is essential. The most commonly used method is plasma enhanced chemical vapor deposition (PECVD).

4.2.5.2.2 Copper indium diselenide and related compounds

A very promising but challenging technology is based on the ternary compound semiconductors CuInSe_2 , CuGaSe_2 , CuInS_2 and their multinary alloy $\text{Cu}(\text{In,Ga})(\text{S,Se})_2$ (referred to as CIGS). Very high efficiencies approaching 19% have been reported for laboratory scale devices [99Con]. For a large scale fabrication of these rather complex compounds two different approaches exist for the deposition of the absorber layer (see Fig. 4.2.13):

- With the selenisation technique, precursor layers are deposited and subsequently annealed in H_2Se vapor. The process is divided in several simple steps. These processes can use “off the shelf” equipment as far as possible and therefore only require the process development. However, this strategy has had limited success until now. Furthermore it limits the composition of the absorber layer to low band gaps in a rich material.
- The process yielding best performance on small area laboratory scale devices is co-evaporation. This procedure gives full flexibility in device optimization. However, it is a real challenge for engineers to design appropriate evaporation sources and maintain efficiency while upscaling.

The selenisation technique is now the basis of the first pilot production and market introduction of CIS modules by Siemens Solar. Aperture area efficiencies of over 12% make these modules attractive for power applications [99Con]. The Center for Solar Energy and Hydrogen Research (ZSW) in Stuttgart, Germany demonstrated co-evaporation processes on 60 cm wide glass substrates [96Dim], [00Pow].

CIGS module fabrication has the same advantageous features of thin film fabrication processes as the other thin film solar cell materials. The typical devices structure shown in Fig. 4.2.14 is based on a soda lime glass substrate.

4.2.5.2.3 Cadmium telluride

Thin-film solar cells based on CdTe are the cells with the longest tradition, but they are really not “of age”. After a long development they arrived at cell efficiencies of 16% and large-area module efficiencies of over 10%. CdTe is a nearly ideal material for thin film photovoltaics because it combines several advantageous properties. Besides an optical band gap close to the optimum for solar energy conversion it is very easy to handle in thin film deposition processes. The congruent evaporation of the compound, i.e. the evaporation of stoichiometric CdTe results in a stoichiometric composition of the vapor. Above a sub-

strate temperature of a few hundred °C the composition is self-stabilizing. High quality material can be deposited at very high rates ($>1 \mu\text{m}/\text{min}$) at substrate temperatures of 450-600°C. Because of the tolerance of the material to defects and grain boundaries, simple processes such as electrodeposition and screen printing are possible and are a good prerequisite for large scale production. The highest quality material and hence the highest efficiencies are obtained with close spaced sublimation (CSS), a modified evaporation process where substrates and sources are very close together with a relatively small difference in temperature so that the film growth occurs close to equilibrium condition (Fig. 4.2.15).

At present there are several attempts to set up production lines for CdTe based modules with capacities in the multi MW range. The area of monolithic thin film modules approaches one square meter. The monolithic thin film module with the world's highest power output has been produced based on CdTe. At BP Solar a monolithic module with a power output exceeding 70 W has been fabricated [00Cun]. In this case the CdTe layer were electrodeposited.

A non technical problem associated with CdTe is its acceptance in the market place because Cd, and to a lesser extent Te as well, are toxic materials although the compound is quite stable and harmless.

4.2.5.3 Tandem cells, concentrating systems

The efficiency of solar cells can be significantly increased by stacking several cells with different band gaps such that the gap energy decreases from the top. Then each solar cell converts parts of the solar spectrum at maximum efficiency. Two cells in series connection have a maximum theoretical efficiency of 41.9%, and 50% can be exceeded with a larger number of cells. Such tandem arrangements can be realized either with a sequence of thin films, as has already been demonstrated with amorphous silicon, or they can be incorporated into concentrating systems.

A problem connected with tandem cells is that with series connected cells an equal number of photons has to be absorbed in each cell. If at all this can only be accomplished at one spectral distribution like AM1.5. Since this distribution changes in terrestrial applications, spectral mismatch will occur. An obvious but complex solution is to provide separate contacts to each cell.

