17

Photovoltaic Systems

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17.1 INTRODUCTION TO PV SYSTEMS AND VARIOUS FORMS OF APPLICATION

The modular nature of photovoltaic generators – consisting of photovoltaic modules – means that energy supply systems can be constructed for an extremely wide power range. The power spectrum ranges from a few milliwatts for wristwatches or scientific calculators, to kilowatt systems in remote area power supplies, for example, for mountaineering lodges or water pumps, to large central photovoltaic (PV) power stations in the megawatt range. An overview on the manifold application areas of photovoltaic systems is given in Figure 17.1.

Photovoltaics are generally considered to be an expensive method of producing electricity. However, in off-grid situations photovoltaics are very often the most economic solution to provide the required electricity service. The growing market all over the world indicates that solar electricity has entered many areas in which its application is economically viable. Additionally, the rapidly growing application of photovoltaics in grid-connected situations shows that photovoltaics are very attractive for a large number of private people, companies and governments who want to contribute to the establishment of a new and more environmentally benign electricity supply system. In parallel, considerable cost reductions are envisaged with the mass production of photovoltaic systems, leading to further attractiveness of this technology and its extension to other fields of applications. In Figure 17.2 the market development for photovoltaic modules is shown, indicating outstanding rates of growth of more than 15% per year in the eighties and early nineties cumulating in up to 40% annual increase in the late nineties and the year 2000.

As can be seen from Figure 17.2, about 45% of all modules installed in 2000 have been connected to the public electricity grid. These applications include both smaller decentralised systems, with the solar modules typically installed on rooftops, as well as

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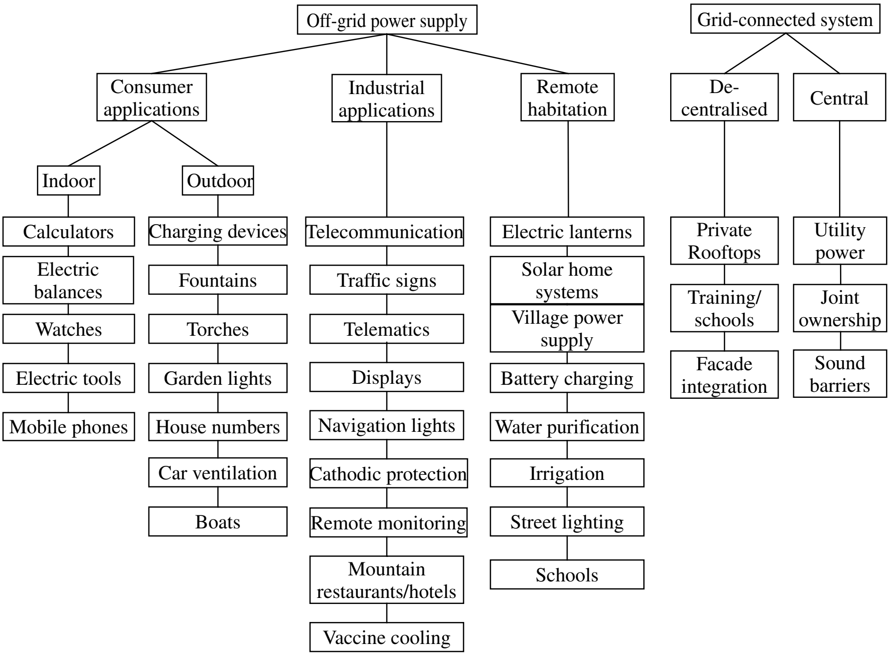

Figure 17.1 Application areas of photovoltaic systems. The applications are subdivided into "off-grid" and "grid-connected" systems

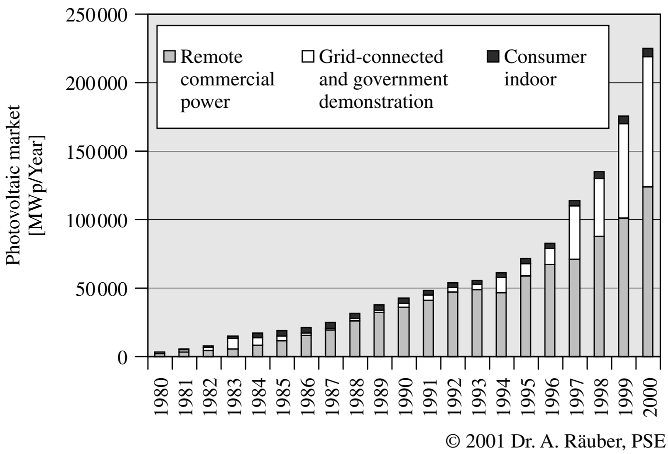

Figure 17.2 Market development of photovoltaic modules in the years 1980 to 2000 [1]

large central systems, with large areas of solar modules usually mounted on dedicated support structures. Still, the majority of the photovoltaic modules are applied in off-grid situations, like consumer products (e.g. camping, caravanning, small appliances), industrial applications (e.g. telecommunication, signalling, cathodic protection, water pumping) and remote habitation (e.g. solar home systems, hybrid systems, village power supply).

17.2 PRINCIPLES OF PHOTOVOLTAIC POWER SYSTEM CONFIGURATION AND THEIR APPLICATION

Photovoltaic systems are solar energy supply systems, which either supply power directly to electrical equipment or feed energy into the public electricity grid. In the following chapters, the most important application areas will be described in detail and pictures of prominent examples will be shown.

17.2.1 Grid-independent Photovoltaic Systems for Small Devices and Appliances

Solar electric power supplies for appliances and small loads in the power range from several milliwatts to several hundred watts are being applied generally because of its cost-effectiveness against a grid connection, in many cases even when the consumer is situated very near to the next grid connection point. Other advantages are their reliability, portability and their environmentally benign production of energy. In very small systems such as wristwatches or scientific calculators, the solar generator consists of one or only a few solar cells. When more power is needed, the individual solar cells are connected together to form solar modules.

An energy storage unit is needed to bridge times when no light or not enough light is available to power the appliance directly. Nickel–cadmium rechargeable batteries are used in most photovoltaically powered appliances, but lead-acid batteries and capacitors (so-called supercaps) can also be used. For caravans, boats and weekend accommodation, special types of car batteries with particularly thick lead plates and special alloys for mobile application can be used. In photovoltaic systems for continuously occupied houses and daily charge/discharge cycles, heavy-duty industrial batteries, the so-called "OpzS" batteries, are most commonly used. They are characterised by very low self-discharge, extremely good tolerance to cycling and thus a long operating lifetime. For small systems, maintenance-free batteries with the electrolyte integrated in matting or in gel form are used. They cannot leak and can thus be operated in any position. As lifetime costs for a stand-alone photovoltaic system are highly dependent on the battery costs, careful selection of the best suited technology for the respective application, operation and battery management schemes are crucial for satisfactory use (see also Section 17.3.1 and Chapter 18 of this book).

A charge controller is included between the solar generator and the battery to prevent it from being overcharged or deep discharged. The charge controller usually has a blocking diode, which prevents the battery from discharging during the night via the solar generator. A good charge controller has very low internal power consumption and includes a load cut-off switch that protects the battery against discharge. Power conditioning may be needed to adapt the voltage level of the photovoltaic system to that of the load. For photovoltaically powered appliances, this is usually a DC/DC converter, which transforms one DC voltage to another. If AC voltage is needed by a consumer, an inverter must be used. This converts the DC voltage delivered by the solar generator or the battery to an AC voltage.

17.2.1.1 Consumer applications

Power systems for appliances and small devices in which the energy supply and demand occur simultaneously do not need an energy storage unit. Pocket Calculators, fans and electric letter balances are examples of such applications [2–4]. As one example of an appliance in the small power range, Figure 17.3 shows an electric balance.

When an electric display is used, these devices are normally powered by dry-cell batteries. As energy demand and photovoltaic energy supply are very well correlated in this application – reading the LCD-display is not possible without light – the system may be designed without any energy storage. Besides environmental aspects, one fact is often neglected – the cost per kWh supplied with dry cells is extremely high – for example, a 1000 mAh dry cell with nominal voltage of 1.5 V contains 1.5 Wh. Its cost of about 1 euro per unit means that the kilowatt hour stored in this way costs about 700 euro/kWh. Not relying on a storage battery means that the system reliability is higher, negative environmental effects are reduced and the comfort in using these systems is increased.

Another example is the fountains that can be found in many public parks, squares, cemeteries and zoos. Usually, the water is recirculated rather than being constantly replenished with fresh water. In general, just a few standard solar modules are sufficient to operate the circulation pump. As circulation during the night or overcast periods is not

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Figure 17.3 Electrical balance for use in households and as letter scale (*Source*: Maul, Bad König) absolutely necessary, a storage element is not needed and the solar generator can be connected directly or via an adaptive converter to the water pump.

17.2.1.2 Photovoltaically powered intelligent emergency telephone

Emergency telephones along motorways and roads across sparsely populated country are necessary, sometimes even life-saving [5]. Extensive cabling can be avoided, both during new road construction and when emergency roadside telephones are subsequently installed, if photovoltaically powered emergency telephones with radio contact to a central receiver station are used (see Figure 17.4).

A solar generator of only a few watts power is sufficient, as the telephones are not used frequently. The "multifunctional emergency call and information system" developed at Fraunhofer ISE does not require external cabling, has an autonomous power supply and

Figure 17.4 Photovoltaically powered emergency telephone (*Source*: Fraunhofer ISE, Freiburg)

operates reliably. In addition to the original emergency call function, contact can be made to various emergency services and information can be obtained. Furthermore, information such as traffic flows and meteorological data can be recorded at the system location and communicated to predetermined central stations.

17.2.1.3 Solar lantern for rural households in developing countries

A photovoltaic application that is particularly interesting with regard to its ecological and social aspects is the replacement of fossil-fuelled light sources – usually petroleum lamps – in remote regions of developing countries with photovoltaically powered lights.

The robust lighting unit illustrated in Figure 17.5 consists of the light, an electronic ballast, the rechargeable battery and a charge controller. During the day, it is connected

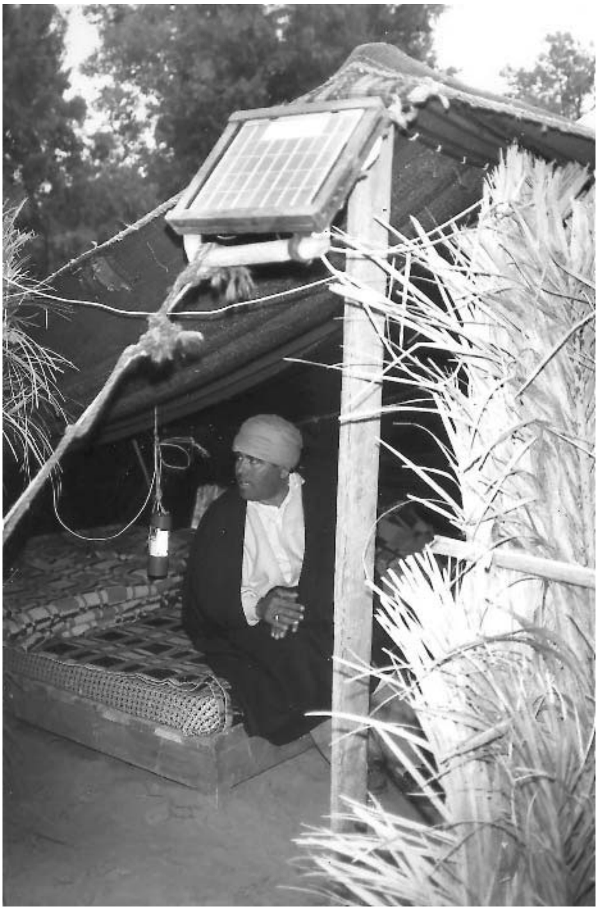

Figure 17.5 Photovoltaically powered light in a hut in Tunisia (*Source*: Ludwig-Bölkow-Stiftung, Ottobrunn)

via a cable and plugged to the permanently mounted solar generator for charging. In the evening it can be used as a portable light inside or outside the dwelling and can be carried and positioned wherever it is most needed. A solar generator with 4 Wp (module size 20×20 cm^2) is sufficient for a daily lighting period of 3 to 5.5 h (depending on the solar radiation). At the same time, the solar-powered light with a luminous flux of about 80 lm is three times as bright as a petroleum lamp.

17.2.1.4 Solar home systems

The designation "Solar Home System" has become a well-defined concept [6–8]. A 50-W photovoltaic module (size about 50×100 cm^2) typically supplies power for three lamps and a black-and-white television set in a single household (Figures 17.6 and 17.7). A lead-acid battery with a charge controller stores the energy from the day for the night and can run alone for two to three overcast days. Depending on the size of the local market, customs duties, taxes and the share of locally manufactured components, the cost of a Solar Home System is between US$500 and US$1500.

In many situations, Solar Home Systems (SHS) offer cost advantages over the classic alternative for electrification, which is the extension of electricity grids into sparsely populated regions and connection of power lines to all rural households [9]. The World Bank assesses the average cost worldwide of grid extension to be US$900 per household. In unfavourable cases, with long distances, difficult terrain and low population density, a power line for one household can cost many tens of thousands of dollars.

The investment needed for this cannot be financed via the low energy consumption of rural households, which ranges between fractions of kilowatt hours and a few kilowatt hours per day. Political decisions to electrify rural areas despite this imbalance have contributed to electricity utilities going into debt in developing and threshold countries, so that necessary investments to modernise distribution grids and power stations cannot be financed. The result is the poor quality of the electric power supply, which can be observed in many regions around the world. Increased privatisation of the power supply is intended to provide a remedy to the described situation [10, 11].

The situation described above is the main reason small diesel generators in the power range of some kilowatts are installed in many remote locations. Because of their low investment costs, they appear economically attractive. However, calculating the lifetime costs shows that the expenses for repair and maintenance of the motor generator and the fuel costs add up to considerably high costs, leading to a situation in which photovoltaics are very often cost-competitive.

