CME 310 Solar Power for Africa

Overview of Off Grid Photovoltaic (PV) Systems

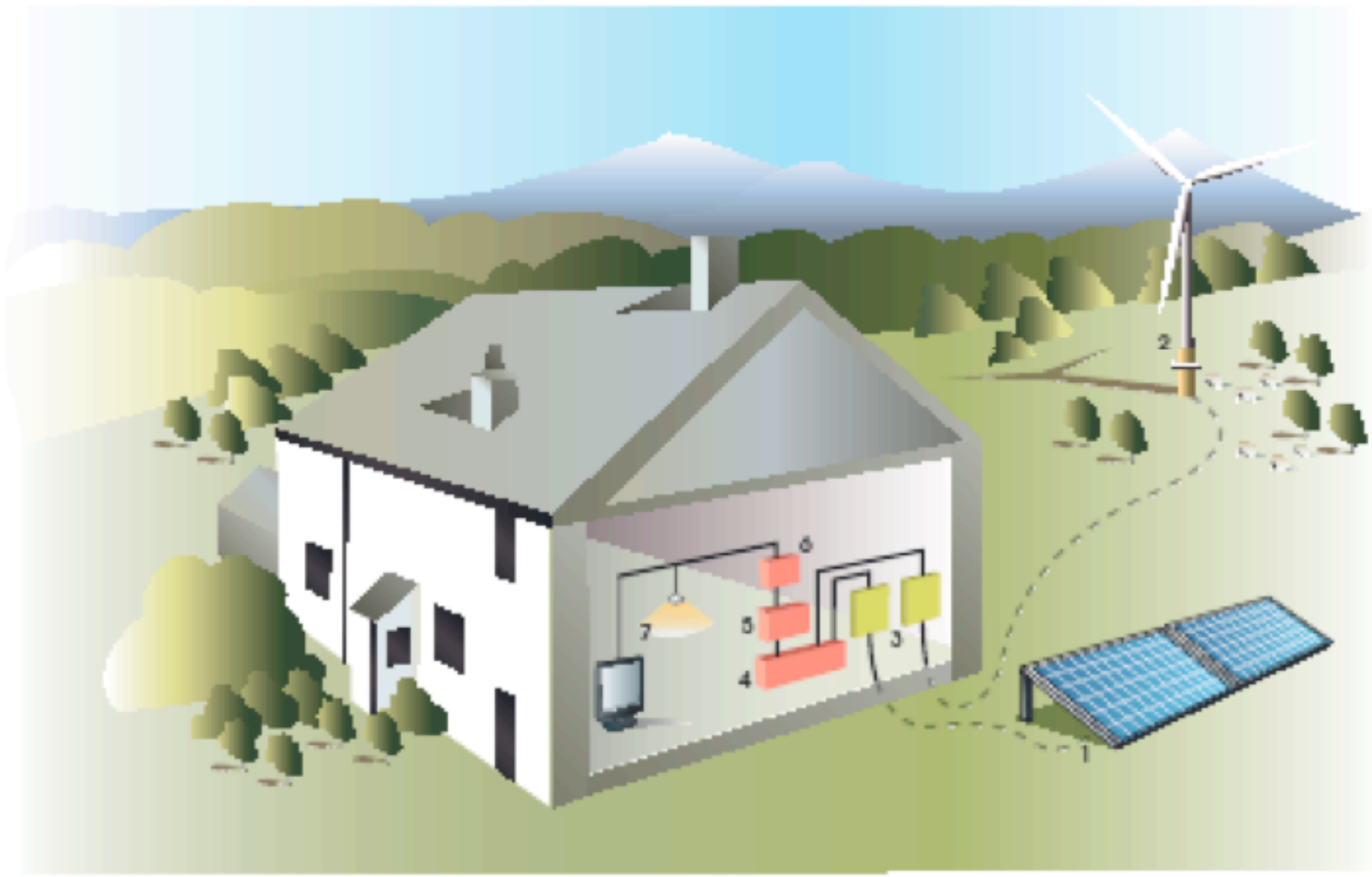

Figure 5.1 Remote and independent: a stand-alone system for a farmhouse.

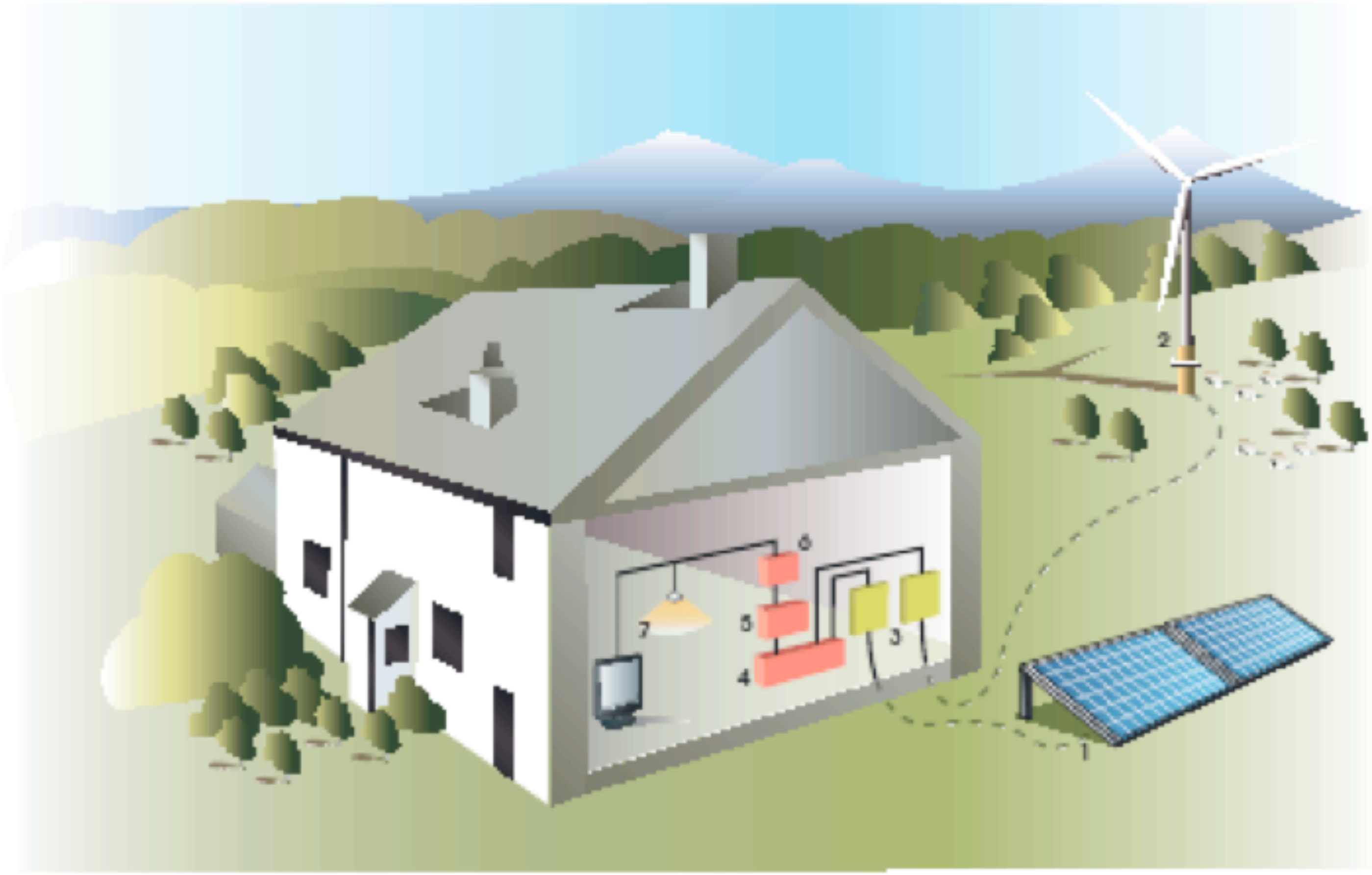

Figure 5.1 Remote and independent: a stand-alone system for a farmhouse.

1) PV Panels
2) Other sources of Power: Wind Turbine, Diesel or Gasoline Generator, Hydropower
3) Charge Controllers
4) Battery Bank
5) AC Inverter/Direct DC systems
6) Fuse box(es)
7) Appliances/Loads

Process for design of an off-grid PV system

1) Determine the needed AC and DC loads
   Typically DC is for lighting and any RV type appliances that inhabitants are willing to accept as substitution for AC appliances (you loose ~50% of the power in conversion to AC)
   The entire system is designed around the anticipated load for an off-grid system and typically it is difficult or impossible to increase this load with the existing system once it is built. So off-grid systems are inflexible in terms of the load. Peak load controls the cost of every component in the system.
2) The total cost (including cost to the environment per kW-hr from the PV system needs to be carefully compared to alternatives
   - Increased insulation and energy conservation
   - Other solar energy sources of heating
   - Biomass and wood heat etc.
3) Once the AC and DC loads are determined the voltage of the PV/Battery system is decided based on the load, distance of transmission from PV to batteries, available battery and PV module voltages and associated costs, step-up or step-down needed for appliance voltage and the associated loss, inverter/charge controller costs.
4) Location for the PV modules must be determined and the solar irradiance must be determined to estimate the power output of the PV modules, the optimal location and the optimal tilt of the PV modules. The need for a tower or other support structures, distance of transmission from PV modules to batteries and needed cabling must be determined.
5) A ventilated housing for the battery bank must be constructed (produces H_2 and O_2 and contains sulfuric acid, batteries may require routine maintenance.

Process for design of an off-grid PV system

1) Determine the needed AC and DC loads
2) Compared to alternatives
3) Voltage of the PV/Battery system
4) Location for the PV modules
5) A ventilated housing for the battery bank must be constructed

6) A detailed plan for burying power cables, grounding and other safety issues needs to be developed. PV modules CAN NOT BE TURNED OFF so consideration of means to block the modules during repair and routine maintenance needs to be considered.
7) A plan for wiring of the facility needs to be developed and the costs assessed including appropriate circuit breakers and grounds.