Concentration of sun light is another approach to reduce the cost of conversion. It is only feasible with direct sunlight which is concentrated by optical elements tracking the sun. If the concentration factor is very high, the cost of the solar cell is only a small part of the system cost. The solar cells can therefore be expensive as long as its efficiency is very high. For this purpose even high cost III-V compounds can possibly be included into tandem systems. These tandem cells are now in the process of being introduced into the space (satellite) market [00Fra], [00Bet].

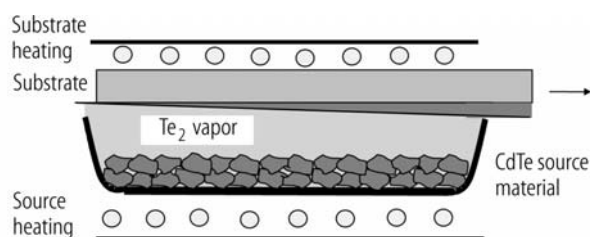


Fig. 4.2.15. Schematic view of a reactor for the continuous deposition of CdTe by close spaced sublimation.

4.2.6 Future developments and new materials

4.2.6.1 Crystalline silicon

4.2.6.1.1 Materials technologies

Crystalline silicon still has considerable cost reduction potential. In the past it has always maintained its dominance in spite of the development of new materials and approaches. The rapid expansion of the market alone will lead to cost reductions by economy of scale. Nevertheless it can be estimated that its cost will not drop much below half of today's cost. Further development of this technology towards even lower cost proceeds in two major directions:

- *Ribbon technology*

The goal of crystalline ribbon technologies is to reduce cost by eliminating the costly silicon sawing process and at the same time minimizing the amount of silicon due to a reduced layer thickness. Several ribbon technologies are under development or in early production. In the most important one, the EFG (Edge Defined Film Fed Growth Process), a self supporting silicon ribbon is pulled from the melt through a die which determines the shape of the ribbon. Today octagon tubes of 5.3 m in length at a nominal average wall thickness of 280 μm are pulled out of a graphite crucible containing liquid silicon and are subsequently separated by a Nd:YAG laser. The resulting sheets of 10 \times 10 cm^2 have a somewhat lower material quality than single crystals and they have a wavy surface. Nevertheless, conversion efficiencies of up to 14.8% were achieved in the production line.

- *Crystalline silicon thin films*

A thin film cell based on crystalline silicon might appear to be a contradiction in the light of what was said in [Sect. 4.2.2](#) about the low light absorption in crystalline silicon. Nonetheless theoretical studies have shown that crystalline silicon films in the range between 5 and 30 μm can have high efficiency provided two conditions are fulfilled. The first is enhanced light trapping by surface texturing and reflection of the light rays. The second is good surface passivation because of the high surface to volume ratio of such films. These films are not self supporting and a suitable substrate has to be found. The substrate consists either of low quality silicon or of foreign substrates such as glass, ceramics or graphite. The choice of the substrate material determines the maximum allowed temperature for solar cell processing. The large number of different approaches can roughly be classified into the three categories:

- 1) Si-layers directly deposited on glass;
- 2) Si-layers on high-temperature resistant substrates;
- 3) Semi-processed monocrystalline Si-layers from Si-wafers transferred onto glass.

The best efficiencies achieved today with thin films are around 10%, but production is not yet foreseeable. A product that is already on the market is the film solar cell by Astropower which, with a thickness of about 100 μm , is not a truly thin film device. A review of the extensive work going on in the thin film crystalline silicon field can be found at [\[00Goe\]](#).

4.2.6.1.2 The silicon supply problem

A big question mark for the future is the source of highly purified silicon for solar cells. 50% of the cost of a module is due to the cost of processed silicon wafers. In the past, the PV industry used reject material from the semiconductor industry that was available at low cost, which created a dependence that is only viable if both sectors grow at the same rate. An additional problem is that the semiconductor market is characterized by violent cycles of boom and bust superimposed on a relatively steep growth curve. In

boom times the materials supply becomes tight and prices increase. This happened in 1998 when even reject material was in short supply and some solar cell manufacturers had to buy regular semiconductor grade material at relatively high cost.

