# PHOTOVOLTAICS IN BUILDINGS

## A Design Handbook for Architects and Engineers

*International Energy Agency, Paris, France*

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XYZ Publishing Company

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## Task 16 "Photovoltaics in Buildings"

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Chapter 1

# Why Photovoltaics in Buildings?

### 1.1 Beyond energy conscious design

The potential threat of global climate change, increasing energy demand of the developing world, and inevitably, although not rapidly, diminishing fossil fuel resources have made sustainable energy supply a planetary issue that has to be addressed by literally every sector of human life. At the same time buildings continue to play a significant role in the global energy balance. Typically they account for some 20-30% of the total primary energy requirements of industrialized countries. With increasing awareness of the ecological consequences of energy consumption, the need for energy and environment conscious building design has become more and more pressing.

The building designer already has a number of sustainable technologies to choose from: premium thermal insulation, advanced heating, ventilation and air conditioning (HVAC) equipment, passive solar architecture featuring climate conscious building orientation and advanced glazing and daylighting options; active solar thermal technologies for space heating and domestic hot water; and energy efficient lighting and appliances. All these measures can and already have significantly reduced especially the thermal energy requirements of buildings. This in turn has increased the share of electricity in the energy balance of the building sector.

Until recently it was not feasible to go beyond the energy conscious building design from merely saving to actually producing high value energy and sharing it with the whole society.

But now a new technology, photovoltaics, has emerged as a viable option. Photovoltaics generate electricity from the renewable resource of sunlight and can be installed on or at the actual building, giving a new dimension to energy conscious design.

### 1.2 The photovoltaic option

Photovoltaic (PV) or solar electric modules are solid state devices that convert solar radiation directly into electricity with no moving parts, requiring no fuel, and creating virtually no pollutants over their life cycle. During four decades of photovoltaic activity the devices originally used in space technology have gradually found their way into numerous applications. The state-of-the-art photovoltaic technology today can be characterized as follows:

- PV modules are technically well proven with an expected service time of at least 30 years.
- PV systems have successfully been used in thousands of small and large applications.
- PV is a modular technology and can be employed for power generation from milliwatt to megawatt facilitating dispersed power generation in contrast to large central stations.
- PV electricity is a viable and cost-effective option in many remote site applications where the cost of grid extension or maintenance of conventional power supply systems would be prohibitive.
- PV technology is universal: the PV modules feature a "linear" response to solar radiation

and therefore may be mass produced and shipped world-wide.

Although photovoltaics has the technical potential of becoming a major clean energy source of the future, it is not yet economically competitive in bulk power generation. Instead, it finds its practical applications in smaller scale innovative "niche" markets, like consumer products, remote telecommunication stations, and off-the-grid dwellings. However, due to rapid technological improvements and the pronounced need for sustainable energy solutions, PV in buildings, also connected to the utility grid, now shows promise of becoming more than just another niche market.

## 13 Combining technology and architecture

Traditionally, PV modules or PV arrays have been mounted on special support structures. However, they can also be mounted on buildings, or even be made an integral part of the building envelope thus creating a natural on-site link between the supply and demand of electricity. Through the use of photovoltaics the consumption of power plant based electricity may be significantly reduced. The buildings may even be turned into small distributed net electricity producers and, as such, offer increasing benefits to all.

From an architectural, technical and financial point of view, PV in buildings today

- does not require any extra land area and can be utilized also in densely populated areas,
- does not require any additional infrastructure installations,
- can provide electricity during peak times and thus reduce the utilitie's peak delivery requirements,
- may reduce transmission and distribution losses,
- may cover all or a significant part of the electricity consumption of the corresponding building,
- may replace conventional building materials and thus serve a dual role which enhances pay back considerations,
- can provide an improved aesthetic appearance in an innovative way,
- can be integrated with the maintenance, control and operation of the other installations and systems in the building,
- can provide reduced planning costs.

Once put in the building context, photovoltaics should not be viewed only from the energy production point of view. Because of the physical characteristics of the PV module itself, these components can be regarded as multifunctional building elements that provide both shelter and power.

Being a mixture of technology, architecture and social behavior, PV in buildings eludes unambiguous evaluation of its cost-effectiveness and market potential. To a large extent, the value of the concept remains to be assessed on a case by case basis given the economical, technological, architectural, social and institutional boundaries of the project under consideration.

## 1.4 Can PV in buildings make a difference?

Photovoltaics harnesses solar energy, an immense resource that, if fully utilized, could exceed the current energy demand of mankind. But can PV in buildings, today a marginal technology, grow to be more than an exotic option for those who can afford it? Photovoltaics can be integrated on virtually every conceivable structure from bus shelters to high rise office buildings or even turned into landscaping elements. Although the exact analysis of the potential of PV in buildings calls for careful assessment of several factors including solar availability on building surfaces, institutional restrictions and electric grid stability, it is easy to become convinced of the large potential of this technology. Even in climates of only moderate solar radiation, the roof top of a single family dwelling can readily accommodate a PV array large enough for electric self sufficiency on an annual basis. There, PV can certainly make the difference. But PV in buildings can prove to be more than that.

For the vast physical potential of the solar resource and photovoltaic technology to materialize in cost-effective applications, it is crucial that large enough markets emerge to cut down the price per watt of PV. The decreasing cost of photovoltaics would then in turn create an expanding market of new affordable PV solutions. Today, PV in buildings appears as the most promising of these candidate markets to bridge the way for PV from the scattered small-scale niche applications to a major power generating technology of the twenty-first century. In this opportunity also lies the fundamental difference of PV and other energy efficiency options for buildings. Should PV in buildings really trigger the snow ball effect of reducing cost and expanding the use of photovoltaics, it would raise the impact of this concept from being merely a stimulating play ground for architects and engineers to genuinely making the difference in the global perspective.

### 1.5 A mission for architects and engineers

The photovoltaic community may have great visions of the future, but PV in buildings is already an option for today with numerous successful examples. Building design is an integral process and photovoltaic technology adds to the choices available for the energy conscious designer, as this handbook is about to show. It is up to the designer to weigh the pros and cons of the various technologies in each individual project, and make the choice. In short, photovoltaics is worth considering

- if the building has access to solar radiation,
- if innovative design options are preferred,
- if the building is or will be energy-efficient by design.

Although an inherently elegant concept, photovoltaics in buildings is not turned into appealing architecture and sound engineering without the concerted professional efforts of several disciplines. Only by working closely together, can engineers and architects combine technology and architecture in a way that may revolutionize our understanding of both energy and buildings.

# Chapter 2

# The Solar Resource

## 2.1 Sun and solar constant

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39 x $10^9$ m and is, on the average, 1.5 x $10^{11}$ m from the earth. This distance compares to about 12000 times the earth's diameter. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by 1.7%. The sun has an effective blackbody temperature of 5777 K. The radiation emitted by the sun and its spatial relationship to the earth result in a nearly fixed intensity of solar radiation outside the earth's atmosphere, often referred to as extraterrestrial radiation. The values for this **solar constant** found in the literature vary slightly due to the measurement techniques or assumptions for necessary estimations. The World Radiation Center (WRC) has adopted a value of **1367 W/m$^2$,** with an uncertainty in the order of 1%.

Compared to fossil fuels, the energy density of the solar radiation is relatively small. The total amount of incident radiation, however, is 6500 times larger than the world's energy demand. Even if only the land-covered part of the earth's surface is considered, the sun could still supply 1900 times our worldwide energy demand.[1]

## 2.2 Available solar radiation and spectral distribution

Solar radiation at normal incidence received at the surface of the earth is subject to two significant phenomena:

- atmospheric scattering by air molecules, water and dust and
- atmospheric absorption by $0_3$, $H_20$ and $CO_2$.

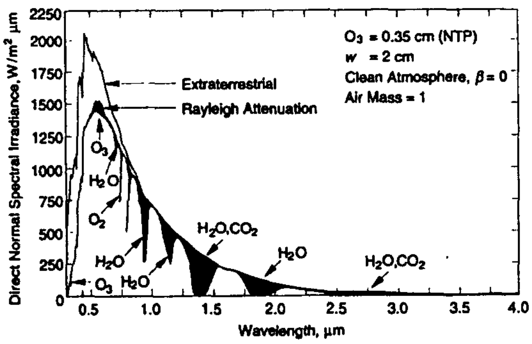


*Figure 2.1 An example of the effects of Rayleigh scattering and atmospheric absorption on the spectral distribution of beam irradiance.*

Figure 2.1 shows the spectral distribution of the extraterrestrial radiation as a function of the wavelength and the effect of scattering and absorption on this distribution for a clear day.

[1] Maybe even more important is the fact that the solar energy incident on our planet is the only continuous source of exergy. Exergy is the valuable part of energy and irreversibly transformed into anergy, the worthless part of energy, during each energy transformation process. When we talk about energy conservation, we really mean exergy conservation, since it is the exergy that we use up. The use of solar radiation to meet our exergy demands means saving exergy stored within thousands of years instead of spending it within a couple of a hundred years.

| | Cloudless blue sky | Misty...cloudy, sun visible as yellowish disk | Cloudy sky |
|---|---|---|---|
| Global radiation | 600...1000 W/m$^2$ | 200...400 W/m$^2$ | 50...150 W/m$^2$ |
| Diffuse part | 10...20% | 20...80% | 80...100% |

*Table 2.1 Irradiance at different weather conditions.*

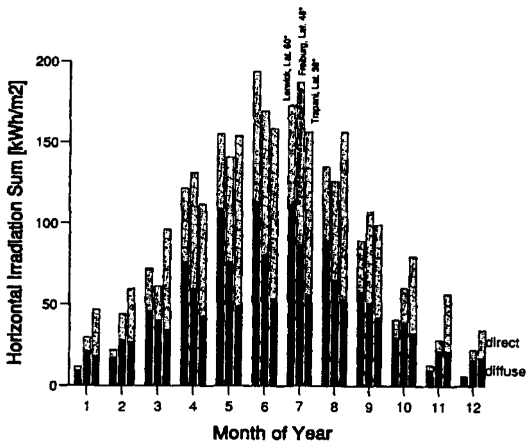


*Figure 2.2 Monthly average daily direct and diffuse irradiation in Lerwick/ Shetland Islands, UK, Freiburg, Germany and Trapani/Sicily, Italy.*

| Location | Latitude | Annual incident energy [kWh/ m$^2$] |
|---|---|---|
| Sahara | 25°N | 2500 |
| Israel | 33°N | 2000 |
| Trapani, I | 38°N | 1800 |
| Freiburg, D | 48°N | 1100 |
| Helsinki, FIN | 60°N | 950 |
| Lerwick, UK | 60°N | 775 |

*Table 2.2 Annual incident solar energy at several locations on a horizontal surface.*

The ratio of the available global radiation on the horizontal surface and the extraterrestrial radiation for the location is called clearness index. The clearness index hardly exceeds 0.75 on very clear days. The global radiation is made of two parts: the direct radiation from the sun itself and the diffuse radiation from the sky (without the sun).

Table 2.1 gives a rough indication of the relation between weather condition, global radiation and the percentage of diffuse radiation.

In many parts of the world, for example in Central and Northern Europe, the diffuse radiation plays an important role for solar energy conversion: here the diffuse part of the global radiation energy amounts to between 40% (summer) and 80% (winter). Figure 2.2 gives examples for different latitudes in Europe. The annually available radiant energy depends on the geographic location and meteorological conditions. Seasonal changes are due to the tilted axis of the earth on its orbit. Table 2.2 shows that the annually available global radiation may vary by a factor of more than 2.5.

Figure 2.3 illustrates well that seasonal changes have a larger effect on the available radiation at higher latitudes (= degrees North or South from the equator). The images of the globe are taken with the sun's view direction towards the Earth in summer (top) and winter (bottom). While Central Europe is highly "visible" by the sun during summer noon, it is hardly recognizable during winter. On the other hand, the entire African continent, as an example for low latitudes, is highly exposed to the sun during the whole year.

Figure 2.4 shows how the intensity of the solar radiation on a flat surface is higher when it is tilted towards the sun. The maximum intensity occurs when the flat surface is perpendicular to the sun's rays. Two-axis tracking of receivers may thus maximize the energy gain at the expense of technical complexity. For fixed receiver surfaces, the energy gain is a function of the slope angle (0°: horizontal, 90°: vertical) and the azimuth angle (0°: South, -90°: East, +90°: West, 180°: North). The distribution of the annual incident energy on a tilted surface as a function of slope and azimuth in Central Europe is shown in Figure 2.5. One can observe that there is quite a large region within 90% of the maximum. This gives some freedom in choosing acceptable surfaces for collection of solar energy, which is an important issue for the integration of photovoltaics in building envelopes.

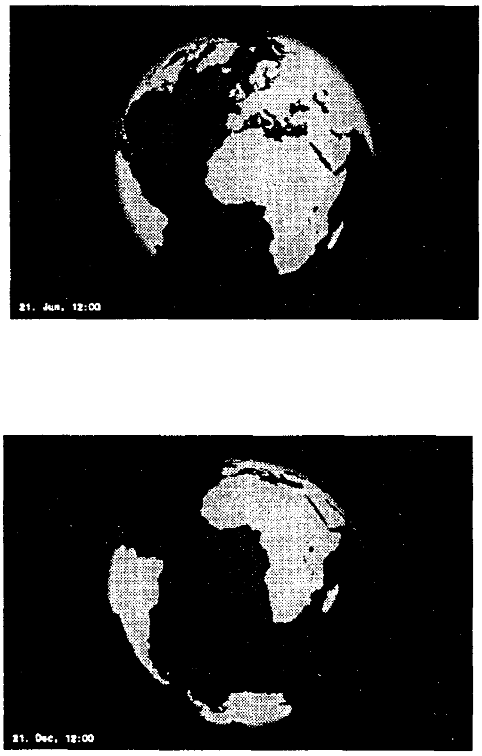

*Figure 2.3 Sun's view of the globe in summer (top) and winter (bottom) around noon in Europe.*

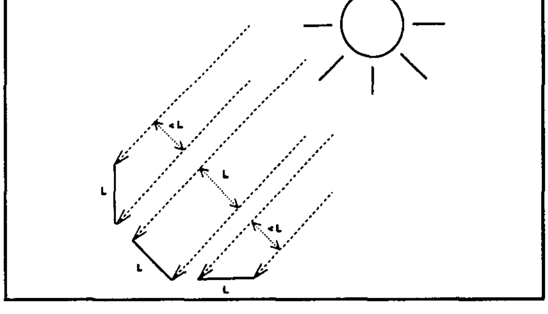

*Figure 2.4 Comparison of a tilted with a horizontal and vertical receiver surface.*

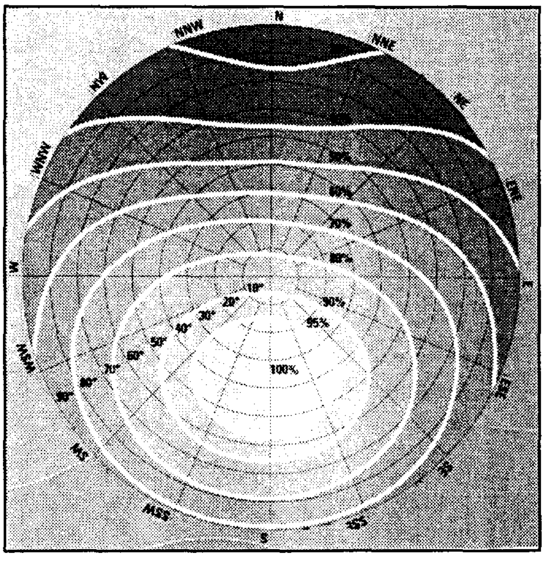

*Figure 2.5 Effect of slope (tilt angle) and azimuth (orientation) on the annual incident energy in Central Europe.*

Chapter 3

# The Photovoltaic Principle

## 3.1 Introduction

The physical phenomenon responsible for converting light into electricity - the photovoltaic effect - was first observed by a French physicist, Edmund Becquerel, in 1839. He noted that a voltage appeared when one of two identical electrodes in a weak conducting solution was illuminated. The photovoltaic effect can be described simply as follows: Light, which is a form of energy, enters a photovoltaic (PV) cell and transfers enough energy to cause the freeing of electrons. A built-in potential barrier in the cell acts on these electrons to produce a voltage which can be used to drive a current through an electric circuit.

The first cells were made from selenium during the last century with only 1 - 2% conversion efficiency. Since then, significant research has been done in this field. Quantum mechanics, developed during the 1920s and 1930s, laid the theoretical foundation for our present understanding of PV. However, a major step forward in solar-cell technology was done during the 1940s and early 1950s when a method called the Czochralski method was developed for producing highly pure crystalline silicon. Other important triggers for the PV industry were the space programs started in the 1950s and also the development of the transistor industry. Transistors and PV cells are made from similar materials, and many of their working principles are determined by the same physical mechanisms.

## 3.2 Cell structure

The basic element in the photovoltaic module is the solar cell which absorbs sunlight and converts it directly into electricity. Figure 3.1 shows the basic structure of a PV cell.

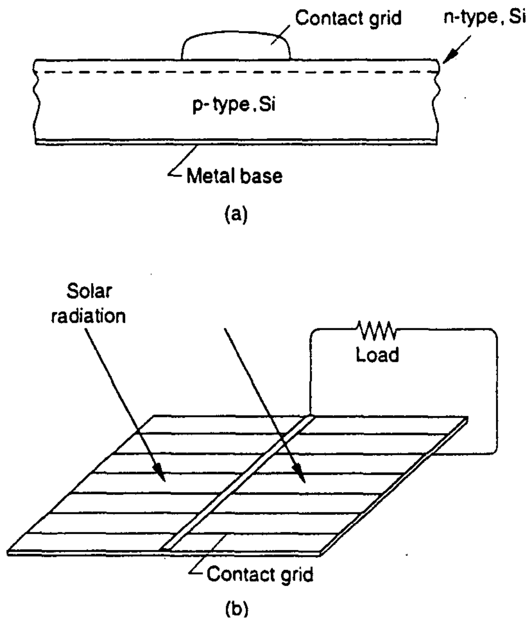


*Figure 3.1 (a) Section of a silicon solar cell. (b) Schematic of a cell, showing top contacts.*

The solar cell consists of a thin piece of semiconductor material, which in most cases is silicon. A semiconductor is an element, whose electrical properties lie between those of conductors and insulators, making it only marginally conductive for electricity.

Through a process called "doping" a very small amount of impurities is added to the semiconductor, thus creating two different layers called n-type and p-type layers. A n-type material has an increased number of electrons in the conduction band (n=negative) whereas the p-type material has vacancies of electrons (p=positive). Typically, phosphorus is used to create the n-type layer and silicon doped with boron makes the p-type layer. Between these two layers a p-n junction is created which is of great importance for the function of the solar cell.

