Chapter 2
Solar Home Systems—A Description of the Technology and Its Applications

2.1 Set-up of a Solar Home System

A Solar Home System comprises a solar PV generator (typically one PV module), a battery charge controller and a battery (Fig. 2.1). These components, as well as the appliances operated by the SHS, are interconnected by the balance-of-system components (cables, switches, plugs and installation material). In some cases, an inverter is also included to enable AC appliances or equipment to be operated.

The PV generator or module transforms solar irradiance into electric power. This power is conducted by BOS components to a charge controller. The charge controller assures controlled charge of the battery and operation of appliances. Typically, DC appliances at the nominal voltage of the battery are used. For some appliances, DC–DC converters are necessary as the nominal voltage of the battery does not match their nominal voltage. In other cases—very occasionally in rural electrification programmes in developing countries—DC–AC converters are used to supply AC appliances. In the following sections, the individual components of a SHS are described and discussed.

2.2 PV Modules and Arrays

The solar PV generator consisting of one or more solar modules converts solar radiation into electricity. The physics behind this conversion is well documented and described elsewhere, such as in [1]. The symbol used for a PV cell, module or array as used in single-line diagrams is shown in Fig. 2.2.

The critical characteristics of a solar cell (and even a solar module) are given in the following Table 2.1.

These figures are typically given for standard test conditions (STC). These conditions are 1000 W/m^2 irradiance, 25 °C solar cell temperature and a radiant

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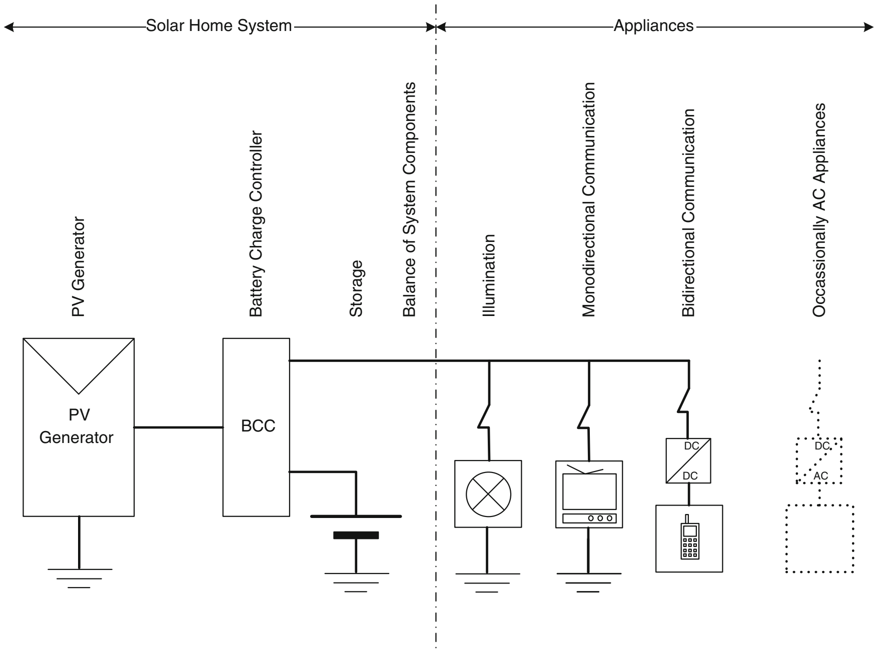
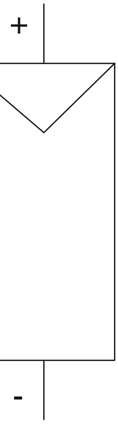


Fig. 2.1 Block diagram of a solar home system

Fig. 2.2 Symbol for a PV cell, PV module or PV generator



spectrum expected for solar radiation at an air mass (AM) of 1.5. AM reflects the ratio of the distance that the solar radiation has to travel across the atmosphere to the shortest distance (perpendicular to the atmosphere). Figure 2.3 shows a typical *I–V* characteristic curve of a monocrystalline solar cell at 1000, 500 and 100 W/m^2 irradiance. The currents and voltages listed above are indicated for the 1000 W/m^2 irradiance. Additionally, the *I–V* characteristics of the maximum power point powers are inserted (Table 2.2).

Table 2.1 Critical characteristics of a solar cell and a solar module

Efficiency, η	The ratio of the output power of the cell at the maximum power point and radiative input (irradiance times cell area)
Open-circuit voltage, V_{oc}	The voltage the solar cell supplies at zero load
Short-circuit current, I_{sc}	The current supplied by the solar cell when it is short-circuited. Unlike most other types of electricity generators, a solar cell may be short-circuited
Maximum power point voltage, V_{mpp}	The voltage the solar cell supplies at its maximum power point
Maximum power point current, I_{mpp}	The current the solar cell supplies in its maximum power point
Maximum power, P_{mpp}	The maximum power achievable at a certain voltage/current point (V_{mpp}, I_{mpp}) of the cell's characteristic. The MPP can be found by plotting the cell's voltage multiplied by the cell's current as a function of the cell's voltage (P(U)). The maximum power point is found at the point where the P(U) slope (dP/dU) is zero
Fill factor, FF	The ratio between the short-circuit current (I_{sc}) multiplied by the open-circuit voltage (V_{oc}) over the maximum power point power (P_{mpp})

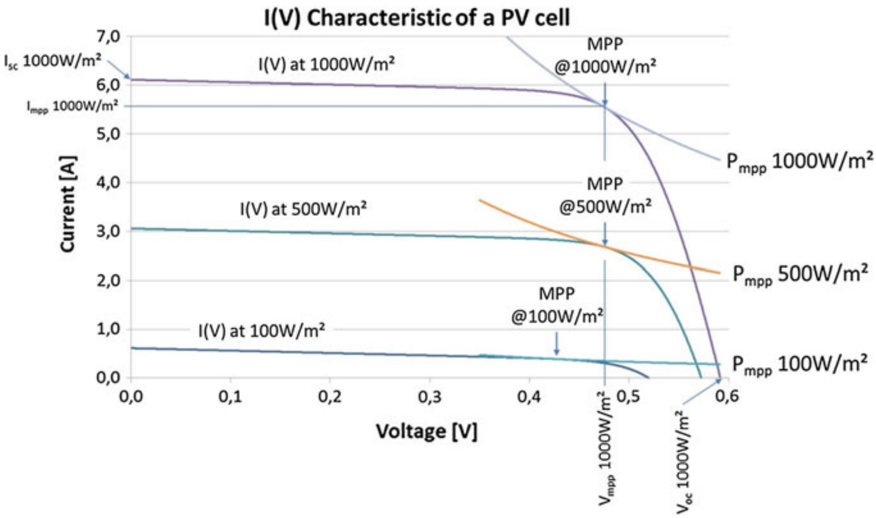


Fig. 2.3 *I–V* characteristic of a monocrystalline silicon PV cell. *Note* All cell temperatures are 25 °C

Table 2.2 Terrestrial module efficiencies at STC

Module type	η (%)	A (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)
Crystalline silicon	22.4	15,775	69.57	6.341	80.1
Multi-crystalline silicon	18.5	14,661	38.97	9.149	76.2
CdTe thin film	17.5	7021	103.1	1.553	76.6
CIGS thin film	15.7	9703	28.24	7.254	72.5
a-Si/nc-Si	12.2	14,322	202.1	1.261	68.8

Source Green et al. [2]

Silicon wafer-based PV technology accounted for about 92 % of the total production in 2014, with multi-crystalline making up 56 % of total production. All thin-film technologies combined account for approximately 9 % of PV modules [3]. The costs of PV modules depend largely on the technology, the quality and the location of manufacturing, purchase and the brand of the modules. Prices for crystalline silicone (mono and poly) solar modules are reported to be 35–44 USDcent/W_p from South and South-east Asia and 52–57 USDcent/W_p for modules manufactured in Korea and Japan in the period September 2014 to September 2015 [4]. However, the price of PV modules has declined significantly over time. In the period before (September 2013 to September 2014), the Korean/Japanese modules cost between 57 and 47 USDcent/W_p while the South and South-east Asian modules cost between 38 and 35 USDcent/W_p [4]. A 2014 market study in Uganda found prices for solar modules to be between 0.8 and 6.67 USD/W_p, with an average price of 2.18 USD/W_p [5].