Decentralised electrification with privately financed Solar Home Systems fits in perfectly with the aim of sustainable and cost-effective rural electrification. Light that allows information and communication for private users and that lengthens the working time into the evening in farms and shops, schools and community centres cannot be underestimated in its importance. It is therefore actively supported by the energy planning authorities of various countries and by multilateral organisations such as the World Bank [12].

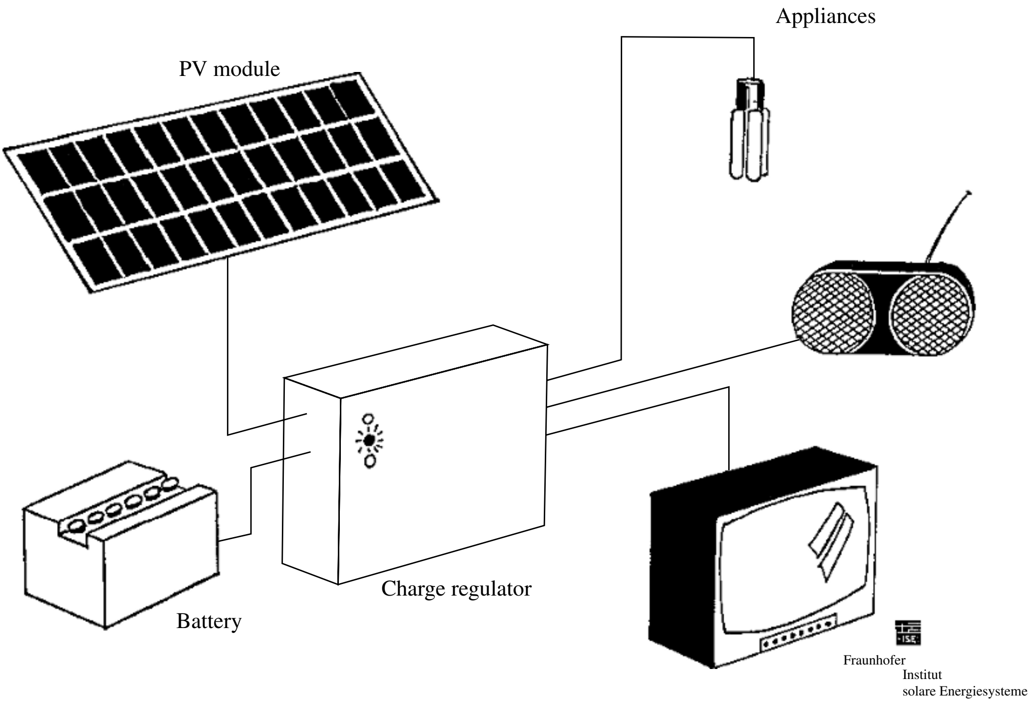

Figure 17.6 Block diagram of a Solar Home Systems to cover the basic electricity demand (lighting and communication) in rural households

Figure 17.7 Sukatani, the first SHS pilot village in Indonesia, was the origin of the currently running rural electrification programme to electrify one million rural households in Indonesia (*Source*: Fraunhofer ISE, Freiburg)

17.2.2 Photovoltaic Systems for Remote Consumers of Medium and Large Size

Electricity also solves other supply problems. Workshops, food storage and processing, telecommunication, health services and tourism normally demand higher daily amounts of energy and power than can be supplied by a Solar Home System. The usual supply levels, classified according to small and medium loads, and local, regional and national supply with the corresponding voltage levels and power ranges, are illustrated in Figure 17.8. For very low power requirements, pure photovoltaic systems with an appropriate energy storage unit are the best option. With increasing power demands, other electricity generators, like wind turbines and solar thermal generators, become technically and economically attractive. Small stand-alone grids that are supplied by various electricity generators are the next step in remote area power supply. With increasing demands, the connection to the public electricity grids makes good sense. Here, of course, all renewable energy technologies can play a role; the decision on their application, however, has to compete with the energy prices of conventional power stations driven by fossil or nuclear fuels. Because of the price reductions in the last years, photovoltaic power technology is cautiously expanding into the range "supply of small and medium loads" at present.

17.2.2.1 Photovoltaically powered telecommunication system

Owing to their high reliability and low maintenance, photovoltaics are already widely used to power remote telecommunication systems, for example, repeater stations. Repeaters are

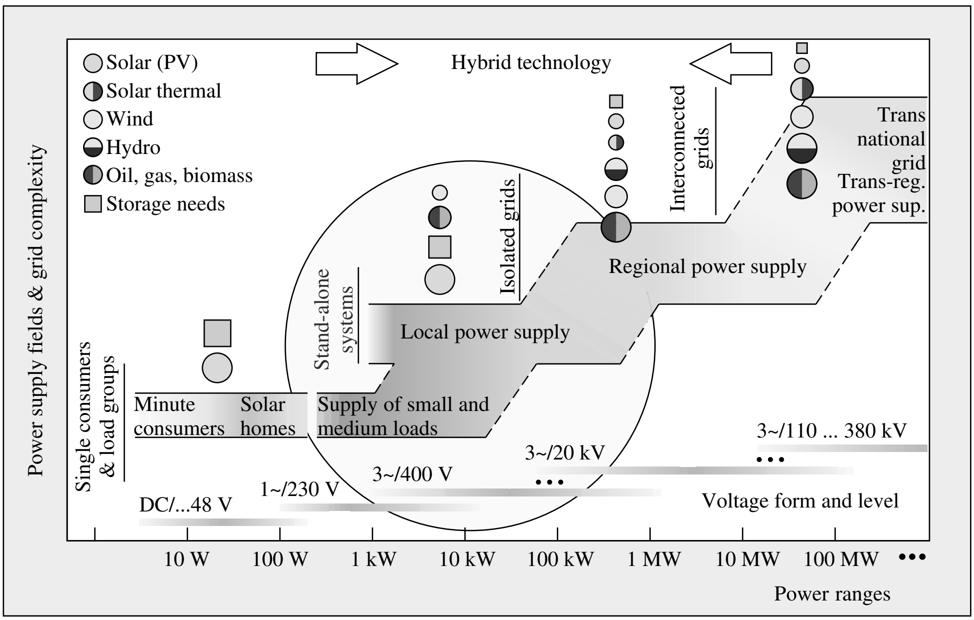

Figure 17.8 Classification of power supply technology for electrification with renewable energy – energy sources, application classes and trends (*Source*: ISET, Kassel [13])

digital radio signal amplifiers that increase the connection reliability of mobile telephones within radio cells and raise the accessibility level throughout the network. In rural areas and in mountainous regions, repeaters often have to be installed and operated at sites remote from the public electricity grid (see Figure 17.9).

Because of seasonal fluctuations in solar radiation in temperate zones, an exclusively photovoltaic power supply leads to very large and thus expensive systems. In order to avoid these disadvantages, the photovoltaic generator may be combined with other power generators. In Figure 17.10 is shown the prototype of a photovoltaic hybrid system, consisting of a PV generator, a battery and a thermoelectric generator used as auxiliary power source. A micro-controlled energy management system ensures fully automatic operation with minimal consumption of fossil fuel and appropriate battery operation management.

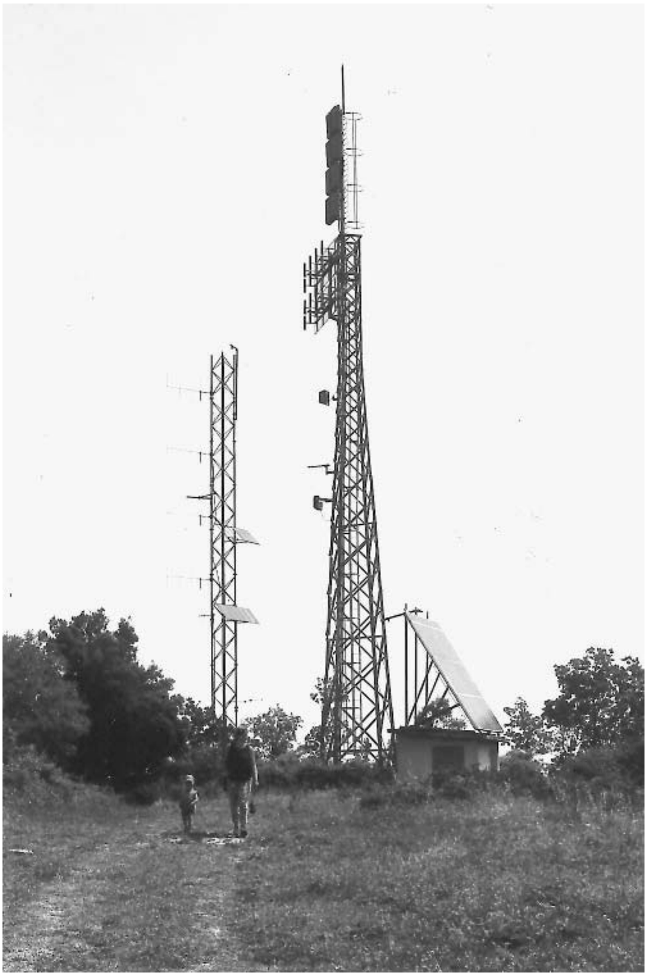

Figure 17.9 PV powered repeater station on a hill in Tuscany, Italy (*Source*: Fraunhofer ISE, Freiburg)

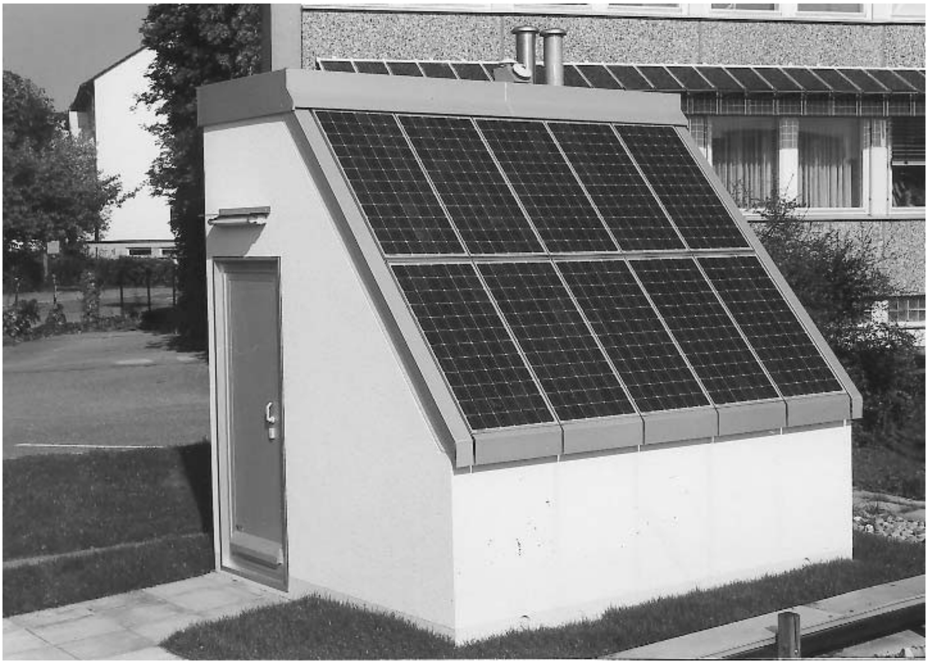

Figure 17.10 Prototype of a hybrid system (photovoltaics and thermoelectric converter) to power a remote repeater station (*Source*: Fraunhofer ISE, Freiburg)

17.2.2.2 PV powered battery-charging stations

Experience with locally centralised battery-charging stations (Figure 17.11) worldwide is by far not as convincing as it is with solar home systems. Normally there is no deep discharge protection (DDP) of the battery foreseen, which besides other effects causes sulphatation of the electrodes and thus an early end of the lifetime of the battery. Using the batteries in a full cycling process means that not the corrosion coefficient but the cycle capability determines the lifetime. Therefore, battery lifetime tends to be very short, only some hundred cycles, especially with locally produced car batteries [14].

Another aspect, which is often neglected with battery-charging station, is that people have to carry a dangerous freight over a quite long distance. In industrialised countries no one would expect this of somebody, even if the means of transport were more comfortable as they are in rural areas of developing countries. The hazard of accidents when transporting batteries, the high risk of wrong connection afterwards and the very poor charge and discharge protection regimes sum up to an unsatisfying operation of this kind of electricity service.

17.2.2.3 Photovoltaic hybrid systems

If higher power is needed or if conventional household appliances and industrial equipment are to be used, a system voltage of 230 or 110 V alternating current is desirable. To increase the reliability of off-grid power supply systems and to reduce the investment

Figure 17.11 A typical PV powered battery-charging station in rural Thailand (*Source*: Fraunhofer ISE, Freiburg [14])

costs for a certain energy service needed, larger systems (i.e. consumption of several kilowatt hours a day) are typically constructed as "hybrid" systems, that is, the combination of a diesel generator and a photovoltaic generator. Depending on the availability of natural resources, other electricity generators like wind converters or hydroelectric power stations may be used to complement the power supply system. A battery bank ensures that power is available continuously. Under favourable weather conditions, the consumer's total energy demand is met by the solar generator operating silently and without exhaust gases. Surplus energy is stored in batteries. During the night or unfavourable weather conditions, the energy demand is initially met by the batteries. If there is danger of battery deep discharge, the diesel or gas-fuelled generator provides the electricity and simultaneously charges the battery.

Even in Europe there are still many houses, hikers' inns and mountaineering lodges that are not connected to the public grid because of the long distances and the resulting connection costs. The only option open to the owners up to now was to install a diesel generator. As they are used to directly supply the consumer load, the diesel generators are often operated in the inefficient partial load range and when they are switched off, no electricity is available at all. However, continuous operation of stand-alone motor generators is undesirable, not only because of the low partial load efficiency, the noise and the exhaust gases but also because of the limited lifetime of combustion motors. Therefore, the Rotwandhaus, a hikers' inn in the Bavarian Alps, which is open throughout the year, was equipped with a hybrid system consisting of a photovoltaic generator, a wind energy converter and a diesel generator (Figure 17.12).