One of the keys for cost reduction is to reduce the silicon content of the product. Present lines of approach are the reduction of kerf loss by wire sawing and use of thinner wafers. The most advanced production lines use wafers of less than 0.2 mm thickness. Thinner wafers are also desirable because efficiency is increased if the right technology is used [97Goe].

If the present standard technology is to continue its dominance, a dedicated solar grade silicon will have to be developed. Even if only a 15% annual growth rate of the market is assumed, there will be a shortage of $5 \cdot 10^9$ t by 2010, which is 2/3 of the demand [00Blo]. Efforts to produce such material have been undertaken in the past but were not successful for two reasons:

- Purity requirements for solar silicon are very high because photogenerated carriers have to be collected over large distances in such solar cells. This demands high carrier lifetimes and therefore an extremely low concentration of relevant impurities. This situation is aggravated by the continued development towards higher efficiencies.
- A dedicated solar grade manufacture is only economical with large scale production. The market has now reached this size and several large chemical companies are setting up a dedicated solar silicon production.

4.2.6.2 Other materials and concepts

The thin film materials described in Sect. 4.2.5.2, CuInSe_2 and CdTe , should also be mentioned here because they are in the very early stages of market introduction and their cost reduction potential appears to be much greater than that of the present technology. It remains to be seen if this promise can be fulfilled. The main problems to overcome are upscaling to a large production volume and long term stability of cells and modules. In the case of CuInSe_2 there is also a question of the availability of the rare element indium for very large deployment.

A very exciting new development is the combination of crystalline and amorphous technologies in heterostructures. Absorption of sunlight still occurs mainly in a wafer of mono- or polycrystalline silicon. The silicon wafer is contacted on both sides with amorphous silicon films. The best results with this approach were obtained by the Japanese company Sanyo. The latest achievement is a conversion efficiency of 20.7% for a cell area of 101 cm^2 . According to the information provided by Sanyo the solar cells have excellent stability. Sanyo has announced that pilot production of this type of cell is already under way.

Dye sensitized cells are another new concept that is considered very interesting. Nano-crystalline dye sensitized solar cells are based on the mechanism of a fast regenerative photoelectrochemical process. The main difference of this type of solar cells compared to conventional cells is that the functional element which is responsible for light absorption (the dye) is separated from the charge carrier transport itself. In the case of the n-type semiconductor TiO_2 (band gap 3.2 eV), this results in a working cycle starting with the dye excitation by an absorbed photon at the TiO_2 /electrolyte interface and an electron injection into the TiO_2 . The injected electrons may migrate to the front electrode (a transparent TCO glass) and can be extracted as an external current. The dye is subsequently reduced by a redox electrolyte that is based on an organic solvent and the redox couple iodide/triiodide. The redox electrolyte also accomplishes the charge transport between the counter electrode (also a TCO glass) and the dye molecules. For a low-resistant electron transfer, the counter electrode is covered with some Pt which acts as a catalyst for the redox reaction. Impure starting materials and a simple cell processing without any clean room steps are permitted, yet resulting in promising conversion efficiencies of 7-11% and the hope of a low-cost device for photoelectrochemical solar energy conversion.

Beside dye-sensitized solar cells, which may be considered as organic/inorganic hybrid cells, other types of organic solar cells currently become of broader interest. These cells can be roughly divided into molecular and polymer organic solar cells or into flat-layer systems and bulk heterojunctions. Organic materials such as conjugated polymers, dyes or molecular organic glasses can show p- or n-type semiconducting properties. Extremely high optical absorption coefficients are possible with these materials, offer-

ing the possibility for the production of very thin solar cells (far below 1 μm) and therefore only very small amounts of needed materials. The variability of organic compounds is nearly infinite. Beside this, the large interest in these materials results from technological aspects as the expected ease of large-scale manufacturing at low-temperature processes and very low costs. The upscaling of organic solar cells into large-area devices, always a big challenge with anorganic solar cells, has already been demonstrated to be straightforward. The energetic pay-back time of organic solar cells is expected to be very short. Considering the fact that light emitting films of plastic materials have been realized it should be possible to achieve efficient photovoltaic conversion also in such materials because this is just the reverse process. Organic solar cells offer the hope of being very inexpensive. Quite a variety of materials, compositions and concepts are being investigated, which reflects the possibilities in terms of device concepts, materials use and materials design. In spite of many still existing fundamental questions, these perspectives and the fact that exploration has only just begun cause a largely growing interest in the development of such cells.

