Chapter 9.

PHOTOVOLTAIC SYSTEMS

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9.1 Components of a PV system

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a ***solar panel***, also called a ***PV module***. For large-scale generation of solar electricity the solar panels are connected together into a ***solar array***.

The solar panels are only a part of a complete ***PV solar system***. Solar modules are the heart of the system and are usually called the ***power generators***. One must have also ***mounting structures*** to which PV modules are fixed and directed towards the sun. For PV systems that have to operate at night or during the period of bad weather the storage of energy is required, the ***batteries*** for electricity storage are needed. The output of a PV module depends on sunlight intensity and cell temperature; therefore components that condition the DC (direct current) output and deliver it to batteries, grid, and/or load are required for a smooth operation of the PV system. These components are referred to as ***charge regulators***. For applications requiring AC (alternating current) the DC/AC ***inverters*** are implemented in PV systems. These additional components form that part of a PV system that is called ***balance of system*** (BOS). Finally, the household appliances, such as radio or TV set, lights and equipment being powered by the PV solar system are called ***electrical load***. The elements of a PV system are schematically presented in Figure 9.1.

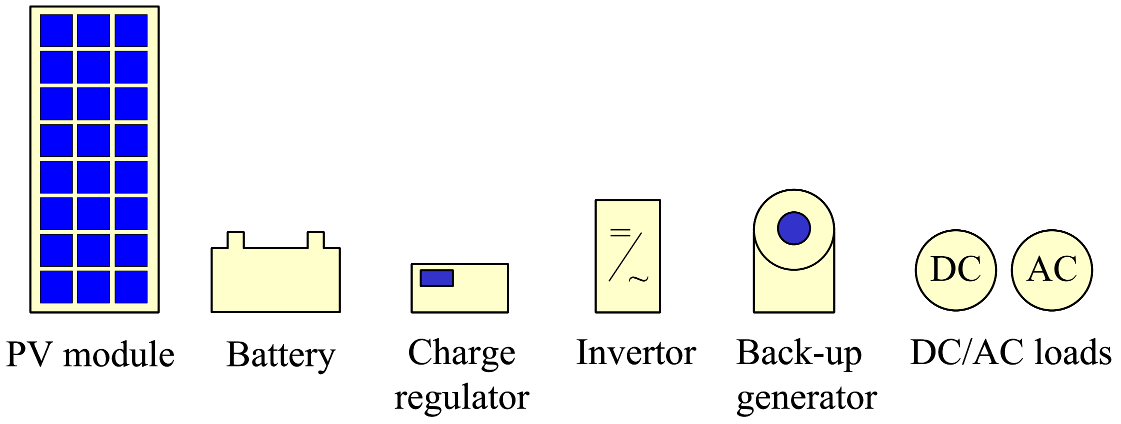


Figure 9.1. The components of a PV system.

In summary, a PV solar system consists of three parts:
i) PV modules or solar arrays,
ii) balance of system,
iii) electrical load.

9.2 PV modules

The solar cell is the basic unit of a PV system. An individual solar cell produces direct current and power typically between 1 and 2 W, hardly enough to power most applications. For example, in case of crystalline silicon solar cells with a typical area of 10×10 cm^2 an output power is typically around 1.5 W_p, with $V_{oc} \approx 0.6$ V and $I_{sc} \approx 3.5$ A. For actual usage, the solar cells are interconnected in series/parallel combinations to form a PV module.

In the outdoor environment the magnitude of the current output from a PV module directly depends on the solar irradiance and can be increased by connecting solar cells in parallel. The voltage of a solar cell does not depend strongly on the solar irradiance but depends primarily on the cell temperature. PV modules can be designed to operate at different voltages by connecting solar cells in series. Table 9.1 contains typical parameters that are used in module specification sheets to characterize PV modules. Four examples of PV modules with comparable power output are included in Table 9.1, such as a Shell module with mono-crystalline silicon solar cells [9.1], a Shell module based on copper indium diselenide (CIS) solar cells [9.1], a Kaneka's amorphous silicon (*a*-Si:H) module [9.2], and a module of First Solar based on cadmium telluride (CdTe) solar cells [9.3]. Electrical parameters are determined at standard test conditions, i.e. 1000 W/m^2 solar irradiance, 25°C cell temperature and AM1.5 solar radiation. Rated specifications are determined from the maximum power point (MPP) of the illuminated I-V characteristic. In order to guarantee performance specifications of modules, modules are sealed for protection against corrosion, moisture, pollution and weathering. The examples of commercial PV modules are shown in Figure 9.2.

Table 9.1 Specification parameters of different PV modules.