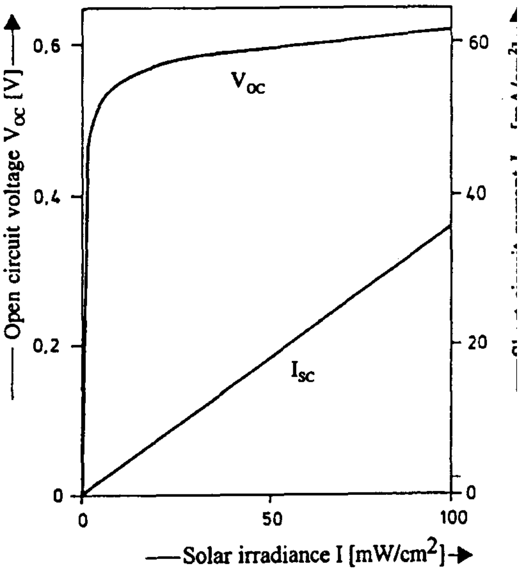


*Figure 3.2 Voltage and current of a silicon solar cell as a function of irradiance.*

The light passes through a "window layer" which is thin and therefore absorbs only a small fraction of it. The major part of the light is absorbed in the absorber layer where it creates free electrons that can flow through a wire connected to both sides of the cell. In order to do so, a built-in electrical field is needed. This field is formed along the zone or junction between the two layers of n- and p-type silicon.

The current produced by the cell is proportional to the amount of incident light (the number of photons entering the cell). Therefore, current increases with the cell area as well as with the light intensity. The voltage, on the other hand, depends on the material used. A silicon cell produces about 0.5 V regardless of cell area. Figure 3.2 illustrates these effects.

### 3.3 Types of photovoltaic cells

**Crystalline solar cells**

The most commonly used cell material is silicon. PV cells made of single-crystal silicon (often called monocrystalline cells) are available on the market today with efficiencies close to 20%. Laboratory cells are close to the theoretical efficiency limits of silicon (29%). Polycrystalline silicon is easier to produce and therefore cheaper. It is widely used, since its efficiency is only a little lower than the single-crystal cell efficiency. Gallium arsenide (GaAs) is another single-crystal material suitable for high efficiency solar cells. The cost of this material is considerably higher than silicon which restricts the use of GaAs cells to concentrator and space applications.

**Thin-film solar cells**

In order to lower the cost of PV manufacturing, thin-film solar cells are being developed by means of using less material and faster manufacturing processes. The major work on thin films during the last 10 years has been focused on amorphous silicon (a-Si). The long-term advantage of amorphous as compared to crystalline silicon is the lower need for production energy leading to shorter energy payback time. With the use of small a-Si cells in pocket calculators, a new market, the consumer PV market, was born. The disadvantage of these cells is the relatively low efficiency that has prevented the breakthrough in the production of power in large installations. However, in building applications, a larger module area for the same nominal power due to the lower efficiency may result in a more uniform appearance and thus become advantageous. Although a-Si cells over 10% efficiency are being produced, this initial value is reduced by approximately 30% due to the light-induced instability called Stabler-Wronski effect. Current research focuses on ways to reduce this effect and to increase the efficiency.

Other interesting thin-film materials are Cadmium-Telluride (CdTe) and CopperIndium-Diselenide ($CuInSe_2$ or CIS). Nowadays, cells made of these materials are produced in laboratories with efficiencies of about 15%. Thin-film crystalline silicon on ceramic substrates is another possible solution being examined today.

In Table 3.1 the most common solar cell materials are summarized.

*Figure 3.3 Monocrystalline silicon and PV cells made of it.*

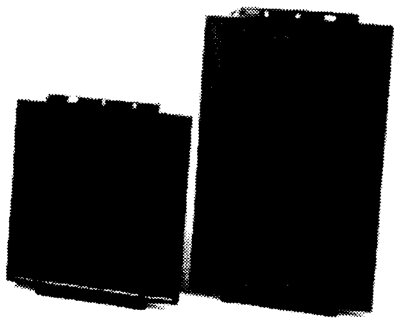

*Figure 3.4 PV modules made of amorphous silicon (a-Si) cells.*

| Material | Theoretical efficiency | Laboratory cell (1994) | Module (1994) |
|---|---|---|---|
| Crystalline Silicon | 29% | 23% | 15% |
| GaAs | 31% | 25% | |
| **Thin film** | | | |
| Amorphous Si | 27% | 12% | 8% |
| CIS | 27% | 17% | 11% |
| CdTe | 31% | 16% | 10% |

*Table 3.1 Theoretical and practical efficiencies of different types of solar cells*

Chapter 4

# Types of Photovoltaic Systems

## 4.1 Introduction

Photovoltaic (PV) systems are of a modular nature. Solar cells can be connected in series or parallel in virtually any number and combination. Therefore, PV systems may be realized in an extraordinary broad range of power: from milliwatt systems in watches or calculators to megawatt systems for central power production. Building power supply systems are usually in the range of several kilowatts of nominal power.

There are two basically different PV systems: those with a connection to an (available) electric grid and remote or "stand-alone" systems. While in the first case the grid serves as an ideal storage component and ensures system reliability, the stand-alone systems require a storage battery. This battery serves as a buffer between the fluctuating power generated by the PV cells and the load. In order to ensure continuous power supply, even under extreme conditions, a back-up generator is often also installed. Building-integrated PV systems have an economical advantage over conventional PV generator systems: The PV modules serve for multiple purposes. They are part of the building envelope, ideally replacing conventional facade or roof material. Modem commercial building facades often cost as much as a PV facade which means immediate or short-term pay-back for the PV system. Depending on the type of integration, the PV modules may also provide shading or noise protection. Here again, the costs for replaced conventional means for these purposes may be deducted from the initial PV costs.

## 4.2 Grid-connected systems

PV systems may be connected to the public grid. This requires an inverter for the transformation of the PV-generated DC electricity to the grid AC electricity at the level of the grid voltage. National and even regional regulations differ widely with respect to the policy of interconnection requirements and reimbursing for PV-generated electricity fed into the grid. In order to support the production of PV-generated power, some utilities offer a better price for the kWh fed into their grid than they charge for the kWh from the grid. In other locations a one-to-one ratio is applied which means the same kWh-price for both flow directions. The third version is to pay less for the generated PV power fed into the grid than for that sold to the consumer. Comparing the rates, the fixed rates for the power connection have to be considered also. Depending on the kind of tariffs, one or two electricity meters have to be used at the point of utility connection. Figure 4.1 shows a block diagram of a grid-connected PV system suitable for building integration.

In grid-connected applications, photovoltaic systems must compete against the cost of the conventional energy source used to supply the grid. PV systems are particularly cost-effective when the utility load and solar resource profiles are well matched. This is, for example, the case in areas with high air-conditioning loads that have their peaks during the peak sunshine hours of the summer day.

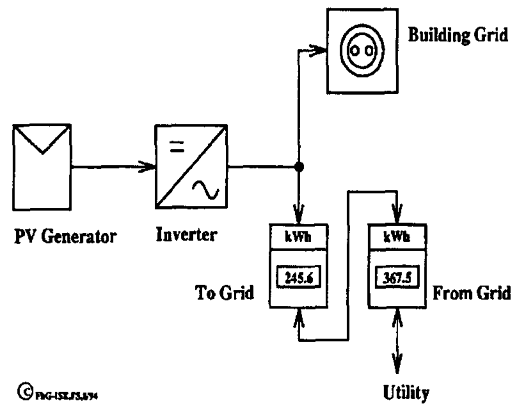


*Figure 4.1 Principle schematic of a grid-connected PV power system.*

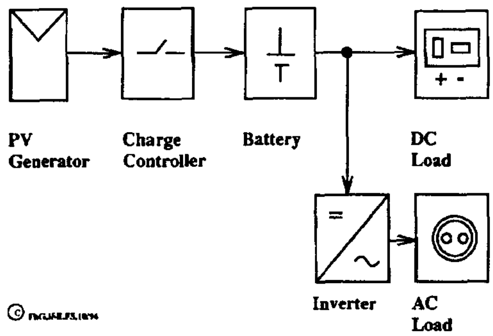


*Figure 4.2 Principle schematic of a stand-alone PV power system.*

### 4.3 Stand-alone systems

PV systems are most effective at remote sites off the electrical grid, especially in locations where the access is possible by air only, e.g. in alpine regions. Their high reliability and low servicing requirements make them ideally suited for applications at (for parts of the year) unattended sites. The costs for a PV system compete in this case against the cost for a grid-connection or other possible ways of remote energy supply.

As stated above, a storage battery is needed. Excess energy produced during times with no or low loads charges the battery, while at times with no or too low solar radiation the loads are met by discharging it. A charge controller supervises the charge/discharge process in order to ensure a long battery lifetime. Like in the grid-connected systems, an inverter, when required, transforms DC to AC electricity. A scheme of such a system is shown in Figure 4.2.

By virtue of the variable nature of the energy source sun, one of the most expensive aspects of a PV power system is the necessity to build in system autonomy. Autonomy is required to provide reliable power during "worst case" situations, which are usually periods of adverse weather, seasonally low radiation values or unpredicted increased demand for power. The addition of autonomy could be accomplished by oversizing the PV array and greatly enlarging the battery storage bank - generally the two most costly system components. By incorporating the additional battery charging and direct AC load supply capabilities of an engine generator (genset) into the PV system design (as shown in Figure 4.3), the need to build in system autonomy is greatly reduced. These systems are often referred to as hybrid systems. When energy demands cannot be met by the PV portion of the system for any reason, the genset is automatically brought on line to provide the required back-up power. Substantial operating cost savings (compared to a genset system without PV) are achieved through the greatly reduced need for genset operation. An additional benefit of this approach is the added system reliability provided by the incorporation of the back-up energy source.

Hybrid systems may contain more than one renewable power source. Adding a wind turbine to a PV genset system is a common combination in areas with -high wind energy potential like coastal or hilly regions. Very often the instantaneous available wind energy is high, while the radiation values are low and vice versa.

### 4.4 Direct use systems

There are applications where the load matches the available radiation exactly. This eliminates the need for any electricity storage and backup. A typical example is the electricity supply for a circulation pump in a thermal collector system.

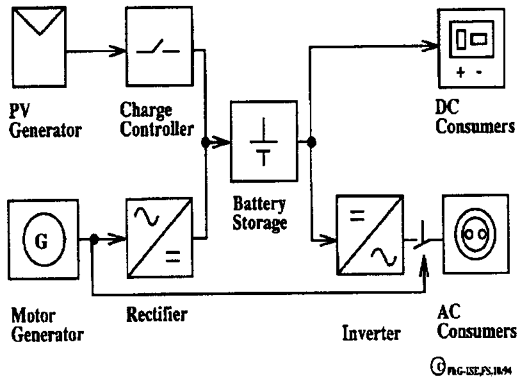


*Figure 4.3 Principle schematic of a hybrid PV power system.*

Section B

# Components

# Principal Contributors

**Chapter 5:** **Photovoltaic Modules**

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**Chapter 9:** **Inverters**

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**Chapter 10:** **Hybrid Power Systems**

# Chapter 5

## Photovoltaic Modules

### 5.1 Introduction

In every building-integrated PV system, the PV module is the basic element of the generator. The number of modules in series will determine the system voltage and the current of the plant can be sized by parallel connection of module strings. The desired output power is the product of system voltage and current.

### 5.2 PV modules

One single silicon solar cell with a surface area of approximately 100 cm2 generates a current of 3 A at a voltage of 0.5 V when exposed to full sunshine. When PV modules first came into terrestrial use, the most common application was to charge 12 V lead-acid batteries requiring a module voltage of 13 to 15 V. Therefore, the typical PV module made of crystalline silicon consists of 30 to 36 cells connected in series with a peak power of approximately 50 W.

A cross-section through a module is shown in Figure 5.1. The module's top layers are transparent. The outermost layer, the cover glass, protects the remaining structure from the environment. It keeps out water, water vapor and gaseous pollutants which could cause corrosion of a cell if allowed to penetrate the module during its long outdoor use. The cover glass is often hardened (tempered) to protect the cell from hail or wind damage. A transparent adhesive holds the glass to the cell. The cell itself is usually covered with an anti-reflective (AR) coating. Some manufacturers etch or texture the cell surface to further reduce the reflection.

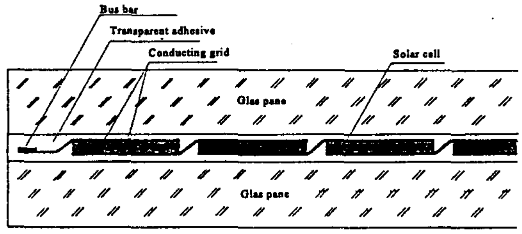



*Figure 5.1 Cross-section through a typical module.*

After the light has passed through the cover glass, the transparent adhesive and the AR coating, it penetrates into the semiconductor material where the electricity is generated. The light-generated current flows out of the cell surface through a metal grid, called the front contact. To reduce resistance losses, it is important that the metal grid is covering parts of the cell surface. On the other hand, blocking a large fraction of the light entering the cell should be avoided. The cell's bottom layer is called the back contact and is a sheet of metal which in connection with the front contact forms a bridge to an external circuit. The module's back side is covered with a layer of tedlar or glass. Often a frame of aluminium or composite material gives the module the needed mechanical stability for mounting it in different ways.

During the last years, grid-connected systems have been a growing application for PV and systems of several thousands of kW have been built. The system voltages in these plants are sometimes as high as 500 to 1000 V and a large number of modules are connected in series. For these purposes manufacturers have developed large area modules of several square meters with peak power outputs of several hundred watts.

There are a large number of module manufacturers on the market and each company may have 5 to 10 different module types. Therefore, there are a variety of modules to choose from.

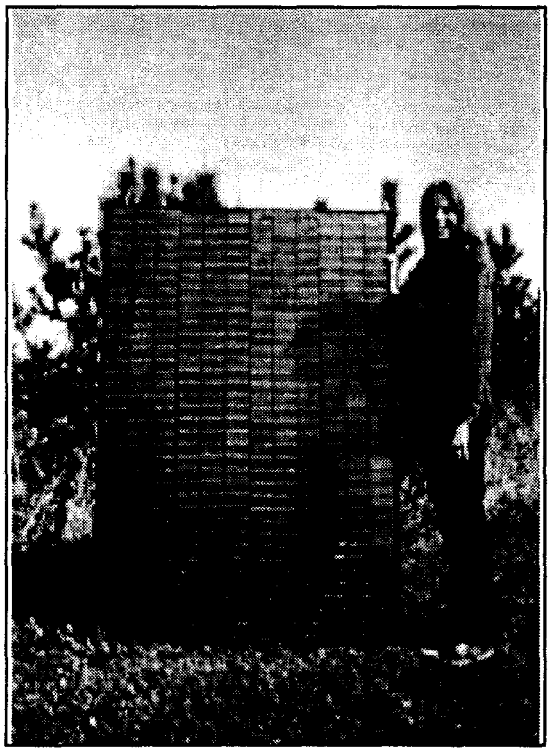


*Figure 5.2 Large-area PV module for building integration.*

## 5.3 Modules for buildings

Standard modules are widely used for building applications, especially to retrofit existing buildings. Their frame, however, impedes an easy and elegant integration into roof and facade.

Omitting the frame leads to "laminates", which can be mounted like glass panes using conventional glazing construction techniques. A specific method of roof integration are "PV Tiles".

PV Tiles, by their design, can be installed very quickly by electrical lay persons. They combine an old and a new technology and conserve the basic appearance of very common roof types.

The increased interest in PV facades has created new options for customized PV modules. To allow a larger creativity, module manufacturers are offering several, sometimes even customized sizes and options to modify the modules' appearance. Chapter 12 covers this topic in more detail.

## 5.4 Definitions, characteristics and performance

In Figure 5.3 characteristic values for a module are shown in an I-V curve. The indicated parameters are explained below. The curve represents the performance at "Standard Test Conditions" (STC), which is a definition used to compare different modules. STC represent an irradiance of 1000 W/m$^2$ at an Air Mass of 1.5 (AM 1.5 spectrum) and a cell junction temperature of 25°C.

$V_{OC}$ is the open circuit voltage of the module, i.e. the voltage of the module when no current is drawn. The $V_{OC}$ is dependent of the cell temperature and decreases with increasing temperature by approximately 0.4 %/K for crystalline material. This value is lower for amorphous cells.

$I_{SC}$ is the short circuit current of the module. Contrary to most other (voltage driven) power sources, a PV module has a short circuit current that is only slightly higher than the operational current. $I_{SC}$ slightly increases with increasing cell temperature by approximately 0.07%/K.

$P_n$ is the nominal power that the module can produce under STC and it is the value that is given on the manufacturer's plate on the back side of the module. This power value is often referred to as the peak power of the module ($W_P$). $U_n$ and In are the corresponding voltage and current values at this point.

The ideal solar cell or module has an I-V curve of rectangular shape (see dashed lines in Figure 5.3). The **fill factor (FF)** indicates the ratio between a real and this ideal cell. Typical values for the FF at STC are between 0.6 and 0.8.

## 5.5 Reading the data sheet

The PV module data sheets must be read with caution because at present there is no uniform way of presenting information. A hypothetical PV module data sheet is provided in Table 5.1.

The example data sheet provides the values at STC. It also notes that the spread of the values is ± 10%. Thus the module power may vary anywhere in the range 44 - 53 W. Further, in actual operation the module will usually not produce the rated power because the solar cells are sensitive to temperature. For the silicon solar cells, the voltage will be derated by 0.0022 V/K rise in temperature above the STC temperature (the current changes only marginally). In bright sunlight, the module temperature is typically 20 ... 40 K above the ambient temperature. Of course, in cold climates, the module could deliver more than its rated power.

Unless the system includes a maximum power point tracker (see chapter 8.2.1), the system typically will not operate at this point. The designer must determine a typical operating point for the system in question and base the module output calculations on this. In stand-alone systems, the system voltage varies only slightly around the battery voltage. In general, the module peak power point voltage $V_{MPP}$ should exceed the voltage to which the battery is charged by approximately 1.5 V.