4.2.7 Applications

4.2.7.1 Survey of applications

PV has the great advantage of being modular in the sense that systems can range from microwatts to megawatts. The earliest and from the beginning fully economical use was and still is in consumer products like watches, calculators etc. New developments are power supplies for portable computers and cellular telephones [95Rot]. In general, it can be stated that PV is economical wherever a low energy demand coincides with high cost of grid extension. Stand alone systems are more complex and more expensive than grid-connected systems because they need energy storage or an auxiliary energy source and a more elaborate power management. The small scale economic applications are of great importance for the development of the PV market because they provide a steady base load which is not dependent on erratic Government support programs, although they are not very important from an energy point of view. The world market for the different applications, their past development and forecast for the next decade is listed in Table 4.2.1. As can be seen by a comparison with Fig. 4.2.1., the prediction for the future development from 2000 was too conservative.

A large future market is seen in another type of stand alone systems: solar home systems and village power in the third world. Two billion people have no access to the grid. Although demand for such systems is high, development of the market depends on subsidies because the potential customers usually cannot afford the investment. The fastest developing application is decentralized grid-connected systems. This market exists only because it is highly subsidized. The subsidies are intended to stimulate markets and bring down prices by economy of scale. A survey of all PV applications is shown in the following sections (see also Fig. 4.2.16).

Table 4.2.1. PV world market history and forecast by application (source: PV News 11/2000).

Market Sector	1990	1993	1996	1997	1998	1999	2000	2005	2010
Consumer products	16	18	22	26	30	35	40	90	140
US off-grid residences	3	5	8	9	10	13	16	40	70
World off-grid rural	6	8	15	19	24	31	35	100	200
Communication/Signal	14	16	23	28	31	35	42	80	190
PV/Diesel communications	7	10	12	16	20	25	30	60	150
Decentralized grid-connected	1	2	7	27	35	60	85	340	1000
Central power stations > 100 kW	1	2	2	2	2	2	2	40	250
Total	48	61	89	127	153	201	250	750	2000