Module type		Shell SM50-H	Shell ST40	Kaneka PLE	First Solar FS-50
Solar cell type		mono c-Si	CIS	a-Si:H	CdTe
Rated power P_{max}	[W_p]	50	40	50	52
Rated current I_{MPP}	[A]	3.15		3.03	0.80
Rated voltage V_{MPP}	[V]	15.9	16.6	16.5	63
Short circuit current I_{sc}	[A]	3.40	2.68	3.65	0.95
Open circuit voltage V_{oc}	[V]	19.8	23.3	23	88
Configuration	[V]	12			
Cells per module		33			
Dimensions	[mm]	1219×329	1293×328	952×920	1200×600
Performance warranty	[years]	25	10	10	20

The PV modules market is at present dominated by modules based on the use of mono- and multi-crystalline silicon, which take about 90% of the market share. Amorphous silicon modules represent around 9% of the market share and the rest (less than 1%) are modules made from CIS and CdTe solar cells. The modules are manufactured in various sizes and are able to deliver power ranging from 5 to 240 W_p. The most advanced crystalline silicon modules have achieved efficiencies above 18%. Commercial modules employing mono-crystalline silicon solar cells have efficiencies from 12 to 16%, modules based on poly-crystalline silicon solar cells exhibit slightly lower efficiencies of about 11% to 13%. The performance warranty of most commercial modules based on crystalline silicon is at least 20 years. The energy bay-pack time is in the range of 2 - 6 years depending on region and climate. Most of the amorphous silicon modules currently on the market have stabilised efficiencies between 4% and 8%. Here, the energy bay-pack time is estimated to be 1-3 years. The best CIS modules have achieved efficiencies around 11%; the commercial CIS modules have efficiencies below 10%. The best modules built for space applications have efficiency more than 20%, in which the gallium arsenide solar cells are employed with efficiency approaching 30%.

(a)

(b)

Figure 9.2. (a) Kaneka's *a*-Si:H PLE module and (b) WorldSolar SW 150 multi-crystalline Si module.

9.3 Balance of system

9.3.1 Mounting structures

The principal aim of the mounting structures is to hold the PV modules securely in place, which usually means that they have to resist local wind forces. When placed in a public area the structures should prevent stealing the modules. The further common requirements are not to cause shading of the modules and to be arranged so that there is an easy access to the modules for the maintenance or repair. The cost of the structures should be low. For integration in buildings, special mounting structures are being developed that together with the modules serve as building elements. Typical examples are PV modules in the facades of buildings, on the roofs of houses, on the roofs of telephone boxes, outdoor lights and warning signs, and in the noise barriers on motorways. The additional cost of placing PV modules on a sun-tracking system makes this configuration not profitable in most PV applications.

9.3.2 Energy storage

The simplest means of electricity storage is to use the electric rechargeable batteries, especially when PV modules produce the DC current required for charging the batteries. Most of batteries used in PV systems are lead-acid batteries. In some applications, for example when used in locations with extreme climate conditions or where high reliability is essential, nickel-cadmium batteries are used. The major difficulty with this form of storage is the relative high cost of the batteries and a large amount required for large-scale application.

The following factors should be considered when choosing a battery for a PV application:

- Operating temperature range (e.g.: -15°C to 50°C)
- Self discharge rate (% per month)
- Cycle life to 80% depth of discharge (DOD)
- Charge efficiency from 20% discharged
- Capacity (Ah) at 10 hr & 100 hr rates (C10 & C100)
- Required frequency for topping up the electrolyte
- Robustness for transport to site
- Resistance to overcharging
- Cost

Lead-acid batteries

The most commonly available lead-acid battery is the car battery, but these are designed mainly to provide a high current for short periods to start engines, and they are not well suited for deep discharge cycles experienced by batteries in PV systems. Car batteries are sometimes used for small PV systems because they are cheap, but their operational life in PV applications is likely to be short.

The most attractive lead-acid battery for use in most PV systems is the flooded tubular plate design, with low antimony plates. Good quality batteries of this type can normally be expected to have operational life of 5 - 7 years if they are properly maintained and used in a PV system with a suitable charge controller. Longer operational life may be achieved if the maximum depth of discharge is limited, but shorter lifetimes must be expected if the batteries are mistreated. Flat plate lead-acid batteries with low antinomy are frequently used as stationary batteries for stand-by applications. However, these batteries are not designed for deep cycling and are therefore not the best choice for most PV applications.

A relatively recent development is the sealed lead-acid battery, which is designed mainly to avoid problems of spillage and the need to top up the electrolyte. Some batteries of this type are sold specifically for use in PV systems, and may be attractive for applications in remote regions where transport to site is a problem. However, they are typically less resistant to extreme temperatures than conventional flooded batteries, and are considerably more expensive.

Nickel cadmium batteries

"Sintered plate" NiCd batteries suffer from the well know memory effect, in which the useful capacity of the battery appears to drop after it has been discharged over many cycles or if it is discharged at low rates. Sintered plate NiCd batteries are not therefore attractive for use in PV systems.