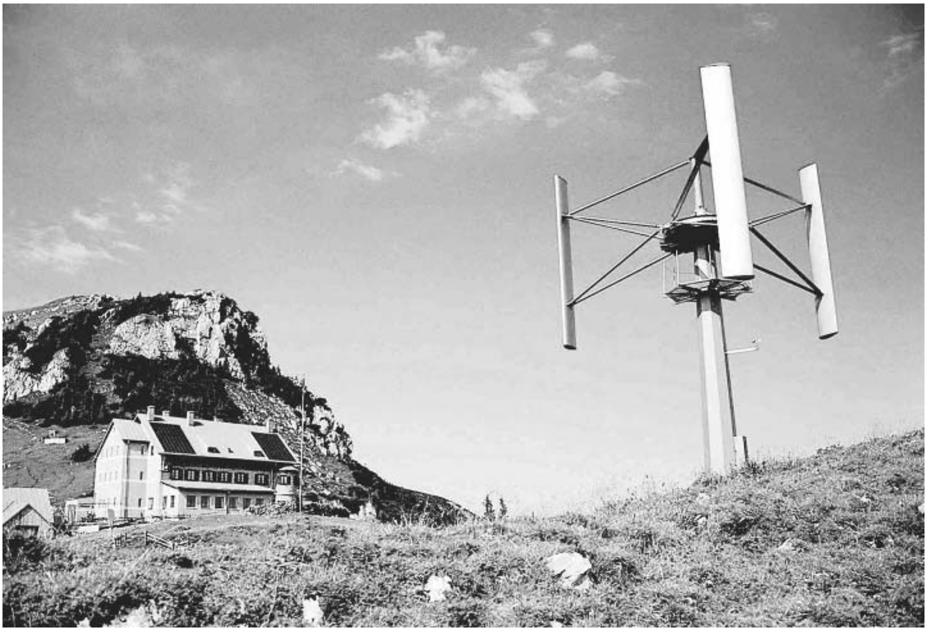

Figure 17.12 Rotwandhaus with its solar generator and wind energy converter (*Source*: Fraunhofer ISE, Freiburg)

When the wind is strong enough, the wind energy converter supplies the power and charges the battery. As soon as the battery is fully charged, the wind energy converter is throttled. An inverter converts the direct current from the battery to 230 V alternating current so that all conventional electrical appliances can be operated. The necessary supply reliability even during extremely unfavourable weather conditions is guaranteed by the diesel generator. A computer monitors and controls the whole system to ensure that the supplied energy is used as effectively as possible.

Most of the hybrid PV-diesel-battery systems realised worldwide are so-called DC-coupled systems (see Figure 17.13).

Different generators are working via separate charge controllers/rectifiers to the DC storage battery. An inverter generates the desired AC sine wave, it builds the AC grid in frequency and voltage; if power generation and consumption are equal, the battery does not take part in the power flow. Otherwise, the battery stores the surplus of generated power or delivers the additional power that is needed by the load. In order to protect the battery against damage, a charge controller, in most cases the PV charge controller, disconnects the inverter before the battery becomes completely discharged. If there is not enough renewable power and if, at the same time, the state of charge of the battery is low or if the consumers need more power than the inverter can deliver, a back-up generator is started from the control system. In this case, the back-up generator supplies the consumers directly with AC power and charges the battery via its own rectifier.

The big advantage of the DC-coupled system layout is that it is proven in many applications and that reliable components are available on the market. The necessity

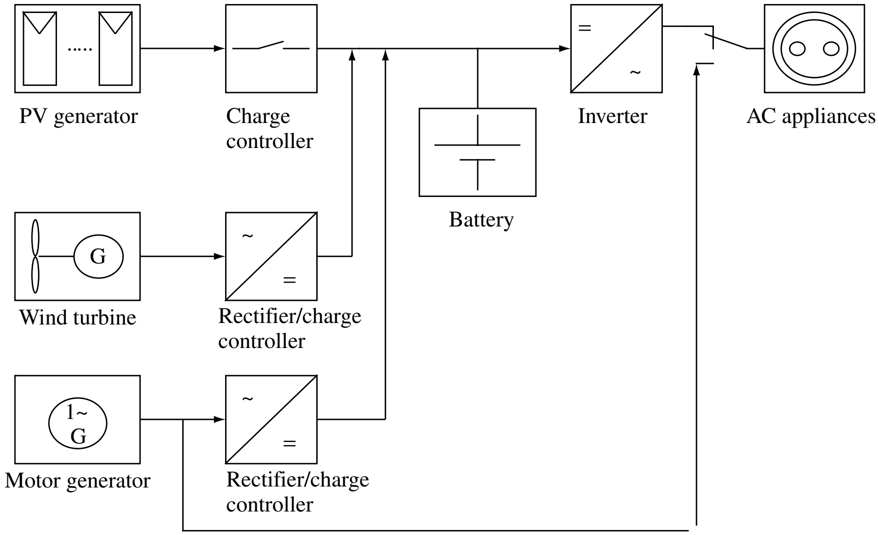

Figure 17.13 "DC coupling" of different electricity generators. Example from the Rotwandhaus, a mountain lodge in the Bavarian Alps

of adapted charge controllers for each generator, however, may lead to systems with relatively high installation costs, which will further increase with the number of the power generators installed.

The other possibility for hybrid system design is the so-called AC-coupled system (Figure 17.14).

The heart of an AC coupled system is a bi-directional inverter. The photovoltaic modules and all the generators are connected to an AC bus bar via suitable inverters. Thus, primarily the AC consumers are supplied with electricity and only the surplus of power is fed back to the storage batteries. Power management is done by only one electronic device, the bi-directional inverter. This may lead to a simplified system concept. The inverter now must be able to work in different modes (charging or discharging the battery), it has to build the local AC-grid in frequency and voltage and it has to be synchronised to any other synchronous electric generator in the system. Because of these high requirements of the inverter, there are only very few bi-directional inverters available on the market, some of which still have prototype character.

17.2.2.4 Village power supply systems

While Solar Home Systems for the decentralised power supply of rural households are considered to be a standard system ready for the market, and while the suitability of PV hybrid systems to power single houses has been proven in various pilot and demonstration programs all over the world, this positive experience is up to now not available for central power stations to supply remote villages with off-grid PV power. Nevertheless, the research and development in rural electrification are increasingly directed towards these systems. The main reason is that with a central system, installation and operation

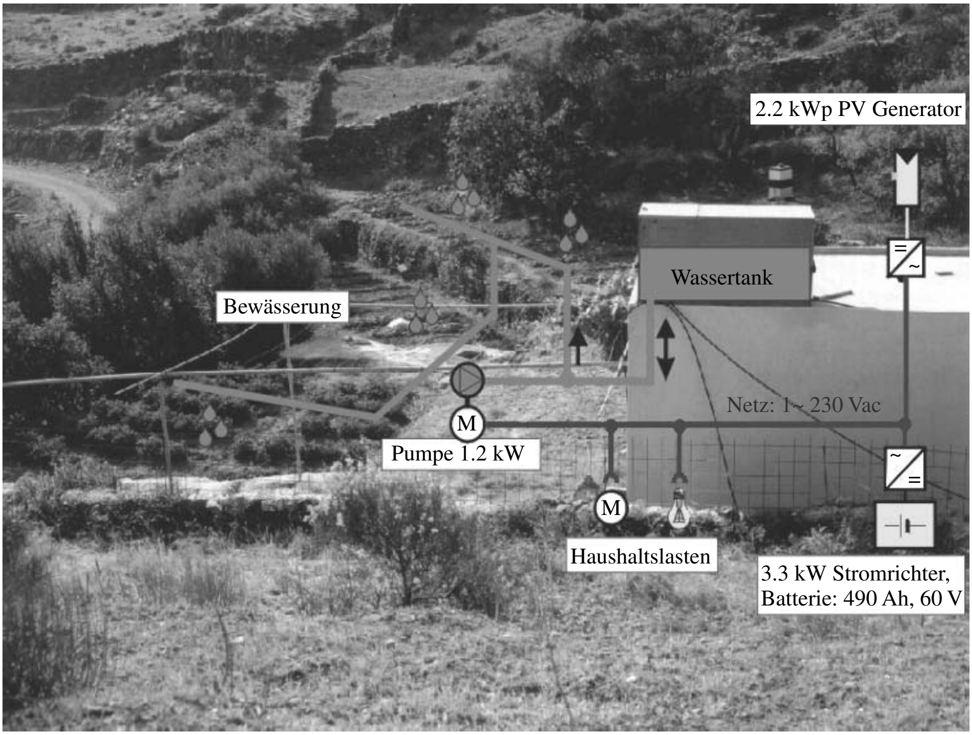

Figure 17.14 "AC coupling" at an example of a three-phase stand-alone power supply system (*Source*: ISET Kassel)

costs may be lowered compared to the single-house supply option. Today, as more and more electric utilities enter the off-grid market, their interest is to lower the cost as much as possible for operation, maintenance, money collection and so on, which is needed to assure a durable energy service. Experience and reports from those having been involved in PV dissemination programmes for rural electrification confirm that technical problems in the village supply are not the main barrier preventing lasting success. Rather, an appropriate introduction method, user involvement at various levels and planning that allows flexible reaction to the situation as it develops are necessary to achieve optimal joint use of the limited resource.

Today there are technical components, like the inverter, the charge controller, the energy management systems, available in various countries, which are much better suited than they were in the early demonstration projects. The R&D efforts in the development of village power supply systems are now focused on the fair distribution of the energy available, and a suitable limitation of the power consumed by each individual household. Prepayment schemes or energy limiters are in development and demonstrated in several companies and international pilot programs. These systems meter system energy consumption in each individual household and cut the load if the pre-set values or the energy budget has been consumed. A typical representative is the village Llavería, where SEBA, a Spanish user association, together with the Spanish company TTA are operating a hybrid system (Figure 17.15).

Figure 17.15 PV-Diesel-Hybrid system in Llavería (*Source*: TTA, Barcelona)

17.2.2.5 Photovoltaic pumping systems

An important field of application for battery-free solar electricity systems are water-pumping stations [15]. In this case, water reservoirs serve as product storage devices.

High-power pumps are applied to draw drinking water from great depths for a whole village. The system shown in Figure 17.16 supplies the drinking water for 4000 people on Sumba Island in Indonesia. Using a 6-kWp photovoltaic system, 40 m^3 water can be drawn every day.

17.2.2.6 Photovoltaically powered water purification

Besides the water provision, the purification of water also becomes increasingly important (see Figure 17.17; [16–18]). Different technologies exist, like chlorination, UV radiation and ozonisation. From this broad range of purification methodologies, the best-suited system has to be chosen and integrated in a complete photovoltaically powered system for continuous and safe operation.

17.2.2.7 Social aspects in off-grid rural electrification

Providing stand-alone photovoltaic systems for remote locations is often defined and approached as a purely technical matter. However, in numerous applications such as mountaineering lodges, rural households or village power supply systems, it has become clear that other aspects in addition to the technical ones affect the optimum use and effective conversion of solar energy into electricity [8]. There is a danger that expectations of a photovoltaic system will be unrealistically high. It cannot really be compared with the "inexhaustible" supply known from the public grid, but must be placed in a realistic perspective defined by the respective context. This must happen actively and consciously as many users (and also planners) of photovoltaic systems underestimate the amount of redundancy, safety precautions and maintenance work necessary to achieve the high level of safety and reliability afforded by the centrally administrated public grid. This means

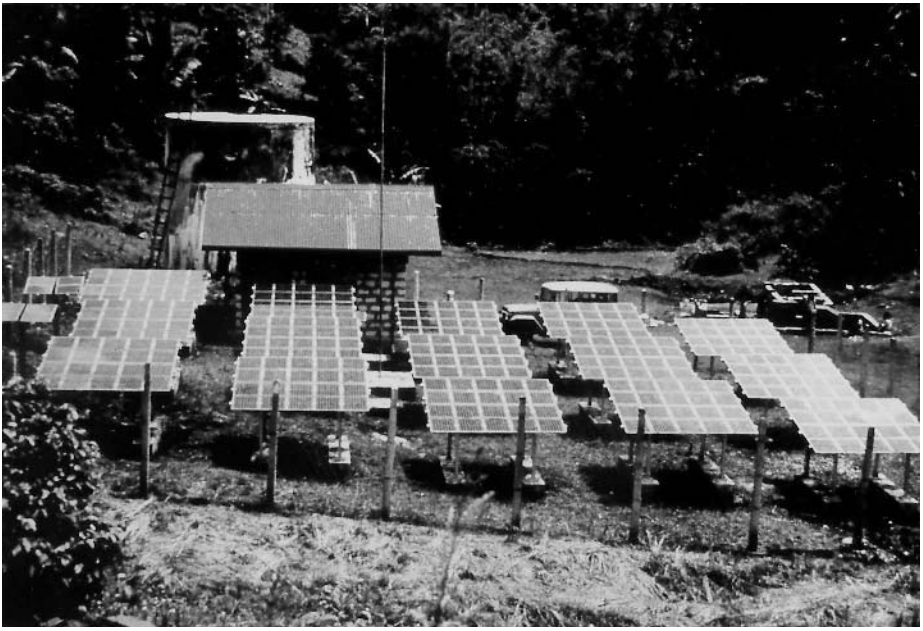

Figure 17.16 Photovoltaically powered system to provide drinking water for 4000 people (*Source*: TÜV Rheinland, Cologne)

that the people involved in the whole process must be taken seriously in their ideas about the design, advantages and disadvantages of the PV system. The behaviour of the users influences the system's performance tremendously, because they may purchase components, may install and/or change the system, determine the use of energy, may take over maintenance jobs and even repair the PV system. From this it becomes evident that the functioning of PV Systems can be optimised when the interaction between the new technology and their users can be improved. From this assumption, at Fraunhofer ISE the user-centred approach on rural electrification, called "socio-technical system approach", was developed.