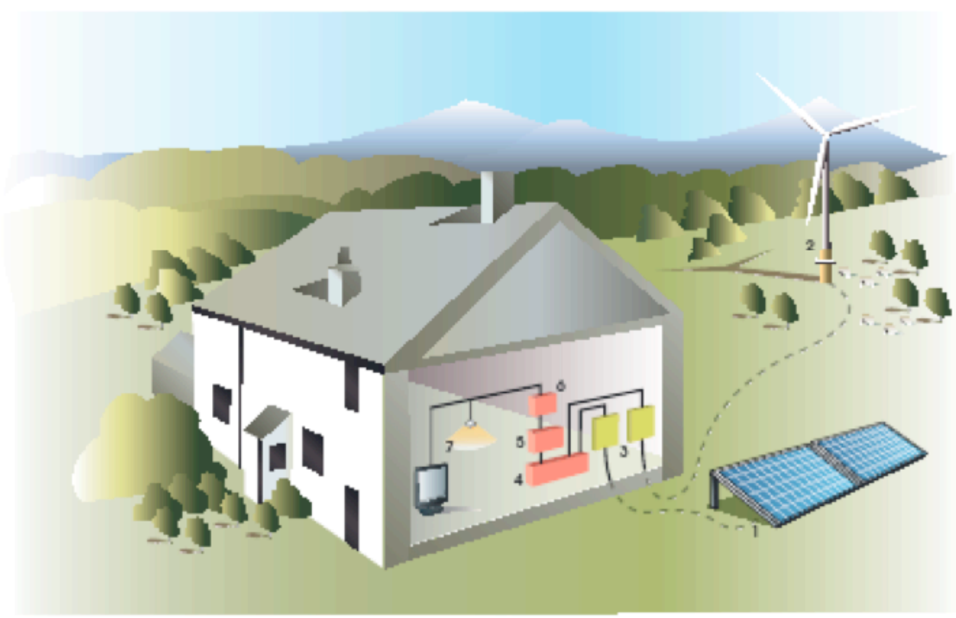

Figure 5.1 Remote and independent: a stand-alone system for a farmhouse.

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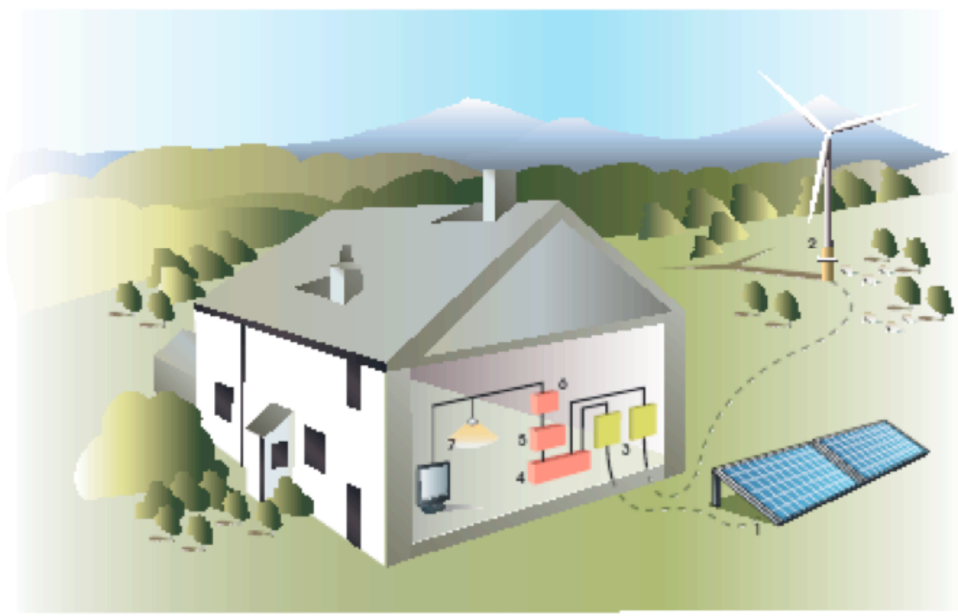

Figure 5.1 Remote and independent: a stand-alone system for a farmhouse.

- *Without battery storage or inverter.* A PV module can supply a DC load directly. A simple example is the type of small solar fountain that floats on a garden pond: the PV sends its current directly to a DC motor driving a pump. The fountain plays only when the sun shines. A more serious application is water pumping for village water supply, irrigation, or livestock watering, where a PV array supplies a DC motor driving a pump that delivers water to a holding tank whenever the sunlight is sufficiently strong.

- *With inverter, without battery storage.* This type of system produces AC power from a PV module or array and is appropriate when AC electricity is useful at any time of day. For example, AC motors are sometimes used for pumping schemes in preference to DC motors because of their rugged reliability and cheapness (although this must be set against the cost of inverters).

Figure 5.2 Off the grid: PV water pumping for a Moroccan village (EPIA/Isofoton).

- *With battery storage, without inverter.* Low-power consumer products such as solar calculators and watches come in this category. So do solar-powered garden lights. Moving up the power scale, a variety of electrical loads, including low-energy lights and a small TV, may be run directly from DC batteries. Many of the solar home systems (SHS's) used in developing countries to supply a small amount of PV electricity to individual families are of this type. A typical SHS comprises a battery, a charge controller and a single PV module (see Figure 1.12). Other examples are DC systems for remote telecoms, security systems, and medical refrigeration.

Figure 1.12 This PV module powers a solar home system in Bolivia (EPIA/BP Solar).

Batteries

Batteries are the most important component for an off-grid PV system

Deep-Cycle Lead-Acid Batteries are needed
(different than car batteries)
Car Battery: Large current for short times not substantially discharged
PV battery smaller currents for longer times with routine discharge cycles
(In developing countries car batteries are sometimes used due to availability)

Self-discharge rates of 3%/month
Coulombic or charge efficiency 85% percent of charge put in that comes out
Voltage efficiency 90% of voltage when discharged
Energy efficiency 75% Coulombic * Voltage

Flooded or Wet cell: liquid electrolyte must be topped up with DI water, need ventilation for H_2, O_2
versus
Sealed or Valve-regulated cell: gas tight valve allows gas to escape on overpressure H_2, O_2 make water internally
Gel electrolyte sealed battery.
Sealed batteries require low maintenance but are more expensive

Batteries

Battery capacity: Ampere Hours (Ah), product of current supplied and time
12V battery provides 20 A for 10 hr is a 200 Ah battery (at 20°C at the 10 hour rate)
(slower discharge leads to larger capacity, lower temperature leads to lower capacity 1% per degree)
For PV we are interested in 100 hour rate
A 200 Ah battery at 12V can provide 2.4 kWh total energy storage.

The PV array must produce more voltage than the battery in order for the system to work.
So we need to know how the voltage of the batter varies during charging and discharging.

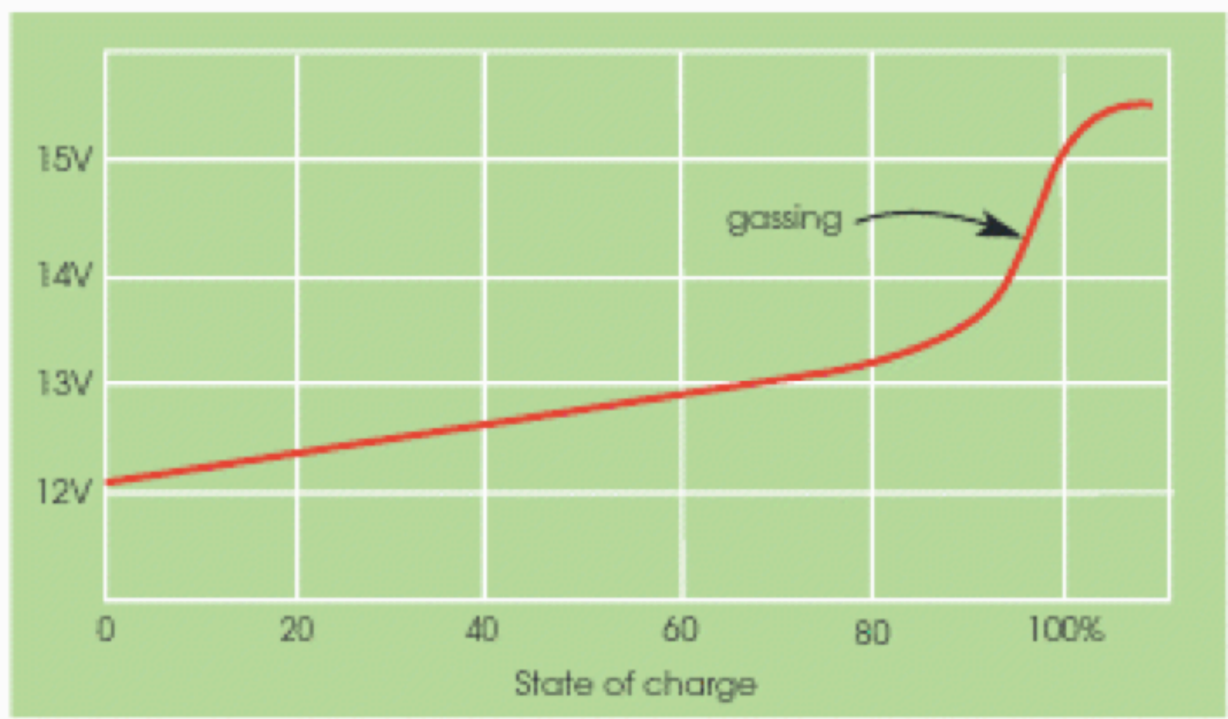

Figure 5.3 Typical charging characteristic of a 12 V lead–acid battery.