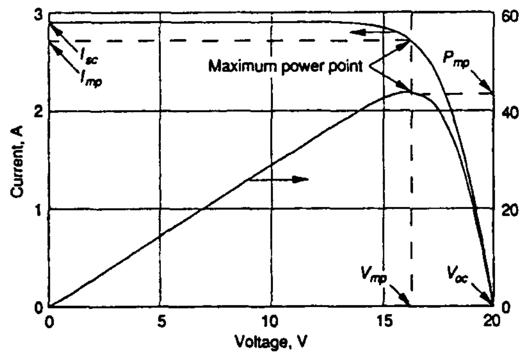



*Figure 5.3 I-V curve and characteristic parameters for a typical module.*

**Module specifications for XYZ48**

**Electrical specifications:**

| | |
|---|---|
| Short circuit current $I_{SC}$ | 3.3 A |
| Open circuit voltage $V_{OC}$ | 21.3 V |
| Current at peak power $I_{MPP}$ | 3.0 A |
| Voltage at peak power $V_{MPP}$ | 16.7 V |
| Maximum power output at 1000 W/m$^2$ and 25 °C | 48.6 W |
| Variation (spread) ± 10% | |
| Voltage decrease with temperature increase | 0.0022 V/K/cell |

**Mechanical specifications:**

| | |
|---|---|
| Front cover | low iron tempered glass |
| Encapsulant | Ethylene Vinyl Acetate (EVA) |
| Backing | White Tedlar™ |
| Solar cells | 100mm x 100mm square cells, 36 in series |
| Edge sealant | Butyl rubber |
| Frame | Silver anodized structural aluminium |
| Termination | Waterproof junction box |
| Electrical isolation | 3000 VDC 10 µA (TYP) |
| Weight | 6.2 kg |

**Environmental conditions:**

| | |
|---|---|
| Ambient temperature | -40°C to +90°C |
| Wind loading | max. 80 km/h |
| Relative humidity | 0 to 100% |

Thermal shock, hail impact and other environmental conditions as per JPL Block V testing. These modules are covered by the standard ten-year limited warranty on power output. Specifications are subject to change without notice.

*Table 5.1: An example of a typical PV module data sheet.*

# Chapter 6

# Photovoltaic Generator

## 6.1 Introduction

This chapter introduces the fundamental knowledge necessary to successfully install a PV generator. Physical characteristics, radiation influence and shading effects are explained, types of PV arrays and mounting technologies are introduced, hazards and their remedies are stated and a principal block diagram of a PV generator is given.

The reader should keep in mind that although these considerations apply to all PV systems, they focus on "PV in buildings". Installed in a facade or a sloped roof, the PV generator will be a factor in the appearance of a building. Thus, it needs special attention with respect to mechanical and electrical as well as aesthetical integration.

## 6.2 Parameters affecting the energy output

A number of parameters affect the possible energy yield of a PV generator (Table 6.1). The most important one is the solar radiation, which is essentially determined by the geographic location and the generator's tilt and orientation.

Further factors to be accounted for include (partial) shading, mismatch of modules in a string, the module operating temperature, resistance of wires and cables, string diodes and soiling.

The effect of generator tilt and orientation on the possible energy yield depends on the ratio of direct to diffuse irradiation. For Central European climate conditions Figure 2.5 shows the relative irradiation on an arbitrarily oriented fixed plane. It is obvious that the exact orientation is not critical. In a wide range of possible orientations more than 95% of the maximum energy is received.

| |
|---|
| Incident radiation |
| Module temperature |
| Partial shading |
| Mismatch of string modules |
| Wire resistances |
| Module soiling |
| String (blocking) diodes |

*Table 6.1: Influences on energy output.*

This statement holds true for an unobstructed PV generator. At locations, where soiling, snow, obstacles or distinct daily or seasonal weather patterns occur, these influences have to be taken into account.

Shading is a critical issue. The PV generator performs best if it is homogeneously illuminated. A small shadow from a leaf, an antenna pole, a chimney or an overhead utility line may seriously decrease the available output power. This is due to the fact, that **the cell with the lowest illumination determines the operating current of the whole series string.** This effect is illustrated in Figure 6.1. It is comparable to a water hose, which is pressed tight at one point, preventing the flow of water in the whole hose.

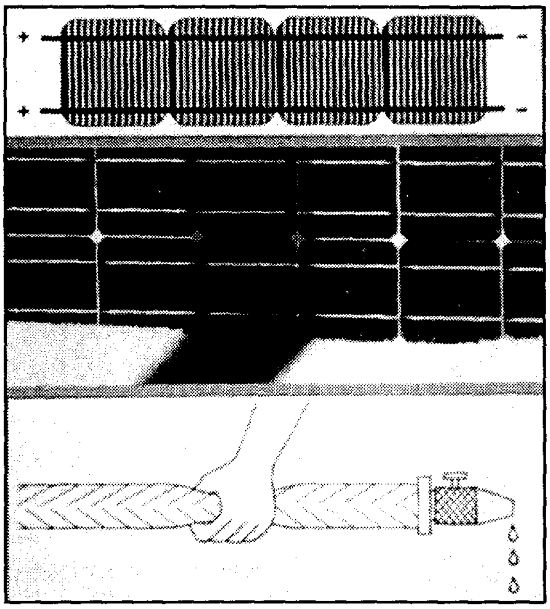


*Figure 6.1 Minor shading can cause a major energy loss.*

Under certain circumstances a partially shaded cell may even be forced into a load mode. This can lead to a thermal destruction of the cell and the respective module. In order to avoid this "hot spot" effect, "bypass diodes" are used to provide a second current path diverting the current from the shaded cell.

Amorphous silicon modules, which cells are long narrow stripes, are less affected by shading than crystalline silicon modules. This is because typical shading objects like trees or street lamp poles usually do not shade a cell over its whole length. Thus in practice the cell current of amorphous silicon cells is only affected by a percentage proportional to the area shadowed. Furthermore, these modules are less susceptive to "hot spot" development.

A similar effect like under partial shading occurs, when modules with different I-V curves are connected in series (module mismatch). The "weakest" module determines the current through all series-connected modules. Therefore, modules within a series string should be closely matched in order to keep mismatch losses as low as possible.

The temperature influences the modules' efficiency by approximately -0.4%/K. For instance, a 15% efficiency decreases to 14.4% at a temperature increase of 10 K. If feasible, modules should be freely vented. An air gap of 10 cm is sufficient in most cases.

Soiling, i.e. accumulation of dust and dirt may reduce the available generator output. Its effect depends mainly on the source of the dust and the tilt angle of the generator. Dust from nearby industrial complexes, major highways and major railway stations may cause a power reduction up to 10%. Usually dust accumulation and self cleaning reach a steady state after some weeks, if the generator tilt angle is at least 15°. In no case it has been economically attractive to regularly clean the modules. In typical residential areas of "moderate climate" zones soiling can be neglected.

In areas of heavy snowfall additional considerations have to be used. If a continuous PV output is desired the PV generator should be mounted rather steep, at least 45°, to allow quick shedding of the snow. A smooth surface eases sliding of the snow. Ideally large, vertically oriented, frameless modules should be used.

### 6.3 Types of arrays and mounting technologies

PV generators on buildings are usually fixed. There are several options for their placement:

- on a sloped roof
  - stand-off
  - integral (modules/tiles);

- at the facade
  - as wall element
  - as protruding shading element;

- on flat roofs
  - stand-off
  - integral.

**"Stand-off"** is a straightforward mounting method well suited for retrofits. Special mounting elements like hooks or mounting tiles are fixed to the roof. A support structure to which the modules are bolted is fixed to the mounting elements. Cable channels collect and protect the string cables, which lead into the building through watertight "feed-throughs", e.g. modified venting elements. Since the cables are exposed to the outdoor environment, they need to be selected accordingly. The support structure should be designed for at least 30 years of lifetime. Thus, aluminium, stainless steel and glass fibre should be the preferred materials.

**Integral mounting** leads to a nicer appearance and cost savings in new buildings. This method uses the PV generator as the building envelope. The modules replace conventional roof or facade covers. This is accomplished by using frameless modules (so-called laminates) in combination with mounting technologies taken from conservatory or conventional glazing construction. The wiring is usually not exposed to ambient conditions. However, the access to the wiring is more difficult, if a thermal insulation is installed in the roof. To remove the air warmed up by the generator efficient venting elements may be included.

A special design of roof-integrated PV modules are **PV tiles.** Prewired tiles can be mounted and connected very quickly and they are accessible from the outside. Several manufacturers offer PV tiles.

**Facades** are an increasingly popular location for PV generators, since they provide multiple purposes for the PV modules. Besides electric power production, PV modules may serve to present corporate identity. Semitransparent modules may serve for daylighting purposes. Installed in front of the facade, modules provide shading for the offices behind. PV facades usually rely on mounting methods for conventional facade elements. Popular mullion/transom constructions (*glossary) have been modified to allow integral cabling. Also, structural glazing technology has been successfully used for PV facades.

On **flat roofs,** PV generators can be installed using very similar techniques as for PV arrays in the open field. In order to avoid penetration of the roof, "weight foundations" are often used, which keep the modules down by gravitation.

## 6.4 Block diagram and components of a PV generator

A PV generator comprises a variety of components. These include: modules, fixation material, mounting structure, bypass diodes, blocking diodes, fuses, cables, terminals, overvoltage/lightning protection devices, circuit breakers and junction boxes. Figure 6.2 gives a schematic diagram of a PV generator and its basic design.

**Standard modules** come with about 20 V open circuit voltage ($V_{OC}$) and approx. 3 A nominal current ($I_n$) (at standard test conditions). For higher power ratings the modules are connected in series and/or in parallel. Several modules in series are called a "string". In some cases it is necessary to protect the string cables and modules against overcurrent. Fuses are used for general overcurrent protection, while blocking diodes prevent current flow into one string from the rest of the PV generator in case this string does not reach its designed operating voltage for whatever reason. However, considering that PV modules are current sources and that modem cables and appropriate wiring methods make a short circuit or a ground fault extremely unlikely, these protection devices may be omitted in some cases.

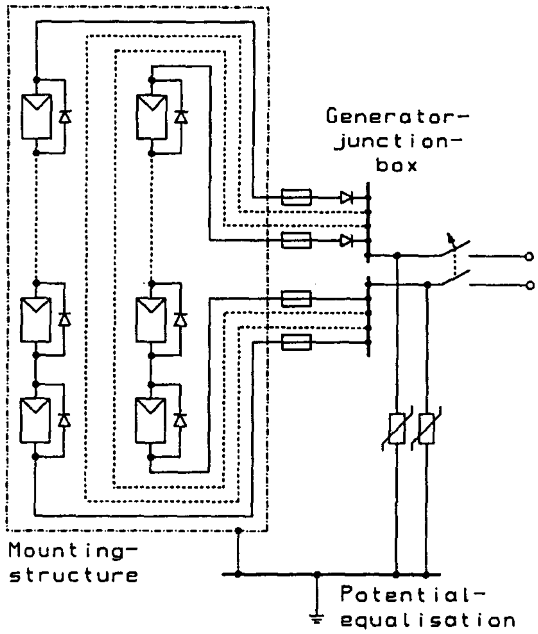



*Figure 6.2 Basic structure of a PV generator.*

In PV strings with open circuit voltages $V_{OC}$ higher than 30 V, **"bypass diodes"** are usually integrated. A bypass diode provides a current path around a module or a part of a module. It protects the bypassed cells in the module, e.g. under partial shading conditions, from operation in a load mode and possible destruction. The need for bypass diodes depends on the system configuration and module specifications.

**Blocking diodes** prevent current flow backwards into a string. This - rather unlikely - operating condition might occur, if ground faults or short circuits happen in a string. It would reduce the generator's power output and at worst could lead to a destruction of cables and modules. However, using modern "protection class II" modules and "ground fault proof and short circuit proof' wiring virtually eliminates the occurrence of such a failure.

**Fuses** protect cables from overcurrent. In PV generators they should be used only if a large number of strings is connected in parallel and the generator's short circuit current could exceed the cable's rated current in one string. In many residential systems the intermodule cables can carry currents of several parallel strings without being overloaded. For instance, most systems in the German 1000-roofs-programme employ 2.5 $mm^2$ cables for string cabling, which are listed for 12 A at 70°C operating temperature when installed in bundles. Thus, under conservative assumptions fuses would be required only in case of more than 4 strings in parallel assuming standard modules..

Cables are usually double-insulated and UV-resistant. They must withstand the elevated temperatures behind the modules. These temperatures can reach 50 K above ambient temperature, if the module backside is covered with thermal insulation material. The size of the cable is determined by the allowable voltage drop along the string at nominal current and thus larger than the nominal operating current of approximately 3 A would require. Using different colors for the + and - connections eases wiring of the junction box.

**Connections** are numerous and very important. A sloppy connection may render a whole string useless or even, in the worst case, cause a fire. Crimp terminations and spring loaded cage clamp terminals are considered most reliable. Plug/receptacle types of connectors are currently being studied, because they offer quick field wiring as well as easy module replacement.

**Overvoltage/lightning protection devices** will keep voltage transients out of the systems. Modern modules are rugged, so they can easily withstand surge voltages up to 6 kV. Electronic components such as bypass or blocking diodes and equipment such as inverters and charge controllers, however, need protection. Therefore, surge arrestors with at least 5 kA peak current ratings are applied at either leg of the PV generator.

**Circuit breakers** between the PV generator and the inverter or charge controller are needed to remove the PV generator's voltage from the main DC line. They must be rated for the generator's nominal short circuit current and open circuit voltage and for DC!

The above-mentioned components are located and electrically connected in one or more **junction boxes.** This box must be suited for the mounting location in terms of IP-protection (*glossary), temperature rating, UV-resistance etc. It should be easily accessible to regularly check the fuses and the overvoltage protection devices and to open the DC circuit breaker(s).

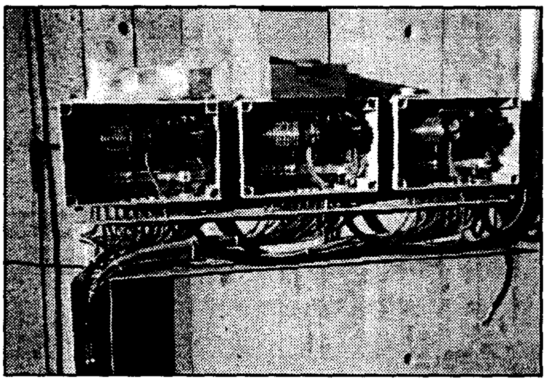


*Figure 6.3 Junction boxes.*

The **mounting structure** holds the modules in place. It must take all mechanical loads, potential wind loads, snow cover, and thermal expansion/contraction with an expected lifetime of at least 20 years. In building applications water tightness is often needed as well. Module mounting and wiring should be simple. The replacement of individual modules should be possible without dismantling the whole PV generator. Advanced mounting structures for PV facades provide easy laying of the string cables, e.g. in integrated ducts.

## 6.5 Hazards and protection

PV modules (and generators) are current sources. There are differences from common electric power sources like the public grid, a motor generator or a battery. This requires some mental reorientation for all people working with either technology. Furthermore PV generators cannot be switched off. As long as the generator is illuminated, a voltage is present at the PV generator output terminals. Installers must be aware of this.

Due to the current source characteristic of the array, overcurrent is not a problem. Under normal conditions a module or a generator can be shorted without endangering the cables. On the other hand certain fault conditions like short circuits cannot be cleared by a fuse. Thus, once a short circuit develops, it can last as long as the sun shines and might cause severe damage to the installation and even start a fire. This fault cannot be handled properly, so the installation of the generator has to be done in a way that virtually eliminates the possibility of such an incident. Using "ground-fault-proof and short-circuit-proof installation provides an acceptable way to cope with this hazard.

If a high system voltage is chosen, it poses the same hazard of electric shock *as* any conventional installation at the same voltage level. National electrical codes address this issue and should be consulted.

Partial shading of modules may cause "hot spot" effects and can damage PV modules. To avoid this, "bypass" diodes should be used according to the module manufacturer's specification.

Overvoltage/lightning hazard depends strongly on the location and the size of the generator.

Modern PV modules are generally very rugged, but electrical equipment like inverters are usually more sensitive. If varistors for overvoltage protection (OVP) are used, attention must be paid that ageing may lead to increased leakage currents through the device. This may eventually lead to overheating and cause a fire. Therefore, these devices should be monitored for increased leakage currents, either by an internal temperature dependent switch or by external insulation monitoring.

## 6.6 Grounding

There are two distinctly different grounding functions:

- Generally metallic enclosures of electrical equipment must be grounded to prevent a hazardous touch voltage, if an internal insulation fault develops. Similarly metallic enclosures of equipment in PV-systems should be bonded to ground. A PV generator's metallic support structure should also be grounded: no touch voltage can develop and in case of a direct lightning strike the grounded support structure may provide a convenient path for the lightning current. (If the PV generator is protected by an external lightning protection system, consideration should be given to leaving the support construction ungrounded to prevent coupling effects via ground.)

  Lightning protection devices should be directly connected to ground on a path as short as possible.

- Grounding of active parts of the PV generator is a different issue. It is possible to ground either leg of the PV generator or use a grounded center tap. This measure assures a well defined potential at the PV-generator. However, not to ground the PV generator seems advantageous in terms of reliability and personal safety. A first ground fault in a floating PV generator would not cause a hazard and the system could by left in operation. At a grounded PV generator the first isolation fault would constitute a shock hazard and should be immediately cleared.

The issue of grounding is dealt with in most countries' electric codes. These codes should be carefully consulted before defining the grounding system for a PV generator to make sure that the local code is obeyed.

## 6.7 Accessibility and protection against electric shock

A person touching a cell of a broken module should be protected against electrical shock. The IEC TC 82 working group WG 3 has drafted safety rules for PV systems: "Safety Regulations for Residential, Grid Connected PV - Power Generating Systems". The draft is based on the standard IEC 364. It offers several "protective measures" against electric shock. These are:

**Safety extra low voltage, protection class III** If the open circuit voltage of the solar array is lower than 120 V (25 °C, 1000 W/m$^2$) and the inverter has an isolation transformer, no special safety actions are necessary. No fence is needed even if the modules can be touched (e.g. at facades and motorway sound barriers).

**Protective insulation, protection class II**
If the solar modules, the array and the cabling are designed under the rules of protection class II (protective insulation) no fences and isolation transformers have to be used even when the open circuit voltage is higher than 120 V. Up to now only a few solar modules with protection class II rating are available.

**Mounting out of reach**
If the solar panels are not specified according to protection class II and the open circuit volt-

age is higher than 120 V, the modules must be installed in a way that they cannot be reached by persons. In Germany the roof of a house is commonly accepted *as* such a place. Most larger PV plants are installed inside a fence because high array voltages are used .

**Special protection actions**

There are some situations where higher voltages ( $V_{OC} > 120$ V) are needed, but fencing is not practicable and an enhanced protection level is desired.

- Alpine PV-projects with varying snow situations (2 - 5 m of snow);
- PV installed on motorway soundbarriers;
- PV on the facade of a building.

In this case the PV-array will be operated floating (not grounded). The inverter has to be equipped with an isolation transformer and an automatic ground fault detection device. As long as there is no ground fault any pole of the DC system can be touched without danger. If a ground fault is detected the solar generator will be shorted and the active poles ($+V_{DC}$ and $-V_{DC}$) will be connected to ground until the failure is found. At utility scale installations the ground fault message will be transmitted automatically to the headquarters by a telephone link and immediate action can be organized.