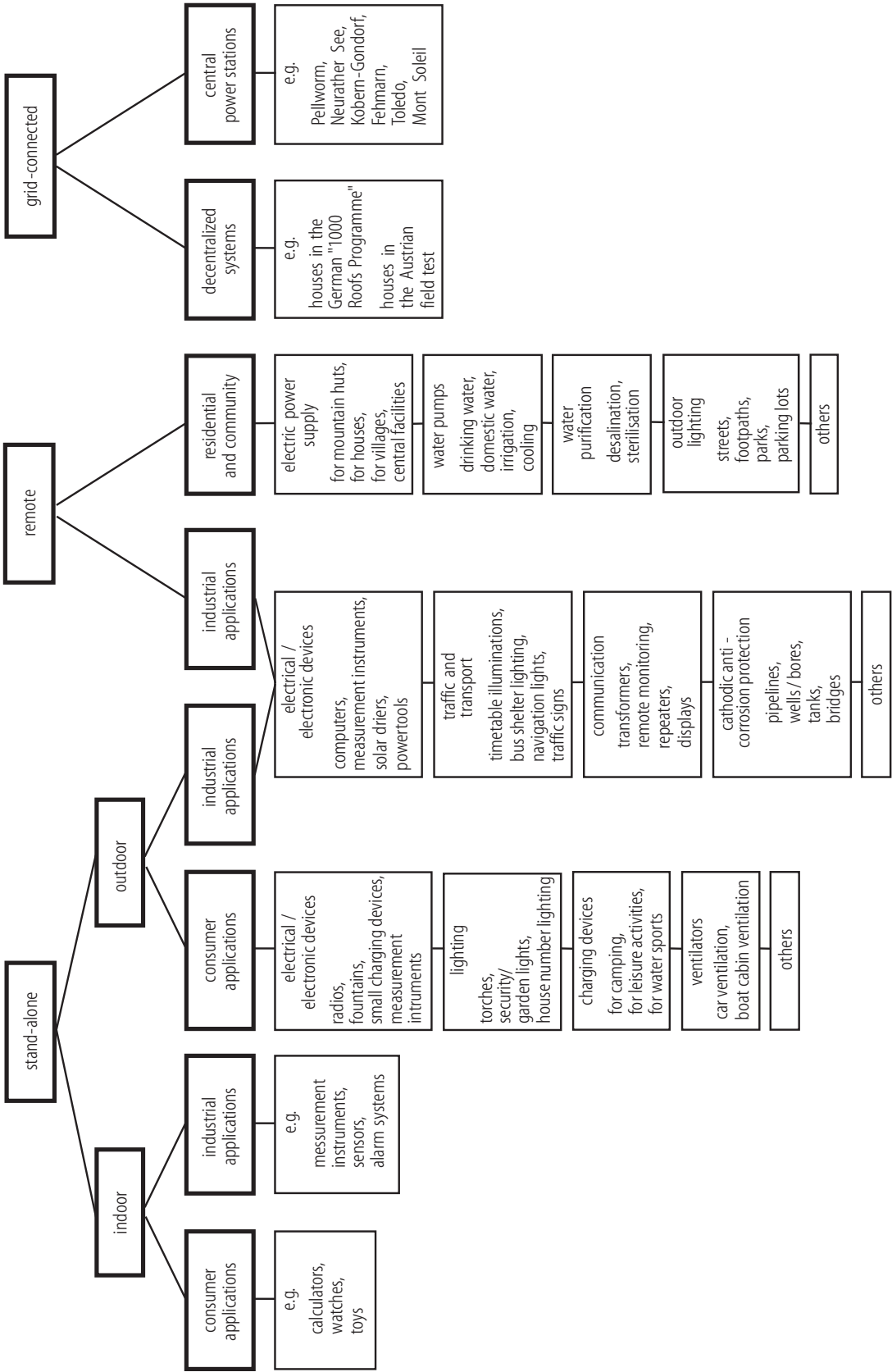


Fig. 4.2.16. Survey of PV systems and applications.

4.2.7.2 Stand alone systems

A photovoltaic power supply for stand alone systems in its simplest form consists of the solar generator, a charge controller, an energy storage and a DC/DC voltage converter (Fig. 4.2.17). A charge controller is needed between the solar generator and the battery to prevent the latter from being overcharged or deeply discharged. The charge controller usually also includes a blocking diode which prevents the battery from discharging during the night.

The system shown in Fig. 4.2.17 represents a purely solar system. Dependent on the climatic conditions the generator and the battery have to be large enough to provide uninterrupted power supply. For geographic areas with large seasonal differences in solar radiation, hybrid systems as shown in Fig. 4.2.18 are common. Another energy source, in this case a fossil generator, is added to supply power in periods of low solar availability. Programs for dimensioning the components in different locations are available and widely used.

Stand alone systems find many applications in the industrialized world but do not contribute much to the energy situation. They can be found in small consumer devices and many other applications such as PV Parking meters, emergency telephones and remote sensing installations. Other, more technical applications are in communications (repeater stations) and cathodic protection of pipelines. They can also supply non grid-connected houses and refuges in the mountains.

The major impact, however, is seen in developing countries. The most important systems are solar home systems, water pumps and village power. Solar home systems supply power for the most basic needs of a rural household such as a few energy saving fluorescent lights and a radio. If a 50 W generator is installed, even a television set can be operated. A typical solar home system is seen in Fig. 4.2.19, and a block diagram in Fig. 4.2.20. It should be stressed that this technology is only the beginning of the solution of rural electrification. Many other problems of social, cultural and not the least financial nature also have to be addressed.

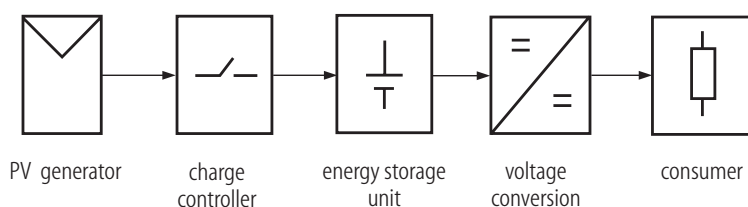


Fig 4.2.17. Block diagram of a basic stand alone system.