Batteries

12V 200 Ah battery shown for constant current discharge
20 A for 10 hours or 2 A for 100 hours

11 V is where damage to battery occurs

For extended discharged state sulphation occurs: lead sulphate crystals form on the plates

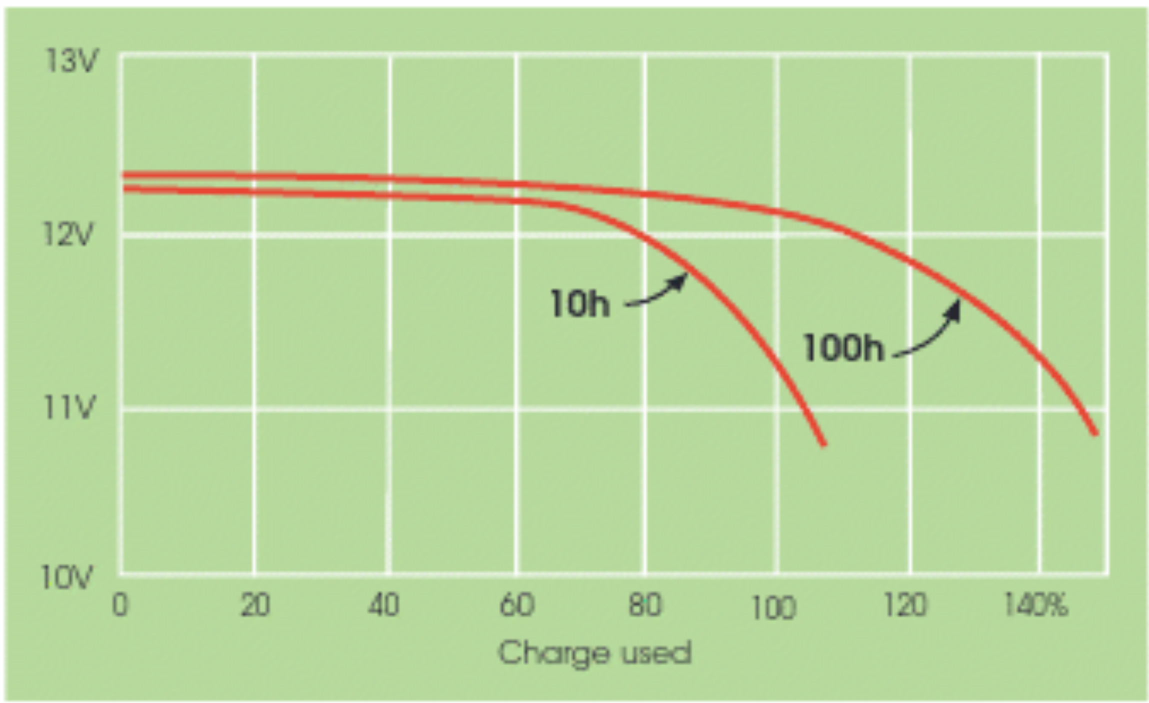

Figure 5.4 Typical discharge characteristics of a 12V lead–acid battery.

Batteries

Fluctuations in sunlight occur over a daily and over a seasonal schedule
These must be planned for in design of the off-grid system

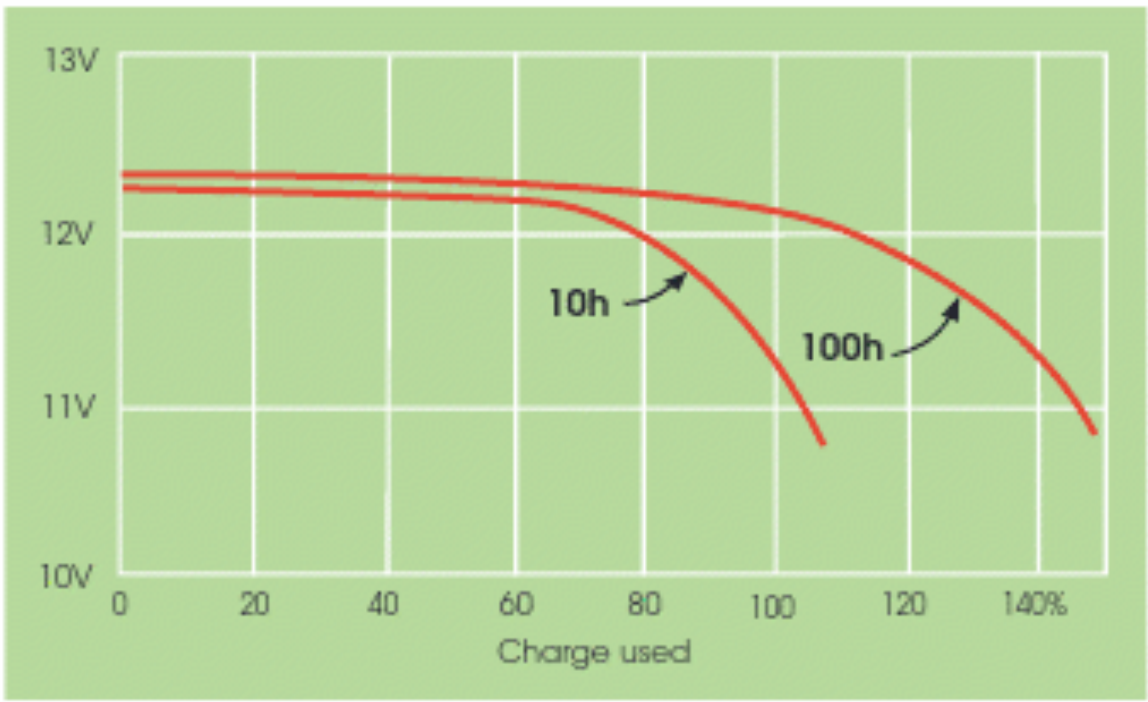

Figure 5.4 Typical discharge characteristics of a 12V lead–acid battery.

Charge Controllers

Control the flow of current from PV array into the battery bank and from battery bank to loads

Prevent overcharging of the batteries and over-discharging when demand exceeds supply by disconnecting PV array above 14V for float charging, 14.4 for boost charging and 14.7 for equalization charging in a flooded 12V battery.

Prevent excess discharging by disconnecting the load when voltage falls to 11 V. Protects the batteries.

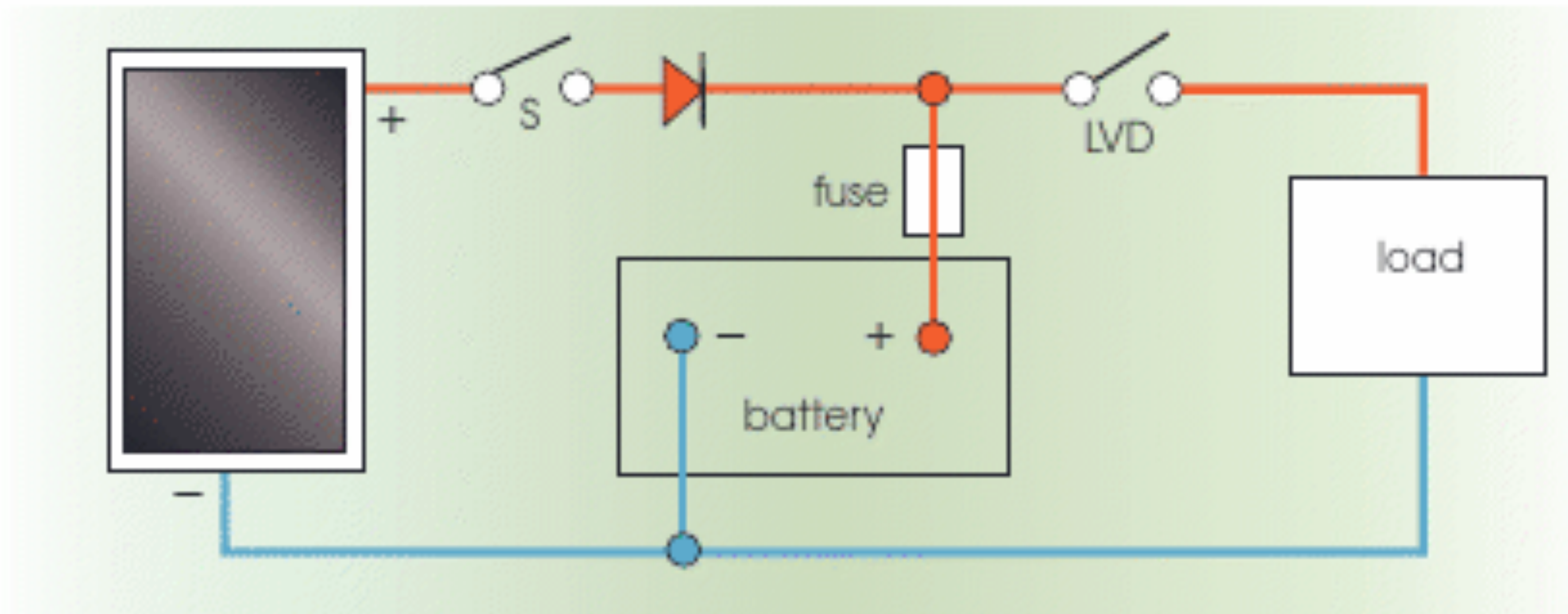

Figure 5.6 Series charge control.