2.3 Energy Storage of the Solar Home System

Obviously, the primary function of a storage system in a stand-alone (autonomous) renewable energy supply system is to be able to supply electricity during periods of low or zero renewable energy input. However, a storage system also plays the role of a power transformer. While the generator supplies small amounts of power throughout the day, the storage system needs to be able to supply multiples of these amounts of power to the loads.

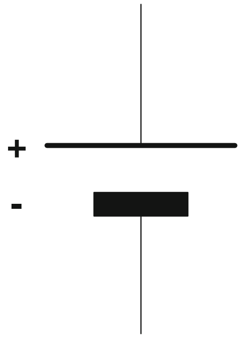
The fundamental information on electrochemical cells and batteries can be found in various reference materials, such as [6, 7]. An electrochemical cell incorporates a positive and a negative electrode, an electrolyte, electrical connectors to the outside of the cell and a casing for the entire set-up. A battery cell is referred to as the technical implementation of an electrochemical cell, where multiple positive and negative electrodes of a certain design are connected in parallel and where separators are implemented in between the positive and negative electrodes to prevent short-circuiting of the electrodes. A battery, a battery storage unit or even an accumulator is referred to as a set-up with multiple battery cells connected in series to achieve the desired DC system voltage and multiple of these series connections are connected in parallel to achieve a desired ampere-hour capacity.

In the context of Solar Home Systems, rechargeable (secondary) batteries are usually used. In the following sections, the term ‘battery’ refers to ‘a rechargeable battery’. Within the literature, rechargeable batteries are often referred to as secondary cells. The symbol for a battery is depicted in Fig. 2.4.

The variables used to describe a battery are [8, 9] as follows:

- State of Charge (SOC) [%]—SOC of a battery presents the total battery capacity as percentage of maximum capacity. It is generally calculated using current integration to determine the change in battery capacity over time.

Fig. 2.4 Symbol of a battery cell or even a battery/battery storage/accumulator



- Depth of Discharge (DOD) [%]—This is very important parameter for designing the system and maintaining the battery life. It is the percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to 80 % DOD is referred to as a deep discharge. An 80 % DOD means the battery with 100 Ah is able to provide only 80 Ah maximum.
- Terminal Voltage (Volts) [V]—It is the voltage between the battery terminals with load. Terminal voltage varies with SOC and discharge/charge current.
- Open-circuit voltage (Volt) [V]—The voltage between the battery terminals with no load applied. The open-circuit voltage depends on the battery state of charge. It increases with the state of charge.
- Internal Resistance (Ohm) [Ω]—The resistance within the battery. It is dependent on the battery state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability is reduced as more of the charging energy is converted into heat.

Ideal storage systems for SHSs are characterised by the following features as shown in Table 2.3.

The challenge for designing and manufacturing of storage for a SHS is to find the optimum balance for these listed properties.

The technical specifications of a battery are [8–10]:

- Nominal Voltage (V)—Nominal voltage is the reported or reference voltage of the battery, which also sometimes referred as 'normal' voltage of the battery. Most of the time, the batteries used in SHS has a nominal voltage of 12 V. The nominal voltage of a battery is made up of the sum of the individual battery cell's voltage which is branched in series. For example, a lead–acid battery cell has a nominal voltage of 2 V. However, six lead–acid battery cells branched in series render a nominal voltage of 12 V.
- Cut-off Voltage—It is the minimum allowable voltage that the battery can be discharged and generally defines the 'empty' state of the battery.
- Capacity or Nominal Capacity (Ah for a specific C-rate)—Capacity of a battery is the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 % state-of-charge to the cut-off voltage. It is calculated by multiplying the discharge current (in Amps) by the

Table 2.3 Required features of SHS storage

Absorption of energy	• At any state of charge (SOC) • At any charging power (even extremely low and extremely high charging powers) • At a high efficiency
Delivery of stored energy	• At any state of charge • At any power (even low or high powers delivered) • Without influence of the state of charge of the storage
Capacity losses	• No reversible capacity losses occur (e.g. no self-discharge of the storage, no auxiliary power needed to operate the battery which would be consumed from the storage) • No irreversible capacity losses occur (e.g. by loss of active material due to weir)
Resilience against periods of SOC < 1	• Periods of low SOC are system immanent in SHSs. Therefore, batteries need to be resilient against these periods of low SOC. The main reasons for low SOC are: • Overnight low state of charge (some hours before last discharge in the night and begin of recharge in the morning) • Low state of charge during periods of low radiation (several days). The battery may not be recharged as the PV modules cannot supply sufficient energy for full recharge of the battery
Immunity against ambient influences	• Ambient temperature and battery temperature • Atmospheric influences (e.g. humidity) • Mechanical stresses (e.g. mechanical shocks)
Lowest possible impact on the environment	• For manufacturing • During operation • After end of service life
Economics	• Low cost for energy throughput

discharge time (in hours) and decreases with increasing C-rate. Battery capacities are given in C_{10} or C_{100} figures. A C_{10} 50 Ah battery can be discharged for 10 h at 5 A $(10\,\mathrm{h} \cdot 5\,\mathrm{A} = 50\,\mathrm{Ah})$ before it reaches the cut-off voltage.

- Nominal Energy [Wh (for a specific C-rate)]—The nominal energy of the battery is the total Watt-hours available when the battery is discharged at a certain discharge current rate (specified as a C-rate) from 100 % state-of-charge to the cut-off voltage. Energy is calculated by multiplying the discharge power (in Watts) by the discharge time (in hours). Like capacity, energy decreases with increasing C-rate.
- Cycle Life (a number given for a specific DOD)—This is very important parameter of a batter. Cycle life is the total number of discharge–charge cycles that the battery can experience before it fails to meet specific performance criteria. It is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and also temperature and humidity. The higher the DOD, the lower the cycle life.
  A typical figure for a grid plate battery is 1000 cycles at a DOD of 20 %. Assuming a 50 Ah battery: 10 Ah can be discharged rendering a DOD of 20 %, then fully recharged for 1000 times before the battery is at the end of its service life.

- Specific Energy (Wh/kg)—It is the nominal battery energy per unit mass, or gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. This figure is of low importance in SHSs.
- Charging Voltage—The voltage that the battery can be is charged when charged to full capacity. Charging schemes generally consist of a constant current charging until the battery voltage reached the charge voltage, then constant voltage charging, allowing the charge current to taper until it is very small.
- Float Voltage—Float voltage is the voltage that usually measured after the battery is charged. Float voltage is the voltage at which the battery is maintained after being charged to 100 % SOC to maintain that capacity by compensating for self-discharge of the battery.
- Charge Current—The ideal current at which the battery is initially charged under constant charging scheme before transitioning into constant voltage charging.

The principle set-up of an electrochemical cell is found in Fig. 2.5. A positive electrode and a negative electrode are connected by an electrolyte in the battery. Externally, a load is branched to two electrodes in case of discharge. In the charging phase, the two electrodes are connected by a DC power supply.

Lead–acid batteries have long been in use for Solar Home Systems. Lithium-ion batteries are a new, very promising technology. They are used in pico SHSs and are expected to play a major role in future SHSs. Therefore, this section will deal with these two types of batteries. Some characteristic data for lead–acid batteries and lithium-ion batteries are provided in Table 2.4. While the nominal voltage is given by the standard electrode potentials of the electrode combination, the other parameters given in Table 2.4 are dependent on the specific technical set-up of the battery (refer to Tables 2.5 and 2.6) and its quality. C refers to the charging and the discharging current of a battery normalized to the nominal capacity of a battery. 1C is the charging/discharging current which may charge or discharge the battery in one hour, 5C refers to the current which may charge or discharge a battery within 1/5 hours (= 12 min), 0.2C refers to the current which may charge or discharge a battery within 1/0.2 hours (= 5 hours).

2.3.1 Lead–Acid Batteries

The history of lead–acid rechargeable batteries goes back to 1854 when first experiments of Wilhelm Josef Sinsteden experienced the development of a rechargeable set of two lead plates in diluted sulphuric acid. Gaston Planté further developed the lead–acid battery in 1859 and he is often cited as the inventor of this first-type rechargeable battery [11]. Lead–acid batteries have been in use for SHSs ever since SHSs were first implemented.