"Pocket plate" NiCd batteries can be used in PV systems, because they have additives in their plates to prolong their operational life and to minimise the memory effect. In addition, they are highly resistant to extremes of temperature, and can safely be taken down to less than 10% state of charge. Their main disadvantage is their high cost compared with lead-acid batteries.

The performance and prices of above-mentioned batteries are summarised below.

Battery type		Lead-acid	NiCd
Cycle time		600 to 1500 cycles	1500 to 3500 cycles
Efficiency	[Ah extracted/Ah restored]	83 to > 90%	71%
Self discharge rate		3 to 10%/month	6 to 20%/month
Range of operation		-15 to +50°C	-40 to +45°C
Investment cost	[€/kWh capacity]	160 - 200	690 - 1590
Specific energy cost	[€/kWh from battery]	0.11 - 0.33	0.20 - 1.06

9.3.3 Charge regulators

Charge regulators are the link between the PV modules, battery and load. They protect the battery from overcharge or excessive discharge. Charge and discharge voltage limits should be carefully selected to suit the battery type and the operating temperature. These settings can significantly affect maximum operational life of a battery. High temperatures tend to reduce battery life because they accelerate corrosion and self-discharge. High temperatures may also increase out gassing during charging and therefore should be controlled. The resistance of lead-acid batteries to freezing is reduced when they are discharged, so batteries should be kept charged when they are left in low temperature conditions during the winter.

PV modules that are used to charge batteries usually operate at an approximately constant voltage, which is selected to suit the local temperature. However some PV systems regulators employ a maximum power point tracker (MPPT), which automatically permits the

PV modules to operate at the voltage that produces maximum power output. Such regulators employ an electronic DC-DC converter to maintain their output at the required system voltage. The benefit of using an MPPT depends on the application and should be weighed against its additional cost and reliability risks. For many applications, it may be equally or more cost effective to operate the system at a fixed voltage.

9.3.4 Inverters

The inverter's main functions are: transformation of DC electricity into AC, wave shaping of the output AC electricity, and regulation of the effective value of the output voltage. The most important features of an inverter for PV applications are its reliability and its efficiency characteristics. They are designed to operate a PV system continuously near its maximum power point. The technology for high-switching-frequency inverters (typically 20 kHz or higher) is made possible by switch-mode semiconductor power devices. Power MOSFETs and bipolar transistors are used in low-power inverters, whereas thyristors are used in high-power applications. Novel devices, such as insulated-gate bipolar transistor (IGBT) inverters are capable of handling several hundred kW, running at frequencies up to 50 kHz. They deliver an AC output wave, which has a form very close to the pure sinusoidal one, with very little filtering at the output. This eliminates the bulky, expensive, and energy-consuming power filters.

The efficiency of an inverter is normally quoted at its design operating power, but inverters in PV systems typically operate for much of their life at partial loads. High partial load efficiencies are particularly important for grid connected inverters operating in central European climates, where the annual mean power output of PV array can be as low as 10% of its peak power. In general, inverters have efficiencies ranging from 90% to 96% for full load and from 85% to 95% for 10% load.

When sizing a grid-connected inverter to operate with a PV array, both the inverter's overload capability and its efficiency characteristic should be taken into account. Optimal system performance is likely to be obtained by using an inverter with a rating of between 70% and 90% of the nominal rating of the PV array, depending on the climate involved and the shape of the inverter performance characteristics. For grid-connected operation, inverters must meet the requirements of the utilities concerning acceptable levels of harmonic distortion (quality of voltage and current output waveforms), and should not emit electrical noise, which could interfere with the reception of television or radio. They must also switch off when there is a grid failure for the safety of the engineers who have to repair the grid. In stand-alone PV systems, the inverter will normally be supplied from the system battery, so partial load operation can be minimised by sizing the inverter to match the loads.

9.4 Load

The appliances, lights and equipment being powered by a PV solar system constitute electric loads of the PV system. Energy-efficient loads contribute to overall system efficiency and economy. In Table 9.2 power consumption of commonly used appliances is listed.

Table 9.2. Power consumption of typical appliances.