Charge Controllers

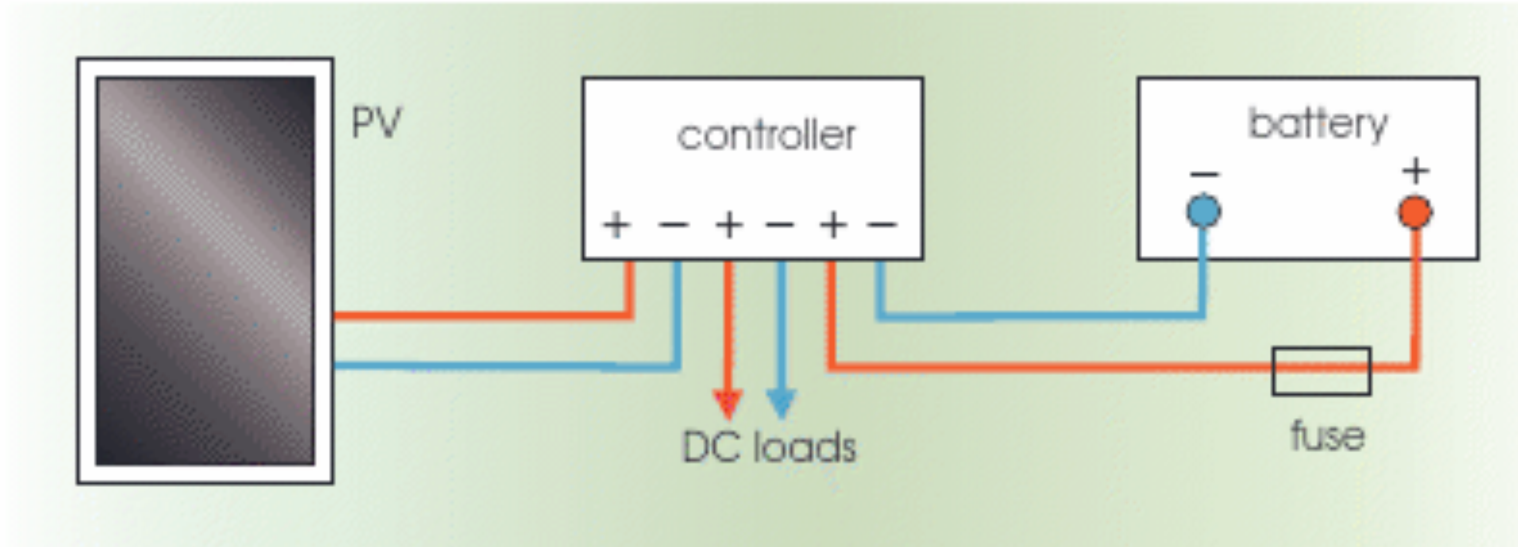

Figure 5.5 A simple scheme for a low-power solar home system (SHS).

- choice of flooded or sealed lead-acid batteries.
- protection against reverse polarity connection of PV modules or batteries.
- automatic selection between boost, float, and equalisation charging regimes, depending on the estimated state-of-charge (SOC) of the battery bank.
- protection against battery overcharging and deep discharging, excessive load currents, and accidental short-circuits.
- prevention of reverse current at night.
- display of such parameters as battery voltage and/or estimated SOC, PV and load currents, and warning of impending load disconnection.

Charge Controllers

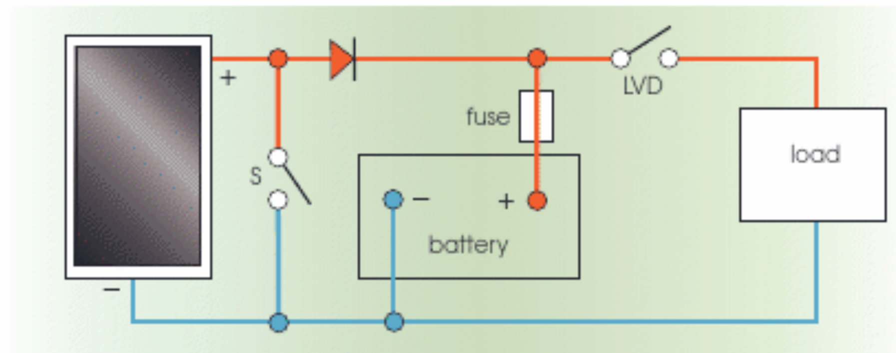

Figure 5.8 Shunt charge control.

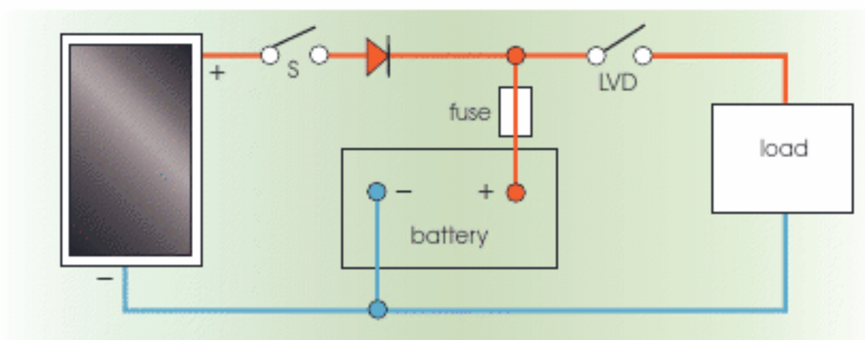

Figure 5.6 Series charge control.

Figure 5.9 This MPPT controller can control a 12 or 24 V system with PV array power up to 500 W_p and MPP voltages up to 100 V. With dimensions 19 × 15 × 7 cm, it weighs 900 g (Steca Elektronik GmbH).

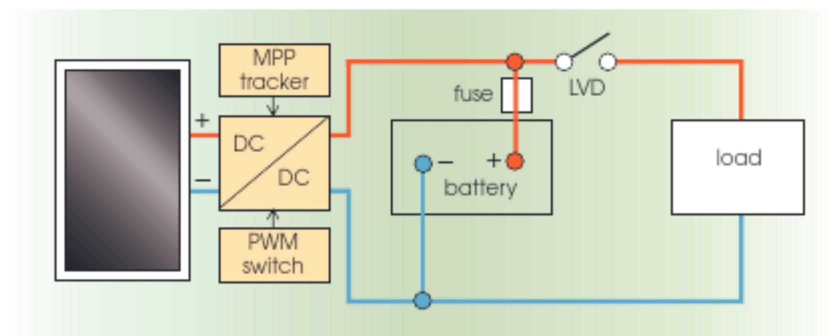

Figure 5.10 Extracting the most from a PV array: the MPPT charge controller.

Inverters

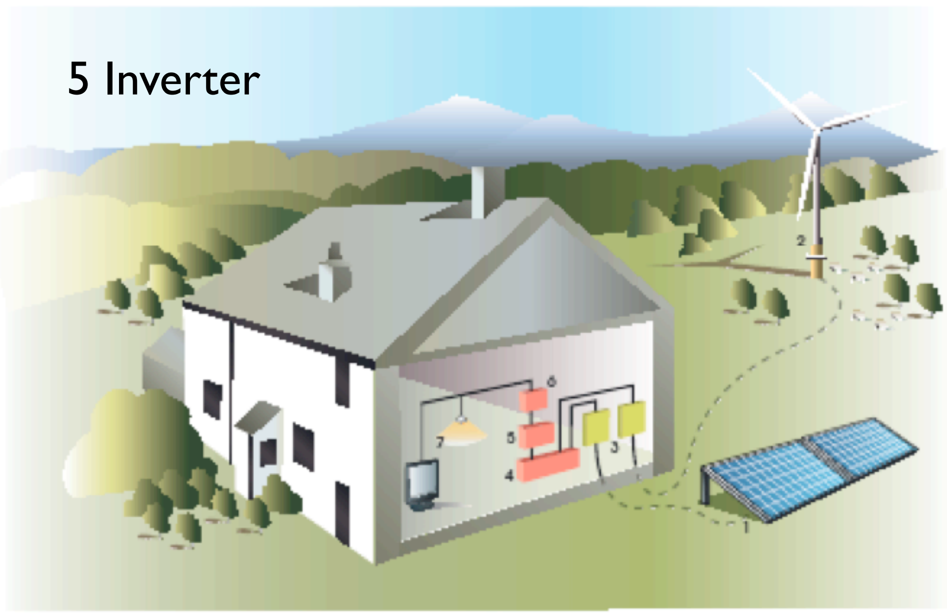

Figure 5.1 Remote and independent: a stand-alone system for a farmhouse.

AC offers flexibility to use "normal" household devices
Grid connected inverters must match frequency and phase to match the grid
Off-grid is self-commutated

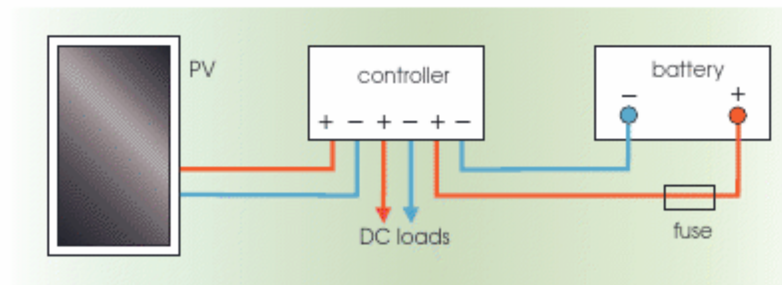

Figure 5.5 A simple scheme for a low-power solar home system (SHS).

- The PV is an array rather than a single module.
- A battery bank replaces a single battery, giving more storage capacity.
- The charge controller has an electronic display (or a set of coloured LEDs) indicating parameters such as battery voltage, SOC, PV current and load current.
- The inverter, connected directly to the battery bank, also indicates its operating conditions.

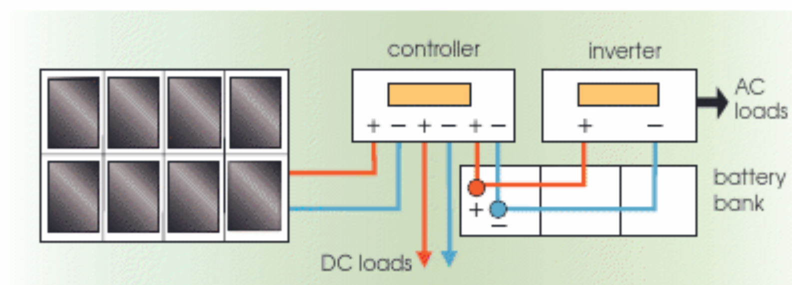

Figure 5.11 Typical connections for a mid-range stand-alone system.

Inverters

- A power rating sufficient for all loads that may be connected simultaneously.
- Accurate control of output voltage and frequency, with a waveform close to sinusoidal (low harmonic distortion), making the AC supply suitable for a wide range of appliances designed to run off a conventional electricity grid.
- High efficiency at low loads, and low standby power draw (possibly with automatic shut-down when all loads are turned off), to avoid unnecessary drain on batteries.
- Ability to absorb or supply reactive power in the case of reactive loads.
- Tolerance of short-term overloads, particularly caused by motor start-up.