To reduce voltage stress on the modules the solar generator of large PV systems can be center tap grounded.

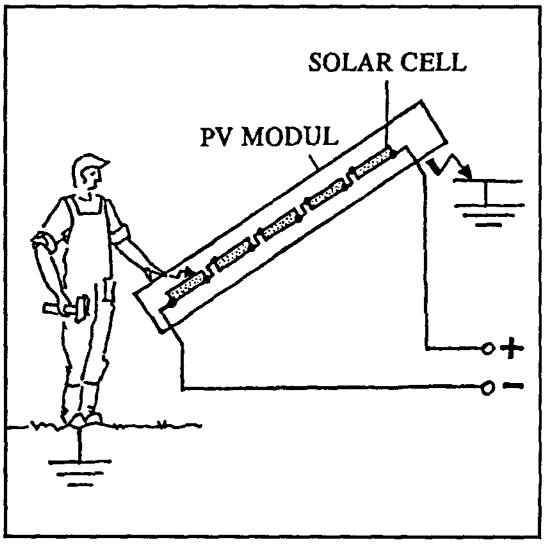



*Figure 6.4 Electrical Safety (IEC TC 82).*

Chapter 7

# Energy Storage

## 7.1 Background

A basic characteristic of sunshine is that it is variable on both daily and seasonable basis. This causes electricity production of photovoltaic modules to vary correspondingly. The mismatch between the electrical load and the electricity production must be balanced by using some kind of energy storage device.

In grid-connected PV buildings an energy storage device is usually not needed, but in off-grid houses the storage element plays an important role. The main characteristics of energy storage systems for PV building applications are cost, cycle life, availability, ease of operation and maintenance. The importance of volumetric and gravimetric energy densities will vary depending on the application. There are several energy storage possibilities from which only a few are suitable for PV-building applications. In Table 7.1 an overview of some energy storage possibilities is shown.

**Present options**

Lead-acid (Pb-acid) batteries and nickel/cadmium (Ni/Cd) batteries are the present options for PV building applications. These two types of batteries are well known and available to the consumer. There are limitations with respect to energy density, cycle life, temperature of operation and toxicity (both lead and cadmium are toxic) associated with both of these systems.

**Medium term options**

Alternative energy storage options are being developed through intense research and development. The sodium/sulphur (Na/S) system has a very high specific energy density. However, for consumer applications like PV in buildings it operates at too high temperatures. Zinc/bromine ($Zn/Br_2$) flow batteries, which have a fairly high specific energy density also, operate at ambient temperatures and necessitate flow-loop infrastructures. The installed cost of these batteries has been projected to be lower than that of improved lead-acid and nickel/cadmium batteries. Advanced lead-acid and nickel/cadmium batteries are also medium term options. Other medium term options are nickel-based batteries such as nickel/hydrogen, nickel/metal hydride, nickel/iron and nickel/zinc batteries.

Sodium/sulphur and zinc/bromine batteries are closer to commercialization than other medium term options. However, because of very good cycling performance, the nickel and nickel/metal hydride batteries have been identified as possible candidates for PV systems. The nickel/metal hydride battery could eventually replace nickel/hydrogen in metal. It can also replace nickel/cadmium systems, thereby eliminating toxic cadmium, unless the later is recycled.

**Long-term options**

Iron/chromium redox flow batteries and rechargeable zinc/manganese dioxide batteries are long term options for PV systems.

| Battery type | Energy density | | Operation temperature | Self discharge at 20°C | Cycle life | Charge-discharge efficiency | Relative price per kWh initial cost |
|---|---|---|---|---|---|---|---|
| | [Wh/kg] | [Wh/l] | [°C] | [Capacity-%/month] | [cycles with 60...80% DOD] | [%] | |
| **Present options** | | | | | | | |
| Lead-acid (vented) | 20...45 | 40...100 | -20...+50 | 2...4[1] | 200...2000 | 70...80 | 1 |
| Lead-acid (sealed, gelled) | 10...30 | 80 | -20...+40 | 2 | 500 | 70...80 | 1...2 |
| Nickel/Cadmium, pocket plate (Ni/Cd) | 15...45 | 40...90 | -20...+50 | 2 | >5000 | 60...75 | 3...5 |
| **Medium term options** | | | | | | | |
| Nickel/hydrogen (NiMH or Ni/$H_2$) | 40...60 | 60...90 | -5...+40 | 15...30 | 3000...6000 | 80...90 | 5...10 |
| Advanced Nickel-iron (Ni/Fe) | 22...60 | 60...150 | -10...+50 | 20...40 | 1000...2000 | 40...60 | 1...1.5 |
| Nickel-zinc (Ni/Zn) | 60...90 | 120 | -10...+60 | 10 | 250...350 | 75 | 2 |
| Sodium/sulphur (Na/S) | 100...250 | 150 | 300...400 | N.A. | 900...2000 | 75...90 | 0.5...1.5 |
| Zinc/bromine (Zn/$Br_2$) | 55...75 | 60...70 | -10...+50 | N.A. | 600...1800 | 70...75 | 0.5...1 |
| **Future options** | | | | | | | |
| Iron/chromium redox (Fe/Cr redox) | N.A. | N.A. | 0...+65 | N.A. | 20000 | 60...75 | 1 |
| Rechargeable zinc/manganese dioxide (Zn/$MnO_2$) | 70 | 160 | -15...+65 | 2 | 200 | | 1...2 |
| Hydrogen storage (Fuel cell, electrolyser, gas storage)[2] | N.A. | N.A. | -20...+50 | 0 | N.A. | 35...50 | 41 |

[1] Lower value for non-antimony and high value for low-antimony batteries
[2] Economical only in large sizes (> 100 kWh energy storage) and for long term seasonal storage.

*Table 7.1 General specifications of energy storage options for PV systems.*

The combination of an electrolyzer, gas storage and a fuel cell makes an ideal energy storage for PV systems. During the summer day excess PV energy is used to power the electrolyzer, which produces hydrogen and oxygen from water. The hydrogen gas is stored in a pressure vessel. At night or in winter, when insufficient PV energy is available, hydrogen from the gas storage and oxygen from the atmosphere are fed to the fuel cell stack, in which gas to water conversion and electricity production takes place. Commercialization of this kind of energy storage systems based on hydrogen technologies is projected for the first years in the new centennial.

## 7.2 Lead-acid batteries

### 7.2.1 General

Lead-acid batteries have been in use for over 150 years and continue to dominate the automotive, power backup and traction markets. The main reason for this is their relatively low cost and their long and reliable service life. They come in many shapes, sizes, types and designs depending on the application. They can be sold as single cells or more commonly as a series combination of 6 cells to form a 12 V battery.

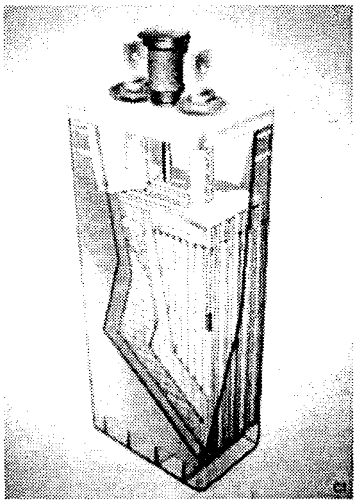
Batteries are often sold by their amp-hours (Ah) of nominal capacity: car batteries by their 20 hour capacity and power backup batteries by their 8-hour capacity. This indicates how much energy can be removed during a single discharge. Small PV systems, up to about 120 Ah, mainly use modified car or truck batteries. Unfortunately, certain types of car batteries are unsuited particularly for solar applications and can have a rather short service life (1-2 years). This is because they have been designed to give high currents for starting a car or truck but not for cycle duty as required in solar applications.

*Figure 7.1 Different lead-acid battery models.*

Until recently all batteries were of the flooded design with the plates and separators totally immersed in acid. For certain remote solar applications, batteries are designed in which additional acid is added to the container to lengthen the time between addition of distilled water. In order to overcome the trouble of periodically adding distilled water, batteries are also being produced as gas recombination batteries. These are sealed lead-acid batteries also known as valve regulated batteries. Here the gas produced during charging recombines in the cell to form water.

### 7.2.2 Structure and principles of operation

All lead-acid batteries have the same general structure. The main components of a single cell are positive and negative plates, terminals, separators, sulphuric acid ($H_2SO_4$), container, terminal sealings and a safety plug. The plug is used mainly to minimize acid mist, but also to decrease the volume of escaping gases generated by gassing reactions occurring at later stages of charging. In Figure 7.2, the general structure and the main components of a single cell stationary battery are shown.



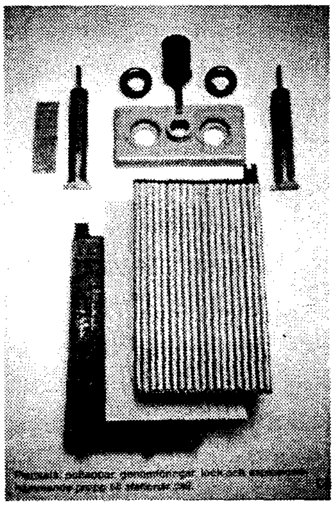


*Figure 7.2 Single cell flat plate stationary lead acid battery*
*a) General structure (top)*
*b) Main components (bottom).*

The negative plate or anode is composed of a negative grid pasted with sponge lead (Pb), the positive plate or cathode is a positive grid pasted with lead dioxide ($PbO_2$). The electrolyte is sulphuric acid ($H_2SO_4$) in water solution, which also participates in the discharge reaction according to:

$$Pb + Pb0_2 + 2\ H_2SO_4 \rightarrow 2\ PbSO_4 + 2\ H20.$$

The reverse reaction occurs during charging, sulphuric acid is formed as lead sulphate is converted into lead and lead dioxide.

The acid concentration in lead-acid batteries varies depending on its use. For car batteries it is approximately 38%, (specific gravity 1.28 $kg/dm^3$), while in standby batteries it can be as low as 32% corresponding to a specific gravity of 1.22 $kg/dm^3$. The nominal cell voltage is 2 V, but the actual open circuit voltage of a fully charged cell is in the range of 2.1 V...2.4 V depending on acid density and temperature. During discharge, the operating cell voltages decrease from above average to the cut-off between 1.75 V and 1.9 V. This cut-off voltage is very important for the battery lifetime as it defines the depth-of-discharge (DOD). The DOD is both rate and temperature dependent (see section 7.5) At very low rates, the battery capacity can actually be higher than the 20 hour or 8 hour nominal capacity thus giving a DOD of greater than 100%. Therefore, at low rates the cut-off voltage can and should be quite high. The capacity increase at low discharge rates has two causes. The first is that the fine pores in the plates do not block as $PbSO_4$ is formed and acid can penetrate deep into the plates. The second reason is that the voltage drop across the battery itself, which is the product of current and the battery's internal resistance, is rate dependent. At low rates, the voltage drop is low and the capacity can be high. During charging the applied voltage must be in the range of 2.3 V...2.5 V per cell in order to charge the battery in a reasonable time. During the later stages of charging, gassing occurs producing hydrogen and oxygen from water. This has the beneficial effect of stirring up the electrolyte and avoiding acid stratification. However, gassing increases the water consumption and also needs routine maintenance.

Acid stratification is caused by the continuous deep discharging and charging of batteries without stirring of the electrolyte between cycles. It is especially problematic in tall cells (> 60 cm) where the acid density can range from > 1.4 kg/dm3' at the bottom to < 1.2 kg/dm' or less on top. This causes non-uniform discharging of the plates, reduces capacity and shortens operating life.

The grids of lead-acid batteries are normally composed of lead plus a variety of metals in concentrations ranging from 0.1% up to 5-8% of the grid weight. Battery grids can be made of pure lead, but due to the softness of the metal, a special manufacturing technology must be applied. Antimony is used in positive grids from 0.5% to 8% to strengthen the grids and to improve its cycling characteristics. But antimony will also increase the gassing reactions and self-discharge. Small amounts of calcium (0.1-0.7% of the grid weight) can also be used to improve grid hardness but it does not improve the cycling performance of the battery as antimony does. However, a battery with calcium has the advantage of lower self-discharge and less gassing than an antimony battery. Other metals such as tin, arsenic and silver may also be added to improve castability, metallurgical and mechanical properties.

### 7.2.3 Lead-acid battery classification

Lead-acid batteries can be classified according to numerous methods such as: sealed or non-sealed; by application: car, power backup, traction; by type of positive plate: flat or tubular. For PV applications a useful classification is:

- antimony (deep cycle)
- non-antimony (shallow cycle).

Antimony batteries cannot be hermetically sealed because antimony promotes the gassing reactions that occur at the end of charging. But antimony can be used with other types of batteries. Tubular plate batteries are often used for cycling purposes with antimony concentrations up to 8% (traction batteries) but are more expensive than flat plate batteries and are usually not available for consumer use. However, PV applications typically have shallow cycles and therefore grid alloys with 1...3% antimony are sufficient. With higher antimony levels gassing and maintenance needs increase too much for most PV applications.

The non-antimony batteries are typically made with calcium alloys and the main advantage of these is reduced maintenance and low self-discharge causing long shelf life. Flooded type batteries must always have a small opening to let the gases escape. Those gases contain hydrogen and oxygen and can be explosive and harmful. If the battery is made as sealed type, the gases formed during charging will recombine in the battery to form water. In order to achieve rapid recombination of the gases, tiny gas passages must be formed between the plates. This is done either by forming an electrolyte of silica gel or by using glass fiber separators. The disadvantage of these batteries, besides the fact that they don't cycle *as* well as those containing antimony, is that it is very important to limit the charging voltage near the end of charge to under 2.35 - 2.4 V per cell. At higher voltages the gassing reaction will be faster than the recombination reaction and the battery will dry out due to the escaping gases. This voltage limit will lengthen the charging time.

### 7.2.4 Factors affecting lead-acid battery life

Service life of a PV battery can be determined by cycle life (if the regular cycling is quite deep) or by positive grid corrosion (if the regular cycling is quite shallow). Normal car starter batteries have thin plates, and both cycle life and resistance to corrosion are low compared with other types of lead-acid batteries. In many cases, especially where the service life is controlled by positive grid corrosion, flat plate batteries with thick lead grids can have an expected service life approaching that of tubular plate batteries.

The useful service life of a battery is normally considered completed when the battery can no longer do the job. This is often when the capacity has decreased to less than a certain percentage (e.g. 80%) of the nominal capacity. The most common failure mode of a battery is the gradual loss of capacity caused by a combination of active material degradation due to cycling and grid corrosion. But other failure modes are possible such as cell shorts, cracked cases or broken plates, which lead to a sudden loss of capacity. The most common factors affecting battery life are listed below:

- deep (>50%) daily discharging, which causes positive plate shedding (sludge formation at the positive plate),
- high temperatures that speed up corrosion,
- prolonged overcharging which increases the rate of corrosion,
- prolonged undercharging leading to sulphation (white spots) and acid stratification which reduces plate capacity,
- antimony levels of 1...3% which increase cycle life.

Other factors such as a low electrolyte liquid level will also severely shorten the battery lifetime.

Sulphation occurs after a battery has been deeply discharged which in PV applications could occur during prolonged cloudy periods. Here lead-sulphate crystals which are always formed during battery discharge begin to grow and convert slowly into a form that is very difficult to recover. Permanent loss of capacity can occur. Additionally, after a battery has been continuously deeply discharged, acid stratification takes place. This can be avoided by overcharging the battery thus forming gases which stir up the acid. In larger systems, air lift pumps can be used to ensure uniform acid density.

### 7.3 Nickel/cadmium batteries

#### 7.3.1 Principles of operation and characteristics

In nickel/cadmium batteries, hydrated nickel oxide (NiO) is the cathode and cadmium (Cd) is the anode during discharge. A potassium hydroxide water solution is used as the electrolyte. The cell discharge reaction is shown below:

$2NiO\text{-}OH + Cd + 2H_20\ 2Ni(OH)_2 + Cd(OH)_2.$

The reverse reaction occurs during charging. However, the reactions are not nearly as simple as indicated particularly at the positive electrode. This is illustrated by the shape of the charging curve presented in Figure 7.3.

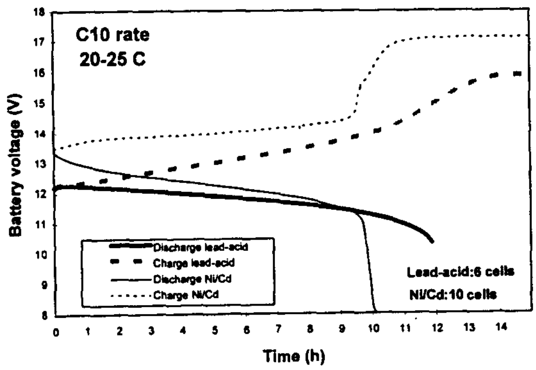



*Figure 7.3 Nickel/cadmium and lead-acid battery voltage during charging and discharging at 25° C and with 10 h rate.*

Nickel/cadmium batteries are mechanically rugged and have a long cycle life. They have better low temperature characteristics down to -20° C. Problems of electrolyte stratification or sulphation like in lead-acid batteries do not occur in nickel/cadmium batteries. The nominal cost per Ah is 3-5 times higher than for lead-acid batteries. The battery can be cycled deeper. High cycle life and the capability to be operated at low temperatures partly compensate the higher investment. The rapid voltage increase during the final stage of charge indicates that the energy efficiency is low if the battery is fully charged. In practice, because electrolyte stirring is not needed like in lead-acid batteries, Ni/Cd batteries do not always have to be fully charged. Typically the end of discharge voltage is 1.0 V/cell.

### 7.3.2 Ni/Cd types available

Nickel/cadmium batteries are available in sealed or vented types. Vented types are made as sintered plate or pocket plate construction. A sintered plate is fabricated by impregnating the active material into a nickel support plate. With this design, a lower internal resistance and sensitivity to variable temperature operation can be achieved than with a pocket plate construction. Here the active material is contained in perforated pockets and features a more rugged plate structure than the sintered type. Batteries with pocket plate design have extended cycle life and the ability to withstand extended periods at partial state of charge without sustaining damage. Sintered plate cells have a tendency to suffer from a "memory effect" phenomenon. This effect is caused by repeated incomplete discharge, which eventually results in capacity reduction, since the "remembered" capacity appears to be smaller than the actual one. This temporary effect can sometimes be eliminated by subjecting the cell to occasional single deep discharge/charge cycle.

Sealed nickel/cadmium batteries were first developed in the 1950s from vented sintered plate nickel-cadmium batteries. The original sealed batteries used the same active material and similar intercell components *as* those used in vented batteries. Since this time, materials and production techniques have improved, enabling the sealed battery performance to improve, both in terms of charge retention and discharge capacity.