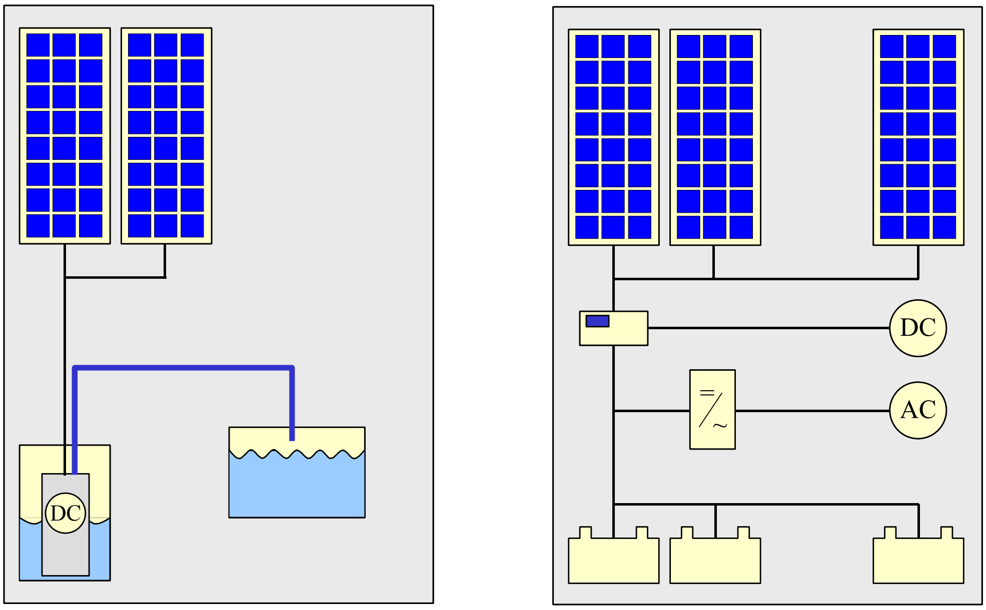
DC	[W]	AC	[W]
Fluorescent light	5-15	Fluorescent light	7-25
Stereo/tape player	40	Stereo/tape player	100
Television (25 cm, color)	45	Computer	50
Refrigerator	50-70	Television (48 cm, color)	60-85
Ceiling fan	20	Refrigerator (100 liters)	90-150
		Cooler	200-300
		Microwave oven	450-750
		Power drill	450-1000
		Toaster	900-1100
		Coffee maker	850-1500
		Air conditioner	3000-4000

9.5 Types of PV systems

PV systems can be very simple, just a PV module and load, as in the direct powering of a water pump motor, or more complex, as in a system to power a house. While a water pump may only need to operate when the sun shines, the house system will need to operate day and night. It also may have to run both AC and DC loads, have reserve power and may include a back-up generator. Depending on the system configuration, we can distinguish three main types of PV systems: stand-alone, grid-connected, and hybrid. In either case, basic PV system principles and elements remain the same. Systems are adapted to meet particular energy requirements by varying the type and quantity of the basic elements. Ads as systems are modular; they can always be expanded, as power demands increases.

9.5.1 Stand-alone systems

Stand-alone systems rely on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and switch off the load in case batteries become discharged below a limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather. Figure 9.3 shows schematically examples of stand-alone systems; (a) a simple DC PV system without a battery and (b) a large PV system with both DC and AC loads.



(a) (b)

Figure 9.3. Schematic representation of (a) a simple DC PV system to power a water pump with no energy storage, (b) a complex PV system including batteries, power conditioners, and both DC and AC loads.

9.5.2 Grid-connected systems

Grid-connected PV systems have become increasingly popular as building integrated application. They are connected to the grid through inverters, and do not require batteries because the grid can accept all of the electricity that a PV generator can supply. Alternatively they are used as power stations. A grid-connected PV system is schematically presented in Figure 9.4a.

9.5.3 Hybrid systems

Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator. Schematically is a hybrid system shown in Figure 9.4b. In order to optimise the operations of the two generators, hybrid systems typically require more sophisticated controls than stand-alone PV systems. For example, in the case of PV/diesel systems, the diesel engine must be started when battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well.

A common problem with hybrid PV/diesel generators is inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then energy, which could be produced by the PV generator is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced. Such problems must be expected if a PV generator is added to an existing diesel engine without installing an automatic system for starting the engine and controlling its output.