Figure 5.12 This family of inverters covers the power range 200W to 2kW (continuous), with system voltages of 12, 24, and 48V (Steca Elektronik GmbH).

High Inverter Efficiency means smaller battery bank and PV array

Inverters

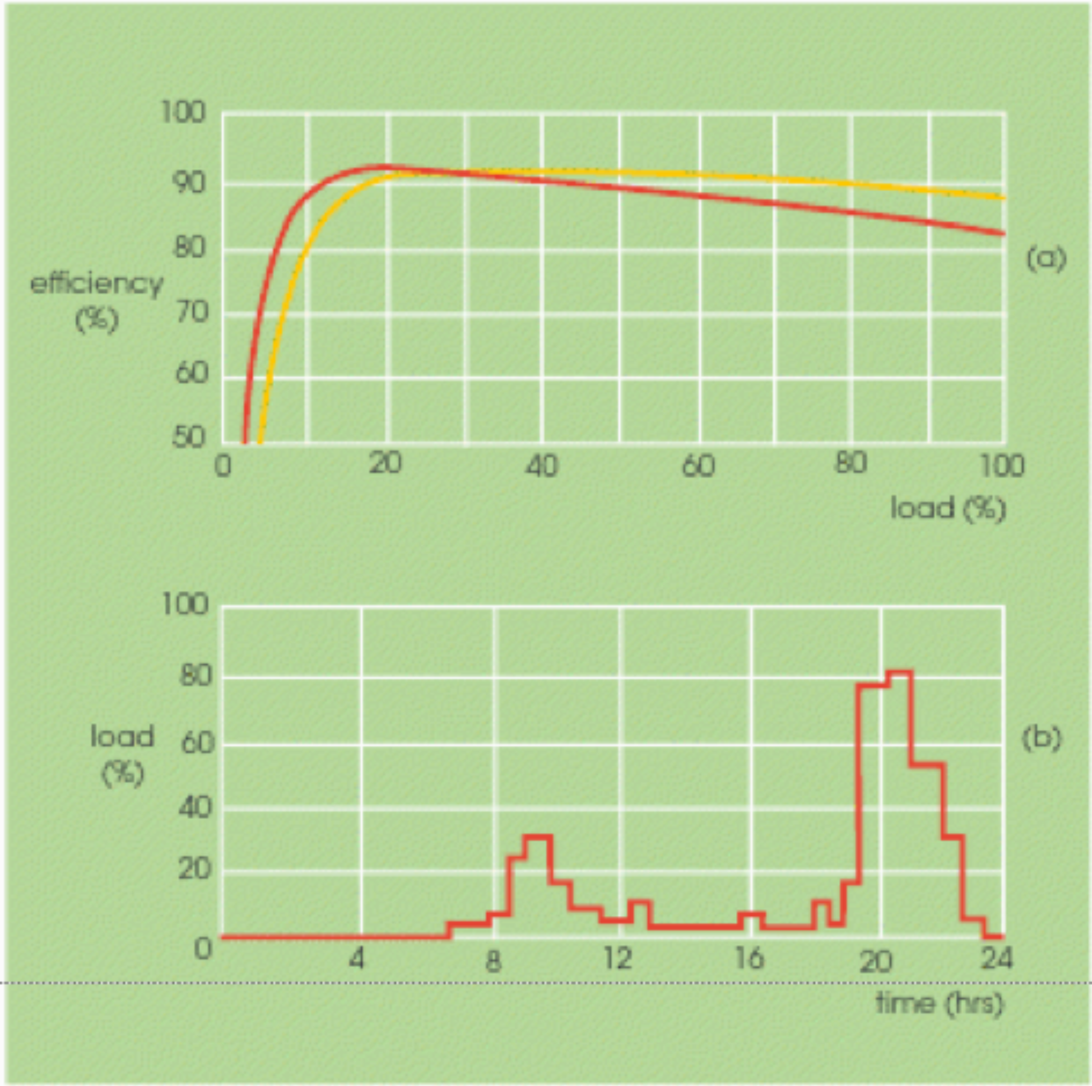

Figure 5.13 (a) Efficiency curves for two types of inverter; (b) a daily load profile for a solar home.

High Inverter Efficiency means smaller battery bank and PV array

Red = low frequency transformer
Yellow = high frequency transformer

Hybrid Systems

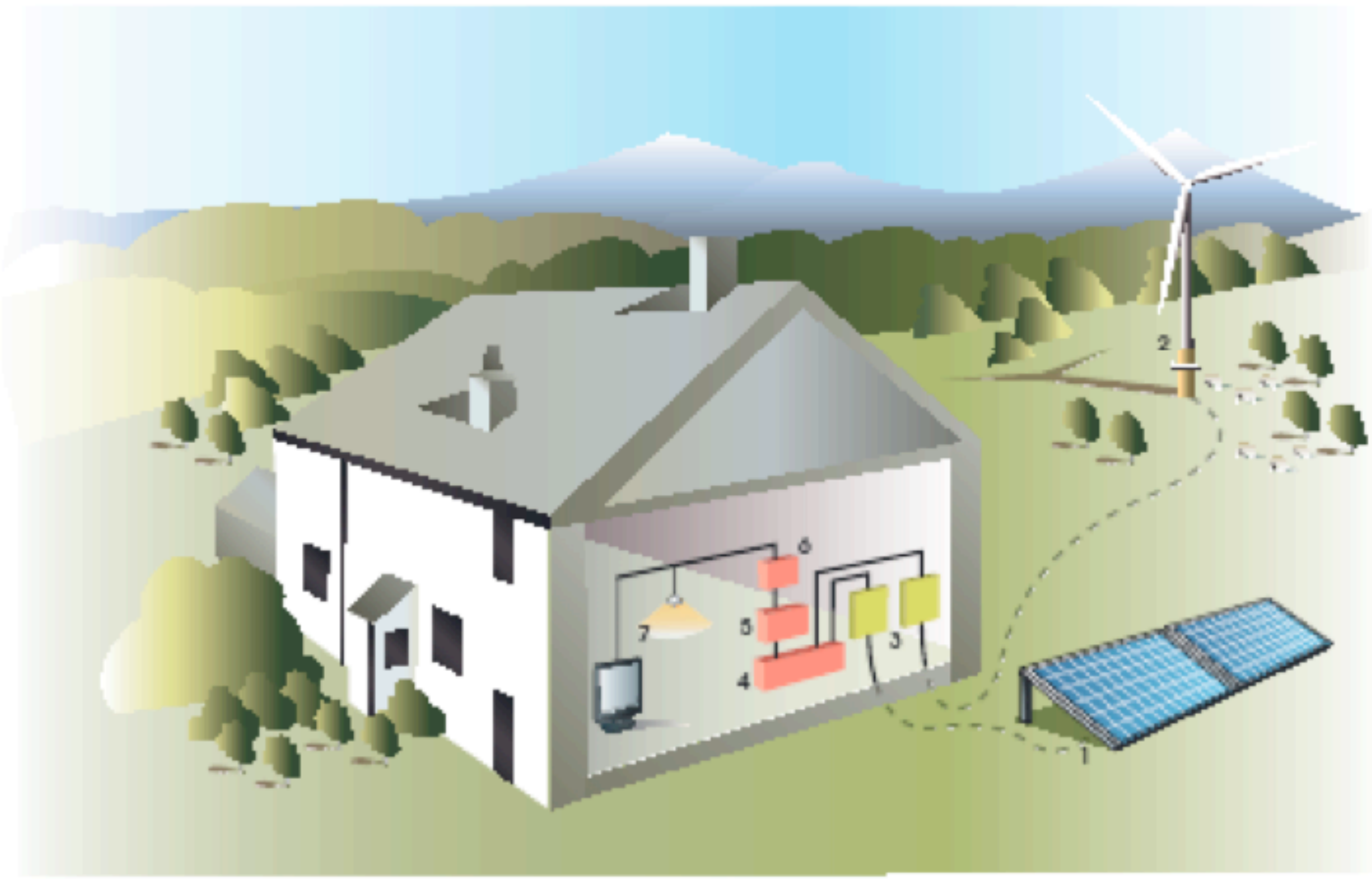

Figure 5.1 Remote and independent: a stand-alone system for a farmhouse.

Hybrid Systems

Diesel-PV Hybrid System

- It may too expensive, in terms of the PV array and battery store, to provide a sufficiently reliable service with photovoltaics, especially where solar insolation is highly seasonal. For example, does it make economic sense to install a PV system that can cope with occasional high load demands in winter when sunlight is in short supply? A hybrid system with a back-up diesel generator may be a better option.
- Diesel engines are very inefficient when lightly loaded, giving poor fuel economy. Low running temperatures and incomplete combustion tend to produce carbon deposits on cylinder walls (glazing), reducing service lifetimes. It is advisable to run engines above 70–80% of full rated output whenever possible. But a lone diesel generator that can cope with occasional peak demands is likely to run at low output much of the time. Better to turn it off and use PV and the battery bank when electricity demand is low. The diesel can boost charge the batteries if necessary, at a high charging rate.
- In addition to rising fuel costs, unpleasant fumes, and the noise of diesel engines, it may be difficult to obtain reliable fuel supplies and engine maintenance services in remote locations. PV needs no fuel and, provided the battery bank is looked after properly, should be low-maintenance.
- If an existing diesel installation needs upgrading, the addition of PV may be a good solution. Being essentially modular, PV may be added in small stages, raising system power capacity in line with increasing demand.