Vented pocket plate Ni/Cd batteries are produced in capacities from 10 to 1200 Ah single cells and monoblocks, while commercially available sealed sintered plate cells range mainly from 0.1 to 23 Ah in sizes of typical primary batteries. Vented sintered plate cells are made up to sizes of 1000 Ah of single cells and monoblocks.

### 7.3.3 Factors affecting nickel/cadmium battery life

In sintered nickel/cadmium batteries, deep-discharging is actually beneficial because the "memory effect" that results from shallow discharge can be avoided. Improvements in the metallurgical structure due to plate fabrication and design are important issues in controlling the "memory effect" and cycle life of the nickel/cadmium batteries. Electrolyte agitation is unimportant for nickel/cadmium batteries, but fouling through carbonation (caused by $CO_2$ in the air, e.g. batteries left near exhaust of diesel generator) of the alkaline electrolyte decreases the battery life.

## 7.4 Safety aspects

Environmental aspects of batteries should be considered from the point of view of the life - cycle of the battery. Environmental safety, i.e. pollution prevention is an important issue. For all batteries, recovery of battery degradation products after their useful life should be controlled.

Battery safety during operation is also important. Gassing during charging produces hydrogen and oxygen gas, which under certain conditions can lead to explosion or fire. In order to avoid this, vented batteries should be placed in a well-ventilated area and away from other electrical components that could produce a spark. The required ventilation depends on the size of the battery and its charging rate. Sealed batteries with low discharge/charge rates can often be stored inside without ventilation, since most buildings are not airtight. However, as a general principle, it is advisable to provide ventilation even when sealed lead-acid batteries are used. Also, batteries should be placed in cool and dry surroundings where possible.

Vented lead-acid and nickel/cadmium batteries are subject to explosion hazard in case the venting valves become plugged. Periodic maintenance can prevent this hazard.

Cell imbalance is also a safety issue and the imbalance occurs when one or more cells in a series string are weaker than the rest, which can lead to cell shorting. It is important to annually monitor the individual cell performance to identify weak or shorted cells. Cells, which are clearly weaker than the average should be removed from the series string since they lead to overcharging of functioning cells. This condition will cause unnecessary gassing. Modern methods to avoid all imbalances are treated in Chapter 8 (e.g. CHarge EQualizing).

Batteries can also be an electrical shock hazard. Insulated tools should always be used. DC isolation switches should be used when working on other parts of the system. Service technicians must be trained about the hazards associated with large battery storage units. The electrical power available from a large storage bank is very high, a short circuit current of 1000 A to 4000 A is readily obtainable from a single cell.

The electrolytes used in most PV system batteries are corrosive. Sulphuric acid in lead-acid batteries, and potassium hydroxide in Ni/Cd batteries can cause burns when in contact with skin. A small amount of electrolyte in the eye can result in blindness if not immediately flushed with water. The use of safety glasses or safety face shields should be mandatory while performing maintenance on these batteries.

## 7.5 Interpretation of the manufacturer's data sheets

Battery manufacturers provide general information such as cycle life, float life, battery capacity, battery voltage and operational temperature range along with cost upon request. Field experience indicates that this information cannot necessarily be applied directly to PV applications. Typical parameters like cycle life and capacity are measured under controlled laboratory conditions. However, in PV applications the operating conditions are quite variable. There is no standard cycle and both high temperatures and poor charging can reduce cycle life by 10% to 50%. The battery capacity (in Ah) also depends upon discharge rate, temperature and cut-off voltage. Thus, performance comparison of batteries of different manufacturers on the basis of their datasheets is not straightforward.

An important battery parameter is its **nominal capacity (Ah).** However, the **usable capacity** of a battery is more important than the nominal capacity and it depends upon how the battery is being charged and discharged. The usable capacity decreases with an increase in discharge rate and decrease in temperature. Usually, if more storage capacity is required, bigger cells are used, and if higher voltage is required, they are connected in series. Batteries are seldom connected in parallel.

The **discharge rate** of a battery is expressed in amperes or in discharge time.

$$Rate(A) = \frac{Capacity(Ah)}{Discharge\ time(h)}$$

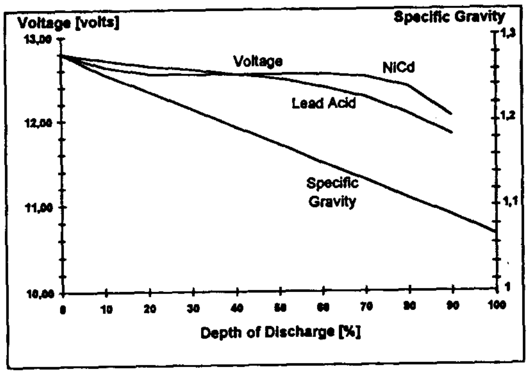



*Figure 7.4 Effect of depth of discharge (DOD) on Ni/Cd and lead-acid battery voltage and specific gravity of lead-acid batteries at a certain temperature during discharge.*

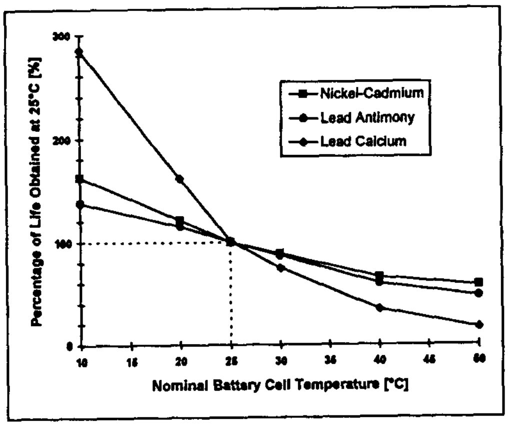



*Figure 7.5 Effect of temperature on lead-acid and nickel/cadmium battery*

For example, if a battery is discharging at a rate that would take 50 hours to fully discharge to the "cut-off' voltage, then the battery is considered to discharge at $I_{50}$ current or "50 h" rate ($C_{50}$). For typical PV applications a $C_{100}$ rate is desirable but *as* low as $C_{500}$ is possible in some cases.

**The battery voltage** depends on the type of battery, state of charge, rate of discharge or charge, temperature and acid density. It is higher while charging than during discharging. Figure 7.4 shows how the specific gravity and voltage of a lead-acid battery and of a nickel/cadmium battery voltage vary with depth of discharge or state of charge during discharge.

Figures 7.5 and 7.6 show the effect of temperature and discharge on delivered capacities and lifetime of lead batteries. It can be seen that with an increase in temperature battery life decreases more with sealed than with flooded lead-acid. Higher discharge rates and low temperatures decrease the delivered capacity. The temperature and discharge rate do not as much effect the Ni/Cd battery capacity as they do in lead-acid batteries.

Battery manufacturers' data sheets provide a general overview or a range of characteristics under an envelope of operating conditions. Hence, testing of the candidate batteries under predicted or simulated PV service conditions is quite important. If this is not possible, the data provided by the manufacturer should be used and extrapolated for the PV conditions.

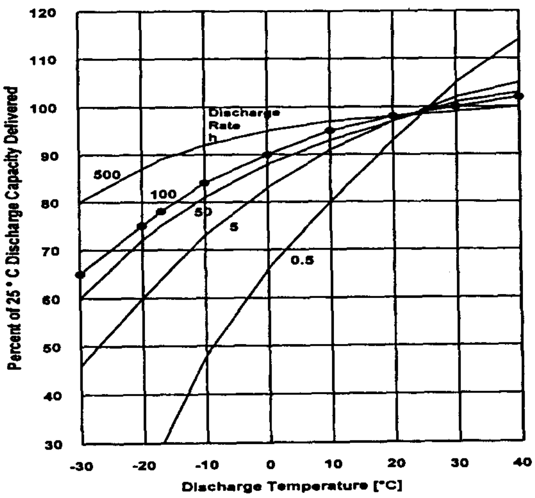



*Figure 7.6 Effect of discharge rate and temperature on capacity of lead-acid batteries.*

## Chapter 8

# DC Power Conditioning

### 8.1 Introduction

The solar generator, the heart of a PV system, fundamentally produces DC currents and DC voltages. This DC power can either

- be used without intermediate energy storage by directly coupled consumers like electric fans or circulation pumps in solar thermal systems,
- be stored in a battery and supply stand-alone systems like small appliances, lamps or even remote houses or
- be fed into the public grid by DC to AC converters.

In almost all cases, special power conditioning units are required for:

- the optimal operation of the solar generator and
- the optimal and safe operation of the connected electrical equipment.

Depending on the application, the following power conditioning units (PCUs) may be needed in a PV system:

- DC to AC converters (inverters),
- matching DC/DC converters (MCs),
- charge controllers.

Considering PV applications in buildings, the inverter is one of the key components. For this reason, inverters for grid-connected as well as for stand-alone systems will be discussed in detail in Chapter 9.

In this chapter, the question of how to connect PV generators to different loads will be answered.

### 8.2 Matching of solar generator and different loads

#### 8.2.1 General

The power produced by a solar generator in a given operating point can be calculated by multiplying the corresponding current and voltage. Doing this from short circuit to open circuit conditions at constant insolation leads to the power curve shown in Figure 8.1.

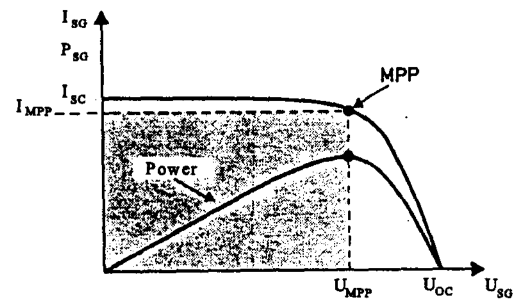



*Figure 8.1 IV curve and power curve for constant insolation.*

The output power is zero when the terminals of the generator are short-circuited or left open, and between these two extreme operating points there is one combination of current and voltage on the IV curve where their product (the resulting rectangular area) is maximal. This special operating point is called the Maximum Power Point or MPP. To gain as much energy as possible, the solar generator should theoretically be operated close to the MPP under all conditions of insolation, temperature and changing loads. However, experience shows that the energy gained by tracking the MPP is often overestimated, especially when the losses in the PCU due to self-consumption and incorrect operation are taken into account. Although many PCUs with MPP tracking capability are available on the market, the value of such an additional component should be evaluated thoroughly.

The following three examples give some general guidelines.

### 8.2.2 Coupling of PV generator and batteries

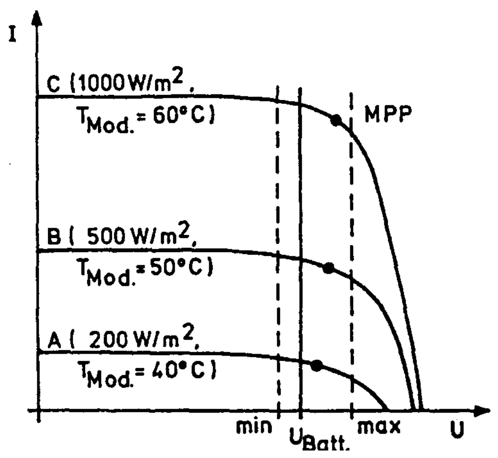



*Figure 8.2 Typical PV generator IV curve for three different insolation values.*

Figure 8.2 shows a typical PV generator IV curve for three different insolation values. In contrast to the IV curves normally given in data sheets, here the influence of increasing module temperature with increasing insolation for a typical way of module mounting has been considered. Furthermore, the N curve of an ideal battery (a vertical line) is shown, which varies within a given voltage range depending on the state of charge (e.g. 11 V to 14.4 V for a 12 V lead-acid battery).

From Figure 8.2 it can clearly be seen that during charging, the PV generator is operated close to the MPP without any additional control if the nominal voltage of the PV generator is chosen appropriately (in practice 33....36 crystalline silicon cells for a 12-V lead acid battery). This statement applies also for direct coupling of PV generators and electrolysers.

### 8.23 Coupling of PV generator and grid-connected inverter

The operating voltage of a PV generator connected to the input of a grid-connected inverter is determined by the control algorithm of the inverter. Therefore, the input characteristic of a grid-connected inverter is a vertical line, as above. The terminal voltage of a battery is determined by its state of charge and cannot be influenced by the operator or by a control algorithm. In contrast, the input voltage of a grid-connected inverter can easily and instantaneously be shifted by an MPP-Tracker implemented either in the hardware or the control software. In general, there is no need for additional power electronics that cause extra energy losses. From this point of view, MPP tracking can be recommended for grid connected inverters.

### 8.2.4 Coupling of PV generator and DC motors or ohmic loads

The IV curve of fans or pumps driven by DC motors can be approximated by sloped lines as shown in Figure 8.3 for three different ohmic loads.

Load curve 2 is optimally matched to the IV curve B at medium insolation, but at lower and higher insolation (curves A and C, respectively) there are considerable energy losses due to mismatch (the operating points are far away from the MPP). In all three cases, there is a clear mismatch at most insolation values - in many cases the best compromise will be system dimensioning according to curve 2. To overcome the mismatching problem fundamentally, a matching DC/DC converter (MC) is switched between the PV generator and the load as shown in Figure 8.4.

It is the task of this MC to keep the operating point of the PV generator close to the MPP under all operating conditions. In contrast to normally used DC/DC converters where the output voltage is controlled and stabilized, in this application the input voltage (PV generator voltage) is kept at a constant value. This voltage can either be manually adjusted by the user or automatically track the MPP by an appropriate control algorithm. The output voltage will vary depending on the input power and load characteristics.

Using an MC can cause a considerable increase in power, especially at low insolation levels, which leads to a much earlier start of pumps and fans etc. Therefore, MCs are often already built into pumps or available as extra components on the market under trade marks such as "Maximizer", "LCB" (Linear Current Booster) or "APW" (Anpaßwandler). Some of these units provide additional features such as an adjustable output voltage limiter ("dimmer") or remote control inputs for submersible pumps.

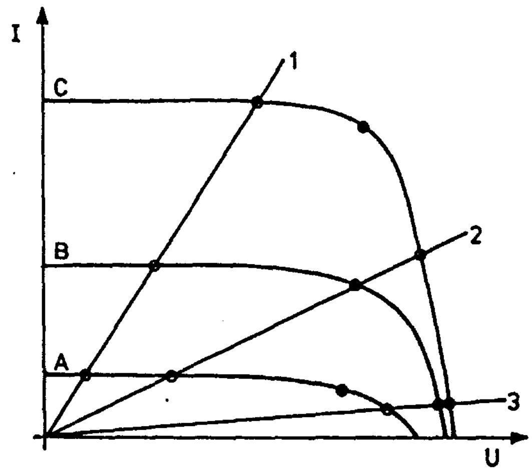



*Figure 8.3 IV curves of PV generator, electric fan (dotted line) and three different ohmic loads.*

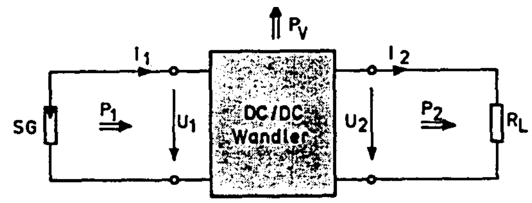



*Figure 8.4 Matching DC/DC converter.*

## 8.3 Maximum Power Point Tracking (MPPT) algorithms

Developing MPPT algorithms is a challenge for every engineer, so a large variety of different types has been invented. The mostly used algorithm is able to find the MPP of the IV curve under normal operation. To find the MPP, the operating voltage of the PV generator is periodically (e.g. every few seconds) changed by a small amount. If the output power of the PCU increases due to this change, the operating voltage will be changed in the same direction at the next step. Otherwise, the search direction will be reversed. The operating point thus swings around the actual MPP. This very simple algorithm can be improved, e.g in order to suppress steps in the wrong direction due to rapidly changing insolation.

## 8.4 Charge controllers

### 8.4.1 General

Most of today's PV applications require energy storage due to time shifts between the energy supply and demand. In a typical power supply for remote houses, this energy storage represents approximately 15 - 20% of the initial cost. Taking into account that during the system lifetime the storage batteries have to be replaced several times, the cost share for batteries can exceed 50% of the total costs over the system lifetime. Experience shows that in most PV applications the battery lifetime is much shorter than expected - sometimes only 2 - 4 years instead of 5 - 10 years as often stated by suppliers. The goal of worldwide intensive research work is to extend the battery lifetime and to develop peripheral battery hardware that is suited to the battery demands.

The main task of a charge controller is to operate the battery within limits defined by the battery manufacturer regarding overcharging and deep discharging. Furthermore, a charge controller can take over automatic and regular "maintenance duties" like equalization charging or overcharging to prevent acid stratification. Advanced charge controllers incorporate a monitoring system that informs the user about the state of charge of the battery and the battery history (e.g. number of deep discharge periods, Ah balance). In larger hybrid systems, the charge controller acts as an Energy Management System (EMS) that automatically starts back-up generators (e.g. diesel gensets) as soon as the battery's state of charge drops below defined limits.

The fundamental principles of state-of-the-art charge controllers as well as an outlook on future developments is presented in the following section.

### 8.4.2 Overcharging protection

As already explained in Chapter 7, batteries must be protected from extensive and prolonged overcharging by reducing the charging current.

Three fundamental principles are commonly used:

**Series controller**

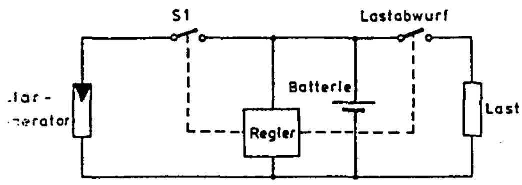



*Figure 8.5 Series Charge Controller.*

To stop the charging process, a switch (relay or semiconductor switch) is connected in series with the PV generator as shown in Figure 8.5. As soon as the battery voltage has reached the end-of-charge voltage, the switch is opened by means of a controller.

One advantage of the series controller is that in addition to PV generators, other energy sources such as wind turbines can also be connected to the input. A disadvantage can be (depending on the circuit design) that the charging process cannot be started if the battery is fully depleted (0 V) because there is no energy to operate the series switch.

**Parallel or shunt controller**

A shunt controller as shown in Figure 8.6 makes use of the fact that a PV generator can be operated in the short circuit mode for any time without damage.

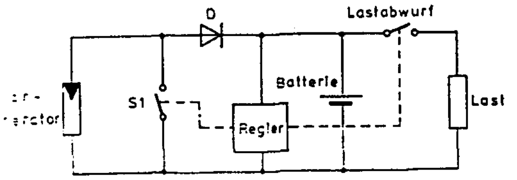



*Figure 8.6 Shunt controller.*

While charging, the current flows through the blocking diode D into the battery. When the end-of-charge voltage is reached, the PV generator is short-circuited by the switch $S_1$. The blocking diode now prevents reverse current flowing from the battery into the switch. Furthermore, it suppresses discharging currents into the PV generator during the night.