Lead–acid batteries consist of a positive and a negative electrode. An electrolyte serves to exchange electrons. Different set-ups of lead–acid batteries have been

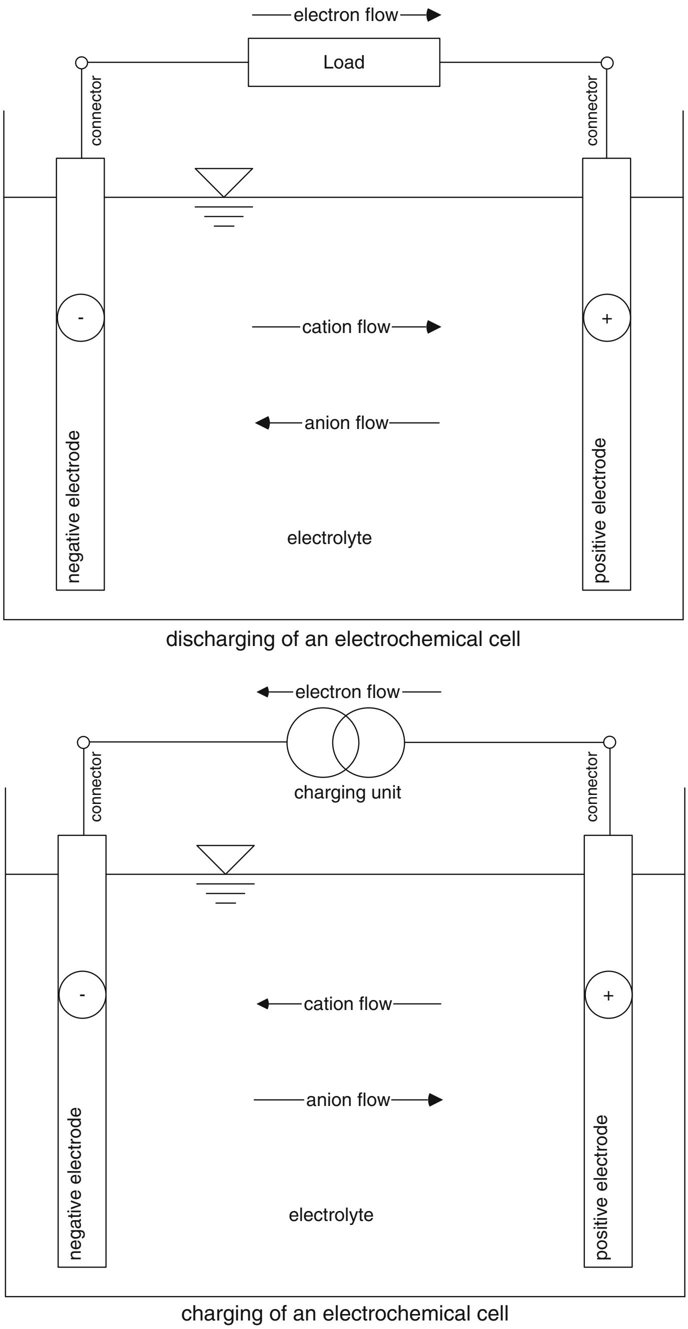


Fig. 2.5 Principle set-up of an electrochemical storage

Table 2.4 Comparative characteristics of lead–acid and lithium-ion batteries

System	Unit	Lead–acid	Lithium-ion
Characteristic			
Nominal voltage	V	2.0	3.3–4.0
Minimum discharge voltage	V	1.75	2.5–3.0
Maximum charging voltage	V	2.4	4.2
Specific energy	Wh/kg	40	135
Energy density	Wh/l	90	320
No. of cycles (@ 80 % DOD)	–	200–300	500–1000
Internal resistance	–	Very low	Low
Charge time	h	8–16	1–2
Overcharge tolerance	–	High	Low (no trickle charge)
Peak load current	C	5	2–30
Best result load current	C	0.2	<10
Self-discharge	%/month	5	<5 (+3 % for protection circuit)
Operation temperature range	°C	−20 to +50	0–45 (wider range for discharge)
Maintenance	–	Required for some technologies	None
Safety issues	–	Thermally stable	Protection circuit mandatory
Toxicity	–	High	Low
Recyclability	–	High	Very low
Cost	–	Low	High

developed, the differences relating to the electrode's designs and to the electrolyte's composition. The overall chemical reaction of lead–acid batteries is as follows:

$$Pb + PbO_2 + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O$$
$$\text{Charged Situation} \rightleftarrows \text{Discharged Situation} \qquad (2.1)$$

Chemical reaction of charge and discharge of a lead acid battery

Note: '→' *refers to discharge of the battery and* '←' *refers to charging of the battery.*

2.3.1.1 Lead–Acid Battery Construction Principles

In order to optimise batteries for different applications, different construction designs have been developed. These relate to their electrode design and to the

Table 2.5 Electrodes in lead–acid batteries

Electrode design	Features	Suitability for SHSs
Grid plate	• Low internal resistance • Considerable service life in float charge condition and at low DOD • Low number of cycles	In SHSs, these plates are applied in enforced form. The grid plate batteries are cheaper than tubular plate batteries; however, their service life is dissatisfactory
Tubular plate	• Rather high internal resistance • Suitable for deep cycling	Highest suitability for SHSs. However, increased cost as compared to grid plate
Large surface plate (Planté type)	• Very low internal resistance • Long service life in float charge condition • Very low number of cycles	Unsuitable for SHSs

nature of the electrolyte (liquid, gel, absorbed in a glass mat). The electrodes in lead–acid batteries are referred to as plates. Both terms are used here.

In lead–acid batteries, the electrolyte contributes to the capacity of the battery by transferring sulphuric acid into water and the electrolyte transports ions.

Battery cells are based on a combination of positive and negative plates. The individual plates were introduced in Table 2.5. The battery types presented in Table 2.7 being suitable for SHSs are available with liquid electrolyte, with gelled electrolyte and in AGM design. The lead–acid battery designs with liquid electrolyte are referred to as low-maintenance, vented batteries, while the gel and AGM batteries are referred to as valve-regulated lead–acid batteries (VRLA).

Battery cells are made up of a set of multiple positive and negative plates connected in parallel. In order to minimise the separation distance between the plates (which reduces the internal resistance by reducing the distance ions have to overcome in charging and discharging processes) and in order to prevent short-circuiting of the positive and negative plates, separators need to be installed in between the plates. These need to be electrically insulating, but permeable for ions. In AGM batteries, the glass mat serves as absorbent for the electrolyte as well as separator between the plates.

Furthermore, individual cells are available on the market (2 V nominal voltage) with different Ah capacity. Multiple cells in series determine the nominal voltage of the battery. However, for simplicity of installation, blocks of multiple cells are available as well. In these blocks, multiple cells are connected in series internally. An exchange of individual cells is not foreseen for these blocks.

2.3.1.2 Lead–Acid Battery Ageing

Typically, the battery of a SHS is discharged in evening hours, and the battery then remains at low state of charge over night before the recharging begins in the morning. It is observed that the daily PV input is insufficient to fully recharge the

Table 2.6 Electrolytes in lead–acid batteries

Electrolyte design	Features	Suitability for SHSs
Flooded (liquid, diluted sulphuric acid)	Ions may commute with low resistance between electrodes	Refilling of distilled water is necessary and possible. The latter has advantages in warm environments with high water consumption. But it is disadvantageous when the maintenance is not ensured Most economical solution when maintenance is ensured at low cost and when the battery operation within voltage limits is guaranteed (no extensive gassing/water consumption due to overcharge)
Gelled electrolyte	The electrolyte is transferred to gel by adding silica to the diluted sulphuric acid. The ion movement is slightly hampered due to the gel form. Therefore, an increased internal resistance is observed	Gel-type batteries have a high investment cost, but they prove economic when refilling of batteries with distilled water is costly. However, mistreatment of batteries by overvoltage is very harmful as electrolyte consumption cannot be compensated
Absorbed glass mat (AGM)	The electrolyte is absorbed in glass mat (AGM). Ion movement hampered due to AGM, therefore increased internal resistance as compared to purely liquid electrolyte	AGM batteries are a compromise between flooded and gel-type batteries. Increased investment cost but proves economic when refilling of batteries with distilled water is costly. However, mistreatment of batteries by overvoltage is very harmful as electrolyte consumption cannot be compensated

Table 2.7 Battery cell designs in lead–acid batteries

Battery designation	+ Positive plate − Negative plate	Suitability for SHSs
OGi	+ Grid plate − Grid plate	Suitable under the condition of modified, enforced grid plates
OPz	+ Tubular plate − Grid plate	Most suitable lead–acid battery but at higher costs than OGi
GroE	+ Large surface plate (Planté) − Grid plate	Unsuitable!

battery. Reaching of the maximum battery voltage is not an indicator for full recharge. Many hours of charge at low current are necessary after the point of reaching the maximum voltage of the battery. The batteries are installed at a certain place and mixing of electrolyte does not take place by mechanical movement of the battery. Solar Home Systems are typically installed in Sunbelt countries with elevated temperatures.