Hybrid Systems

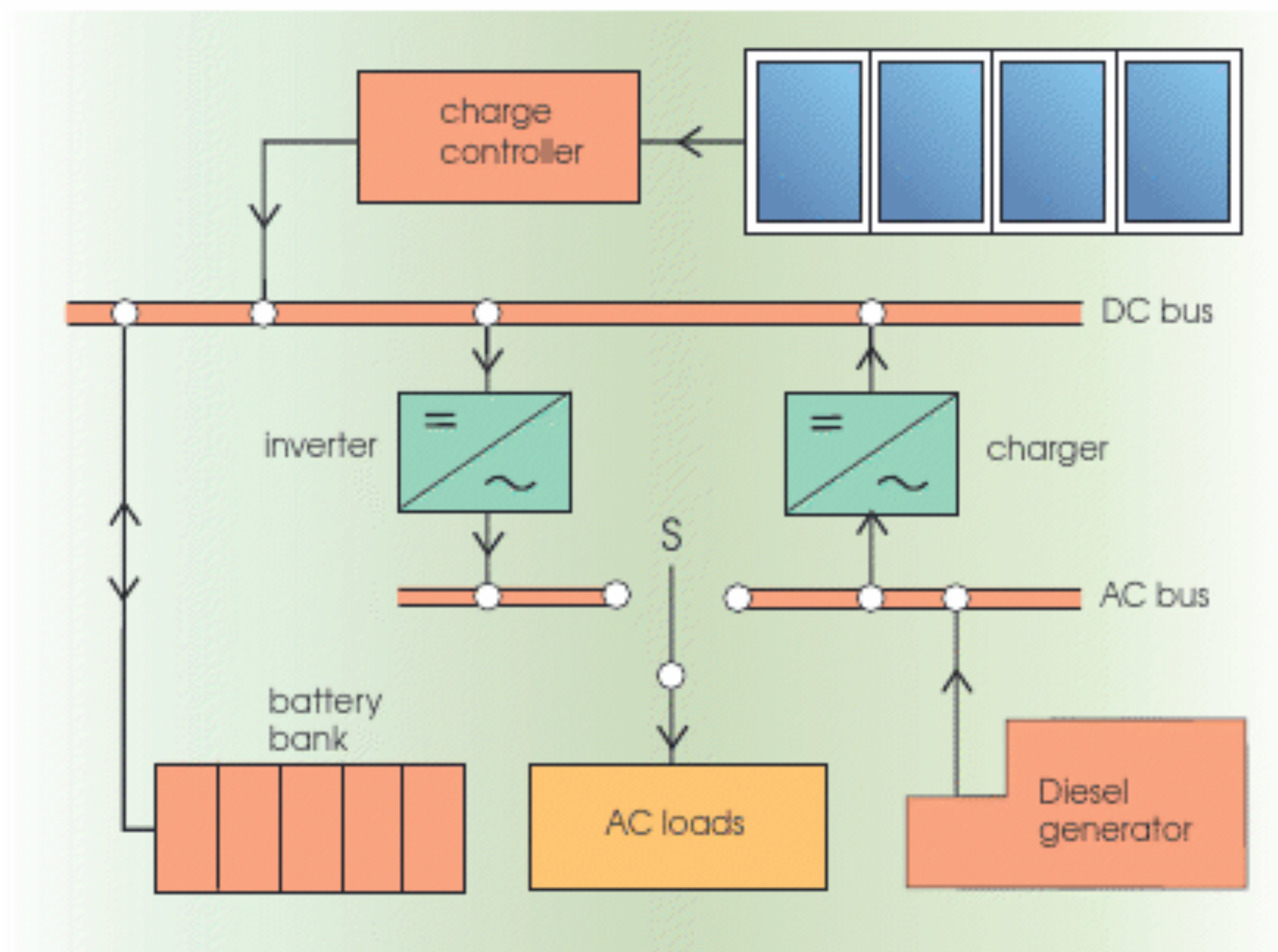

Figure 5.14 A PV–diesel hybrid system.

System Sizing

Sizing problem is the most difficult of system design

Estimate the total amount of electricity required on an average day.

Appliance		Power (W)	No.	Average hrs/day	Average Wh/day
Light		11	8	3	260
TV		60	1	4	240
Computer		60	1	3	180
Refrigerator		80	1	24 (on-off)	500
Kettle		1000	1	0.2	200
Microwave Oven		700	1	0.4	280
Food Mixer		400	1	0.15	60
Washing Machine		800	1	0.6	480
				Total	2200

Figure 5.15 Appliances and energy requirements for a stand-alone system.

– in this case 2200 W h (2.2 kWh) per day. This is the amount of electrical energy to be supplied by the PV system and is fairly typical for a solar home system (SHS) that includes a good range of modern appliances (by contrast, simple SHSs in developing countries based on a single PV module and a battery often provide just 200–300 W h/day). In this case the home-owners wish to use standard AC appliances, so an inverter must be included in the system.

System Sizing

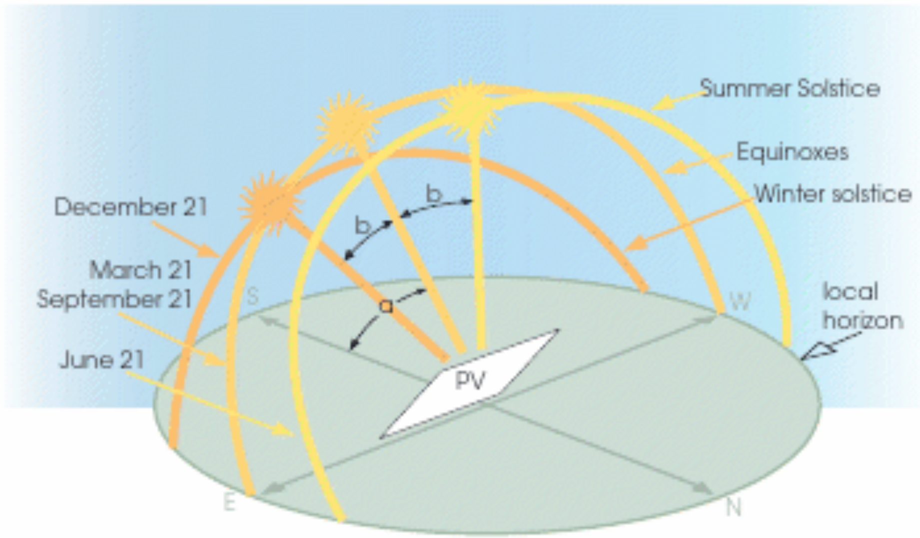

Figure 3.8 Solar trajectories.

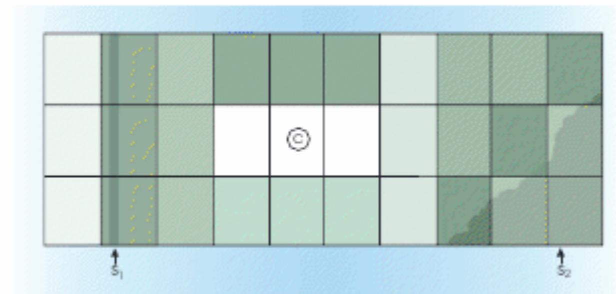

Figure 3.10 Arranging module strings to reduce the effects of shading.

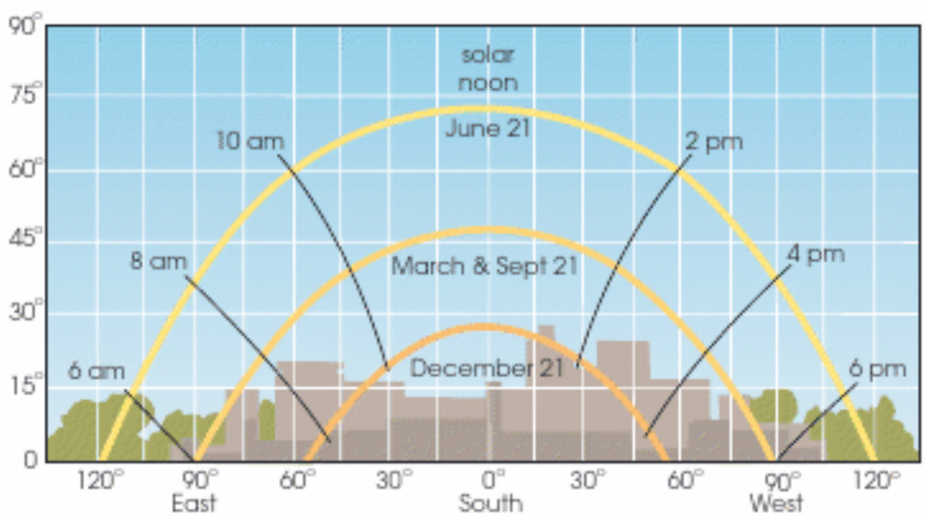

Figure 3.9 Shading effects.

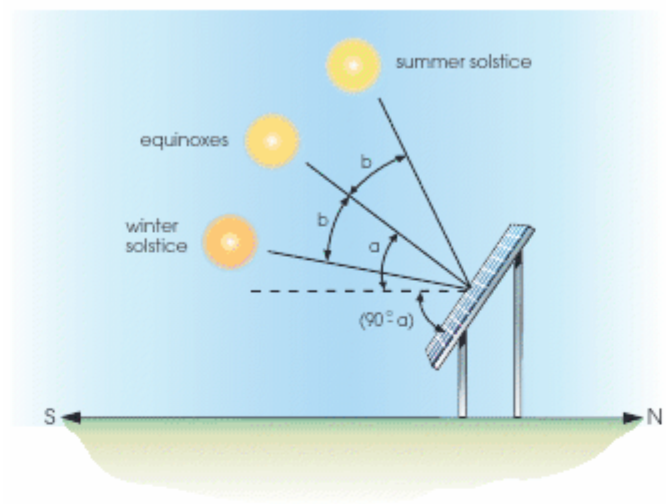

Figure 3.11 Aligning a PV array.