In contrast to the series controller, this kind of charge controller will also reliably start charging with a fully discharged battery, because the switch has to be energized only when the battery is fully charged. Most of the charge controllers available on the market are based on the shunt principle.

When the end-of-charge voltage is reached for the first time, the battery is not yet fully charged. The missing 5 - 10% of charge can be added to the battery by keeping it at the endof-charge voltage level for a prolonged period while the charging current slowly decreases. How can such a charging regime be implemented by the series and shunt controllers described above, which can only switch the full PV generator current on and off? The technique used to achieve this behavior is Pulse Width Modulation (PWM) as shown in Figure 8.7.

As soon as the battery voltage reaches the end of charge voltage, the charging current is dropped to zero by either opening the series switch or closing the parallel switch. As a result, the battery terminal voltage decreases. The charging current is enabled again when the battery voltage drops below a threshold that is approximately 50 mV/cell lower than the end of charge voltage. This sequence repeats periodically and while the charging pulses become shorter and shorter with increasing state of charge. The average charging current decreases while the terminal voltage is more or less constant.

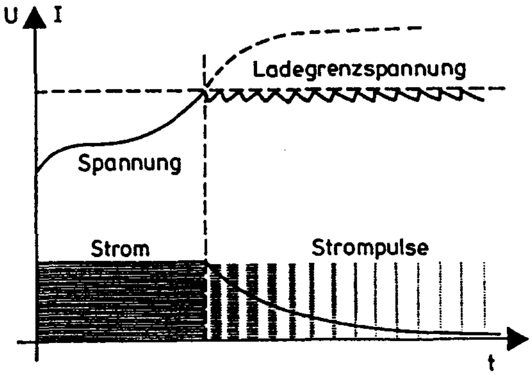



*Figure 8.7 Battery voltage and current during charging.*

**DC/DC converters, MPPTs**

Both the battery voltage and the PV generator voltage vary during operation due to the changing state of charge and boundary conditions such as temperature or insolation. In principle, this leads to a certain mismatch between the battery voltage and the optimum PV generator voltage and therefore causes energy losses. These losses usually are overestimated. If the components are chosen appropriately as shown in Figure 8.2, the energy losses are in the range of a few percent when using direct coupling via series or shunt controllers compared to ideal matching by DC/DC converters and MPPT! Experience shows that charge controllers based on DC/DC converters are not relevant when PV systems' energy output is to be maximized!

Nevertheless, there are two advantages in using such charge controllers:

- there is a greater flexibility in selecting modules and batteries and
- in case of very long wires from PV generator to battery, the generator operating voltage can be chosen much higher than the battery voltage, resulting in lower currents and wiring losses.

The necessity of a matching DC/DC converter has to be checked carefully in any case.

**Charging strategies**

Simple charge controllers are equipped with only one threshold for the end-of-charge voltage. This threshold should be adjusted to 2.3 V/cell for lead-acid batteries at a cell temperature of 20 °C. If the cell temperature differs more than 5 K from this reference temperature, the end-of-charge voltage has to be corrected by -4 to -6 mV/K according to the battery manufacturer's recommendations. More highly sophisticated chargers provide several voltage thresholds combined with timers. They therefore allow e.g. regular overcharging (gassing) of the battery to prevent stratification of the electrolyte. These intervals are based on experience, e.g. gassing every 4 weeks and after each deep discharge cycle. The total gassing time should be restricted to 10 hours per month. During charging, the end-of-charge voltage should be limited to 2.5 V/cell. After that the float voltage should be 2.25 V/cell.

Attention: Never overcharge sealed (maintenance-free) batteries!

### 8.4.3 Prevention of deep discharge

To achieve maximum service lifetime of lead-acid batteries, deep discharge cycles as well as prolonged periods in partially charged conditions should be prevented. When the deep discharge threshold is approached, the load should be disconnected. The load cut-off voltage depends on the battery type and the discharge current. In PV applications it should be relatively high, e.g. 1.80 - 1.85 V/cell. To allow high, but short discharge currents, e.g. to start refrigerators, an appropriate time delay td must be incorporated as shown in Figure **8.8.**

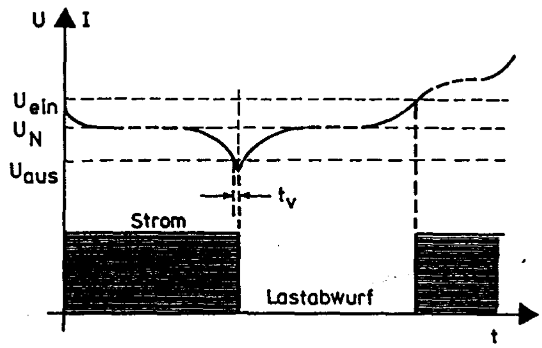



*Figure 8.8 Voltage thresholds for deep discharge protection.*

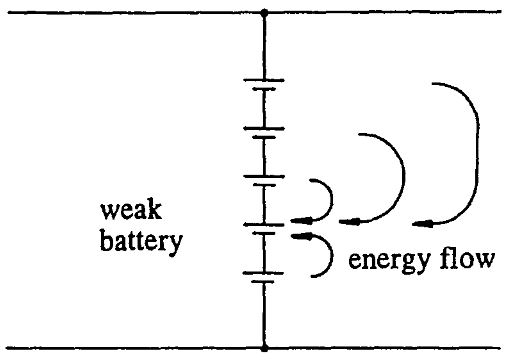
A very important feature is that the load should be connected to the battery after deep discharge only if an adequate amount of charge has been fed into the battery, i.e. the battery voltage is above 2.2 V/cell.

### 8.4.4 Future trends

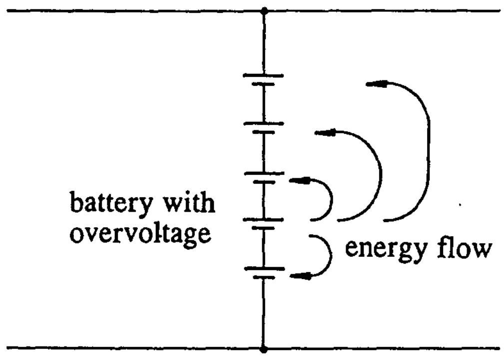
Experience shows that the battery is the "weak link" in a PV system. In the future, specially designed PV batteries should be provided by the manufacturers that withstand deep cycling and partial charging. Furthermore, the simple charge controllers used today should become more "intelligent". One aspect is that a battery is a varying system that changes its major parameters over its lifetime. _Intelligent charge controllers recognize these variations and adapt themselves to the aging battery. In laboratories, there are first examples of such controllers and energy management systems based on neural networks and "fuzzy logic".

Another attempt to extend battery lifetime is the use of so-called CHarge EQualizers (CHEQs). Conventional charge controllers assume that all cells of a high voltage battery string are in the same state-of-charge and therefore simply monitor the overall terminal voltage. In practice, however, each cell has its individual characteristics such as capacity, self discharge etc. This non-ideal behavior of the cells may lead to large inhomogenities in the state-of-charge of cells causing deep discharge or even inverse charging of weak cells or overcharging of other cells.

The new CHarge EQualizer system prevents these inhomogenities by charge transfer between individual cells as shown in Figure 8.9.




a) *Support of weak cells by strong cells.*




b) *Energy transfer from fully charged cell to remaining cells.*

*Figure 8.9 Operating principle of CHarge EQualizers.*

# Chapter 9

# Inverters

## 9.1 General

A photovoltaic (PV) array, regardless of its size or sophistication, can generate only direct current (DC) electricity. Fortunately, there are many applications for which direct current is perfectly suitable. Charging batteries, for example, can easily be done by directly connecting them with a solar module. Inverters are required in systems which supply power to alternating current (AC) loads or feed PV electricity to the utility grid.

Inverters convert the DC output of the array and / or battery to standard AC power similar to that supplied by utilities. Inverters are solid state electronic devices. Broadly speaking, these inverters may be devided into two categories:

- stand-alone and
- utility-interactive (or line-tied).

Both types have several similarities but are different in the layout of the control circuit.

The stand-alone inverter is capable of functioning independently of the public utility grid. The correct timing of the 50/60 Hz AC output is done by an internal frequency generator.

Utility-interactive inverters have the added task of integrating smoothly with the voltage and frequency characteristics of the utility-generated power present on the distribution line.

For both types of inverters the conversion efficiency is a very important consideration > 90% for $P/P_n > 0.1$).

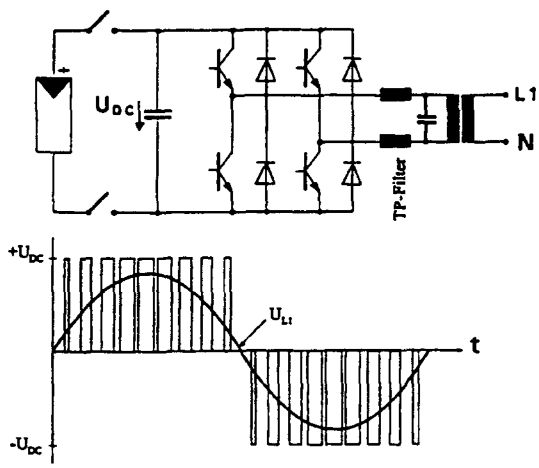



*Figure 9.1 The full bridge inverter circuit.*

## 9.2 Inverters for stand-alone applications

In many stand-alone photovoltaic installations alternating current is needed to operate common 230 V (110 V), 50 Hz (60 Hz) household appliances. Therefore, DC electricity from the battery bank has to be converted to alternating current. The conversion is done by a device called stand-alone or self-commutated inverter. High conversion efficiency is essential for the use in autonomous systems with battery storage. Common stand-alone inverters operate at 12, 24 or 48 V DC.

The shape of the output waveform is an indication of the quality and cost of the inverter. In general it is advisable to install sine wave inverters. By using a control unit with pulse width modulation the switches in Figure 9.1 can be operated in such a way that a sine wave is shaped. The output signal can be improved further by using a low pass filter at the inverter output. For the operation of sensitive loads the harmonic content of the output voltage should be low (THD - non 50/60 Hz oscillations -

lower than 3 - 5%, cost: 1.5 US $/W, 1994).

For some applications a square-wave inverter can be used. This device is based on a 50/60 Hz switched full bridge circuit and is a lot cheaper than a sine wave unit. Conversion efficiency is good but the harmonic content is much higher. Some appliances can be overheated or damaged when connected to a square-wave inverter.

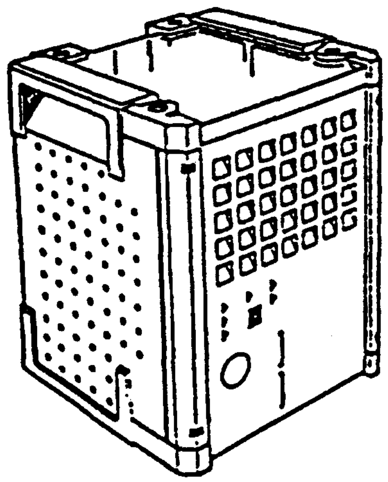


*Figure 9.2 Inverter for a stand-alone system.*

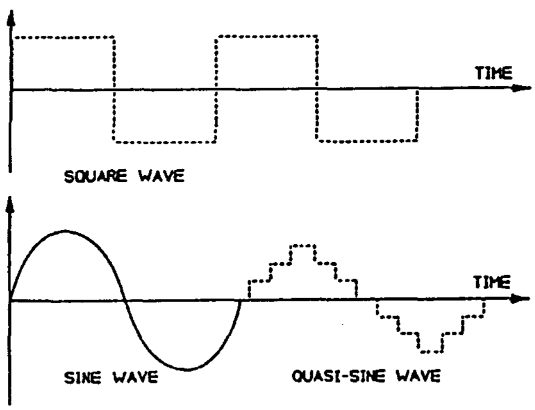



*Figure 9.3 Inverter waveforms.*

The third waveform shown in Figure 9.3 is quasi-sine wave or modified sine wave. This waveform has multiple steps and closely approximates a true sine wave. Modified sine wave is the form of power that modem stand-alone inverters produce and that is acceptable to many AC appliances. Modem inverters are from 85% to 95% efficient and draw minuscule amounts of power in standby mode (for example: 1 W, wake up: 10 W).

In stand-alone applications sizing of the inverter is very critical. The unit must be large enough to handle motor-starting surge inrush currents and the resultant short-duration peak loads. However, care must be taken to avoid oversizing the unit because it will not deliver its peak efficiency when operated at only a fraction of its rated power (see Figure 9.4).

Ideally an inverter for a stand-alone photovoltaic system should have the following features:

- surge capacity (2...4 times P„),
- low idling and no-load losses,
- output voltage regulation ,
- low battery voltage disconnect,
- low harmonics,
- high efficiency,
- low audio and RF-noise.

## 9.3 Grid-connected inverter

### 9.3.1 General

With a photovoltaic array on the rooftop of his house a home owner can produce electric energy for his residential loads (Figure 9.5). Grid connected photovoltaic plants become part of the utility system. The essential device of a grid interactive photovoltaic installation is the inverter. It acts as an interface between the solar array and the utility grid.

The utility-interactive inverter differs from the stand-alone unit in that it can function only when tied to the utility grid. This inverter converts direct current produced by the solar cells into "utility grade" alternating current that can be fed into the distribution network. The utility-interactive inverter not only conditions the power output of the photovoltaic array, it also serves as the system's control and the means through which the site-generated electricity enters the utility lines. It uses the prevailing line-voltage frequency on the utility line as a control parameter to ensure that the PV system's output is fully synchronized with the utility power.

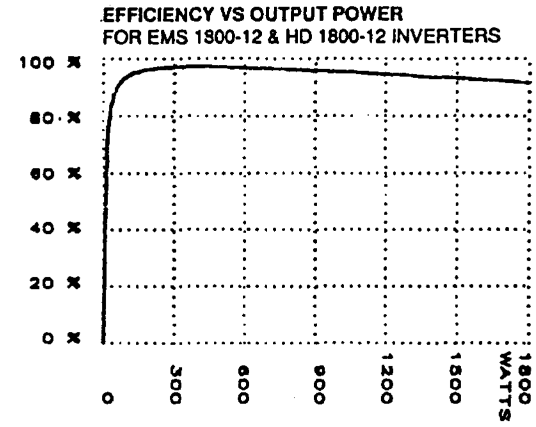
The overall system performance depends heavily on PCU performance. The waveform of the inverter output current should be of almost perfect sine wave shape.

The static power inverter includes a possible means for controlling the entire photovoltaic system. This includes sensing the available array power and closing a grid (AC) side contactor to begin operating as soon *as* possible after sunrise. At night the inverter should be completely switched off.

The control logic of the inverter should include a protection system to detect abnormal operation conditions such as:

- earth fault, DC-side;
- abnormal utility conditions (line voltage, frequency, loss of a single phase);
- inverter switch off when the power stage is overheating.

The inverter should be protected against transient voltages with varistors on the DC- and on the AC-side. The power available from the solar array varies with module temperature and solar insolation. The inverter has to extract the maximum power out of the solar array. Therefore it is equipped with a device called "Maximum Power Point Tracker" (MPPT-unit). With the help of the MPPT-unit the inverter input stage varies the input voltage until the maximum power point (MPP) on the array's IV-curve is found. A new MPP should be searched at least every 1 to 3 minutes.



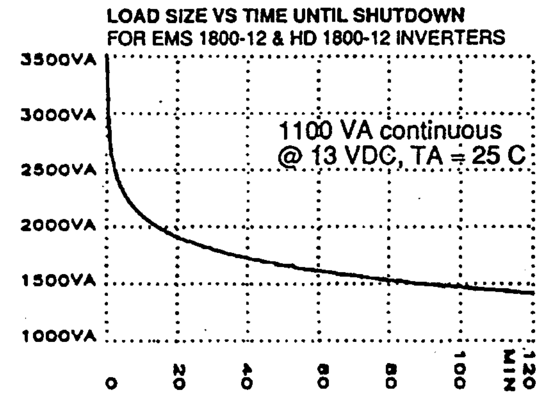




*Figure 9.4 Efficiency and overload capability of a quasi-sine wave inverter.*

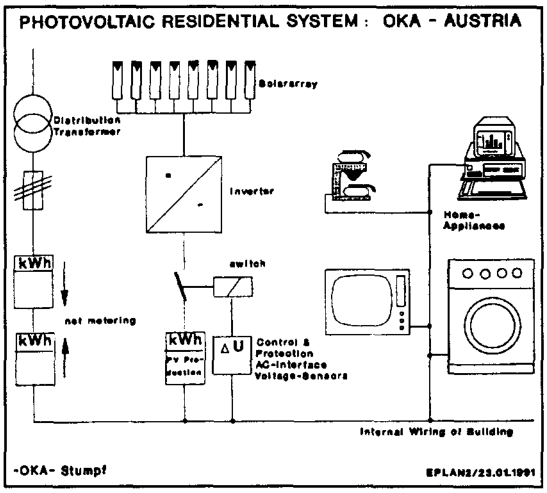



*Figure 9.5 Utility-interactive PV system.*

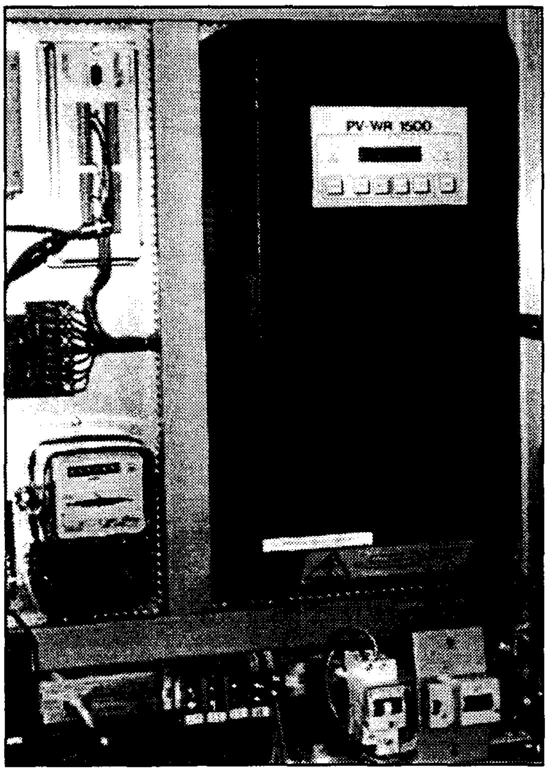



*Figure 9.6 Utility-interactive inverter, 1.5 kW*

### 9.3.2 Inverter specific data

Basic information to be obtained from the inverter manufacturer or dealer:

- Cost (including any required options),
- Array compatibility: number of modules per string, power tracking range,
- Utility compatibility: power quality, harmonics, power factor, electrical isolation, islanding prevention,
- Energy performance: weighted-average efficiency, no load losses, standby losses,
- Warranty provisions,
- Maintenance & repair.