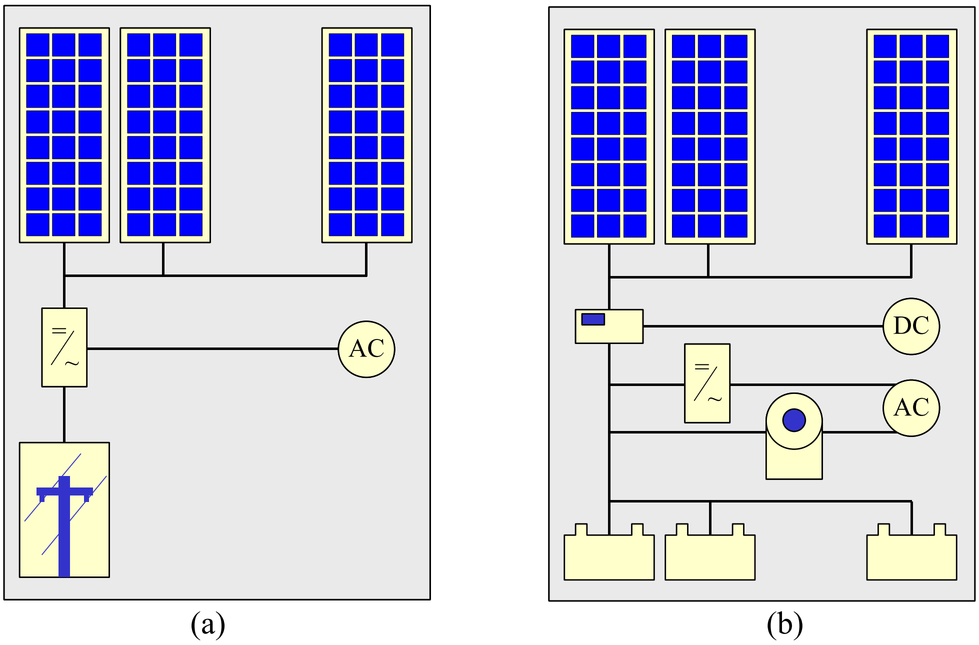


Figure 9.4. Schematic representation of (a) a grid-connected PV system, (b) a hybrid system.

9.6 PV system design

9.6.1 Sizing of PV system

Sizing of a PV system means determining how much energy is required to run the system and how many PV modules are needed to generate it. A PV system has to generate enough energy to cover the energy consumption of the loads (lights, appliances, equipment) and energy used by the system itself. The accurate design of a PV system is usually carried out using a computer model, which calculates the energy yield of the PV system for a particular location. The size and configuration of solar array is then optimised in order to match the energy yield of the system to the energy consumption of the system. The energy yield of a PV system depends on the type of PV modules, the characteristics of a PV inverter, the orientation of the modules, and meteorological conditions.

9.6.1 PV system design guide

If such models are not available, then a rough estimate of the sizing of a PV array and batteries can be calculated using the following design rules.

1. Determine the total load current and operational time
2. Add system losses
3. Determine the solar irradiation in daily equivalent sun hours (EHS)
4. Determine total solar array current requirements
5. Determine optimum module arrangement for solar array
6. Determine battery size for recommended reserve time

1. Determine the total load current and operational time

Before starting determining the current requirements of loads of a PV system one has to decide the nominal operational voltage of the PV system. Usually, one can choose between 12V or 24V nominal voltage. When knowing the voltage, the next step is to express the daily energy requirements of loads in terms of current and average operational time expressed in Ampere-hours [Ah].

In case of DC loads the daily energy [Wh] requirement is calculated by multiplying the power rating [W] of an individual appliance with the average daily operational time [h]. Dividing the Wh by the nominal PV system operational voltage, the required Ah of the appliance is obtained.

EXAMPLE: A 12 V PV system has two DC appliances A and B requiring 15 and 20 W respectively. The average operational time per day is 6 hours for device A and 3 hours for device B. The daily energy requirements of the devices expressed in Ah are calculated as follows:
Device A: 15W×6h = 90Wh
Device B: 20W×3h = 60Wh
Total: 90Wh+60Wh = 150Wh *150Wh/12V =* ***12.5*** *Ah*

In case of AC loads the energy use has to be expressed in the DC energy requirement since PV modules generate DC electricity. The DC equivalent of the energy use of an AC load is determined by dividing the AC load energy use by the efficiency of an inverter, which is typically 85%. By dividing the DC energy requirement by the nominal PV system voltage the Ah is determined.

EXAMPLE: An AC computer (device C) and TV set (device D) are connected to the PV system. The computer, which has rated power 40W, runs 2 hours per day and the TV set with rated power 60W is 3 hours per day in operation. The daily energy requirements of the devices expressed in DC Ah are calculated as follows:
Device C: 40W×2h = 80Wh
Device D: 60W×3h = 180Wh
Total: 80Wh+180Wh = 260Wh
DC requirement: 260Wh/0.85 = 306Wh 306Wh/12V = ***25.5*** *Ah*

2. Add system losses

Some components of the PV system, such as charge regulators and batteries use energy to perform their functions. We denote the use of energy by the system components as system energy losses. Therefore, the total energy requirements of loads, which were determined in step 1, are increase by a factor of 20 to 30% in order to compensate for the system losses.

EXAMPLE: The total DC requirements of loads plus the system losses (20%) are determined as follows:
(12.5Ah + 25.5Ah) × 1.2 = 45.6Ah

3. Determine the solar irradiation in daily equivalent sun hours (EHS)

How much energy a PV module delivers depends on several factors, such as local weather patters, seasonal changes, and installation of modules. PV modules should be installed at the correct 'tilt-angle' in order to achieve best year-round performance. It is also important to know whether a PV system is expected to be used all-year round or only during a certain period of a year. The energy produced in winter is much less than yearly average and in the summer months the generated energy can be more that the average.