Six ageing processes can be observed in lead–acid batteries [12, 13]:

(i) Sulphating
The active mass of a lead–acid battery consists of small nuggets of lead (negative plate) and lead oxide (positive plate). By discharging, these nuggets are turned to lead sulphate (both positive and negative plate). Sulphating is the development of large lead sulphate crystals from the initially small nuggets of the discharged battery. These large crystals cannot be cracked to the initial size of the nuggets, even by long-term charging. The crystals develop, when a lead–acid battery is not fully recharged shortly after discharge or when a battery is kept at low state of charge over a longer period of time. Sulphating is the major ageing process in lead–acid batteries of solar home systems. Sulphating leads to the loss of active material and to an increase of the internal resistance of the battery. Both serve to reduce the capacity of a lead–acid battery.

(ii) Corrosion
Corrosion occurs as the positive and negative plates are submerged in sulphuric acid. In particular, the positive plate's components suffer corrosion. The ohmic resistance increases due to corrosion. Situations may occur where the current conductors are interrupted, which leads to a full failure of the battery cell. Reasons for corrosion are high charging voltage (overvoltage), high battery temperature, high concentration (density) of the electrolyte, poor conductor material (grid in OGi and conductors in Pz batteries) or stratification of electrolyte in the battery cell leading to areas of high concentration of the electrolyte.

(iii) Softening
Cycling (charging and discharging) of batteries leads to increase and decrease of volume of the active mass (as Pb and PbO_2 are turned to $PbSO_4$). This, however, leads to a reduction of the firmness of the active mass paste. The contact between the active nuggets and the current conductors is deteriorated leading to an increased internal resistance of the plate.

(iv) Grid Growth
The oxidation products of the grid leads to an increased volume of the grid, which may lead to short-circuiting of positive and negative plates. The short circuit within a cell leads to the full failure of the cell.

(v) Dendrite Development
Dendrites develop when high discharge currents occur, when batteries are deep cycled or when high electrolyte concentrations occur at certain points (in case of stratification). Growing dendrites can puncture the separator and ultimately can lead to short-circuiting between the plates.

(vi) Separator Destruction
Separators may be destroyed by mechanical stress (e.g. dendrites poking the separator) or by chemical decomposition. The separator's destruction leads to short-circuiting of the battery cell.

2.3.1.3 Other Effects

Electrolyte Stratification: Stratification occurs due to charging. The higher the concentration of sulphuric acid in the electrolyte, the higher the density of the electrolyte, as stated above. As the water is dissociated, the concentration of the sulphuric acid electrolyte increases. Therefore, high-density electrolyte is generated at the active mass in the charging process. This high-density electrolyte sinks to the bottom of the cell casing. The high-density electrolyte—i.e. high concentration of sulphuric acid in the electrolyte—is a major cause of wear processes, as shown below. However, electrolyte stratification is the only ageing process that can be reversed in battery operation. Electrolyte stratification occurs in both flooded and AGM batteries. The effect is insignificant in gel batteries as the sulphuric acid is well fixed within the gel.

Drying of batteries: Continuous water loss occurs in a lead–acid battery. The decomposition of water to hydrogen and oxygen occurs above an electrode voltage of 1.3 V. However, the voltage of a battery is 2 V. As a consequence, the level of the electrolyte decreases over time. When active mass is not submersed in electrolyte, it cannot contribute to the capacity of the battery. Furthermore, decomposition of water increases the concentration of sulphuric acid in the electrolyte, which contributes to the corrosion of the plates.

Temperature: An increase in ambient temperature of 10 K decreases the battery service life by 50 %. Battery service life is given in datasheets for an ambient temperature of 20 C. Another limitation of ambient temperature is towards low temperatures. Below −5 °C the risk of the electrolyte freezing increases. When batteries are deep discharged, the electrolyte is composed mainly of water. Frozen water (ice) has a larger volume than does liquid water, so freezing can lead to cracking of the battery cell casing.

2.3.1.4 Lead–Acid Battery Safety

Here, the two situations that can be influenced by the SHS project management and the SHS users are considered: The operation of lead–acid batteries and the post-operation of lead–acid batteries.

Operation of Lead–Acid Batteries

Lead–acid batteries continuously emit hydrogen and oxygen whenever the battery's voltage is above the water decomposition voltage. The hydrogen and oxygen decomposition increases with charging voltage. The relative volume of hydrogen and oxygen produced creates an explosive gas mixture. Under charging conditions, 0.42 L of hydrogen is generated per Ah.[1] Therefore, special precautions are important in the vicinity of lead–acid batteries. DIN EN 50272-2 [14] gives a

[1]Mind, 0.42 l/Ah figure is valid per individual charged cell!

formula for the minimum ventilation of a battery room. As an example, according to [15] which applies the DIN EN 50272-2, a 12 V 50 Ah flooded lead–acid battery requires 0.075 m^3/h of ventilation. Special care needs to be taken in the very close vicinity of batteries. In the 1980s, a battery terminal was on the market that incorporated fuses to protect the battery from short circuits in the cabling—which was in principle a sensible approach. However, a blown fuse would be a source of ignition in the vicinity of the battery and these battery terminals were therefore forbidden at short notice. Any potential sources of fire or sparks must not be installed in the vicinity of lead–acid batteries. This includes disconnection of the battery during charge, as any interruption of a circuit under current may generate a spark. Furthermore, measures against electrostatic charge and consequently measures against any source of sparks are necessary. Therefore one requirement is the use of antistatic clothing when dealing with batteries.

The internal resistance of batteries is relatively low, but their capacitance is relatively high. Therefore, short circuits lead to very high currents. Short circuits need to be prevented under all circumstances. Isolated tools for the installation of batteries that prevent short-circuiting the poles are necessary. The cabling connecting the battery to a charge controller should be installed using two individual cables that are separated by a minimum distance. Rodents or termites can destroy the insulation of the battery cabling, causing a short circuit when the positive and the negative cables are in close distance. Fusing of the battery at the battery pole is not possible for the reasons given above.

In the case of flooded lead–acid batteries, diluted sulphuric acid may be spilled during installation, maintenance and accidentally during their operation. Precautions should be taken to prevent harm to persons and to the environment when dealing with these batteries.

Post-Operation of Lead–Acid Batteries

The two main harmful materials of lead–acid batteries are sulphuric acid and lead. These materials are also valuable resources. Therefore, the collection and recycling of worn lead–acid batteries are of importance for both environmental and economic reasons.

2.3.1.5 Lead–Acid Battery Recycling

The recycling of lead–acid batteries requires in the first step the collection of the batteries in the field and the transportation to recycling facilities. There, the material separation, the purification of the resulting raw material is undertaken. Finally, the recycled material needs reintegration to the circulation of material. In all processes, environmental emission restrictions need to be complied with and economic considerations need to be considered.

Barriers to the collection of batteries occurs when SHS users are suspicious about the reasons for the need to exchange a battery [16]. The organisation and the infrastructure required for the collection and transportation of old batteries to a central recycling facility may be a logistic challenge in scarcely populated areas. These challenges can be overcome by paying users an amount for their old batteries and for paying the transporters. Multiple recycling methodologies exist and a good overview is given by Schützenmeister et al. [17]. Batteries need to be emptied and then dismantled. The lead-bearing components, the grids, terminals, bridges (lead antimony/calcium alloys) and the active materials (Pb, PbO_2, $PbSO_4$) need to be metallurgically reprocessed. The plastic casing may be used to contribute to the heat demand of the metallurgical processes by combustion, as implemented by some manufacturers [18]. Other approaches include grinding the casings to generate high-value compounds that can be reused. The off-gas needs purification by adding oxygen at temperatures of 1100 °C.