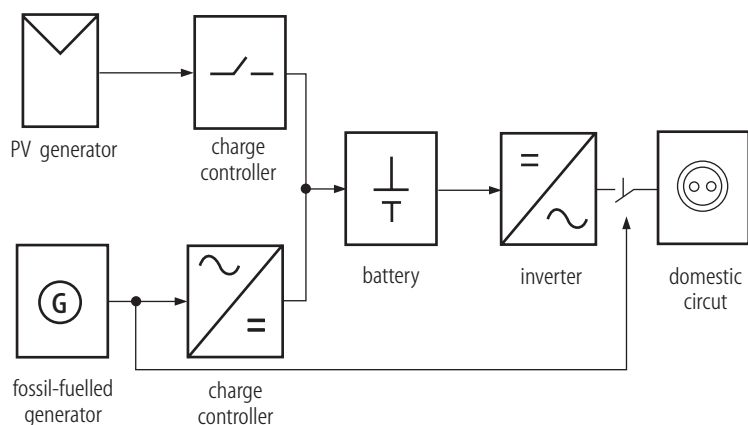


Fig 4.2.18. PV-fossil hybrid system.

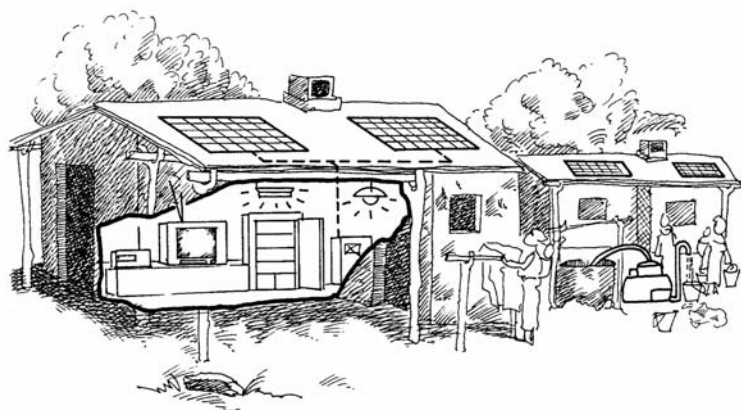


Fig 4.2.19. Illustration of a solar home system.

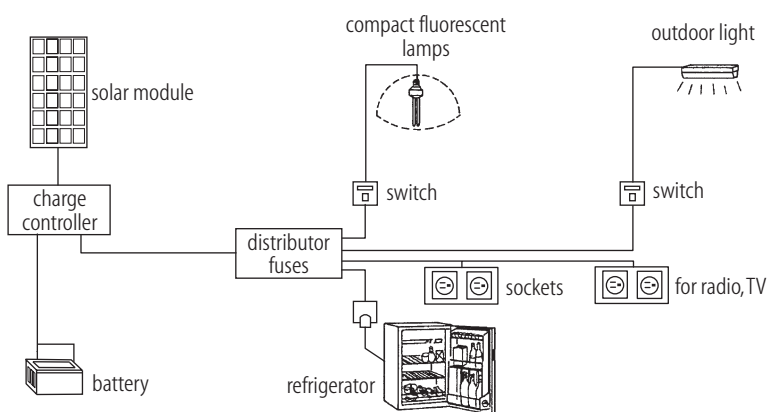


Fig 4.2.20. Block diagram of a solar home system for off-grid power supply.

4.2.7.3 Grid-connected systems

As can be seen in Table 4.2.1, grid-connected systems are the fastest growing sector of PV. Most common are roof mounted generators as in Fig. 4.2.21 but also PV facade claddings are growing (Fig. 4.2.22 and Fig. 4.2.23). PV modules in buildings can replace roofing material or facade cladding, which can reduce construction cost. As was pointed out in [Sect. 4.2.3](#), the potential of PV in buildings is very high. Since this sector depends very much on favorable conditions such as subsidies, easy connection to the grid and favorable reimbursement of electricity fed to the grid, great differences exist between nations in the size and growth of the grid-connected market. The most advanced countries in this respect are Japan and Germany where legislation was passed to support decentralized PV. In Japan there is a 70000 roof program and in Germany a 100000 roof program. In addition, PV electricity fed into the grid has to be reimbursed at 0.5 € in Germany. It can be expected that other countries will follow this example.