In the PV language, 1 equivalent sun means the solar irradiance of 1000 W/m^2. This value corresponds to the standard, at which the performance of solar cells and modules is determined. The rated parameters of modules (see for example Table 9.1) are determined at solar irradiance of 1 sun.

When solar irradiation data are available for a particular location than the equivalent sun hours can be determined. For example, in The Netherlands the average annual solar irradiation is 1000 kWh/ m^2. 1 sun delivers 1000 W/ m^2 = 1 kW/m^2. It means, the Dutch average annual solar irradiation can be expressed in $\frac{1000\,kWh/m^2}{1\,kW/m^2}$ = 1000 equivalent sun hours, which means 1000 h/356 days = 2.8 h/day. The map in Figure 9.5 shows a rough estimation of the daily equivalent sun hours for an average annual solar irradiation.

EXAMPLE: PV system site is in The Netherlands. From the map in Figure 9.4 the daily ESH is 3 hours.

4. Determine total solar array current requirements

The current that has to be generated by the solar array is determined by dividing the total DC energy requirement of the PV system including loads and system losses (calculated in step 2 and expressed in Ah) by the daily equivalent sun hours (determined in step 3).

EXAMPLE: The total DC requirements of loads plus the system losses are 45.6Ah. The daily EHS for The Netherlands is 3 hours. The required total current generated by the solar array is 45.6Ah/3h = 15.2A.

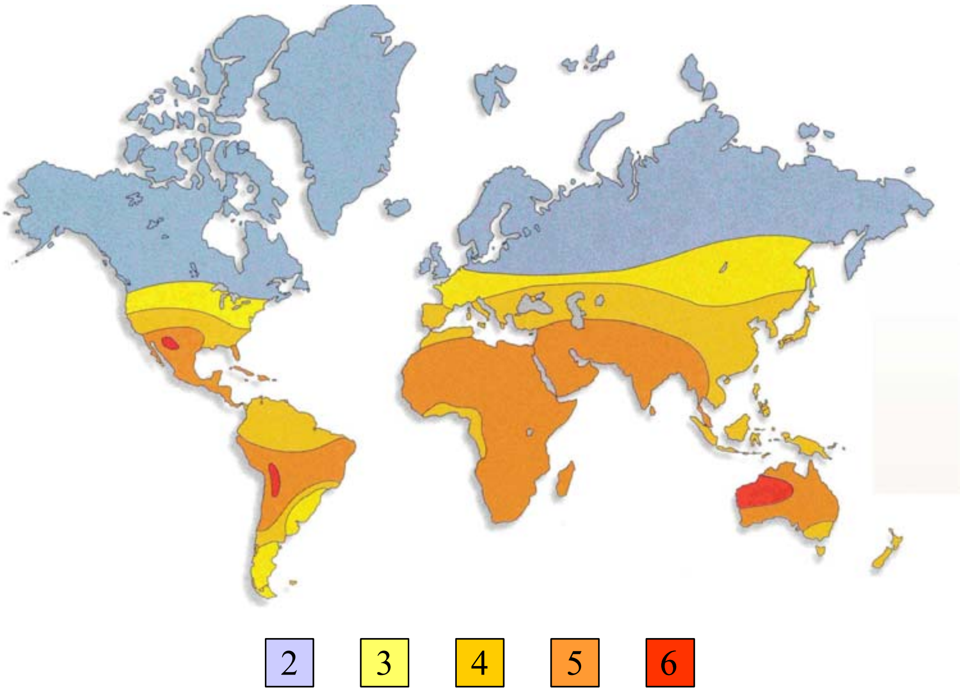


Figure 9.5. World insolation map. This map roughly divides the world in five regions based on a yearly average of daily hours of sunlight.

5. Determine optimum module arrangement for solar array

Usually the PV module producers manufacture a whole series of modules that differ in the output power. The optimum arrangement of modules is the one that will provide the total solar array current (as determined in step 4) with the minimum number of modules. Modules can be connected in series of in parallel to form an array. When modules are connected in series, the nominal voltage of the PV system is increased, while the parallel connection of modules results in a higher current in the PV system.

The number of modules in parallel is calculated by dividing the total current required from the solar array (determined in step 4) by the current generated by module at peak power (rated current in the specification sheet). The number of modules in series is determined by dividing the nominal PV system voltage with the nominal module voltage (in the specification sheet under configuration). The total number of modules is the product of the number of modules required in parallel and the number required in series.

EXAMPLE: The required total current generated by the solar array is 15.2A. We have Shell SM50-H modules available. The specification of these modules is given in Table 9.1. The rated current of a module is 3.15A. The number of modules in parallel is 15.2A/3.15A = 4.8 < 5 modules. The nominal voltage of the PV system is 12V and the nominal module voltage is 12V. The number of modules in series is 12V/12V = 1 module. The total number of modules in the array is 5 × 1 = 5 modules.