Situations may occur where out of service lead–acid batteries are transported across continents for recycling where local recycling does not meet environmental standards [19]. In other situations, when world lead prices are low or the collection of out of service batteries is complex (low density of worn batteries, difficult access to batteries) or when recycling is not supported by legislation, recycling might not take place at all. However, collection of lead–acid batteries is highly recommended at this point—refer to Sect. 2.12.

2.3.2 Lithium-Ion Batteries

Lithium-ion (Li-ion) battery materials have been developed since the 1960s. Li-ion batteries exist as both primary and secondary batteries. Secondary Li-ion batteries were developed in the early 1990s by Sony Corporation, and today, they are found in pico solar home systems with a nominal capacity of a few Ah. These pico SHSs are supplied by a PV module with an output power capacity below 10 W_p.

Lithium-ion batteries have a number of advantages over lead–acid batteries. They can be deep discharged, they do not produce hydrogen gas, their charging and discharging efficiency is well above 90 % and they survive many more cycles than do lead–acid batteries. Their power to weight ratio is also very high. The big disadvantage of lithium-ion batteries is their price, which is three- to fourfold higher than that of a comparative lead–acid battery—although the cost of lithium-ion batteries is declining more quickly than anyone expected. Lithium materials are also highly reactive and battery safety management is therefore very important. And while recycling of lead–acid batteries is well known, state-of-the-art recycling of Li-ion batteries is still under development although lithium materials are non-toxic and can be readily recycled.

Of the different Li-ion technologies that are available, the lithium iron phosphate batteries (LiFePO) appear to be the most suitable for use in SHSs. Their voltage is 3.3 V per cell, their capacity is in the range of 160 mAh/g, they are relatively secure and stable and their price is lower than that of most other lithium chemistry battery types [18]. Another advantage is their nominal voltage of 3.3 V, which allows set-ups within the voltage range of the standard 12-V battery found in Solar Home Systems. When discharging, the voltage drop during the discharge is not as high as for lead–acid batteries [20]. This again is advantageous for the appliances operated by the SHSs. In cycle life tests, LiFePO batteries have proven to be very efficient. They retain 80 % of initial capacity after 1600 cycles [20].

2.4 Battery Charge Controllers

As mentioned in Sect. 2.3, charge controllers are necessary in order to protect batteries from harmful over-voltage and undervoltage. They also protect batteries against unintentional discharge by the PV module. Additionally, charge controllers also protect the appliances in SHSs that are connected to the battery via the charge controller. A feature of a charge controller whose importance cannot be underestimated is the information that it provides the user on the SHS's condition, and the state of charge of the battery in particular. Table 2.8 presents the characteristics of an ideal charge controller [21].

2.4.1 Maximum Power Point Tracking

The ideal working point of a PV module is the maximum power point MPP and its current/voltage is dependent on the solar radiation and the PV cell temperature. The PV cell temperature itself is dependent on the solar radiation as well as the ambient temperature and wind speed. The *I–V* working point of a battery is mainly

Table 2.8 Characteristic of ideal battery charge controllers

Reference	Characteristic
System	Low self-consumption High efficiency Self-adaptation to system voltage (12 or 24 V) Ampère rating for PV and load terminals according to the component's nominal data
Battery	High voltage protection Low voltage protection Optimised charging strategy State-of-charge determination
User	Adaptation to the user Mechanical and electrical robustness Self-explanatory indication User and installer friendliness Ample and solid connection terminals

dependent on the battery's state of charge and the available power from the charger (in SHSs the PV module). When directly connecting a PV module to a battery (via a simple charge controller) the cross section of the component's respective *I*–*V* characteristics determines the working point—which might not be the module's MPP. Therefore, maximum power point trackers may be implemented. Basically, MPP trackers are DC–DC converters controlled by a control unit. The DC voltage on the PV side is set to match the V_{mpp} of the module while the charging voltage and current on the battery side is set to reflect the power available from the PV side. Whether or not the extra cost and the overall efficiency of a MPP tracker justify its implementation for the gain of additional energy from the PV module/generator will depend on multiple factors. MPP tracking charge controllers are available for PV generators of a nominal power of 125 W, e.g. [22]. Maximum power point trackers are described in detail in [23].

2.4.2 Miscellaneous Requirements of Battery Charge Controllers

Battery charge controllers suffer in harsh environmental conditions. Some very practical requirements of battery charge controllers have been determined from experience gained in past SHS projects [24, 25]. Charge controllers are implemented in regions where users and installers might be used to different writing systems than the manufacturer. In some cases, users or installers might be illiterate. Therefore, indications on the charge controller need to be self-explanatory and independent of writing systems.

Data sheets indicating which connection terminal relates to which components and to which polarity will not be available for the duration of the charge controller's service life. Therefore, the indication on the charge controller needs to be rigid and remain visible over the longer term. Simple stickers on charge controllers will not survive the service life of a charge controller.

It is evident that charge controllers should be protected against reverse polarity and an indication of reverse polarity by an acoustic or by a light signal has proven to be very helpful for installers. Charge controllers should be resilient against any sequencing order of component's connection. When the PV module is connected to the charge controller first, the charge controller needs to control the voltage at the load's terminal preventing harm to the load by overvoltage and preventing harm to the charge controller.

The installation of a charge controller should be in a central place of the building. Users should at any time be able to get system's information from the charge controller. The factor of proud demonstration of the charge controller and the system's state to visitors should not be underestimated for the diffusion of the technology. The charge controller should be installed in a position which does not allow children to satisfy their scientific curiosity and to tinker with the charge controller. However, ideally even the young children should be trained on the features, advantages and disadvantages of manipulating the charge controller.

Walls and other structural components in rural dwellings might be of low quality. Fixing of charge controllers might cause harm to these structural components. Charge controllers should allow sufficient rigidity of the casing for minimum fixing to the wall and charge controller's self-support.

2.5 DC–DC Converters

The typical supply voltage of a SHS is the voltage of a 12-V battery, which may vary from 14.8 V in case of boost charge of flooded batteries and 10.8 V just before load cut-off. For mobile charging, 4 V is required. Other appliances, such as laptops, require 19.5 V for their operation. DC–DC converters in SHSs should be optimised for high efficiency in operation and zero consumption in standby mode. They should not be plugged directly to the battery as in this case the deep discharge protection of the charge controller is inoperative.

Charge controllers have been on the market with an outlet of a different voltage than the battery voltage. The voltage was adjustable. However, this risks that the user set voltage at the charge controller does not match the voltage demanded by the appliance, hence harming the appliance. Ideally, individual DC–DC converters are used for individual appliances. These DC–DC converters are branched to the DC bus at the load outlet of the solar home system's charge controller.

2.6 Balance-of-System Components

Balance-of-system components have major significance for the correct and optimal operation of SHSs. However, two challenges exist:

(a) the correct selection of the components, and
(b) the professional installation of these components.

In contrast to conventional electricity installations in private homes, solar home system installations deal with DC, with low voltages and with high currents. The following precautions are necessary [24, 26]:

- Arcing within switches may be a problem. The choice of appropriate switches which are suitable to switch DC is necessary.
- Switches should indicate *on* and *off* by inscription (not by a control lamp). In case of the battery charge controller's load cut-off the user should be in the position to switch off all loads. (It has been observed that many loads went on during daytime when the family members were outside of the home and the

charge controller reconnected the loads to the battery. In this case, the battery did not get the full PV power for recharging at daytime.)

- Plugs and sockets should protect against reverse polarity.
- To prevent reverse polarity during installation cables should be colour-coded. The national standard for positive pole and negative pole must be applied throughout the entire installation.
- Plugs and sockets should not allow connecting conventional AC appliances to the DC system.
- The low voltage supplied by solar home systems implies high currents to supply a load (remember: Power = Voltage · Current). Therefore, the cross sections of cables should comply with the conducted currents. The plugs and sockets as well as the switches should comply with the currents occurring.
- The overall power losses in cabling reducing the overall efficiency of the SHS should be kept low. Proposed figures are below 5 % for the cabling between charge controller and the load (cross section of cables 2.5 mm^2), less than 1 % between charge controller and battery (cross section of cables 4 mm^2) and less than 3 % between charge controller and PV modules (cross section of cables 2.5 mm^2).
- Cable connections need to be executed professionally to prevent resistance and voltage drop at the joints.
- In many cases, surface-mounted installations are found in SHS dwellings. Rodents are a major menace for these installations. Cables which are difficult to protect by fusing (e.g. the battery cabling) should be installed in independent, distant wiring for plus and minus poles.
- All cables should be well fixed to the wall. Cables should be strain relieved before they are fixed to component's connections.
- Cables connecting the PV module to the battery charge controller are partly exposed to sunlight. These cables must be UV resistant.