The electrical circuit of a grid-connected system is very simple because there is no need for storage (Fig. 4.2.24). The most important part besides the modules is the inverter which converts DC into AC. Inverters have to perform on high standards concerning the quality of the electricity delivered. They also have to prevent islanding, i.e. they have to turn off when the grid is switched off. After initial problems with reliability inverters, they have achieved very long lifetimes today.



Fig 4.2.21. Roof-mounted, grid-connected residential system.



Fig 4.2.22. Facade-mounted solar system in Freiburg, Germany.



Fig 4.2.23. Solar sun shades at facade in Freiburg, Germany.

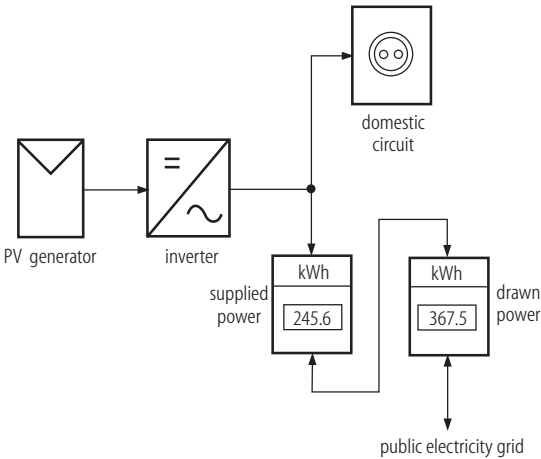


Fig 4.2.24. Block diagram of a grid-connected system.

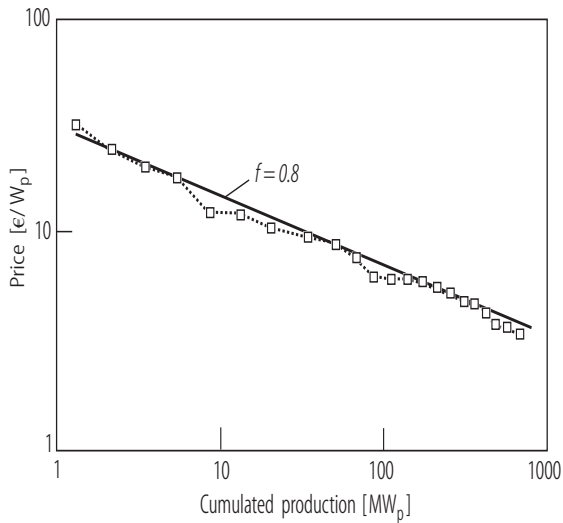


Fig 4.2.25. Learning curve of PV modules.

4.2.8 Cost and energy balance

4.2.8.1 Cost

The most crucial factor regarding the application of PV is cost. The present silicon based technology leads to costs which are roughly five times higher than grid electricity in industrialized countries. In the past we have seen large cost reductions for PV systems. Further reductions can be expected. Two factors are important for cost reduction:

- Market expansion and economy of scale;
- New technologies.

Cost reduction by market growth is a well established experience for most industrial products. It can be expressed by a learning curve in which cost (or price) is plotted versus the cumulated production. This learning curve for PV modules is shown in Fig. 4.2.25. It shows, averaged over many years, a factor of 0.8 which means that for every doubling of accumulated production volume prices drop by 20%. Accumulated production is the sum of all PV produced throughout history. It should not be confused with the yearly production figures given in Table 4.2.1. If the present trend continues, prices can be expected to be one half of the present level by 2010. This is still not sufficient to be competitive with grid electricity, but one of the interesting properties of PV is that the profitable market grows exponentially with decreasing cost. At the level expected in 2010, for instance, PV can be fully competitive with decentralized diesel generators. In this manner there is hope that the expansion of the market will become self-supporting at some point.

The learning curve discussed so far is purely empirical. It includes cost reduction by larger production volume and evolutionary improvement of technology. It will therefore mainly apply to the present crystal-line silicon technology. Breakthroughs in technology and in particular new materials can accelerate the learning curve, but sudden deviations cannot be expected.