System Sizing

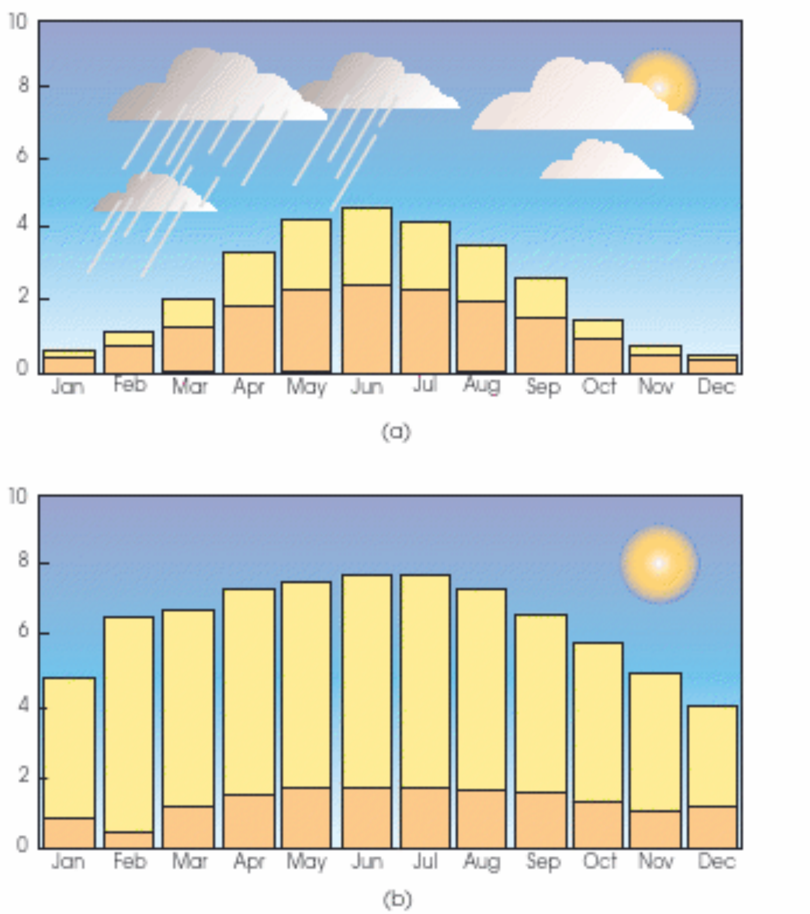

Figure 3.12 Average daily solar radiation in kWh/m^2 on a horizontal surface: in (a) London or Amsterdam; (b) in the Sahara Desert.

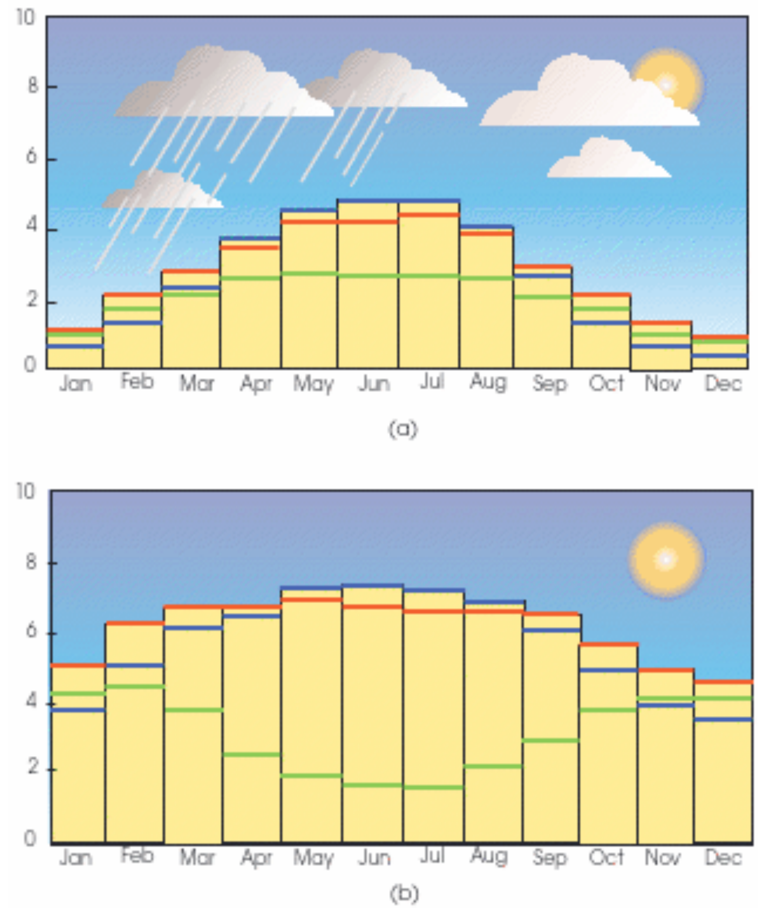

Figure 3.13 Daily solar radiation in kWh/m^2 on south-facing inclined PV arrays in: (a) London; (b) the Sahara Desert. In each case three values of tilt are illustrated: 0° (blue), the latitude angle (red), and 90° (green).

System Sizing

of *peak sun hours* for estimating an array's annual output. This involves compressing the total radiation (direct plus diffuse) received throughout the year into an equivalent duration of standard 'bright sunshine' ($1\,kW/m^2$). The same concept may be used for daily radiation. For example, if an inclined array receives an average insolation of $3\,kWh/m^2$ per day in April, this is considered equivalent to 3 peak sun hours; so an array rated at (say) $2\,kW_p$ is predicted to yield $3 \times 2 = 6\,kWh$/day. Although it is an approxima-

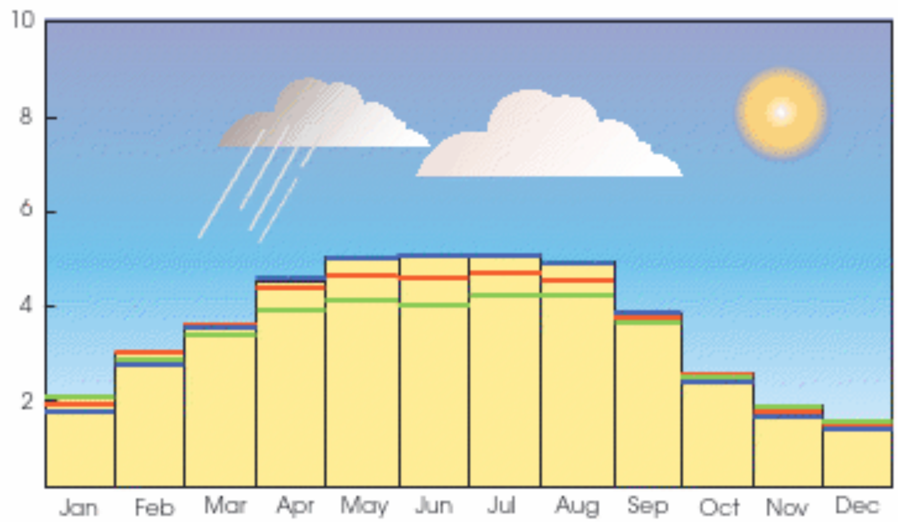

Figure 5.16 Daily solar radiation in kWh/m^2 on south-facing inclined PV arrays for a location at latitude 48°N in southern Germany. Three values of array tilt are illustrated: 33° (blue); 48° (red); and 63° (green).

At this stage the system designer must surely discuss alternatives with the homeowners. For example they might agree to restrict their demand for 2.2 kWh/day to the months March to September, covering the main holiday period, in return for a smaller PV system at lower cost. Over this 7-month period the 33° tilt angle is a good choice. The 'worst' month is now taken as March, for which the average daily radiation is $3.5\,kWh/m^2$. This figure can be used for sizing the array. The homeowners will have to make do with considerably less electricity over the winter months, unless the total is boosted by an alternative energy source. Or perhaps they will agree to forgo use of the refrigerator, microwave oven and washing machine, and cut down on the drinking of coffee! Unlike the 'professional' PV systems mentioned in the previous section, a 'leisure' installation should offer plenty of opportunities for energy saving, trading convenience and reliability against cost.

System Sizing

Using the peak sun hours concept we may express the average daily amount of electricity available for running the home's appliances, E_D as:

$$E_D = P_{PV} S_p \eta \quad (5.1)$$

Where P_{PV} is the rated peak power of the PV array, S_p is the number of peak sun hours per day in the month of interest, and η is the overall system efficiency (discussed below). Therefore the peak power of the array is given by:

$$P_{PV} = E_D / S_p \eta \quad (5.2)$$

In the case of the holiday home, E_D = 2.2 kWh/day, S_p = 3.5 h in March, and we will assume a system efficiency of 60% ($\eta = 0.6$), so that:

$$P_{PV} = 2.2/(3.5 \times 0.6) = 1.05 \text{ kW}_p \quad (5.3)$$

We therefore predict that a PV array rated at just over 1 kW_p will supply the daily load requirement of 2.2 kWh during the months March to September.

System Sizing

- *PV modules (0.85).* Power output is less than the rated value in standard 'bright sunshine' (1 kW/m^2), due to such factors as raised cell operating temperatures, dust or dirt on the modules, and ageing. Also, modules are not generally operated at or close to their maximum power point (unless a controller with MPP tracking is used).
- *Battery bank (0.85).* The charge retrieved from the battery bank is substantially less than that put into it (see Section 5.2.1).
- *Charge controller, blocking diodes, and cables (0.92).* There are small losses in all these items.
- *Inverter (0.9).* This is a typical figure for a high-quality inverter, bearing in mind that it must sometimes work at low output power levels (see Section 5.2.3).