The socio-technical system approach originates from work and organisational psychology and was applied first to labour organisations in Europe. When new technologies were introduced, it was found that not only the technology had to be designed according to the needs of the organisation but also the social organisation needed restructuring to increase the productivity. The approach is based on the open system theory in which the introduction of technology consists not only of hardware and software but also of orgware [19], the human part of the socio-technical system.

"Applied on stand-alone electricity systems" means that a properly reflected energy concept in the planning phase is the basis for the system design. But it is not only the quantity of components and their power consumption that finally determine the energy consumption in the PV system. The users have a decisive influence on the energy consumed, on the energy management carried out to optimise the energy available from the PV generator and to undertake the first level of maintenance (cleaning the PV module,

Figure 17.17 Photovoltaically powered purification unit at a wind powered water pump in Balde del Sur de Chucuma/Argentina (*Source*: Fraunhofer ISE, Freiburg)

re-filling battery water etc.). Therefore, involving them in the operation of the PV system, making them responsible for operation and maintenance is not only a measure to reduce the costs but also to increase their own satisfaction with the energy service provided (see Figure 17.18) [8, 20].

The users also play a decisive role in the evaluation of photovoltaic systems. They make the final decision on whether photovoltaics is a practicable and useful form of electricity generation for them. Satisfaction with the systems is – apart from economic arguments – the factor determining their further dissemination. Only contented operators will recommend this form of electricity generation to further potential users, which is certainly the most effective form of advertisement. In order to best adapt the system to

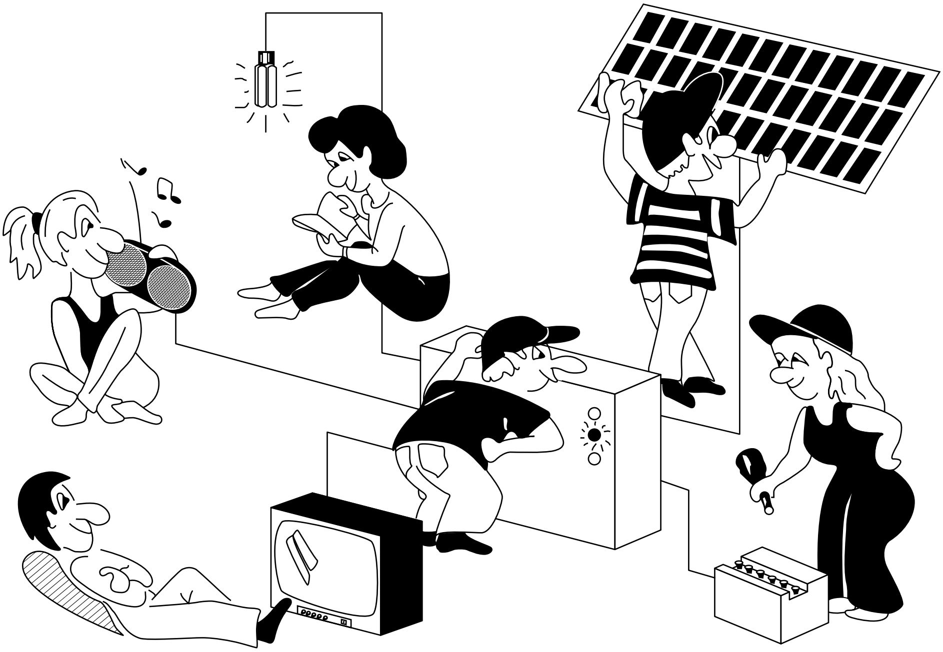

Figure 17.18 A photovoltaic stand-alone system consists not only of technical components but also of the users interacting with the technology on different levels

the particular needs of the intended users, they must be involved from the start in the process of system dimensioning, construction, installation, use and maintenance. The aim of adaptive measures must be to motivate the user to adapt his/her consumption patterns to the electricity generation profile, as one aspect, and at the same time to match the technical system to the demand and usage customs of the users.

17.2.2.8 Economic aspects in off-grid rural electrification

In Figure 17.19(a) the cost breakdown of a solar home system in the first year is presented on the basis of data available in a project on rural electrification carried out by the German Agency for Technological Co-operation GTZ GmbH. As expected, the purchase costs of the different components are the dominating factor. The photovoltaic module typically represents the major single cost component [9].

However, regarding the lifetime costs of such a system after 20 years of operation shows a completely different picture (Figure 17.19b). The proportion for the PV module decreased to about 12% and the costs for new batteries as well as the efforts for maintenance and repair become the most important factors.

The reason for this shift in the cost distribution is the difference in the quality and reliability of the components. PV modules are highly standardised and worldwide-validated certification procedures have been established, both leading to high-quality components. Up to now, no equivalent standards have been available for the balance

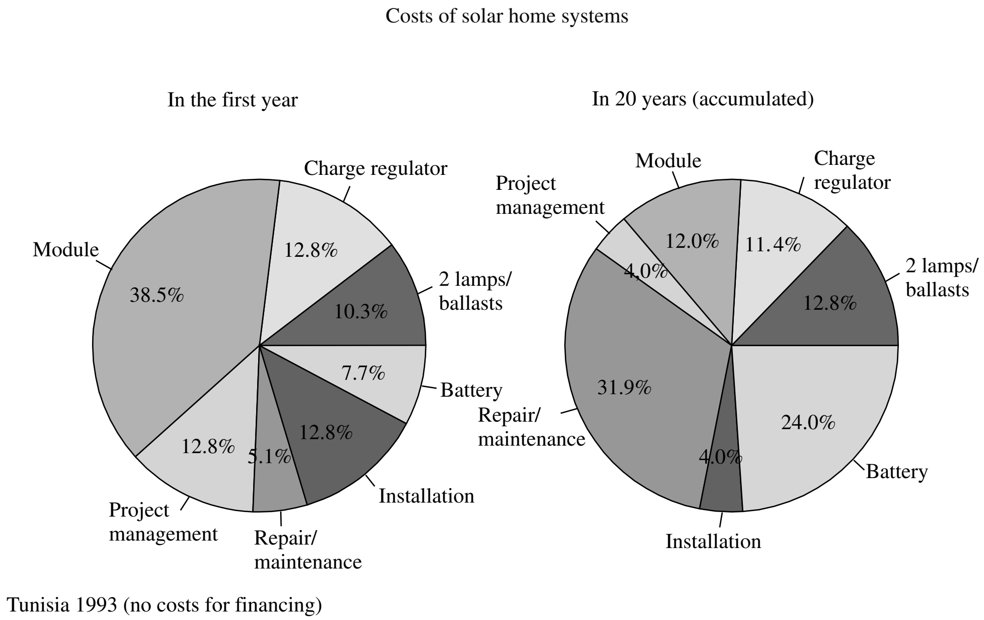

Figure 17.19 Cost breakdown for Solar Home Systems [7]: (a) year of installation; (b) cumulative costs after 20 years of lifetime

of system components (BOS), that is, battery, charge controller, installation material and the electric appliances.

To achieve highly reliable systems, recommendations for the quality improvement of Solar Home Systems and their components have been prepared in different institutions together with industry partners worldwide and are currently being introduced and implemented in national and international standardisation committees. The guarantee of high-quality standards is seen as the main necessity to bring in financing agencies and companies. Up to now, the risk that is due to the uncertainty about the durability and the handling of PV systems can be identified as one of the main barriers for bank, insurance companies, private fee for service providers, governments and last but not the least, for the users of the systems for becoming involved in this new technology.

The main components of small PV-systems are the PV module, the storage battery, the charge controller, if necessary a DC/AC inverter, the appliances (lamps, radio, TV sets, refrigerators, fans etc.) and the installation material (safety boxes, cables, plugs, sockets etc.). While today and at least in the near future, the PV module will be imported from industrialised countries – in some developing countries the module assembly has already started – all the other components are suited for local production. Of course, these components have to fulfil the high-quality standards as well, which are needed for all components in a PV-system. This is the reason in today's larger PV programmes for rural electrification often components from industrialised countries are used.

However, there are several reasons for the assumption that in the near future – and in reality this development has already started in many countries – good quality components will be produced locally. The proximity to the markets, that is, close matching with the users' needs and desires, the lower price of the components due to the lower expenses for manpower and the better commercial situation (no import barriers), the ability to repair and replace faulty components very quickly and the promotion by local governments show clearly that there is a large potential for local production.

Today, many local manufacturers work in joint ventures with industrialised countries, which may bring benefits for both sides, quick establishment of a production line of high-quality products for the local partner and increased market shares for the foreign partner. If local producers make wise use of international and national quality rules and quality control bodies, they will increase their market competitiveness considerably [21].

PV-systems have a high investment price, while the running costs are normally lower than those of the conventional alternatives. To overcome the barrier of high price for low-income customers, commercial and to-be-developed financing schemes have to be used. In the following list, the characteristics of the different delivery models applied in rural electrification are given (Figure 17.20).

- Cash and carry:
  typical: the dealers are based in main cities; customer comes there and pays system cash; ownership is transferred with payment; user is responsible for installation; operation and maintenance is done by the users.
- Cash sales:
  typical: the dealers are based in main cities and operate a salesmen network; customer pays system cash; system provider installs the system; ownership is transferred with payment; user is responsible for operation and maintenance.
- Dealer credit:
  typical: dealers with local offices; customer pays system on credit directly offered by system provider (down-payment plus instalments); system provider installs system; ownership is transferred with contract conclusion; user is responsible for operation and maintenance supported by system provider.
- Instalment credit:
  typical: dealers with micro-finance institutions; customer pays system on credit channelled from financial institution through system provider to customer (instalment =

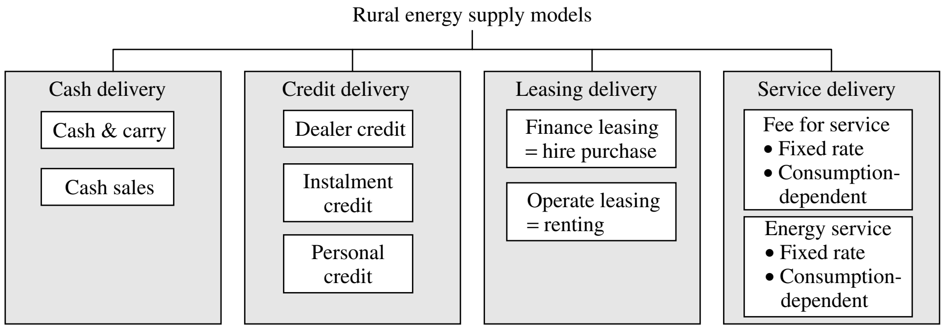

Figure 17.20 Categorisation of different delivery models in off-grid rural electrification

redemption plus interest); system provider installs system; ownership is transferred with contract conclusion; user is responsible for operation and maintenance supported by the system provider.

- Personal credit:
  typical: customer enters loan agreement with the financial institution of his choice to purchase system from a system provider of his choice; for other characteristics see cash and carry, cash sales.
- Operate leasing/renting:
  typical: customer rents system for payment of regular leasing fee; system provider is the owner of the system; system provider is responsible for installation and operation and maintenance of the system.
- Finance leasing/hire-purchase:
  typical: customer leases system for payment of regular leasing fee; system provider owner during basic leasing period; ownership title transferred with payment of remaining amount; system provider installs the system; user responsible for operation and maintenance.
- Fee-for-service:
  typical: dealer, service company (e.g. utility), customer pays regular service fees for electric service through individual power supply system or village power supply system; service provider is the owner of the system and responsible for installation, operation and maintenance.
- Energy service:
  typical: ESCO (energy service company), customer pays regular service fees for services such as light, communication, cooling and so on; service provider is the owner of the system and responsible for installation, operation and maintenance.

17.2.3 Decentralised Grid-connected Photovoltaic Systems

17.2.3.1 Rooftop PV generators

Photovoltaic systems can be connected to the public electricity grid via a suitable inverter (Figure 17.21). Energy storage is not necessary in this case. On sunny days, the solar generator provides power for the electrical appliances in a house. Excess energy is supplied to the public grid. During the night and overcast days, the house draws its power from the grid [22, 23].

Photovoltaic systems operating parallel to the grid have a great technological potential [24]. However, without subsidies from government or utilities, they are not yet financially competitive. Therefore, in the last few years in various countries, programmes have been initiated that push the dissemination of grid-connected systems, for example, the 70 000 PV roofs programme in Japan or the 100 000 PV roofs programme in Germany (see Figure 17.22). In addition, national laws on paying higher fees for renewable electricity fed into the grid, like in Germany 99 Pfennig, in Spain 66 Pesetas per kWh, make it more and more attractive for private consumers and investors to become engaged in photovoltaics.

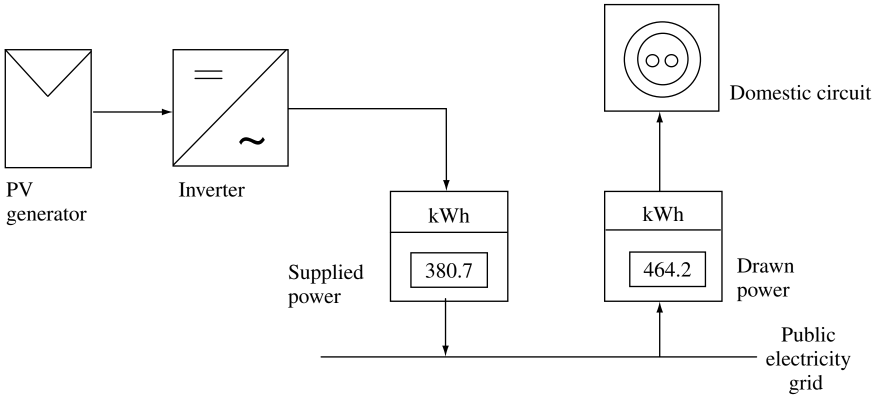

Figure 17.21 Block diagram of a grid-connected photovoltaic generator. The location of the two energy meters may vary depending on the applied payment scheme

Figure 17.22 Grid-connected photovoltaic roof on a private house in Germany (*Source*: Fraunhofer ISE)

17.2.3.2 Building integration

Standard modules are most commonly used for retrofitting buildings with PV systems, as little alteration of the building is required. Usually, they are mounted on the roof using an intermediate, added mounting structure. Integration into the building envelope is more difficult and few examples exist (see Figure 17.23). By contrast, frameless modules, so-called laminates, can replace conventional glass panes and thus allow easy integration.