6. Determine battery size for recommended reserve time

Batteries are a major component in the stand-alone PV systems. The batteries provide load operation at night or in combination with the PV modules during periods of limited sunlight. For a safe operation of the PV system one has to anticipate periods with cloudy weather and plan a reserve energy capacity stored in the batteries. This reserve capacity is referred to as PV system autonomy, which means a period of time that the system is not dependent on energy generated by PV modules, and is rated in days. The autonomy of system depends on the type of loads. For critical loads such as telecommunications

components the autonomy can be 10 days and more, for residential use it is usually 5 days or less.
The capacity [Ah] of the batteries is calculated by multiplying the daily total DC energy requirement of the PV system including loads and system losses (calculated in step 2 and expressed in Ah) by the number of days of recommended reserve time. In order to prolong the life of the battery it is recommended to operate the battery using only 80% of its capacity. Therefore, the minimal capacity of the batteries is determined by dividing the required capacity by a factor of 0.8.
EXAMPLE: The total DC requirements of loads plus the system losses are 45.6Ah. The recommended reserve time capacity for the installation side in The Netherlands is 5 days. Battery capacity required by the system is 45.6Ah × 5 = 228Ah. The minimal battery capacity for a safe operation is 228Ah/0.8=285Ah.

Sizing of a PV system can be carried out using a worksheet in which the PV system design rules are summarized.

Worksheet for the PV system design guide:

Daily DC loads requirements			
DC load	W ×	h =	Wh
Total DC loads energy use:			

Daily AC loads requirements			
DC load	W ×	h =	Wh
Total AC loads energy use:			
/0.85 = DC energy requirement			

1	Daily DC energy use (DC loads)		
1	Daily DC energy use (AC loads)	+	
1	Daily DC energy use (all loads)	=	
	PV system nominal voltage	/	
	Daily Ah requirements (all loads)	=	
2	Add PV system losses	×	
	Daily Ah requirements (system)	=	
3	Design EHS	/	
4	Total solar array current	=	
5	Select module type Module rated current	/	
	Number of modules in parallel	=	
	PV system nominal voltage		
	Modules nominal voltage	/	
	Number of modules in series	=	
	Number of modules in parallel	×	
	Total number of modules	=	
6	Determine battery capacity Daily Ah requirements (system)		
	Recommended reserve time	×	
	Usable battery capacity	/	
	Minimum battery capacity	=	

9.7 Economics

9.7.1 PV system cost

The use of PV systems requires an initial capital investment, but thereafter the running costs are very low. The purchase price of a PV system typically contains four main costs:

- PV array;
- Balance of system;
- Transport and installation costs, mainly in remote/mountainous areas;
- Project management, design and engineering.

The relative contributions of these costs to the total price of an installed system depend on the application, the size of the system and the location. As a rule of thumb, a cost of PV modules is half of the cost of a complete PV system.

PV module costs

In general, the cost of the PV modules dominate the price of large grid connected system, but represent less than one third of the purchase price of a small stand-alone generator for rural electrification in remote location. The prices of PV modules have been reduced substantially in recent years, partly by improved efficiencies, partly by improved manufacturing techniques, and partly by economies of scale in production. The prices of PV modules are expected to continue to fall for some years to come as production levels grow, and as new lower cost thin-film solar cell technologies take an increasing share of the market. The current estimate of total production costs of PV modules is above 3 €/Wp for crystalline Si modules and above 2 €/Wp for thin-film amorphous Si modules. The retail price depends, among other factors, much on the quantity supplied.

The effective cost of PV modules can be lowered when a module is integrated with other product. For example, special modules are being developed for integration into the facades of buildings, where their costs can be offset against the costs of the cladding materials, which they replace. Modules are also being developed for other architectural applications, including semi-transparent glazing and sound barriers for motorways.

Balance of system costs

In stand-alone PV systems, battery costs usually dominate the BOS cost. Since battery technology is well established, there is limited potential for future cost reductions. Battery costs depend strongly on type and quality. Typically, a lead-acid battery of 100Ah capacity costs from 30 to 50 €. The lifetimes of most PV system batteries are only 5-7 years, so battery replacement costs must be taken into account when assessing the economics of PV systems.

In grid-connected systems, the main balance of system cost is that of the inverter and grid interface. PV inverters are not yet made in large quantities, so prices for small inverters up to 1 kW is 1 €/W, and for 2 - 5 kW inverter is 0.5 €/W. Larger inverters are usually less expensive but most are still made individually. The lifetime of inverters, which are fully protected against voltage spikes and overloading, is usually assumed to be similar to that of a PV array.