For the reasons above, many of the conventional AC installation material are not suitable for SHS installations.

Installers need to be well trained. The creation of awareness for quality and safety issues is very important. In order to prevent installers' tinkering, regular and independent quality control is highly recommended.

2.7 Inverters

There has been a long debate on inverters in solar home systems in order to operate AC appliances. Pros are enabling users to apply a wider range of appliances. Cons are the tendency of users to connect all sorts of appliances to an inverter and hence overloading the SHS. Overloading the SHS finally leads to power shortages which in consequence lead to users' frustration. In some cases, inverters are inevitable as no suitable DC appliance is available on the local market.

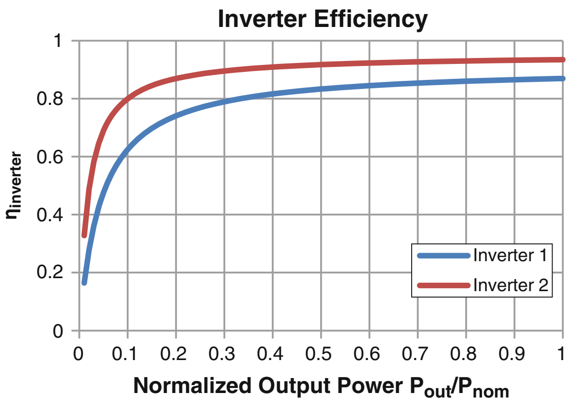


Fig. 2.6 Efficiency of two different inverters

Inverters supply different output waveforms. The simplest and most economical inverter supplies rectangular output. The next level is trapezoid output. Finally, the most desirable output is a sinusoidal waveform. However, the sinusoidal output is given with different quality which is characterised by the harmonic content. The waveform and the harmonic content of inverter's output impacts on the electromagnetic compatibility and hence on the disturbance of radio and TV signals.

Inverters should have a high efficiency over a wide power range. Therefore, the efficiency characteristic over the load is required. Inverters should allow short-term overload (very few seconds) in order to cope with start-up power demand of consumers. Finally, it is very important to decide on stand-alone inverters as grid connected inverters are dependent on the frequency and voltage lead of the public grid. They will fail in SHS applications.

The following Fig. 2.6 shows the characteristic of two different inverters. In part load, their efficiencies differ considerably. However, many loads in SHSs are far from the nominal power of an inverter as the inverters are designed to supply all loads considered to operate simultaneously. The energy demand to operate one of these loads therefore burdens the SHS heavily. Consider the following example: A 150 W output power inverter is implemented to operate a TV set (60 W), a radio/CD player/woofer system (20 W), six CFLs (10 W each) and a mobile charger (6 W). In case only the mobile is charged inverter 1 demands 14.1 W while inverter 2 demands 9.3 W. The example highlights another issue in the discussion on pros and cons of inverters in SHSs. Inverters represent another component in the overall efficiency chain of SHSs. Their losses need to be compensated for by the PV generator, which increases the system's cost.

2.8 Appliances for Use in Solar Home Systems

Typical energy services demanded by users of solar home systems are

- bidirectional communication by mobiles,
- illumination,
- monodirectional communication and entertainment by radios, CD players, woofers, by TV and by DVD players,
- ventilation for human comfort,
- refrigeration for food and beverages.

The order of importance may vary from region to region. The number of energy services is limited by the electricity output of solar home systems. Solar home systems again are limited by economic considerations. In some regions, some appliances may be redundant, e.g., radios or TV when no radio/TV signal coverage is given. The appliances transfer the electricity of solar home systems to the desired energy service. The approach of supplying energy services rather than units of electricity should be in the focus of solar home system implementers. This background leads to the considerations necessary for the selection of appliances for solar home systems.

Table 2.9 gives a list of selection criteria for SHS appliances. However, many of the criteria are contradictive (e.g. quality versus price) and the supply chain's challenge is to find the optimum balance for local conditions.

2.9 Operation and Maintenance

Components of solar home systems suffer weir leading to the end of the service life and the multiple-level challenge of exchanging the parts. Operation and maintenance influence the weir processes positively or negatively. Problems found in the operation of PV systems, operation and maintenance guidance are given in [27–30] (Table 2.10).

Component manufacturers supply maintenance proposals which should be considered. The information in these information leaflets complements the above said. With all the proposals for operation and maintenance, the stakeholders in solar home system implementation need to consider that members of a rural household have so many other, non-SHS-related issues to take care of that the maintenance of the SHS has low priority and cannot be fully satisfied at all times. Therefore, maintenance-free components (e.g. valve-regulated batteries, electronic fusing of charge controllers) are highly recommended.

Table 2.9 Selection criteria for SHS appliances

Selection criteria	Comment
Appliance's voltage	SHSs typically supply a nominal voltage of 12 V DC.
Appliance's voltage tolerance	While the nominal voltage is 12 V the battery's voltage may vary from ~ 10.5 V (before load cut-off) to ~ 14.4 V (boost charge) which represents the input voltage to the appliance.
Power demand in operation	Mind the limited amount of electricity a SHS may supply.
Power demand in stand-by	This must be zero.
Efficiency	The appliance's efficiency needs to be high. Needless to comment.
Service life	A long service life is desirable to reduce efforts of spare part supply.
Rigid design	Appliances in SHSs suffer a hard life: humidity, dust, great temperature fluctuations, and user's handling—to name a few.
Optical design	Different cultures demand for different designs. Design is a comfort factor.
Quality	Quality is the integration of the above criteria. Generally, quality is defined by the stakeholders involved in SHS and the priority of criteria may be very individual. The authors propose to rank efficiency, service life, and rigidity as most important quality criteria.
Cost	Obviously cost of any components play a role in the decision process for an item. The challenge of the supply chain is to balance between cost and quality of components.
Availability on the local market	High efficient appliances exist on the world market. However, typical SHS users cannot approach the world market. Any appliance may fail. For the listed reasons, spare part supply in the vicinity of users is of high importance.
Ecological hazard	All appliances will reach the end of their service life by natural weir or by accidental destruction (e.g. CFL). In this case, the emission of the appliance should not cause ecological hazard (refer to mercury in CFL).

2.10 Sizing of Solar Home Systems

The concept behind the sizing of a solar home system is the technical, economic, social and ecological optimisation of the various components—the PV module, the battery and to some extent the charge controller and when applicable the inverter, as well as the operating philosophy, which involves the energy management system, load shedding, and dumping of generated energy. Backup systems are not considered here. However, occasionally users recharge their SHS batteries at a charging station which may be considered backing up the system.