Figure 17.23 Facade integration on the Mataro Library in Barcelona, Spain (*Source*: IES-UPM)

They enable the use of a wide product spectrum from the glazing industry. Demands by building owners and architects have stimulated some PV production firms to produce customised modules. These can be "trimmed" for every purpose to a certain extent. Such modules are offered with several options:

- Variable dimensions up to 6 m^2.
- "Arbitrary" connections of cells.
- Choice of colour.
- Crystalline cells in black, dark blue, light blue, greenish violet and bronze and amorphous modules mostly in brown shades.
- Various inter-cell distance to allow transmission of light (crystalline modules). Amorphous modules can even be made semi-transparent, by incorporating many microscopic holes into the Si layer.
- Rear surface covers can be matched to the colour of cells; they can also be used to influence daylight (e.g. diffusing).
- Cells can be selected to have the same colour.
- The front surface grid can be matched in colour.

By integrating PV cells into conventional double-glazing cells, other functions can be combined with PV (e.g. sound protection). Modules that are to be integrated into a building envelope need to allow enough clearance around the edges. Cells and junction boxes must be placed at an adequate distance to the edge. If not, problems such as partial shading or assembling problems may occur.

17.2.3.3 The Japanese residential PV promotion program

One of the worldwide largest dissemination programs has been launched in Japan in 1994. In the following years the number of small grid-connected systems skyrocketed [25]. This programme was to some extent combined with low-interest consumer loans and comprehensive education and awareness activities for PV. The programme makes blocks of funds available to PV system retailers in a competitive bid programme.

In 1997, the "New Energy Promotion Law" was introduced with subsidies for PV and a target of 400 MWp by 2000 and 4600 MWp by 2010. Up to the end of 1998, about 15 000 small grid-connected systems with an average capacity of about 3.6 kWp have been installed; in 1999 alone, about 18 000 systems were installed. This led to cumulated installed capacity of 200 MW in Japan by the end of the year 1999 (see Figure 17.24).

It appears that the Japanese programme has brought down the PV prices over the last years substantially along with the continuously decreasing subsidies. They were reduced from 50% of the total investment costs in 1994 to about 30% in 1999. The upper limit for rebates has been reduced from 900 000¥ per kW in 1994 to 270 000¥ per kW in 2000 (see Figure 17.25).

A result of this effort is that Japan is now the world leader in the development of grid-connected systems. This success is the direct result of a conscious policy to promote PV technology, both for reasons of national energy security (Japan imports most of its fuels) and for reasons of economic development (Japan aims to dominate PV manufacturing to the same extent as it dominates the production of electronic equipment).

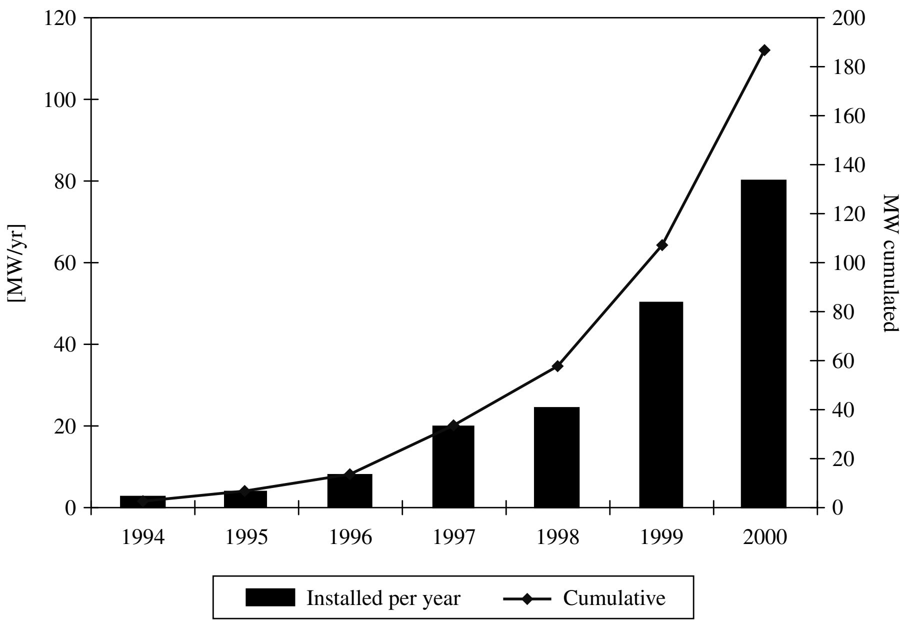

Figure 17.24 Japanese residential PV promotion programme: development of installed capacity and average capacity [25]

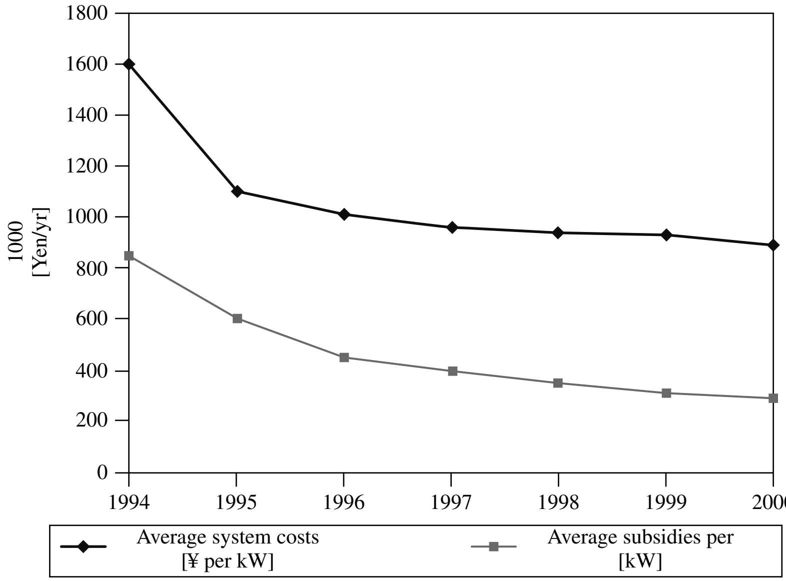

Figure 17.25 Japanese residential PV promotion programme: development of investment costs and rebates 1994–2000 [25]

17.2.3.4 The German 100 000 photovoltaic roofs programme

The German government has made climate protection one of its key policy issues. A 25% carbon dioxide reduction target by the year 2005 compared to 1990 levels was announced. The use of renewable energy sources can help achieve this ambitious goal. By 2010, the German government wants to double the contribution of renewable energies to the total energy demand. In 1998, the use of renewable energies in Germany reached 284 PJ of primary energy demand, which corresponds to a penetration rate of 2% of the total primary energy demand or 5% of the total electricity demand [26].

As the German government and administration are organised in accordance to the federal structure of the country, federal, regional and local authorities are promoting the use of renewable energy sources in many different programmes. The Federal Ministry of Economics and Technology (BMWi) will support within the 100 000 Roofs-PV-Programme the installation of up to 350 MW of photovoltaics (see Figure 17.26). One billion DM will be spent between 1999 and 2004 by giving favourable credit conditions by the government bank KfW, that is, for PV systems between 1 and 5 kW, a soft loan for a 10-year credit is offered with an interest rate that is 4.5% below market conditions.

Since 1991, the "Electricity Feed Law" regulated the input and favourable payment of electricity from renewable energies by the utilities. In 2000 the law was replaced by the "Renewable Energy Law (EEG)" with improved conditions. This law serves as the basis for the implementation of renewable energy technologies in Germany. For electricity generated by photovoltaic generators, the payment amounts to (at least) 99 Pfennig (i.e. about 0.51 €) per kWh for PV systems installed until December 31, 2001. Starting with January 2001 this minimal payment limit will be reduced each year by 5%, that is, for an

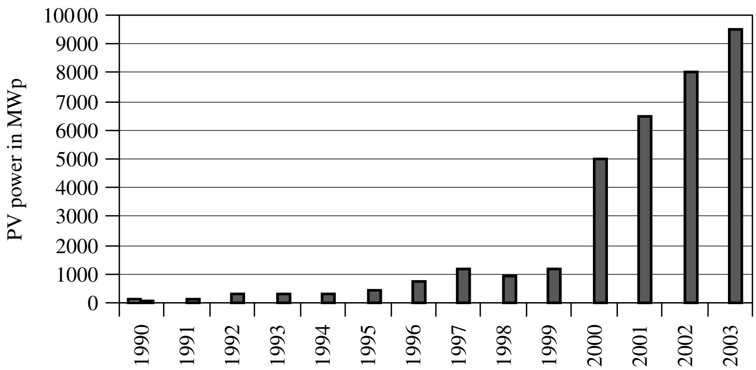

Figure 17.26 Installation already done and prospects of grid-connected photovoltaic systems in Germany (*Source*: Deutscher Fachverband Solarenergie DFS)

installation done in the year 2002 "only" 95 Pfennig will be valid and for an installation finished in 2003 and connected to the public electricity grid 90 Pfennig will be valid. This law expires when a cumulative power of 350-MW photovoltaics has been reached.

17.2.4 Central Grid-connected Photovoltaic Systems

17.2.4.1 Utility systems

Whereas the photovoltaic systems discussed earlier are usually small decentralised systems in the lower kilowatt range, it is also possible to build large central photovoltaic power stations in the higher kilowatt to megawatt range. It is then possible to feed directly into the medium- or high-voltage grid.

One of the most impressive installations done in the late nineties was the megawatt power plant at Toledo in Spain (Figure 17.27).

Another architectural well-designed solution is the megawatt power plant on the roof of the new fair in Munich, installed in 1999 (Figure 17.28).

17.2.4.2 Joint ownership

In Germany, 60% of the total population live in rented apartments. Consequently, they will generally not be able to install grid-connected PV plants on the rooftops of their house. When these people become interested in PV, they can only become PV owners if PV projects are established with "joint ownership". To create this, a legal entity is set up to deal with the project management as well as with the related financial questions and the distributing scheme of the profits generated through the investment. In most cases, contracts are signed between various project partners to resolve management issues during project realisation (see Figure 17.29).

Contracts contain operational, financial and legal items concerning the collaboration of the different parties in project realisation. Signing parties are mostly the project

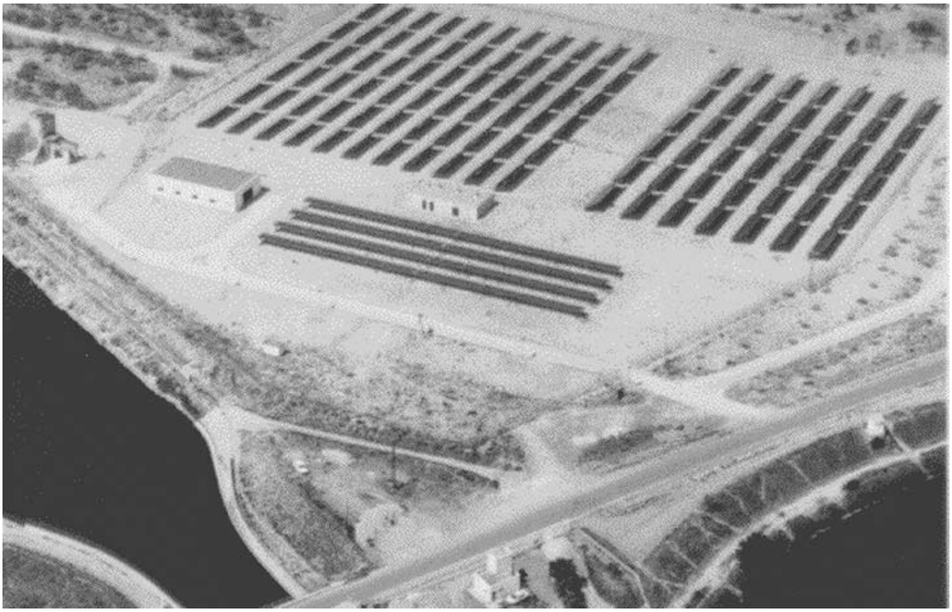

Figure 17.27 Central PV system installed at Toledo (*Source*: IES Madrid)

Figure 17.28 Central PV system installed on the roof of the new fair in Munich, Germany (*Source*: Siemens Solar)

developer, the owner of the electricity grid, the end owner of the PV system and the so-called limited partners. The projects are financed either by purely equity capital of the owners or by a mix of equity and debt capital through credits. The (major) portion of the capital is generated by the project through a public placement. In this case, transaction costs are minimal and risk-funding is supplied by the larger public participating with risk equity (see Figure 17.30).

17.2.5 Space Application

The number of artificial satellites launched by the world's nations exceeds more than 5000. Some of them return to Earth as part of their mission and others fall to Earth after

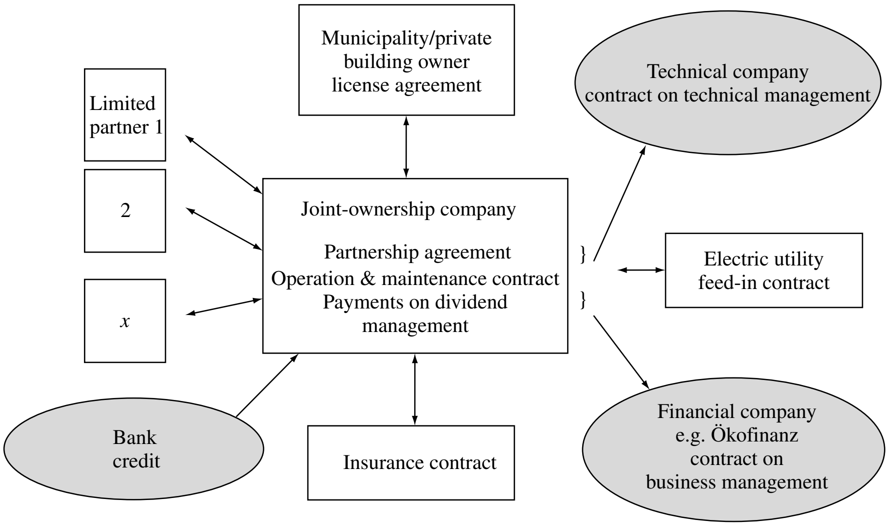

Figure 17.29 Example of the organisational structure of a joint ownership project [27]

Figure 17.30 Joint ownership PV installation of 100 kW on the soccer stadium Freiburg, Germany [27]

their orbits decay. Those that remain in orbit number about 2300 and in addition there are about 5700 items of “space debris”, such as rocket bodies, apogee kick motors and so on, making a total of some 8000 manmade objects currently in orbit around the Earth.