4.2.8.2 Environmental effects and energy balance

A very comprehensive study evaluating all previous results about environmental and energy aspects has been undertaken recently [98Moe]. With regard to environmental effects the operation of PV generators does not entail any adverse impacts. On the other hand, manufacture of solar cells and modules has to be considered. Numerous studies have been carried out with the outcome that emissions are at the level of normal chemical and mechanical manufacturing and are well controllable. Another aspect is the availability of raw materials. For silicon there is absolutely no limitation, but for some thin film technologies relatively rare materials like In in CIS films are required. Even in this case, studies have shown that multi GW production is possible without straining the resources.

Toxicity of materials incorporated in modules is in most cases of no concern. The only materials that cause concern are Cd and Te in CdTe cells. Even in this case the compound is quite stable and the main impediment for the success of this material may be acceptance by the customers.

Recycling of PV modules has been investigated both practically and theoretically. There are no problems encountered with recycling. No recycling facility for modules exists today because of their long lifetime. There is simply nothing to recycle. By re-use of the most energy intensive parts of the modules it is even possible to recoup some of the energy content. This effect is not included in the energy pay-back times quoted in Table 4.2.2.

Energy pay-back time is defined as the time which the energy source – in this case the PV module – has to operate in order to recover the energy consumed for its production. In the strict sense only renewable energy sources can have an energy pay-back time since all other means of energy generation need an input of primary energy. In [98Moe] all past evaluations have been adjusted to be comparable:

- Use of constant irradiation factors;
- Only the modules, no systems components were included;
- Production technologies studied were close to present production technologies.

The mean energy pay-back times for the different technologies are listed in Table 4.2.2. The pay-back times now have to be compared with the lifetime of the modules. For mono- and multicrystalline cells most manufacturers give a warranty of 25 years which can be interpreted as a practical lifetime of at least 30 years. For the newer thin film technologies 10 year guarantees are customary, but this is due to limited experience. The consequence of Table 4.2.2 is that PV modules generate between 4.1 and 6.7 times more energy than is required for their production. A further point in this connection is that today's manufacturing technology is not optimized for minimum energy input but for lowest cost. Since energy is relatively inexpensive, it can be concluded that the potential for pay-back time is significantly lower than shown here.

Table 4.2.2. Mean energy pay-back times for the different PV technologies.

Technology	Mean pay-back time [years]
Mono-Si	7.3
Multicrystalline Si	4.6
a-Si	2.8
CIS	1.9
CdTe	1.5

4.2.9 Conclusions

Photovoltaic energy generation is probably the most elegant way to utilize solar energy. PV is the direct conversion of solar radiation into electricity. It has many attractive features like operation without moving parts, no emissions, high temperature, no noise, high modularity etc. On the other hand there are also serious problems associated with the use of photovoltaics. At present the most serious drawback is the high cost. Nevertheless there are many economic off-grid applications even today. Cost is expected to go down as production volume increases, but it is doubtful whether the cost of PV electricity can reach the cost of central power plants. On the other hand there is first the need to reduce CO₂ emissions and secondly the exhaustibility of fossil resources. Therefore the cost – internal or external – of fossil energy will go up as PV gets gradually cheaper. If and when the two will meet remains an open question.

Decentralized grid-connected systems have many attractions. They do not consume valuable land area and they generate electricity right where it is consumed. Such systems have a large potential even in densely populated countries. This potential can be further increased by utilizing unused agricultural land or simultaneous use for PV and crops. Should PV become a significant energy source, another (maybe more serious) problem will arise. The intermittent nature of sunshine makes storage or another auxiliary energy source mandatory. If seasonal variations of PV output have to be compensated, inexpensive seasonal energy storage is required. At this time no such technique exists, at least not at reasonable cost. In the distant future storage of hydrogen in depleted natural gas reservoirs seems a possibility.

The PV market today is based on the conventional monocrystalline or multicrystalline silicon technology. This technology, despite its relative maturity, still has considerable cost reduction potential. Even lower cost can be expected from thin film materials. The most promising materials are: amorphous silicon, copper indium gallium diselenide and cadmium telluride, but many other materials are also under investigation. In the more distant future even more innovative concepts and materials might be developed. The large variety of possible approaches and the high R&D interest make it very likely that PV will have a bright future.

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