In view of all these uncertainties, plus the vagaries of the weather, oversizing a PV array by a reasonable amount – say 20% – is often recommended. In the above example 1.2 kW$_p$ would obviously improve reliability of supply, but it is, as ever, a question of cost. An alternative is to regard PV

System Sizing

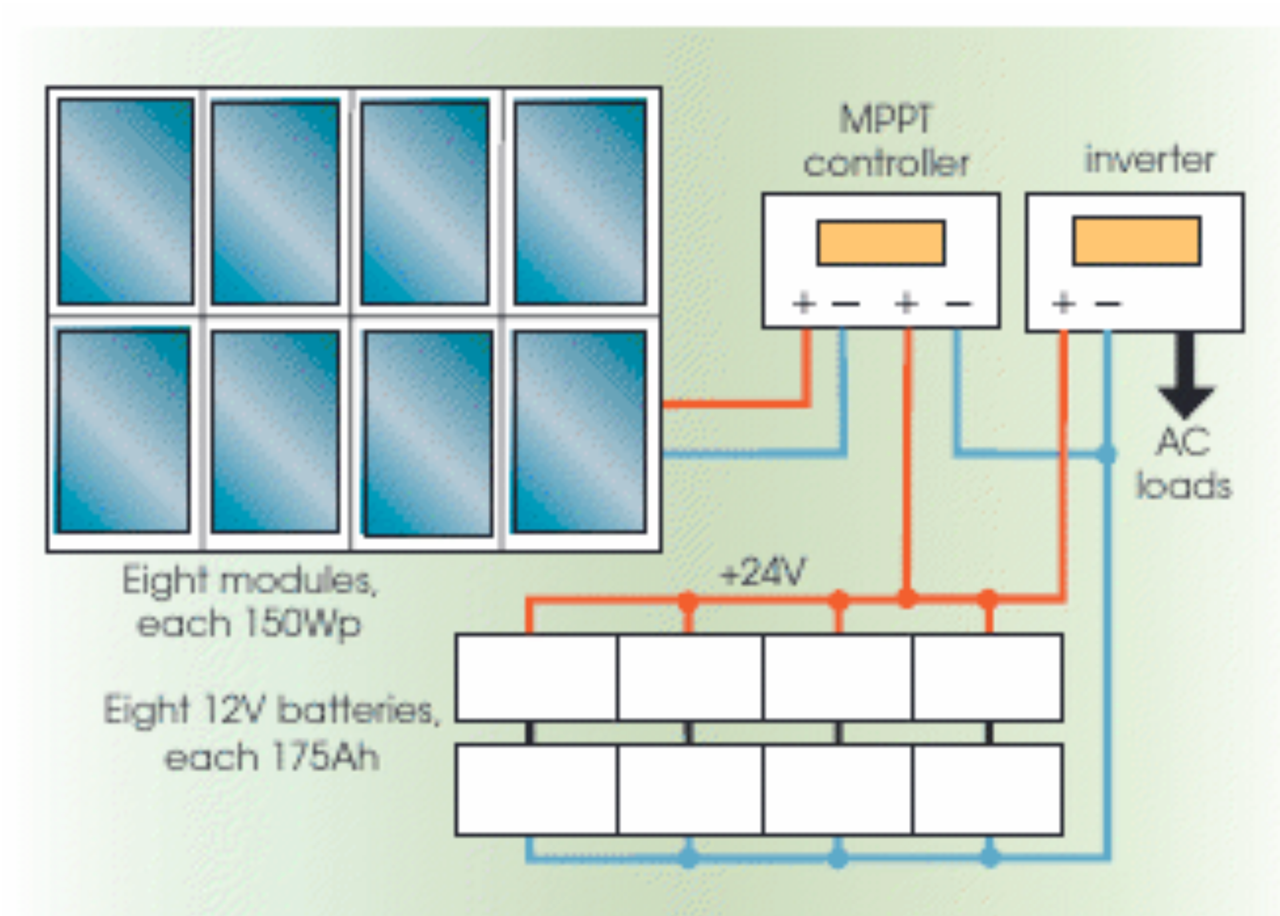

Figure 5.17 A suitable system for the holiday home.

This specification could be met, with a reasonable amount of oversizing, by an array of (say) eight PV modules rated at 150 W_p each (1.2 kW_p total), together with a bank of (say) eight 12 V batteries rated at 175 A h each (16.8 kWh total). The electricity yield, and hence system reliability, could be further improved at modest cost by specifying a MPPT charge controller. The modules could be connected in series, or series–parallel; the batteries as four parallel strings of two units each to give 24 V DC. The main components of the system are illustrated in Figure 5.17.

Water Pump in Developing World

Figure 5.27 PV for a village water supply in Niger (EPIA/Photowatt).

- *Type of pump.* Of the many types of pump on the market, *centrifugal* designs are widely used to raise water against pumping heads up to about 25 m (the height difference between the water table and tank's input pipe). Multi-stage versions can cope with higher heads. A centrifugal pump has an impeller that throws water against its outer casing at high speed, the kinetic energy then being converted to a pressure head by an expanding output pipe. Centrifugal pumps are compact, robust, and well-suited to PV applications, but they are not normally self-priming and must therefore be kept submerged. This makes them suitable for pump/motors positioned below the water table. Alternative *displacement* or *volumetric* pumps including various self-priming types are more suitable for lower flow rates from very deep wells or boreholes.
- *Type of motor.* DC motors are generally more efficient than AC ones, but more expensive. AC motors are very rugged and need little or no maintenance, so are suitable for submersion at the bottom of a well; but inverters are needed to convert PV electricity to AC, adding to the capital cost. Among DC motors the *permanent-magnet* type is often preferred; but all conventional designs use carbon brushes that must be periodically adjusted or replaced, making submersion awkward. Modern *brushless* DC motors overcome this difficulty, at a cost.
- *Matching the motor and PV array.* Ideally, the PV array should be operated close to its maximum power point (MPP) in all sunlight conditions. Unfortunately the resistive load offered by most motors does not allow this to happen, so a MPP tracking controller based on a DC to DC converter may be inserted to improve matching and increase efficiency.

A typical scheme for village water supply is illustrated in Figure 5.26. A submersible pump/motor, protected by installation underground, raises water to a storage tank whenever sunlight falling on the PV array is sufficiently strong. From there it is fed by gravity to one or more taps. In previous sections we have often discussed the need for battery storage in stand-alone systems. But one major feature of water pumping is that the water tank replaces batteries as the energy store, using PV electricity directly to increase the potential energy of the raised water.

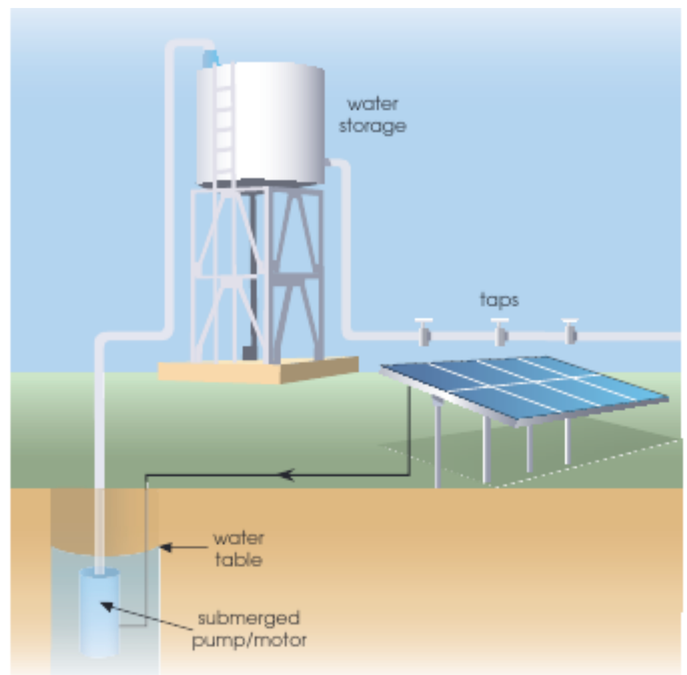

Figure 5.26 A system for village water supply.

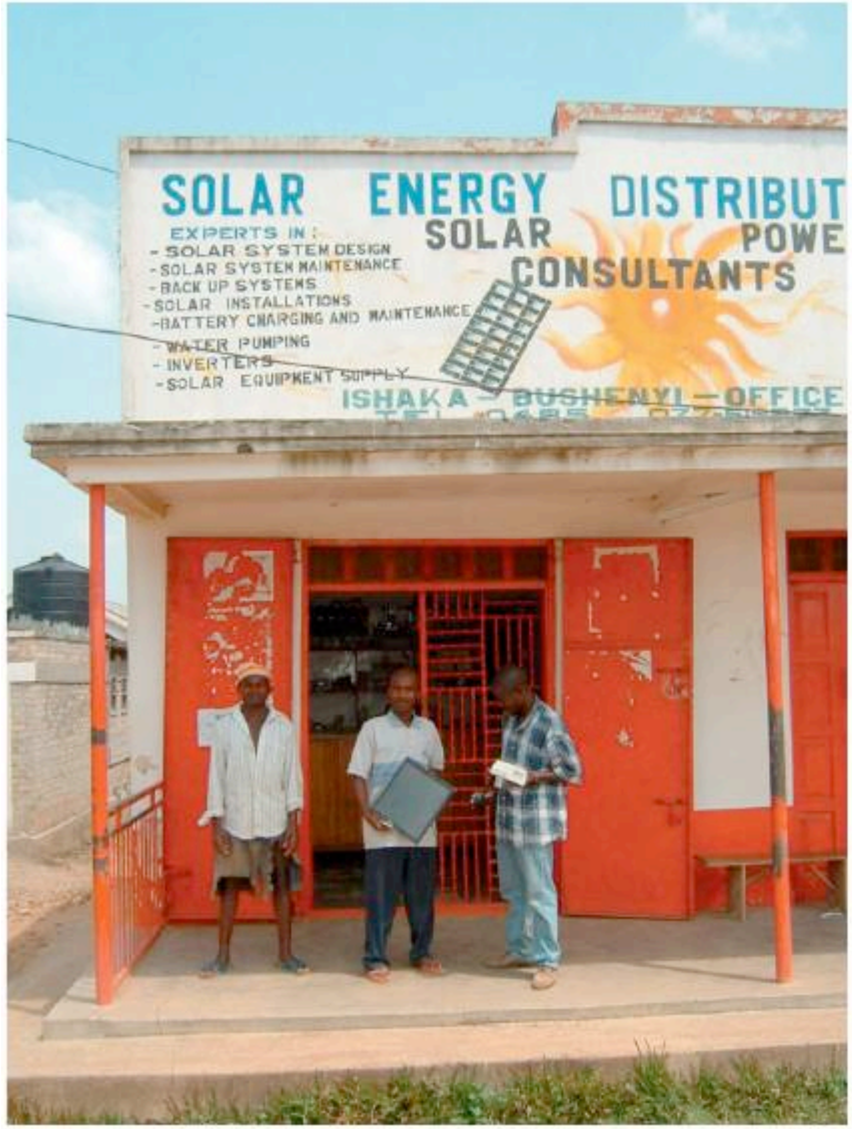

Figure 6.8 Selling solar in Kenya (EPIA/Free Energy Europe).