Satellites can be classified by their function since they are launched into space to do a specific job. The type of satellite that is launched to monitor cloud patterns for a weather station will be different from a satellite launched to send television signals across Canada. Below, the classification into nine different types of satellites is given as well as a prominent representative of each of it:

- Astronomy satellites, for example, Hubble Space Telescope
- Atmospheric studies satellites, for example, Polar
- Communications satellites, for example, Anik E
- Navigation satellites, for example, Navstar
- Reconnaissance satellites, for example, Kennan, Big Bird, Lacrosse
- Remote sensing satellites, for example, Radarsat
- Search and rescue satellites, for example, Cospas-Sarsat
- Space exploration satellites, for example, Galileo
- Weather satellites, for example, Meteosat (see Figure 17.31)

17.2.5.1 The international space station ISS

The International Space Station is the largest and most complex international scientific project in history (Figure 17.32). When it is complete the station will represent a move of unprecedented scale off the home planet. Led by the United States, the International Space Station draws upon the scientific and technological resources of 16 nations: Canada, Japan, Russia, 11 nations of the European Space Agency and Brazil. More than four times as large as the Russian Mir space station, the completed International Space Station will have a mass of about 502 000 kg. It will measure 120 m across and 95 m long. Assembly is planned to be completed by 2004. Most of the 256-kW solar arrays will be delivered by United States; only Russia will provide a science power platform that can supply about 20 kW of electrical power. This PV generator – worth about 450 million US$ – will be the largest object ever transported by human being into space. Each of the 6560 solar modules consists of 40 8*8 cm^2 mono-crystalline silicon cells. Cell efficiency will be around 14.5%, which seems to be not very outstanding; however, when the production of the cells started in 1988, the technology of the much more efficient GaAs cells – up to 26% is now possible – was not yet available.

17.2.5.2 The unmanned airplanes "Pathfinder" and "Helios"

The Pathfinder is one of several unpiloted prototypes under study by NASA's ERAST (Environmental Research Aircraft and Sensor Technology) program, a NASA-industry alliance that is helping develop advanced technologies that will enable aircraft to study the Earth's environment during extremely long flights at altitudes in excess of 30 km. The Pathfinder is a remotely controlled, solar-powered flying wing, designed and built as a proof of concept vehicle for a much larger aircraft capable of flying at extremely high altitudes for weeks at a time. Pathfinder is constructed of advanced composites, plastics and foam, and despite a wingspan of nearly 30 m, it weighs only about 300 kg. Current from solar arrays provides power during daylight, while stored energy allows flight after dark. The batteries allow an endurance of about 2 h in darkness.

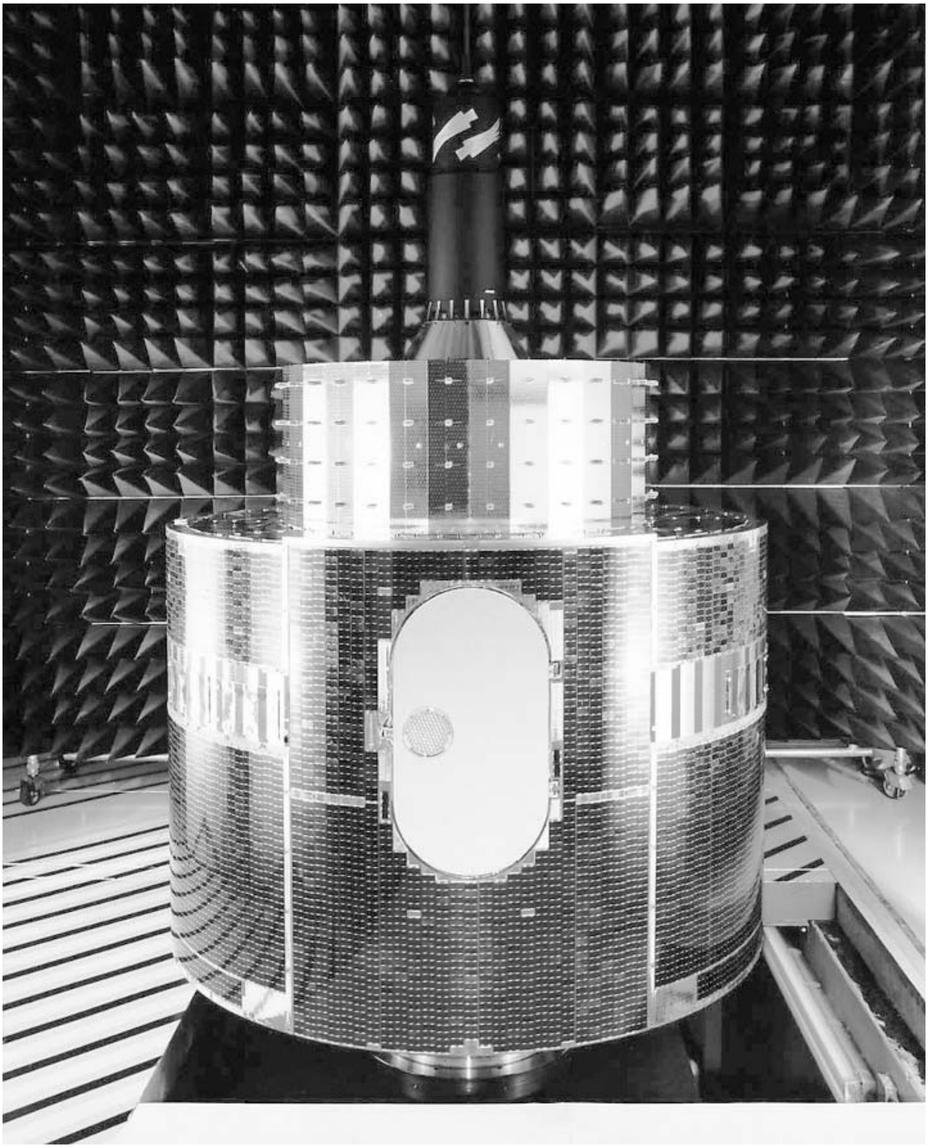

Figure 17.31 The weather satellite Meteosat, developed by the European Space Agency ESA

A further development of the Pathfinder is the Helios Prototype (Figure 17.33). The craft has a wingspan of 80 m, $2\frac{1}{2}$ times that of the solar-powered Pathfinder's flying wing, and longer than the Boeing 747 jetliner. Helios, which is relatively cheap to run and is harmless to the environment, is being developed mainly for commercial uses. Since the plane will be able to observe the Earth from a high-level altitude and will also function as a relay station for radio communications, its potential applications include weather observation as well as a collection of information in case of volcano eruptions and/or earthquakes.

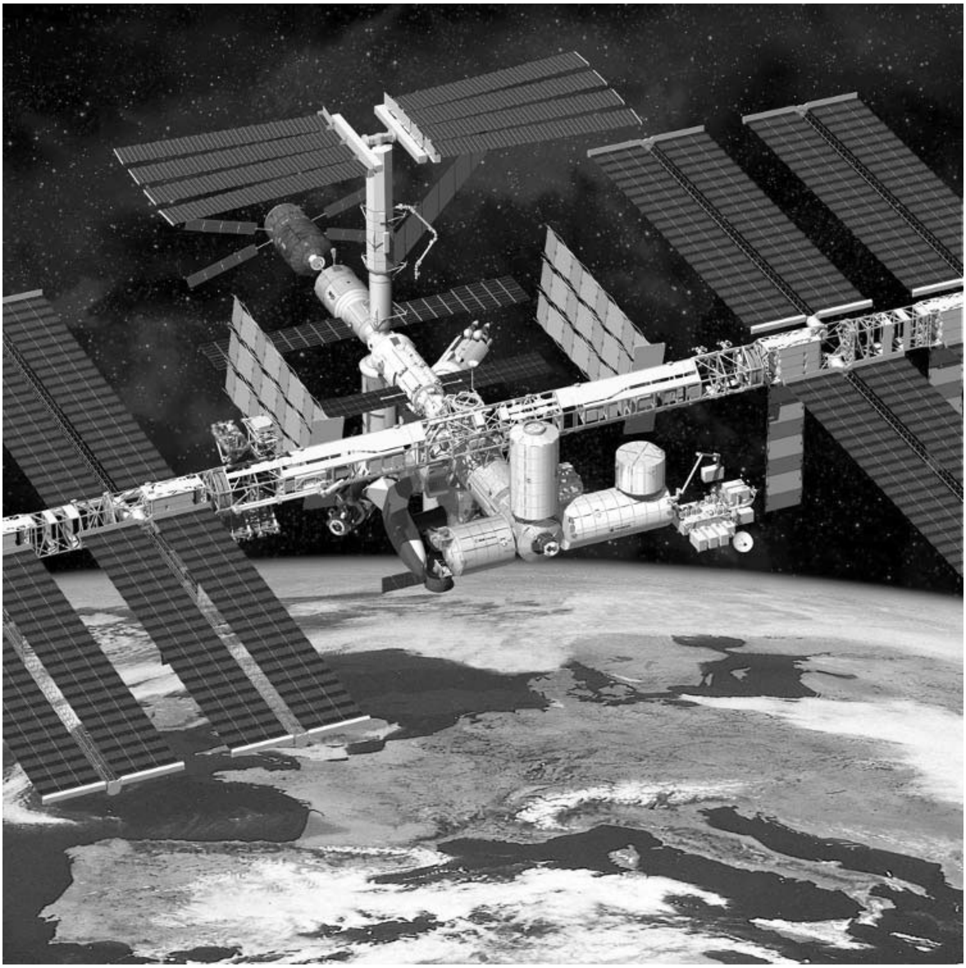

Figure 17.32 The International Space Station

17.3 COMPONENTS FOR PV SYSTEMS

As has been seen in Section 17.2.2.8, the so-called balance of systems play a key role in the lifetime costs of photovoltaic systems. Therefore, the main components will be described as a summary; for more details, see the respective chapters in this book.

17.3.1 Battery Storage

Stand-alone PV systems require energy storage to compensate for periods without or within sufficient solar irradiation, such as during the night or during cloudy weather. In all cases in which electric energy storage is required, the classical electrochemical accumulator battery is the most convenient form of energy storage for a PV system, especially since its DC (direct current) characteristic allows for direct connection between

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC99-45186-3 Date: September 1999 Photo by: Tom Tschida

Helios Prototype in flight over lakebed during second battery-powered flight

Figure 17.33 Helios, an unmanned prototype aircraft for flights at 30 km of altitude

the PV generator and the battery, without need for any conversion or transformation of the supplied PV energy.

Unfortunately experience has shown that in stand-alone PV systems, the battery appears to be the "weakest point" of the system, since its lifetime expectancy is usually an order of magnitude lower than that of all the other PV system components, and thus 30% of the lifetime costs of solar off-grid systems or even more may be attributed to the storage. Although a variety of storage technologies are under development, the lead-acid battery still is, and will be for some years to come, the working horse for electricity supplies in remote areas.

Typically, the storage battery of a stand-alone PV system is dimensioned to ensure, if the solar irradiation is insufficient, that the envisaged loads can be powered for at least 3 to 4 days. The result of such typical dimensioning is that the daily depth of discharge of a PV battery is in the range of about 25 to 30% of its rated (10 h) capacity. Furthermore, the dimensioning of the PV generator may usually be assumed to cover the entire energy

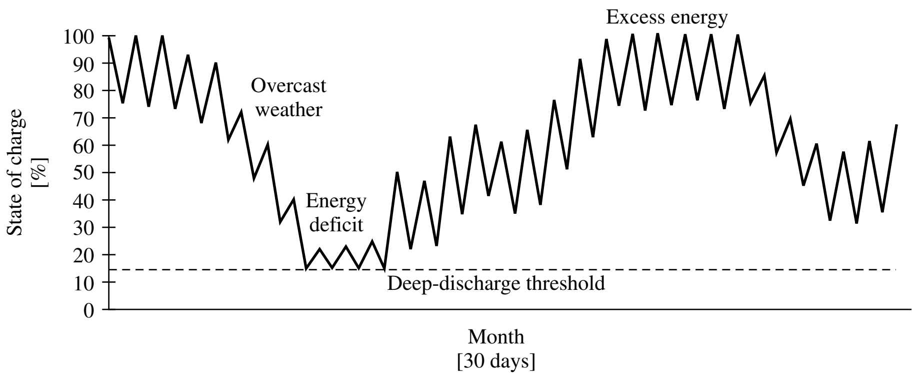

Figure 17.34 Operating conditions of batteries in PV systems

demand of the envisaged loads under average irradiation conditions. These two basic assumptions allow the following points regarding the typical operating conditions of a battery in a stand-alone PV system to be deduced (see also Figure 17.34):

- *Excess energy operation*: In summer, any PV system operates under excess energy operating conditions, since it is designed for lower (average) solar irradiation conditions. As a result, the battery reaches the maximum charge voltage threshold nearly every day at midday or during the early afternoon, and, until evening, it is fully (100%) charged. During the night, the battery discharges and in the morning, at sunrise, it reaches its minimum state of charge, approximately 70% of its rated capacity. During the next day, it repeats the same charge cycle as during the previous day and is again fully charged in the evening. These are optimum operating conditions for a PV battery.
- *Energy deficit operation*: In winter, if not significantly over-dimensioned, the same PV system will encounter energy deficit operating conditions more or less frequently. Each time cloudy weather (without direct sun) persists for some days, the state of charge of the battery will gradually diminish and sooner or later the battery voltage will drop below the minimum discharge voltage threshold. Unless the user reduces consumption voluntarily, the result will be that the DDP cuts off the load. Load cut-off will be maintained by the DDP until the battery is recharged during the next sunny day and reaches a reasonable voltage level, allowing the DDP to switch the load on again. During winter, depending on how carefully the user manages his/her PV system, the battery may very frequently suffer long periods of harmful deep discharge.
- *Float cycling operation*: During those days when the battery reaches neither the 100% full charge condition nor the minimum discharge voltage threshold, it cycles in a semi-charged float condition that is difficult to characterise. However, in comparison to the other two previously described operating conditions, this intermediate operating condition is of little overall significance for the life of the battery since it does not occur nearly as frequently as the other two.