Site information needed for inverter selection:

- PV system size: kW peak,
- Electrical environment: DC system voltage, local safety code requirements, single-phase or 3-phase system,
- Physical environment: type of location, humidity, dust, temperature, noise,
- Utility connection requirements: safety, power quality, trip limits, protection details.

Recommended inverter specifications:

- High conversion efficiency > 92% for $P/P_n > 0.1$,
- Low start-up and shut-down thresholds,
- Power factor > 0.85 (satisfies local utility requirements),
- Low total harmonic distortion of output current: k < 3% at full power (EN 60555),
- Maximum power point operation,
- No shut down if the array power exceeds rated power: -> current limiting function,
- Low power consumption at night: $P_o < 0.5\%$ of $P_n$,
- Automatic disconnect at utility fault conditions (deviations of V, f),
- Automatic restart after fault is cleared,
- AC-ripple of array voltage < 3%,
- Low level of audible noise,
- Low level of RF-emissions measured on AC- and DC-side, VDE 871 B (1.1.1996),
- Type of cooling, e.g. fan,
- Electric isolation between DC- and AC-side,
- Overvoltage protection at-DC- and AC-side,
- High availability.

### 9.3.3 Line-commutated inverter

The traditional line-commutated inverter is commonly used in drive units for induction motors. The power stage is equipped with thyristors (SCR, silicon-controlled rectifier). For solar applications the control unit has to be modified to allow for MPP-tracking. Furthermore the driver circuit has to be changed to shift the firing angle from the rectifier mode (0°<a<90°) to the inverter mode (90°<a<180°). In Europe this type of solar inverter is available with a rated power of 1.5 kVA as a single phase unit. 3 phase devices are installed in larger PV systems. Up to a rated power of 300 kVA 6 pulse units are used (SMA, PV-Neurather See, RWE). 12 pulse inverters are a little more expensive but do not produce so much harmonics (2 times 450 kVA, PV-Toledo / RWE & Endesa & Union Electrica Fenosa).

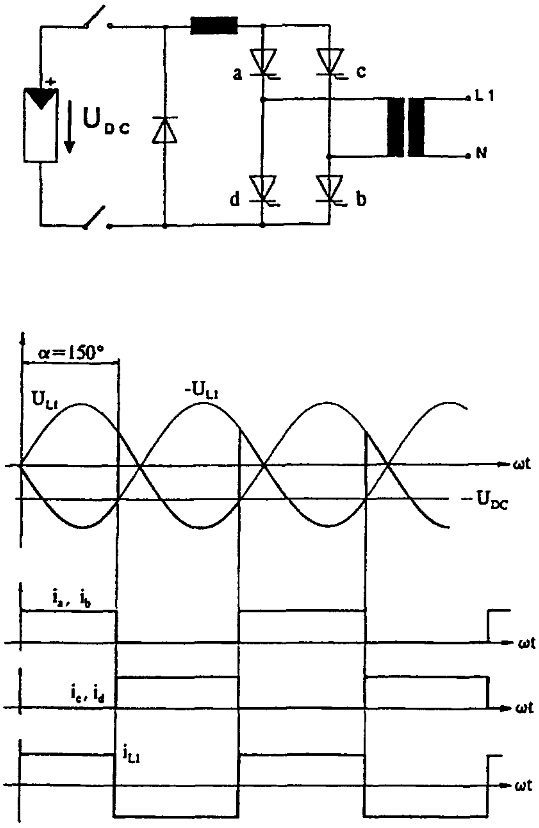



*Figure 9.7 Line-commutated inverter.*

Thyristor type inverters need a low impedance grid interface point for commutation purposes. A line-commutated inverter should not be used if the maximum power available at this grid extension is less than 5 times the rated power of the inverter. The advantage of the line-commutated inverter is its low price (0.6 to 1 US $/W). The disadvantage of this system is the poor power quality of the AC electricity. The harmonic content of the current fed into the grid is quite large (Figure 9.8). Without additional filter circuits the limits of the European Standard EN 60555 will be exceeded. Another disadvantage is the poor power factor which is measured to be 0.6 to 0.7 inductive (Figure 9.10). External phase shift equipment has to be installed to meet the utilities' power factor requirements (better than 0.9). For small systems (<10 kW) the best choice is to use a pulse width modulated inverter unit with MOSFET power transistors or an IGBT power stage.

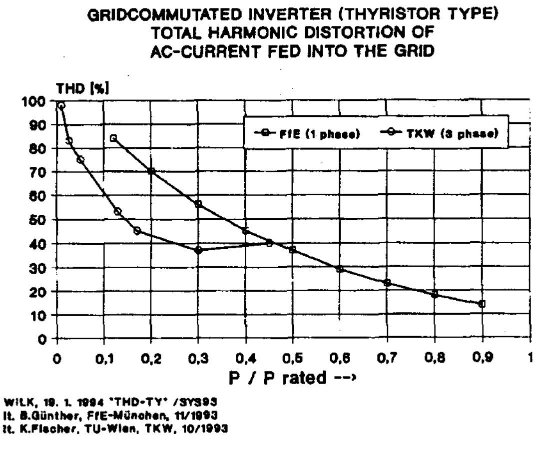



*Figure 9.8 Total harmonic distortion of AC current, line-commutated inverter.*

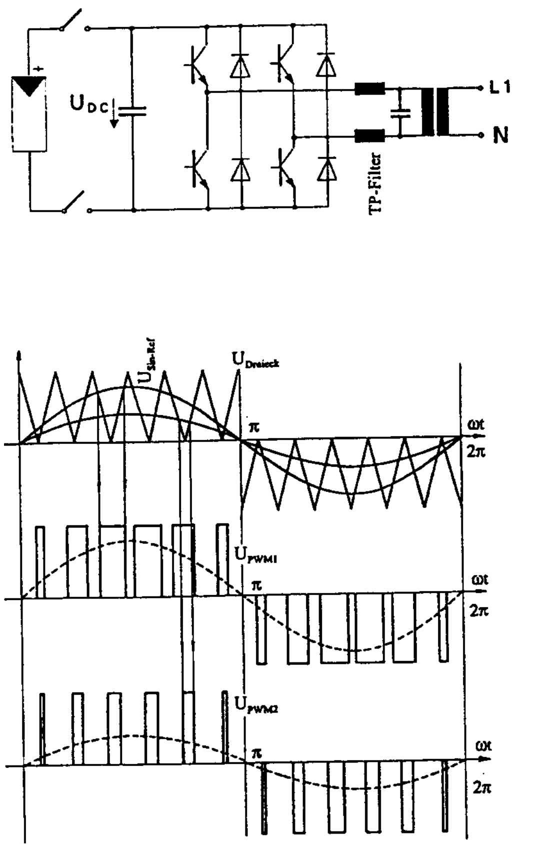



*Figure 9.9 Self-commutated inverter with pulse width modulation and low frequency transformer.*

### 9.3.4 Self-commutated inverter

With pulse width modulation (PWM) an almost perfect sine wave is shaped (THD<1%). Figure 9.9 provides the information on how pulses of different length and polarity are combined in order to form a sine wave. Lower harmonic distortion can be achieved by using higher switching frequencies. But switching losses will rise with higher frequencies and overall efficiency will be lower. Several different semiconductor devices can be used in the power stage of a self-commutated inverter:

- MOS transistors,
- IGBTs (isolated gate bipolar transistors) or
- GTO thyristors (gate turn off thyristors).

MOS transistors are used in units up to 5 kVA. They have the advantage of low switching losses at higher frequencies.

GTOs are used in very large installations (100 kVA and more). Because of the limited switching frequency the shape of the sine wave is not perfect and additional filtering is needed.

The isolated gate bipolar transistor (IGBT) is composed of a power pnp-transistor and a n-channel MOS-transistor in Darlington configuration. For turning on the device a voltage has to be applied at the gate. The required driving power is very low (mW to W) and depends on the input capacity of the gate and the switching frequency. Because the on-state voltage drop is 2 V DC, the system voltage should be higher than 200 V. With the presently available IBGTs inverters up to 200 kVA can be built without paralleling the power switches. The power stages of IGBT inverters have an uncomplicated structure. IGBTs are readily available in half-bridge configuration.

#### Power Factor

Self-commutated inverters can be easily connected to the grid (self-commutated, line-synchronized) presenting the advantage of near unity power factor, not loading the grid with reactive power or requiring large power factor compensation networks (Figure 9.10).

#### Input Ripple

The inverter is operating in a switching mode and current pulses are drawn from the DC source (PV array). Therefore, the inverter's input voltage is not constant. A ripple can be measured upon the array voltage. A too large ripple reduces the power output of the system because the array cannot be operated in the maximum power point of the IVcurve.

#### Overload Capability

The inverter must be able to limit the output current to a safe level if the input is overloaded by the solar array. This happens at special weather conditions with irradiance values of more then 1000 W/m$^2$ (snow reflections, multiple reflections on white clouds). The inverter varies the input voltage to higher values and reduces the output power of the array by leaving the maximum power point. Most system designers decide to use inverters with power limiting function. Therefore,

$$1.2 < P_{ARRAY}/P_{INVERTER} < 1.4$$

is a good choice. Some line-commutated inverter units switch off at overload conditions. In this case the ratio of $P_{ARRAY}/P_{INVERTER}$ should not exceed the value of 1.

### 9.3.5 Solar inverter with high frequency transformer section

The low frequency (50/60 Hz) transformer of a standard inverter with pulse width modulation is a very heavy and bulky component. When using frequencies of more than 20 kHz, a ferrite core transformer is the best choice. For a 1.8 kVA inverter this type of transformer has the size of a fist and is a lightweight component.

The inverter consists of 5 sections (Figure 9.11):

a) width modulation
b) high frequency inverter with pulse width modulation
c) high frequency rectifier
d) low pass filter
e) output stage.

This type of inverter needs two additional stages compared to the inverter concept in Figure 9.9 (Standard PWM inverter). Because of the high switching frequencies a lot of filters are needed at the input and output side of this inverter to avoid radio frequency emissions. In general electric household appliances have to operate within the limits of VDE 871 B (1.1.1996). Up to now most inverters of this type are only specified according to VDE 871 A.

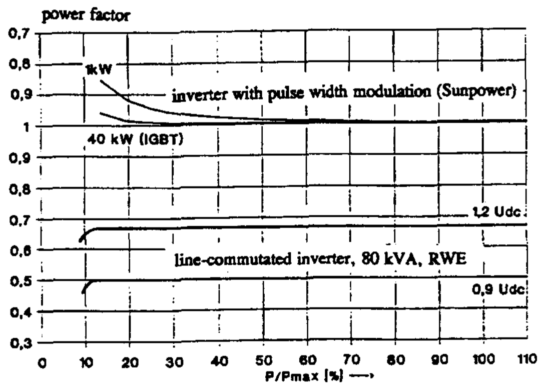



*Figure 9.10 Power factor of different inverters.*

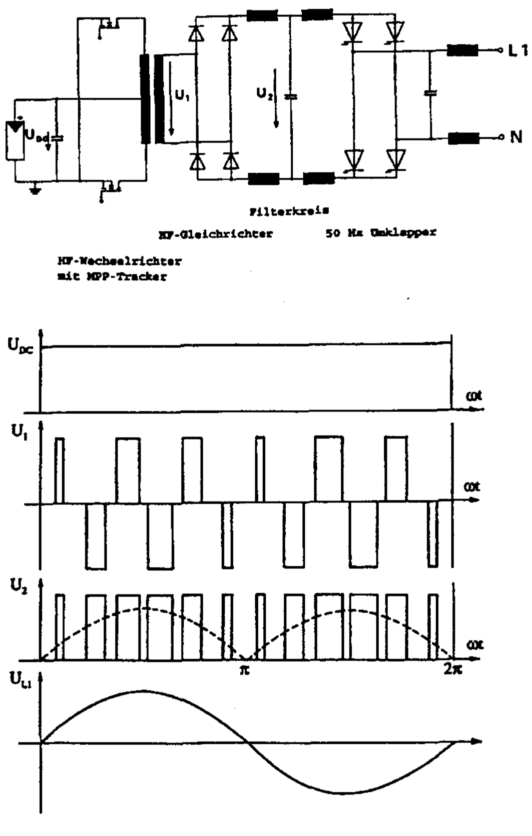



*Figure 9.11 Inverter with high frequency transformer section (SMA PV WI? 1800).*

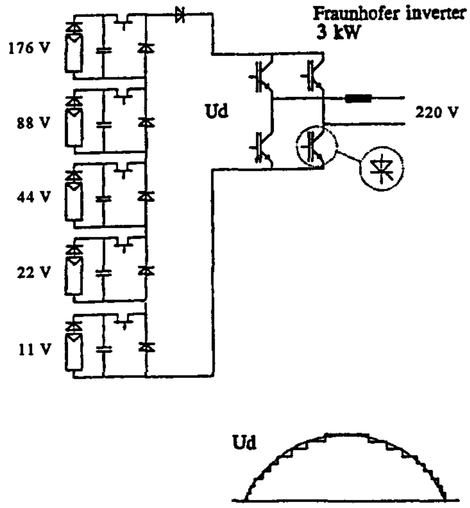



*Figure 9.12 The FhG-ISE Inverter.*

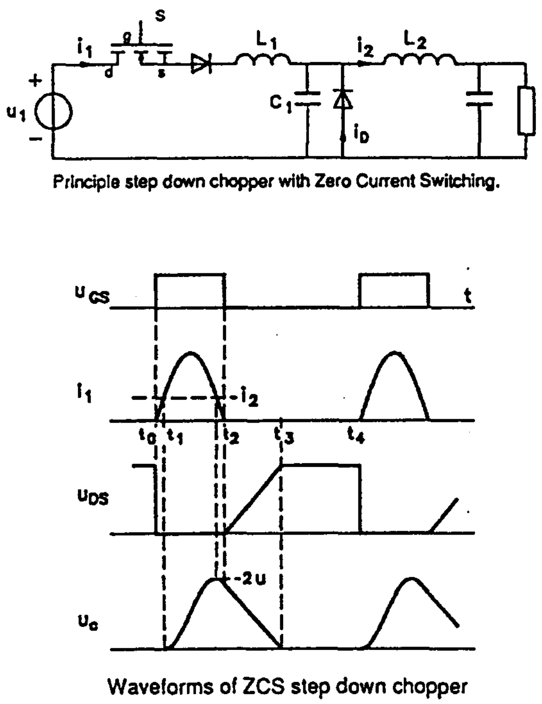



*Figure 9.13 Zero Current Switching Principle.*

### 9.3.6 Transformerless inverter with binary switching concept

This type of inverter was especially designed by FhG-ISE for photovoltaic applications. The principle is based on using 5 different PV arrays (Figure 9.12). The array voltages are e.g. 11 V, 22 V, 44 V, 88 V and 176 V. The voltage values are ordered according to the binary system. Triggered by a sine-wave generator and fast high-power switches a 230 V AC wave form can be synthesized with 5 bit accuracy.

The electronic switches connect as many arrays in series as necessary to follow the shape of the grid's voltage continuously. Some of the unique features of this inverter are:

- high efficiency,
- low no load losses (7 W/10 kW),
- low harmonic content,
- low weight, small size.

Due to the special working principle, the solar generator has to be wired in a more complex way. Five times more cables and lightning protection devices are needed for this special design. There is no maximum power point tracking device included. Depending on the weather conditions not all of the 5 arrays are loaded with the optimal voltage.

A similar working principle can also be applied to stand-alone applications.

### 9.3.7 Inverter with resonant switching stage

The traditional power conditioning units are often referred to as "hard-switching" inverters. The term hard-switching is used because the current flow is interrupted by changing the conductance of the power switch (this is done via a control signal on the control input of the power device). During switching the voltage over the power switch increases and just after a short time (100 ns to several ms) the current flow decreases rapidly. During this time the dissipation in the power switch is relatively high, while the very fast current and voltage transients can cause Electro -Magnetic Interference problems (EMI).

The term "soft-switching" inverter is used for high frequency units based on the principle of resonant switching technology. This technique emerged for power supply technology in recent years. Due to the resonance phenomenon the current becomes zero at certain times (depending on the resonance frequency). The resonance effect is initiated by opening or closing the electronic switch. If it is switched off exactly when the current is zero, the switching loss will be very low (Zero Current Switching -ZCS). It is also possible to switch off when the voltage is zero (Zero Voltage Switching - ZVS). Because of the low switching losses this operating principle allows very high frequencies (10 kHz to 10 MHz). Because of the high switching frequency all capacitive and inductive components can be small and relatively cheap.

In Figure 9.13 the basic principle of a ZCS quasi resonant DC converter is shown. Due to the use of new magnetic material for the high frequency (RF) transformer the physical size of that component can be reduced (100 W--size: 3x3x2 $cm^3$, while for a normal 50/60 Hz toroidal transformer the diameter is 10 cm and the height is about 5 cm).

### 9.3.8 Module-integrated converter

In grid-connected operation the PV generator is connected to the utility grid via a DC/AC converter. In a standard configuration the PV generator consists of a number of parallel strings which in turn consist of solar modules connected in series.

Depending on the system size the string voltage in grid connected systems reaches values from about 50 V up to over 700 V. In such a system a lot of DC cabling is required carrying a relatively high current, which causes some losses. PV installations with a central inverter have shown problems with respect to high DC voltage levels, risk of DC arcs, fire hazard and protection. Most of these problems can be overcome by a careful system lay-out, special cabling and DC switches / fuses, which increases the cost at system level.

The integration of PV module and inverter into so-called "AC-Modules" (also referred to as MIC, Module Integrated Converter ) offers interesting possibilities to overcome the problems mentioned above. The module integrated converters generate floating AC power at module level.

The AC modules do justice to the inherent modularity of photovoltaic building blocks. A PV system can be connected simply at 230 V AC level with standard low cost AC installation techniques. For AC modules both hard and soft-switching inverters are applied.

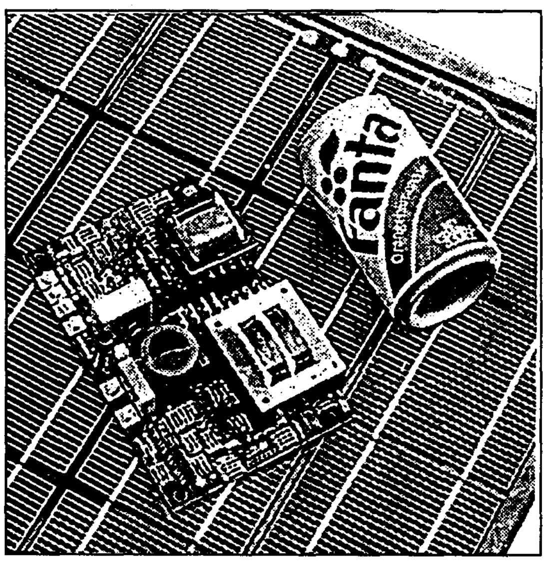



*Figure 9.14 Module Integrated Converter (110W, Mastervolt 130).*

Because of the specific structure and location of AC modules, several aspects are a matter of concern:

- because of the location of the AC modules the converters are operating under severe climatic conditions;

- the inverter of an AC module should be very reliable, because of difficult access and a higher number of devices installed (MIC: 110 W vs. Standard: 1.800 W);
- Islanding protection has to be realized in each unit or a central device must be installed to guaranty safe operation (info bus cabling);
- earth leakage detection is necessary in each AC module inverter.