PV's energy output is relatively linear to the solar input when compared to solar thermal collectors or wind energy converters which have a cut-in level of the renewable energy source impacting on the energy output of the systems. Therefore,

Table 2.10 Maintenance of SHS's components

Component	Operation and maintenance
PV generator	Regular cleaning is necessary as PV module's soiling reduces the sunlight's transmission to the solar cells and reduces solar cells' power output or leads to the hot spot effect. However, solar modules are mounted at difficult to access places, e.g. rooftops or on poles for optimal irradiation conditions and for theft control. This makes cleaning of PV modules difficult and in some cases a hazardous job. Corrugated iron rooftops or thatched roofs may not withstand cleaning persons walking on those surfaces—a hazard for the well functioning of the rooftop as well as for the person. Improvised ladders may constitute a hazard for the user. Cleaning intervals are dependent on the location (precipitation, air composition, air humidity) and may be between biweekly and yearly.
Cabling	Regular visual inspection is recommended to reveal destruction by rodents or by UV sunlight degradation. Cable connections may be checked by careful tensile test.
Battery	Flooded batteries require regular topping up of distilled water. Valve-regulated batteries cannot be refilled. For all types of batteries, a clean surface is recommended to prevent leakage currents between the battery poles along wet dust on the battery's surface. Dealing with batteries requires precaution. Flooded batteries may emit harmful sulphuric acid by spillage. In all batteries, short circuit of the battery poles lead to disasters of different type. In the operation of batteries, regular full charge is highly recommended especially for lead–acid batteries. High-level charge controllers support the optimised operation of batteries by indicating the state of charge.
Battery charge controller	Battery charge controllers are almost maintenance free. However, some might have lead fuses. The connection of the fuse to the connector might corrode. Fuses might blow. The challenge in case of a blown fuse is to get the appropriate rating and fuse design in the near vicinity of the SHS. Otherwise, users tend to improvise a solution which may be harmful for the charge controller.
Appliances I (maintenance)	Protection against dust while they are not in use. It is proposed to cover radios, TV sets and all the appliances related to information and entertainment. Simple cloth can prevent plenty of dust deposit.
Appliances II (operation)	Generally, appliances should only be in operation when they are needed. Thereby, the charge controller's indications should be considered to optimise the load management in the SHS dwelling. Regular full recharge of the battery should be enabled to prolong the service life of this vulnerable component.

the sizing of solar home systems is rather simple when a certain level of error is accepted—which is applicable in the case of SHSs. Detailed time step simulation software may increase the accuracy of the results when the models of the components reflect the components characteristic. Furthermore simulation may contribute to the understanding of the system behaviour. However, plenty of impacts and errors which cannot be foreseen by the software and the user of the software make the use of these software packages a rather academic exercise when it comes to SHSs. The following back of envelope approach is developed from [23, 31–33]. Despite the above said, realistic assumptions should be taken when applying the following approach for SHS sizing. Overoptimistic assumptions lead to power shortages and these in turn lead to frustration of users. The figures applied in the following formula are educated guess figures or figures set to demonstrate an example.

2.10.1 Determination of the Energy Demand

1. Determine the nominal voltage of the system (V_{sys}). As many DC appliances are available on the market with a nominal voltage of 12 V and as only little energy is supplied by SHSs (<200 Wh/d), 12 V is proposed as nominal voltage for SHSs.
2. Determine the total Watt-hours per day (E_{demand}) for each appliance used.

   - Add the Watt-hours needed for all appliances together to get the total Watt-hours per day which must be delivered to the appliances.
     For example,

$$
\begin{aligned}
E_{\text{demand}} &= \sum t_i \cdot P_{i\_\text{appliance}} \\
E_{\text{demand}} &= 4\,\text{h/d} \cdot 10\,\text{W}_{\text{illumination}} + 8\,\text{h/d} \cdot 7.5\,\text{W}_{\text{radio}} \\
E_{\text{demand}} &= 100\,\text{Wh/d}
\end{aligned}
\tag{2.2}
$$

Determination daily energy demand.

3. Determine the total Watt-hours per day needed from the PV modules.

   - Determine the overall subsystem efficiency:

$$
\begin{aligned}
\eta_{\text{sub\_sys}} &= \text{PR} \cdot \eta_{\text{BCC}} \cdot \eta_{\text{bat}} \cdot \text{AF}_{\text{bat}} \cdot \eta_{\text{cabling}} \\
\eta_{\text{sub\_sys}} &= 0.7 \cdot 0.9 \cdot 0.8 \cdot 0.8 \cdot 0.95 = 0.38
\end{aligned}
\tag{2.3}
$$

Subsystem efficiency of a SHS.

where

– PR is the performance ratio of the PV module reflecting the difference between the power output of the module under STC conditions and the real power output (incorporating mismatch between the maximum power point and the real working point of the module, temperature impacts on the power output of the PV module, soiling and circumstances of low irradiation);

– η_{BCC} is the battery charge controller's efficiency;
– η_{bat} is the Wh efficiency of the battery;
– AF_{bat} is the ageing factor of the battery. Mind, a long period of time, SHS batteries are operated at lower efficiency than the datasheet efficiency—this needs consideration;
– $\eta_{cabling}$ is the cabling efficiency mentioned earlier;
– The figures given above in the formula represent educated guess figures. The may vary for individual components.
– Divide the result from 2.2 (determination of E_{demand}) by the subsystem efficiency to get the daily energy demand required from the PV modules (E_{PV}).

$$\begin{aligned} E_{PV} &= E_{demand} \big/ \eta_{sub\_sys} \\ E_{PV} &= 100\,\text{Wh/d}/0.38 \\ E_{PV} &= 261\,\text{Wh/d} \end{aligned} \tag{2.4}$$

Determination energy demanded from the PV modules

2.10.2 PV Modules Sizing

- Determine the monthly mean irradiation G at the site of the SHS from sources (e.g. MERRA, Meteonorm, NASA).
- Determine the month of the lowest irradiation and the respective irradiation (G_{min}).
- The nominal (STC) power of the PV module is given by

$$\begin{aligned} P_{PV} &= \frac{E_{PV}}{G_{min}} \cdot 1000\,\text{W/m}^2 \\ P_{PV} &= \frac{261\,\text{Wh/d}}{4000\,\text{Wh/m}^2\text{d}} \cdot 1000\,\text{W/m}^2 \\ P_{PV} &= 65\,\text{W}_\text{p} \end{aligned} \tag{2.5}$$

Determination of the nominal STC power of the modules

- Note: The nominal PV power is given at STC which is 1000 W/m. Therefore, the multiplication factor of 1000 W/m^2 is necessary in

$$\begin{aligned} P_{PV} &= \frac{E_{PV}}{G_{min}} \cdot 1000\,\text{W/m}^2 \\ P_{PV} &= \frac{261\,\text{Wh/d}}{4000\,\text{Wh/m}^2\text{d}} \cdot 1000\,\text{W/m}^2 \\ P_{PV} &= 65\,\text{W}_\text{p} \end{aligned}$$

- Equation 2.5. In other words, the unit W_p for a solar module indicates the power output (W) at 1000 W/m^2 irradiance (p = peak).
- Determine a PV module which has this nominal power (or slightly higher) at a nominal voltage of 12 V (i.e. approximately 17 V MPP voltage) or determine a number of PV modules to be connected in parallel and in series to deliver this nominal power at the nominal system voltage. This can be a challenge with today's PV modules which are designed for grid connected PV systems and their nominal voltages are far beyond the required 12 V. Furthermore today's nominal PV modules' powers are well beyond 65 W_p.

2.10.3 Battery Sizing

- The battery should allow for a certain number of days of autonomy.
- The battery should not be discharged below a certain state of charge (SOC)—which is 1—DOD under this number of autonomy days.
  - Therefore, the battery's capacity E_{bat} is

$$\begin{aligned} E_{\text{bat}} &= E_{\text{demand}} \cdot n_{\text{autonomy}}/\text{DOD} \\ E_{\text{bat}} &= 100\,\text{Wh/d} \cdot 4\,\text{d}/0.6 \\ E_{\text{bat}} &= 666\,\text{Wh} \\ &\textbf{Determination of battery's capacity}. \end{aligned} \tag{2.6}$$

  - Note: from the above the battery's capacity E_{bat} is given in Wh while batteries are offered in Ah-capacity C_{bat}. Therefore, the C_{bat} from the E_{bat} and the voltage of the battery is determined.

$$\begin{aligned} C_{\text{bat}} &= E_{\text{bat}}/V_{\text{sys}} \\ C_{\text{bat}} &= 666\,\text{Wh}/12\text{V} \\ C_{\text{bat}} &= 55.5\,\text{Ah} \\ &\textbf{Ampère hour rating of the battery} \end{aligned} \tag{2.7}$$

The contradictive recommendations (low DOD versus small battery capacity) make it difficult to size the battery. Finally, it needs to be accepted that the battery is the weakest component in SHS installations. In any case, deep cycle batteries should be implemented when they are on the market. In order to reduce maintenance efforts, valve-regulated batteries should be applied.

2.10.4 Battery Charge Controller Sizing

- The battery charge controller must comply with the system's voltage (V_{sys}).
- The PV input should refer to the PV module's short-circuit current. According to standard practice, the sizing of solar charge controller is to take the short-circuit current (I_{sc}) of the PV array and multiply it by 1.3.
- The rated load output of the charge controller needs to comply with the sum of all loads connected to the charge controller.
- Challenges are inverters: The DC power demand and current rating might be very large and might not comply with the DC output of the charge controller. In some cases, inverters have their own deep discharge protection incorporated. In those cases, inverters may be branched directly to the battery. However, the charge controller's state-of-charge determination will be misled by this phantom load. The users are not in the position to manage their loads accordingly when the inverter is branched directly to the battery.