Accordingly, the operating conditions and lifetime of a PV battery are primarily determined by the number of days when the battery reaches 100% full charge condition (which is the optimum) and the number of days when it reaches the minimum discharge voltage threshold (worst operating condition). If the PV generator has been dimensioned to be too small for the envisaged loads, the battery will reach deep discharge conditions more frequently during the year and its lifetime will be short. If, instead, the PV generator is over-dimensioned, the battery will reach 100% full charge conditions nearly every day of the year, and its lifetime will be longer.

As battery lifetime is one of the key factors that determine lifetime costs of the whole stand-alone Photovoltaic system, one must obey a complex set of rules when aiming for maximum battery lifetime, that is, choose the best suited technology for your application, define properly suited end-of-charge and end-of-discharge thresholds, avoid deep discharge, avoid acid stratification in the electrolyte, avoid high battery temperatures, assure frequent full charging, avoid individualisation of single cells in a series of connected batteries and so on [28, 29]; for more details see Chapter 18.

In Table 17.1 the most important rules to achieve long battery lifetime are summarised.

It must be pointed out that some of the rules are generally in contradiction to each other (e.g. full charging needs high voltages but high voltages accelerate corrosion). In photovoltaic stand-alone systems, it may be difficult to follow these rules at all times. A compromise must be found between the demands of the battery for regular recharging and the investment into expensive photovoltaic generators, so energy may not be available during low insulation periods for recharging of the battery. As the application of the rules is the responsibility of the charge controller, it becomes evident how complex the technical design for this important electronic system component can be.

17.3.2 Charge Controller

Although photovoltaic systems can be used without charge controllers and this practice can be found very often in small PV systems, it has to be stated that while planning the long-term operation of a stand-alone photovoltaic system, it is a must to avoid overcharge and deep discharge. As has been seen in the previous chapter, battery costs over the lifetime of a PV system take the major share of the cost of the system. Battery lifetime again depends to a large degree on its operation strategy.

Table 17.1 Rules for battery management and their positive effects when they are applied

Rule for battery management	Effect when applied
Avoid high voltages during charging on the battery	Less corrosion and loss of water
Avoid low voltages during discharge of the battery	Less corrosion
Avoid extended periods without full charging of the battery	Less sulphatation
Avoid deep discharge	Less sulphatation and growth of dendrites
Avoid reverse charging of the cells	Less degradation of negative electrodes
Avoid stratification of the electrolyte	Less sulphatation
Avoid high battery temperatures	Slower ageing processes
Overcharge the battery slightly once a month	Frequent full charging is assured

The charge controller is the link between the solar generator, the battery and the load. It prevents both overcharging and deep discharging of the battery. A list of the most important requirements of the charge controller follows.

- Low internal consumption (<5 mA).
- High efficiency value (96 to 98%).
- Load disconnection if deep discharge occurs (current-dependent, discharge cut-off voltage, if possible).
- Regular charging at a higher voltage to promote gassing.
- Temperature compensation of the charging cut-off voltage (4 to 6 mV/K).
- Reverse poling impossible.
- Breakdown voltage of the semiconductor components at least twice the open circuit voltage of the solar generator.
- Integrated overvoltage protection (conducting capacity limit by a 8/20 norm impulse: 3 kA per installed kWp of the solar generator).
- Ambient temperature (0 to 50°C standard model).

When system complexity increases, then other aspects have to be considered in designing a stand-alone PV system: with appropriate energy management schemes, the use of the electricity generated and the lifetime of sensitive system components can be further optimised, for example, switching off less priority loads, switching on water pumps to access energy to fill a water storage, starting the back-up generator to avoid critical situations for the battery. These energy management units have to be designed specifically for the foreseen application. As described earlier, it is highly recommended that the system displays units that inform the user about the current status of the system and give them advice about how to react in an appropriate way.

17.3.3 Inverters

Inverters are power electronic devices used in various photovoltaic (PV) system configurations:

- grid-connected systems
- stand-alone systems with rechargeable batteries
- pumping systems without storage batteries.

17.3.3.1 Inverters for grid-connected systems

The planning of a grid-connected photovoltaic system begins with the choice of a suitable inverter. This determines the system voltage on the DC side, and the solar generator can then be configured according to the input characteristics of the solar inverter. The inverter is the second most important component of a grid-connected photovoltaic system (after the solar generator). Its task is to convert the direct current generated by the solar cells to a 50-Hz alternating current conforming to the grid. In contrast to inverters intended only for stand-alone operation, those intended for parallel operation must respond just as well to the grid characteristics as to the solar generator performance. As all of the solar current flows through the inverter, its properties fundamentally affect the behaviour and operating results of the photovoltaic system.

Apart from the efficient conversion of direct to alternating current, the inverter electronics also include components that are responsible for the daily operation mode. They ensure that operation starts at the right time in the morning as soon as the solar cells deliver enough power. Unsuccessful start attempts require energy from the grid and should be avoided by good controls. During the day, the optimum working point on the I-V characteristic curve shifts according to the fluctuations in solar radiation and module temperature. Intelligent inverter control includes maximum power point (MPP) tracking and continuous readjustment to the most favourable working point. Protective devices are also integrated into the inverter, which automatically disconnect the system if irregularities in the grid or the solar generator occur.

Today most inverter models are additionally equipped with data loggers and measurement computers, which allow the power, voltage, current and other operating parameters to be recorded continuously. These data can be read out at intervals via a serial interface with a laptop computer and analysed.

17.3.3.2 Inverters for stand-alone systems

Because of the specific operating conditions of stand-alone inverters, different design aspects have to be considered.

In a typical domestic power supply, the ratio of the peak power to the average power is about 25:1, so the inverter must have a high efficiency of approximately 90%, particularly in the partial load range (5–10% of the rated power). Only a few inverters satisfy this condition together with a sinusoidal output voltage and the capacity to withstand short-term, double to triple overloading. Depending on the requirements, both sinusoidal and rectangular waveforms can be used.

The most important requirements on inverters for stand-alone photovoltaic systems are summarised in the following list.

- Large input voltage range (−10% to +30% of the rated voltage).
- Output voltage as close to sinusoidal as possible.
- Little fluctuation in the output voltage and frequency.
- ±8% voltage constancy, ±2% frequency constancy.
- High efficiency for partial loading; an efficiency value of at least 90% at 10% partial load.
- Ability to withstand short-term overloading for appliance starting conditions, for example, two to three times the rated current for 5 s for refrigerators and washing machines.
- Lowest possible overvoltages for inductive and capacitive loads.
- Half-wave operation possible, caused by power reduction with a diode, for example, in hair dryers.
- Able to withstand short circuits.

However, the following restrictions apply to the use of inverters with a rectangular waveform:

- Because the voltage level at the zero crossing is not clearly defined, the function of some appliances with electronic controls (e.g. modern washing machines) is affected.
- The steep voltage gradients destroy resistors in simple power supplies (e.g. in freezers) by overloading.
- The steep voltage gradients result in increased noise and heat generation in transformers and motors. Further, a reduction of about 10% in the efficiency value must be expected.

17.3.4 Auxiliary Generators

In general, diesel generators are used today in larger photovoltaic hybrid systems with an energy demand of around 10 kWh/day. For systems with a daily energy demand of a few hundred watt hour up to a few kilowatt hour, small combustion motors, small fuel cells, thermoelectric generators (TEG), thermophotovoltaic generators (TPV) or appropriate thermodynamic converters such as small Stirling motors all come into question in principle. If adequate commercial availability is regarded, at present the choice is narrowed essentially to small combustion motors (diesel, petrol) with a coupled generator, and thermoelectric generators. While the investment costs and the availability in nearly all countries make petrol and diesel generators very attractive, the inherently high reliability, low maintenance and the almost silent operation and simple remote starting facilities speak for the application of thermoelectric generators in small photovoltaic hybrid systems (Table 17.2).

Table 17.2 Comparison of the characteristics of small, commercially available auxiliary generators [30]

	Small combustion motors		Thermoelectric
	Petrol	Diesel	
Electric power range	>0.3 kW	>3 kW	>0.03 kW
Efficiency value at full load	App. 5–15%	App. 20–25%	App. 3%
Adjustability	Good	Good	Limited
Remote starting	Yes, >3 kW	Yes	Yes
Reliability	Medium	Medium	High
Maintenance demand	High	High	Low
Environmental acceptability	Pollution emission CO_2 emission Noisy	Pollution emission CO_2 emission Noisy	Pollution emission CO_2 emission Almost silent
Commercial manufacturers available	Globally	Globally	Few
Fuel:			
Type	Petrol	Diesel	e.g. propane/butane
Availability	Medium	High	Medium
Consumption	0.6–1 l/kWh	0.4–0.5 l/kWh	2–2.5 kg/kWh

A significant disadvantage of combustion motors is their need for regular maintenance. Car manufacturers recommend for diesel motors a change of the lubricant at least every 10 000 km. If we assume an average speed of 50 km/h, this means that after 200 h of operation a complete service is necessary. Keeping in mind that a back-up generator in a stand-alone system is working in optimised systems at least for 2 h and in conventional systems for about 6 to 8 h a day, this means that in optimised systems every 3 months and in conventional systems every 30 days a complete maintenance service has to be calculated. Together with the high costs for fuel transport, this is the main reason for the low attractiveness of combustion motors in off-grid electrification.

17.3.5 System Sizing

In addition to the quality of the system components and the construction of the system, the sizing of the solar generator and the storage battery plays an important role in the operating reliability of a photovoltaic power supply. The dimensions of the solar generator and the storage battery determine what proportion of the consumer's energy demand can be met by the photovoltaically generated electricity. A photovoltaic system should be sized in accordance with the other planning steps:

1. Determination of the energy demand and optimisation of the consumption: This step includes determining the energy demand of the intended consumers as exactly as possible and investigating possibilities for saving energy by reducing the power consumption of the appliances or systems used.
2. Development of the concept: Setting the voltage level (in many cases this is determined by the user) and thus the type of photovoltaic system (DC, AC, combined DC and AC, grid-connected, stand-alone, with or without a back-up generator).
3. Choice and dimensioning of the system components for power conditioning: Converters to match the power generation and consumption sides are chosen according to the system type. The efficiency values of these components often have a decisive influence on the system energy balance and thus must be taken into account when sizing (step 4). This applies particularly to inverters used to supply power to conventional 230-V appliances.
4. Sizing the solar generator and the storage battery.
5. Dimensioning the solar charge controller.
6. Dimensioning the cables: The voltage drops occurring in cables should not be ignored, particularly in larger systems operating at a low voltage level.

It may be necessary to iterate steps 1 to 4 several times. For example, the result obtained in the sizing step 4 may demand a further reduction in consumption or a change in the system concept (e.g. incorporation of an additional generator), for various reasons (insufficient area for the solar generator, system cost etc.).

Generally, several variants are considered during the planning stage, which differ in aspects such as supply reliability, cost, maintenance demand and electrical and structural configuration. The priority given to each aspect depends on the particular application intended for the photovoltaic power supply. For a system that is required to operate completely autonomously, the supply reliability is decisive, whereas this issue is of secondary importance for a household supply in which a back-up generator is included anyway.

The operation behaviour of the photovoltaic system is characterised and evaluated with the help of a suitable computation procedure. It is particularly important to know the system's operation behaviour with regard to the supply reliability and the effective use of the photovoltaically generated electricity.

The optimal tilt angle for the solar generator depends on the specific conditions under which the system is operated. A clear distinction must be made between grid-connected and stand-alone systems. Grid-connected systems are generally optimised to achieve the maximum possible annual yield. As all of the energy output from the solar generator is used either by direct consumption or by being fed into the public electricity grid, the system yield has the same dependence on the orientation and tilt angle as the solar radiation incident on the solar generator (Figure 17.35).

The optimum tilt angle of about 30° is smaller than the average solar zenith (equal to 90° latitude), as the major share of the solar radiation is incident during the warmer six months for the Central European climate.