AC modules have a potential to realize PV systems in a cost-effective way. System design with high modularity can be achieved combined with reduced installation cost and lower cabling losses. Up to now the principle has been demonstrated by several companies. Field experience has to be gained yet.

## 9.4 Inverter costs

Up to now the expenses for solar modules tend to dominate system costs of residential PV installations (50%). The power conditioning unit of many grid-connected PV applications costs less than 13% of the total expenses. As inverters are electronic solid state devices, they have a high cost reduction potential. Starting mass production (MIC), the price could be reduced rather rapidly. With the "Photovoltaic Rooftop Programmes" organized in several countries solar inverters are produced in a number of several hundred to more than thousand.

Prices already came down from 6500 US $/kW in 1985 to 1100 US $/kW in 1994. Thyristor type inverter units with more than 10 kW rated power are now available for 600 US $/kW (SMA, 1994).

## 9.5 Inverter reliability

Plant availability is determined very much by the performance of the inverter. Module failures are not very often the reason for PV system outages. Overload conditions often occur at alpine sites. One thyristor type inverter automatically stops operation and starts again the next morning. Many inverters adapt to DC-overload with a current limiting function. Some devices are very sensitive to overvoltage and undervoltage conditions on the utility grid. Overvoltages can be measured at the end of long grid extensions when only few loads are connected. This situation is quite common on a sunny sunday afternoon in a rural area grid.

When operating pilot plants with prototype inverters, it should be possible to reach availabilities of more then 95% after the first months of testing and optimizing. Normally the repair activities are completed within several hours. Most energy losses are caused by the time it takes to get the spare parts from the inverter company. Small inverters are easier to send to the company for repair.

If the PV system is hit by a lightning stroke the inverter will be damaged almost certainly.

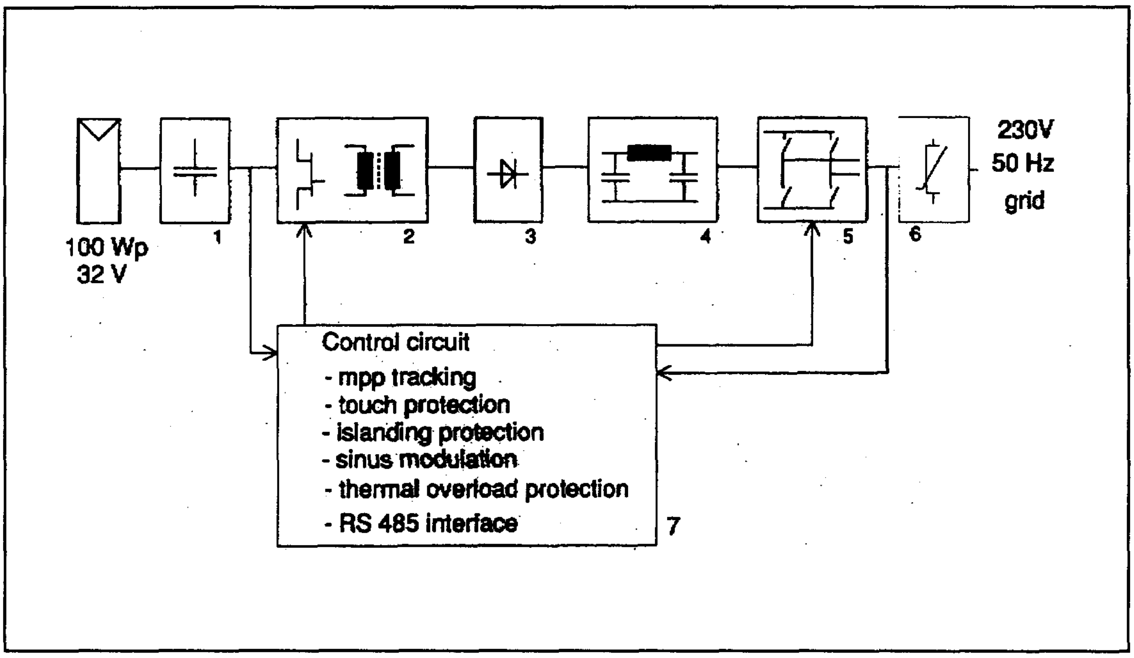



*Figure 9.15 Block diagram AC module (OKE/ECN).*

## 9.6 Integration of PV systems into the utility network (Inverter - utility interface)

### 9.6.1 General

Grid-interactive photovoltaic systems are co-operating with the utility network. Since the interconnection involves the two-way flow of energy, each side has responsibilities. The PV system must incorporate features that ensure safety and quality of the utility service. This results in specific requirements on the power conditioning hardware (Figure 9.16). When the photovoltaic system is interconnected with the utility distribution network a two-way flow of electric energy will be established (Figure 9.17).

**Solar Fraction**

Only a certain fraction of the PV electricity can be used in the appliances of the residence at the same time it is generated. The utility grid will absorb excess photovoltaic generated energy during midday hours when residential energy usage is relatively low (Figure 9.18). During bad weather conditions and at nighttime the utility generators will supply electricity to the residential loads (back-up). The solar fraction depends on the size of the solar array and the load curve of the house and is presented in Figure 9.19. If the PV system is very small almost all produced PV electricity will be consumed in the loads of the residence. The larger the PV array will be the more PV electricity is fed into the distribution network of the power company.

**Metering**

Most utilities in Europe have adopted net metering (Figure 9.17). Two seperate, reverse blocked meters for sold and purchased electric energy are installed. To get precise information on the amount of PV electricity produced by the solar electric system, an-additional meter is recommended (meter 1, Figure 9.17).

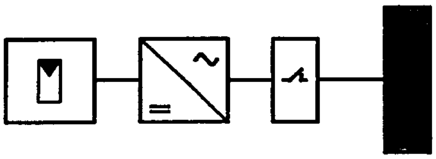


*Figure 9.16 Grid-interactive PV system.*

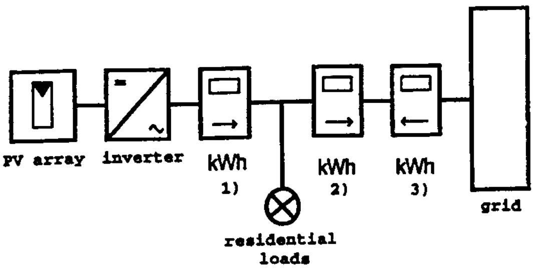
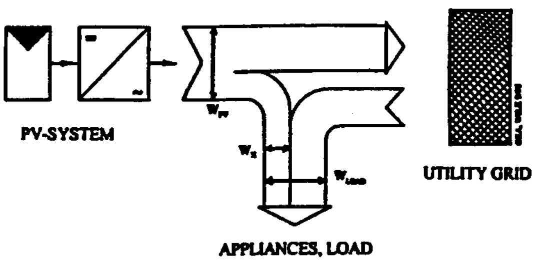



*Figure 9.17 Metering, residential PV system.*




$$\text{Direct Use Fraction} = \frac{W_E}{W_{PV}} \qquad \frac{kWh}{kWh}$$

$$\text{Solar Fraction (I)} = \frac{W_E}{W_{LOAD}}$$

$$\text{Solar Fraction (II)} = \frac{W_{PV}}{W_{LOAD}}$$

$$\text{Grid Fraction of PV-Production} = \frac{W_{PV} - W_E}{W_{PV}}$$

*Figure 9.18 Energy flow between PV system, utility grid and household loads.*

Meter 2 (Figure 9.17) is a 3-phase unit that counts the amount of electricity sold to the power company. Meter 3 is the standard 3-phase instrument which is used to measure the electric energy purchased from the power company. Meter 2 will not be needed if the PV system *is* operated in a country where a buy - sell ratio of unity is applied. In this case meter 3 will count up and down (Switzerland).

### 9.6.2 Utility Interface Requirements

For the utility company linemen safety and power quality is a major concern. Utility people are used to having a one-way flow of electricity in most parts of their distribution network. When they are switching off one feeder at the substation, they do not expect that a dead line will be energized by a PV system. With the installation of dispersed PV generating units in the distribution network the utilities have to modify their traditional manner of operating the grid. Furthermore the operational differences between an autoproducer with a rotating generator and a PV inverter have to be accepted.

Key issues:

- PV system becomes part of the utility system;
- Inverter must satisfy utility grid quality requirements;
- Linemen safety is a major concern;
- PV systems should never energize a "locked out" or dead line;
- Automatic disconnect of inverter at utility fault conditions;
- Lockable outdoor disconnect switch (accessible to utility personnel);
- Operating at essentially unity power factor;
- Electrical isolation between PV system and grid.

Utilities of European countries have adopted different safety concepts at the PV/utility interface. In most cases the inverter has to be disconnected within 5 seconds when a utility fault condition occurs.

Although most inverters are not able to operate without the grid voltage (islanding) many utilities only connect a PV system to the grid if a 3-phase voltage relay is installed. The inverter must be disconnected from the grid by the relay in case the output voltage exceeds or falls below predefined limits. The recommended range for the voltage tolerance is 80 - 110% of nominal voltage (Germany, Spain, Italy, Austria). All three phases must be monitored to be able to detect the loss of the grid voltage. Even if a single phase inverter can keep the voltage stable on one phase (islanding) the voltage relay will detect the loss of the voltage of the remaining 2 phases and switches off the whole unit. In Austria an external 3-phase relay must be used. In Germany the internal control unit of the inverter has to do the monitoring of all 3 phases. In Switzerland the inverter is connected to one phase and no relay has to be installed. In Germany and in Austria an outdoor disconnect switch is needed when 3-phase inverters are used. The main switch has to be accessible to utility personnel. Whenever the inverter output exceeds any of the pre-defined conditions during operation (over/under voltage, over/under frequency) the PV plant has to be disconnected automatically from the grid. Reconnection to the grid is to be attempted only after a certain time delay (3 minutes) to enable grid control systems to attempt fault correction. The overall intention of these measures is to prevent the inverters from harmful influences from the grid as well as to protect the grid network, including all loads, from inverter failures (see also IEA PV Power Systems Implementing Agreement Task V).

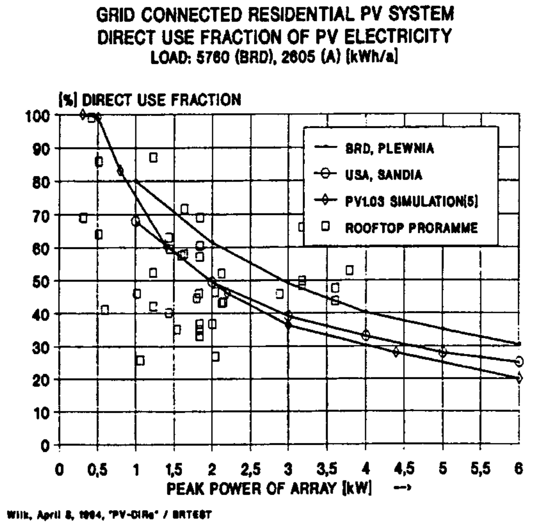



*Figure 9.19 Annual average fraction of PV system output coincident with on-site loads.*

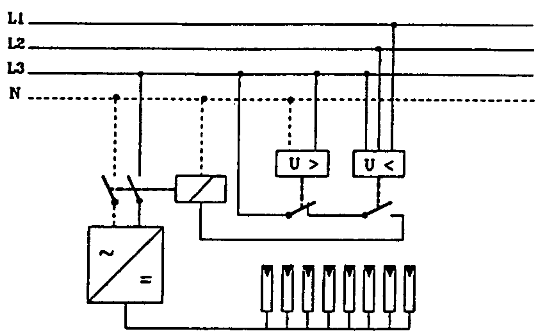



*Figure 9.20 Safety concept for a singlephase inverter PV installation.*

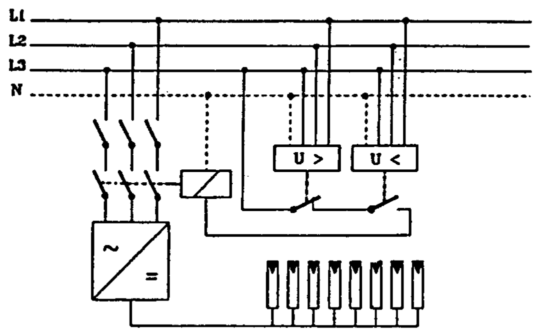



*Figure 9.21 Safety concept for a 3-phase inverter PV installation.*

### 9.6.3 Inverter specifications related to utility requirements

The inverter must detect utility fault conditions and disconnect itself immediately within 5 seconds. "Islanding" must be prevented under all circumstances.

Fault conditions are:

- over / under voltage (e.g. 80% - 110%)
- over / under frequency (50/60 Hz +/- 1%)
- loss of one phase.

In Germany inverters have to be designed to monitor the voltages of all 3 lines of the grid. This regulation applies to 1-phase and 3-phase inverters. With this feature included grid outages should be detected and "islanding" can be avoided easily. In Switzerland single phase units can be connected to the grid without 3-phase monitoring. In this case "islanding" has to be prevented by other means (inverter software etc.). Austrian utilities rely on 3-phase monitoring with an over-/undervoltage relay that must not be part of the inverter (similar to Spain, Italy). The price of a protection relay equals approximately 0.5% of the total system cost. The relay can easily be checked with a small test box.

The advantage of this method is that utility personnel do not have to check many different types of inverters but have to check only the standard relay. After the fault is cleared, the inverter has to restart operation again automatically.

## 9.7 The value of PV electricity

The value of PV generated electricity is judged very differently from country to country. Different buy-sell ratios can be found. In most countries the value of PV electricity will be higher if almost all solar electricity can be used in the home owners appliances. If the principle of "avoided costs" is used, the value of excess energy will depend on the utility's generating costs. In many countries generating costs are varying with time of day and underlie seasonal variations. A combination of different generating units is used by the utilities with different actual costs of generation. As several utilities purchase electricity from autoproducers at the rates of "avoided costs" identical tariffs are often used for **PV** systems and small hydro power plants. In countries with a special PV funding system the buy-sell ratio becomes almost unity (e.g. Germany).

Several countries have special tariffs for **PV** autoproducers that include "external costs" of traditional electricity production. Some communities decided to pay even higher rates for electric energy generated in PV plants, like

- Burgdorf / Switzerland SFr 1.- / x kWh
- Freising / Germany DM 2.- / x kWh.

Further discussions in Switzerland will eventually lead to the application of the principle of "marginal costs". The value of PV electricity would then be approximately 0.3 SFr/kWh. This is the price of 1 kWh that is produced by a newly-built conventional power plant.

## 9.8 Efficiency issues, electric yield

The electric output of a grid-connected PV system heavily depends on the performance of the inverter. As all the precious solar electricity passes through the power conditioner to be fed into the grid, inverter efficiency is a very important quality. In Central Europe's climatic conditions PV plants are operated at rated power only for several hundred hours a year.

Overall system performance depends heavily on the inverter characteristics:

- stand by losses: power consumed at nighttime by the micro processor control unit (1 - 17 $_{WAC}$ for a 2-kW system);
- self consumption: $P_0$: 0.5 to 4% of rated power, DC input power needed to start inverter operation (for driver circuits, magnetizing the transformer core etc.);
- maximum efficiency: 88 to 94% for 2-kW inverters.

Stand-by losses will be accumulated over 4380 nighttime hours. This energy flows from the grid to the inverter unit. Self consumption reduces the available DC input power during approximately 4380 operating hours of the plant (daytime, Central Europe).
Self consumption influences the monthly values of inverter efficiency. Because of many hours of part-load conditions in wintertime, the inverter efficiency will then be lower (Figure 9.23).

To optimize the annual electric output of a PV plant it is essential to match the array size and the rated power of the inverter. The peak power of the solar modules should not be lower than the rated power of the inverter to avoid part-load operation. If the array is too large, energy will be lost because of the current limiting function at inverter overload conditions (see Figure 9.22).

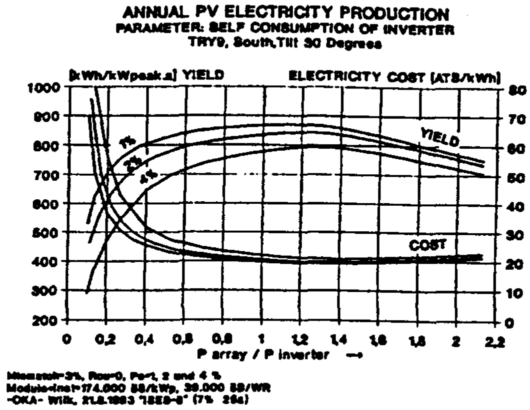



*Figure 9.22 Annual electricity output of grid-connected PV plant in Munich/Germany.*

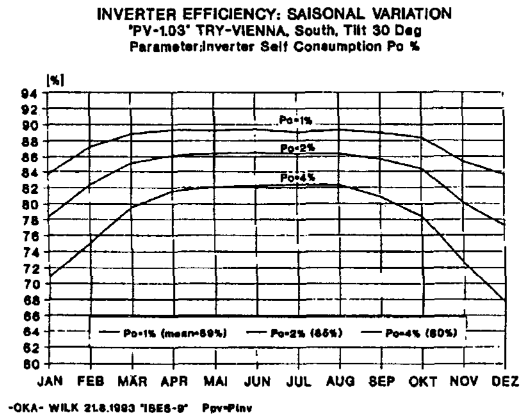



*Figure 9.23 Inverter efficiency, seasonal variation (Vienna).*

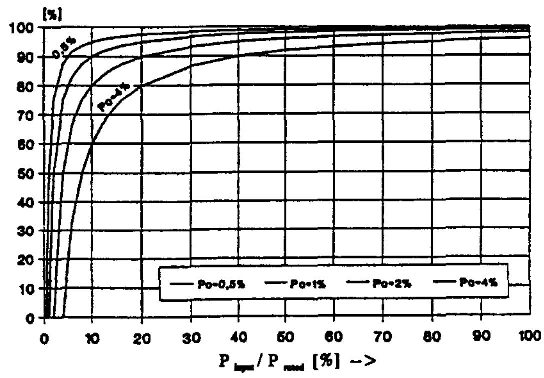



*Figure 9.24 Calculated inverter efficiency as a function of $P_0$.*