Many charge controllers are designed for the same Ampère rating at the PV module and at the load connectors. The decision will have to be taken for the highest rating in those cases. Many charge controllers determine the system voltage automatically when they are branched to the battery. However, these charge controllers do not connect and adequately charge 24-V battery by a 12-V module!

2.11 Standards for Solar Home Systems

Standards have multiple functions: They guide stakeholders involved in SHSs on quality matters, and they allow comparing components on the market. Standards give guidance in:

- How to select components and systems,
- How to install systems,
- How to maintain systems,
- How to operate systems.

Despite the costs of having components and systems tested and certified by independent agencies and despite the risk of fraud with certificates—obeying standards is highly recommended. Technical standards should include:

- Hardware description with component specifications and warranty,
- Certification required,
- Installation of module and batteries,
- Circuit protection and charge controls,
- Wiring,
- System monitoring,
- Documentation,

- User's manual,
- Technician's technical manual,
- Packaging and delivery of the system and
- Maintenance.

One of the first standards related to Solar Home Systems was given by [26]. Now the International Electrotechnical Commission (IEC) Technical Committee 82 develops standards for systems of PV power systems. This includes components from the solar cell down to appliances such as LED lamps [34]. IEEE offers a wide range of standards on Solar Home Systems [35]. Buschenhenke [36] gives an overview over standards available for PV generators, module support structures, batteries, charge regulators, loads, system installation and wiring, grounding, lightning protection and documentation. Additionally, many national standards exist for SHSs as listed in [37] or presented in [38].

2.12 The Market Chain and Key-Stakeholders for Solar Home Systems

In order to establish Solar Home Systems at a site, numerous stakeholders are involved.

Holtorf et al. [39] present the key-stakeholders within the SHS environment. To supply a SHS to a user in many cases international component manufacturers are needed as not all countries have manufacturing sites for all components of SHSs. In particular, PV modules are not manufactured in all countries of the world. International system integrators are needed to assemble suitable systems from the components available on the international market. However, in some cases national system implementers deal directly with international manufacturers. National component manufacturers supply components to the national system implementers which in turn supply local entrepreneurs with components or SHS kits. These local entrepreneurs may be members of the national system implementer's business network, or they may supply themselves with components on a case to case situation from different national system implementers. International system integrators have been found which rely on a network of local entrepreneurs in order to disseminate their products.

Apart from the members of the supply chain, other institutions are important for the dissemination of SHSs. They may give funding, they may consult, they deal with legislative aspects of SHSs, they train on multiple levels, they assure quality and they finance SHSs. Those are referred to as immaterial impacts in Fig. 2.7. A discrete assignment of the above tasks to individual stakeholders presented in Fig. 2.7 cannot be given.

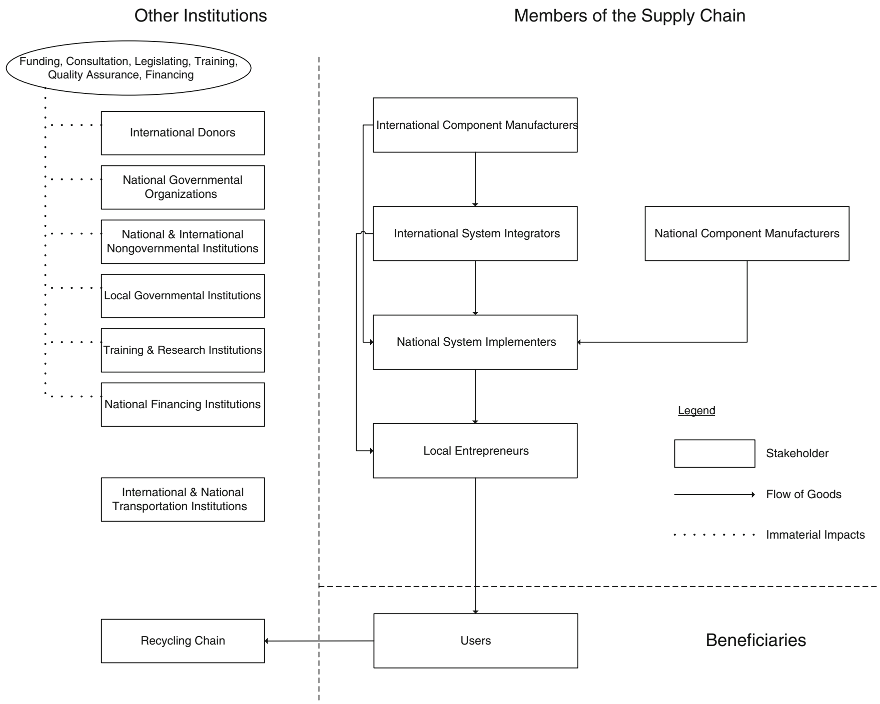


Fig. 2.7 The market chain and the key-stakeholders for SHSs

Two stakeholders need particular highlighting:

I. The transportation industry:
SHSs cannot be disseminated without the collaboration with the transportation industry. International haulers transport anything from major cities to major cities. Transportation time is an issue in some cases. For example, cross-border trading may be a challenge, especially when goods such as lead–acid batteries are kept in containers in a hot customs areas for longer periods of time. Lead–acid batteries suffer self-discharge and high temperature leading to extensive wear under such circumstances.
Another challenge is overcoming the last mile from a rural outlet in a village to the user. Local entrepreneurs often need to rely on public transport, which does not serve stand-alone users. SHS components are bulky and /or heavy and motorcycle taxis or bicycles may not be in the position to transport an entire system at once. Additionally, the transportation of sensitive components on rough roads and paths need special attention in order to protect those sensitive goods. SHS components may have suffered plenty of weirs before they are implemented at the user's site.

II. The recycling industry:
After the components' service lives, those components need disposal. Ideally, they are returned to the materials cycle and valuable though harmful material is recycled—refer to Sect. 2.3.1. However, collection of worn components may be a challenge. It was reported that users are reluctant to exchange their batteries and return those to the supplier for reasons of mistrust. Collection and recycling of wasted components may not be economical in periods of low world market prices for raw material. Or recycling may simply be unfeasible as in the case of some components in some countries. Transportation to other countries having the necessary recycling facilities might be uneconomical. Legislative provisions may reduce harmful on the spot disposal of worn SHS components such as batteries.

2.13 Summary

The application of solar PV systems in developing countries has been tested, optimised and disseminated throughout the world over the last decades. Field experience with PV rural electrification has shown that the performance of solar home systems is not always entirely satisfactory. Understanding the technical specifications for each component used in a SHS is very important when designing the system. The requirements for components and systems vary significantly from country to country. Partly this is due to differences in country-specific characteristics or regional availability. It means that programme designers need to be well informed about these technical requirements for system components and to have information on the specifications provided by the manufacturer. Due to a lack of standards, the qualities of components that penetrate into the rural markets vary considerably.

When a solar PV system fails, it is usually assumed that the solar module is faulty. However, when things go wrong with a solar PV system, it is usually the other system components or the appliances that are powered by the PV generator that are found to be the real cause of the fault. This is mainly because PV modules are highly standardised and are certified using internationally validated procedures, but by contrast, there are few equivalent standards and procedures available for balance-of-system components, component matching or installation quality, even though the quality of these components has a dramatic influence on user satisfaction and operating costs.

A major cause for disappointment lies in the under sizing of systems leading to power shortages. It is highly recommended not to be too optimistic when grading components' efficiencies and derating factors, hence when sizing individual components. However, users tend to opt for a cheaper (undersized) system. Balancing between the realistic sizing and the users' acceptance of costs requires a high level of communication between users and implementing institutions.

Although PV technology is regarded as being very low maintenance, system component failures increase the operating costs over the lifetime of the SHS and this has to be factored into the purchase decision. The upfront costs are also relatively high and for those living in rural areas in developing countries, the cost can be equivalent to many months of income. Therefore, financing schemes are just as important as are the technical issues and also need to be carefully considered when implementing a Solar Home System programme. This topic is discussed in depth in the following chapter.

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