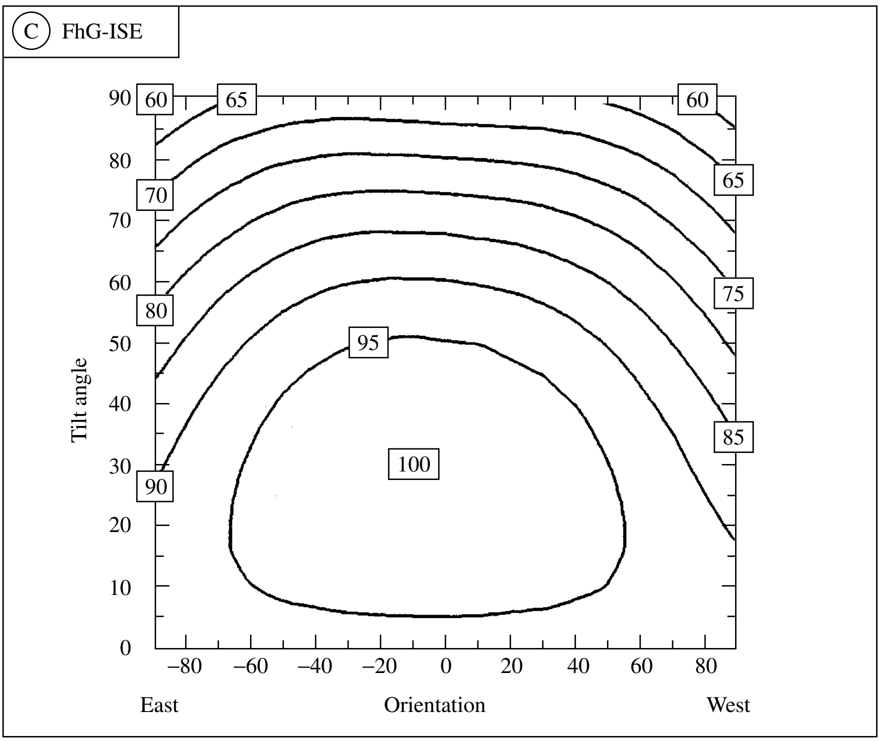

Figure 17.35 Dependence of the annually used solar energy from a grid-connected system dependent on the orientation and tilt angle (percentage values relative to the maximum used solar energy; orientation 0 = south, for the northern hemisphere)

In stand-alone systems, the fundamental difference in operating behaviour as compared to grid-connected systems is due to the storage battery. As stand-alone systems generally have to achieve a certain, pre-determined solar fraction within a given operating period, the decisive time within that period for the system sizing is the one during which the radiation level is lowest. The optimal tilt angle depends not only on the radiation characteristic but also on the system itself. Figure 17.36 shows the optimal tilt angle, for which the solar generator area is minimal for the relevant pre-determined solar fraction, and the corresponding solar generator power.

Whereas in summer, the storage capacity does not have any effect on the optimal tilt angle (solid line), a dependence can be observed in winter (dotted line); higher solar fractions lead to less steep inclinations, particularly for small storage capacities. The explanation for this difference is the variation in the daily radiation in winter. If the storage capacity is small, sunny days lead to surpluses, so that the available radiation cannot be fully used. Thus, on overcast days, the (weak) diffuse radiation must be used optimally, with a less steep slope (smaller tilt angle) as a result.

17.3.6 Energy-saving Domestic Appliances

On average, a four-person household in Germany consumes about 3500 kWh electricity per year, if electricity is used neither for space heating nor for water heating. In order to meet this demand, for example, with a grid-connected photovoltaic system, about 4-kW rated power, that is, a module area of about 40 m^2, would be needed in Southern Germany. With a module price of about 4 € per watt of rated power, the solar modules alone would cost €16 000. In view of these high investment costs, the potential for saving energy with the appliances used in the household should be exploited as far as possible, rather than investing in a large system.

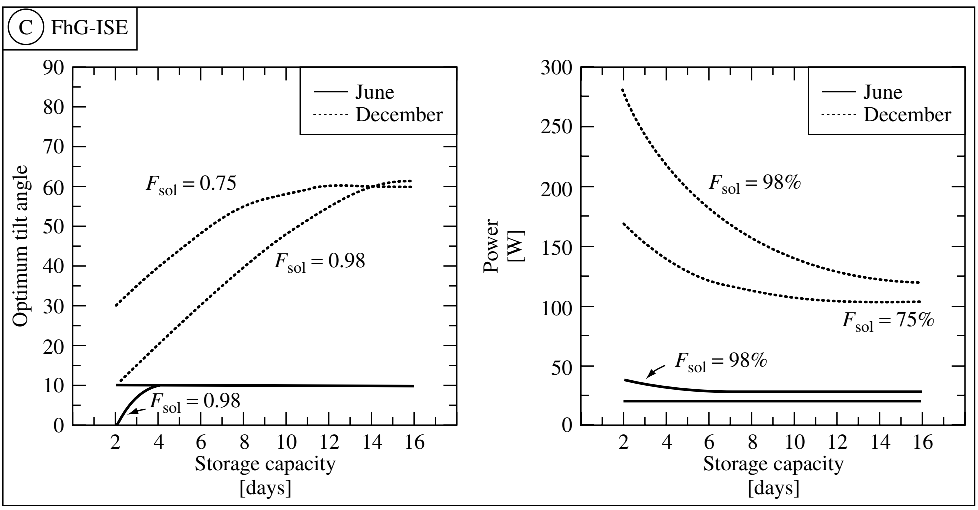

Figure 17.36 Optimal tilt angle for minimising the solar generator size and corresponding values of the solar generator power as a function of the storage capacity

Table 17.3 Electricity consumption (kWh/year) of household appliances

Appliance	Wasteful	Average	Energy saving
Refrigerator (upright,	270	230	87
No freezer, 100 liter)	(100%)	(85%)	(32%)
Freezer (upright, 200 liter)	800	426	168
	(100%)	(53%)	(21%)
Refrigerator/freezer combination	625	343	267
(upright, 200 liter)	(100%)	(55%)	(54%)
Washing machine (without a hot	522	366	280
water connection)[a]	(100%)	(70%)	(54%)
Washing machine (with a hot	–	–	202
water connection, 60°C)[b]	–	–	(38%)
Dishwasher (without a hot water	614	481	296
connection)[c]	(100%)	(68%)	(48%)
Lighting	438	–	87
(5 × 60 W)[d]	(100%)	–	(20%)

[a]Use: 3 full loads per week, each with 5 kg of washing
[b]Relative to a machine with 522 kWh/year
[c]Use: 5 loads per week with 10 settings per load
[d]Use: 4 h per day

Table 17.3 demonstrates how large the potential is for saving energy with household appliances. The absolute electricity consumption is given for a wasteful, an average and an energy-saving appliance in kilowatt hour per year. The table shows that the electricity consumption for some appliances can be reduced by up to 80%, without a loss in convenience, simply by using modern, energy-saving models. It is also evident that connecting the washing machine and the dishwasher to a non-electric hot water supply can reduce the electricity consumption still further.

Refrigerators and freezers, washing machines and dishwashers are purchases that are expected to last for many years. Thus, it is certainly worthwhile investing in energy-saving appliances that have a particularly low electricity and water consumption.

If energy saving is taken seriously, a four-person household can achieve an annual consumption of about 700 kWh, not including electricity for building services (electric doorbell, outside light, heating pump etc.). Even when not completely energy-optimised, a four-person household can manage with an annual consumption of 1500 kWh, including building services.

17.4 FUTURE DEVELOPMENTS IN PHOTOVOLTAIC SYSTEM TECHNOLOGY

17.4.1 Future Developments in Off-grid Power Supply with Photovoltaics

Rural electrification with photovoltaics has become a rapidly emerging market in the last few years. While grid extension is getting more and more difficult because of the high costs of connection in remote households with their relatively low-energy consumption for lighting and communication, about two billion people worldwide stay without access to electricity as the modern form of energy supply. As the population, especially in rural areas of developing countries, grows rapidly, there are more people each day without access to electricity than the day before!

This is why in many countries rural electrification programmes have been initiated. These programmes explicitly foresee the application of photovoltaic systems to provide electric power to remote rural households and public facilities, for example, Argentina has electrified 300 000 households and 6000 public facilities, in Morocco all villages in rural areas shall be electrified within the year 2010, which takes into consideration that about 200 000 households have to be supplied by photovoltaics; in many other countries such as China, Indonesia, India, Sri Lanka, Philippines, Mexico, Bolivia, Kenya, Uganda or South Africa large programmes do exist or are in preparation for realisation in the near future. The World Bank as one of the major support organisations in rural electrification is involved in more or less all these national programmes, thus helping to cover the high up-front costs of PV rural electrification and establishing innovative financing schemes. Most of these programmes today concentrate on Solar Home Systems, as these systems are relatively easy to install and operate. However, the key for success or failure of these programmes lies in the establishment of appropriate infrastructures for installation, operation and maintenance of these systems as well as in the introduction of schemes for quality certification, microfinancing and adequate involvement of the users [9, 21, 31].

After some disastrous experiences with village power supply systems in the seventies and early eighties, they see today a revival in many rural electrification programmes. The reason for this is that much better suited and more reliable components are available today and that more and more utilities or other energy service companies (ESCO) are starting to enter the market. With these new players a different concept appeared, which is the provision of energy service instead of selling PV systems. In Argentina, for example, the companies getting engaged in rural electrification – and benefiting from the subsidy scheme set-up there – have to sign a contract of serving the rural population with electricity for at least 45 (!) years. Here, often village power supply systems are applied: a small electric grid is created that may be considered as similar to the already existing public electricity grid. However, because of the strong limitation of the resources compared to a large electricity grid, new models have to be developed to plan, market, operate and sell this service. The involvement of the users in these central systems is seen as essential as the behaviour of the whole community does have a major impact on the appropriate use of the limited power and energy provided. Appropriate financing schemes, such as prepayment meters or the involvement of microfinancing institutions in the whole process, are new developments that will have to be elaborated further in the near future.

Today about two billion portable appliances are used worldwide and the market is rapidly growing. In the near future, the doubling of this number is expected. Watches, laptops, mobile phones, palm pilots and so on are characteristic for the new information society. This means the future of information is free of cables. Most of these devices are powered by batteries, but they are often flat and have to be recharged at a grid-based charging station. Photovoltaics are considered to be one of the best solutions to cover the often low-energy demands of these grid-independent devices. First prototypes do exist. The development of the market will be successful if adapted systems can be developed that can cope with the often extreme restrictions of miniaturisation and the often lacking availability of sunlight or at least of artificial light. Highly efficient solar cell highly miniaturised and also efficient energy conversion and new product design adapted and suited to the energy source will be the key factors of a successful market penetration.

In parallel to the power supply of the appliances themselves, a need arises for repeaters of the signals to be transmitted, which will be lower in its energy and power demands but will have to guarantee permanent availability. As these repeaters will have to be located on peaks or tops of hills and mountains, grid connections will be very often too expensive. Therefore, low-maintenance hybrid systems will gain a natural market where they can compete with the extremely high requirements concerning reliability and ease of operation.

In all stand-alone applications, the storage unit is one of the technical components that still needs the most development. Often described as the weakest link in the chain, it is responsible for a large share of the costs in long-term operation. Thus, optimisation of the interaction of all components in the system with the aim of reducing the overall lifetime costs is today the main issue on this sector. As also the battery industry has recognised, there is a great need for the development of better battery management principles, adaptation of the existing battery technologies to the charging and discharging requirements in photovoltaic systems and the development of completely new and better suited storage units.

17.4.2 Future Developments in Grid-connected Photovoltaic Systems

Today's electricity supply systems in industrialised countries are based on a structure with large central power stations that supply consumers via a dense distribution grid. This structure will suffer increasingly in the liberalised markets, as it is not flexible enough in the choice of primary energy sources to allow energy flows and energy costs to be optimised. In addition, obtaining authorisation for large technological power plants or grid extensions will become more and more complicated. Furthermore, this type of capital-intensive structure could hardly be implemented for comprehensive electrification in developing countries. There are several ongoing approaches to develop novel grid structures, which enable both the optimisation of existing grids in industrialised countries and ecologically acceptable electrification in threshold countries. These approaches aim to help in a transition to a decentralised structure of small and medium sized generators. In these concepts new devices such as cogenerations sets, fuel cells, renewable energy systems, such as photovoltaics, wind, micro hydro, biomass and so on, can play a key role (Figure 17.37).

However, because of specific operational constraints of all these components, new devices have to be incorporated in such a structure to achieve an optimised use of these new technologies. Short-term energy storage consisting of locally installed batteries or flywheels, power quality management (also on the low voltage side to reduce voltage breakdowns and compensate harmonic distortions) and intelligent communication systems between the single components and a central energy management unit have to be applied.

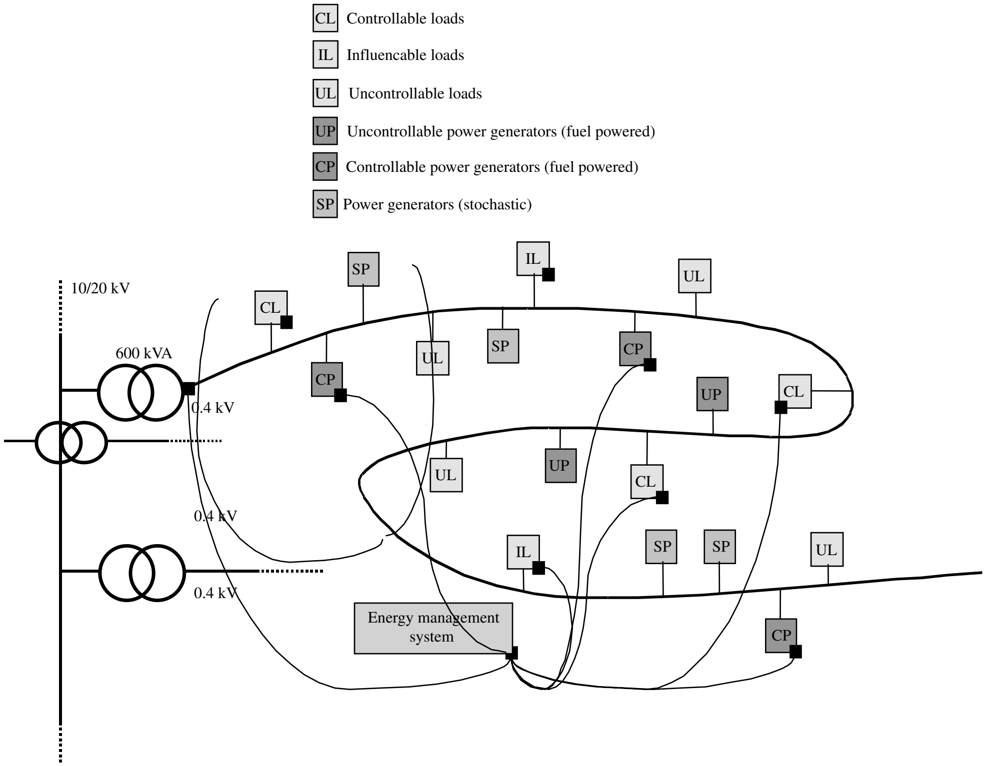

Figure 17.37 Future, decentralised grid structure with superimposed communication network

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