Transport and installation costs

The costs of transport and installation are particularly high in remote and mountainous areas. However, organisations, which work in such areas, are aware of these costs, but they are attracted by the modular nature of PV generators, which can be transported easily.

Project management, design and engineering costs

These costs are falling as experience grows with the application of PV systems, and designs are becoming standardised. For example, "PV lighting kits" are now available for rural electrification applications, and PV powered water pumps are sold as packages.

Overall systems cost

Typical system costs in Dutch, German, and Austrian rooftop programmes were reported to be around 13 €/Wp. Interesting in this case is the opportunity to replace conventional building materials by PV modules. Saving costs of these components is not taken into account in these prices. The relative contributions of different PV system components for 1 kW_p rooftop system are as follows:

- module 53%
- inverter 22%
- mounting 12%
- rest 13%.

For grid-connected PV power stations up to 500 kWp the costs range from 8 to 16 €/Wp. The high cost is a consequence of a very limited experience with PV power stations. The cost of stand-alone systems depends strongly on their configuration. Generally, the PV module costs average around 30% of the system cost, as compared to about 50% for the grid-connected systems.

9.7.2 PV electricity cost

A simple estimate of the cost of electricity produced by a PV system may be determined from:

- installed system price [€],
- total operating and maintenance (O&M) costs over the system lifetime [€] (often negligible apart from battery replacement costs),
- installed system nominal power output [Wp]
- annual yield [kWh/(year × kW_p)]
- payback period [years] (dependent on the rate of return and the predicted lifetime of the system).

The required payback period will depend on the rate of return, which is expected by the investor, and the predicted lifetime of the system. When comparing the cost of electricity generated by PV systems with that from other sources, it is common to assume lifetimes of 20-30 years for all PV system components except for the batteries, which typically have lifetimes of only 5-7 years.

The cost of electricity unit [€/kWh] is calculated

Electricity cost = Cost (System + O&M)**/(Yield × Installed power × Payback period)**

EXAMPLE: Typical PV system costs in a rooftop application are 13€/W_p.= 13000€/kW_p. This means the system and O&M costs per installed power. Typical annual yield of multi-crystalline silicon modules in The Netherlands is 750kWh/(year× kW_p). The payback time is expected to be 20 years.
The electricity cost is 13000€/kW_p / (750kWh/(year×kW_p) × 20 years) = 0.87€/kWh.

The energy costs of stand-alone systems depend strongly on the application. Experience learns that when only a small amount of electricity is needed, then PV systems can be cost competitive compared to grid extensions for distances of less than one kilometre in many parts of Europe. This type of PV systems is particularly attractive in remote mountainous terrain, where grid extensions are very expensive. In circumstances where grid connection costs are particularly high (e. g., where power lines must cross a road or railway line), or where the load is likely to be moved (e. g., lights for urban bus shelters) then small PV systems may be the most cost effective option even if the load is located no more than a few 100 meters from the grid. Sometimes the choice of power supplies is severely limited, e. g. in protected regions, such as national parks, the installation of grid extensions is often prohibited for environmental reasons.

The actual electricity cost for the rooftop systems is in the order of 0.35 - 0.9 €/kWh for Western Europe and 0.25 - 0.60 €/kWh for southern Europe. These kWh prices should be compared with customer grid tariffs, which are in the range of 0.15 - 0.19 €/kWh. It is clear that PV electricity cannot compete yet with electricity from the grid. Nevertheless, in several applications PV electricity is already economically attractive.

9.8 PV systems installation and operation

9.8.1 Installation

In most cases PV modules contain sheets of glass, which protect the solar cells, and therefore they should be handled with care. Orientation of the panel has to be accurate to within 20° of the right direction. The support structure determines a tilt-angle of a module. In roof-mounted systems, adjustment of the orientation and tilt angle is usually quite difficult.

Lead-acid batteries that have vents should be supplied dry-charged so that they can be filled with acid at the site of installation. After the battery is filled, acid should never be emptied out. When installing batteries, special care should be taken to connect them with the right polarity and in the right configuration (series-parallel).

For systems connected to the mains, there is only one voltage rating for the whole installation. However, the low DC voltage in PV systems could have several different voltages at the same time. The correct polarity should be maintained in all connections. Using a red wire for all positive connections and a black one for negative (ground) is advisable.

9.8.2 Operation

PV systems can generate high voltages. Safety is therefore very important in order to avoid accidents and damage of expensive components and equipment. For safety reasons, solar arrays are normally earthed, either by placing a matrix of metal in the ground under the array, or by using conventional earth rods.

It is normally not necessary to protect solar array from direct lightning strikes, provided that their mounting structure is well earthed. However, inverters or other electronics controls connected to the array should be protected. Blocking diodes are installed in solar arrays to prevent reverse current flows into the modules, which may damage the modules and cause energy losses. By-pass diodes are incorporated into modules to prevent damage of arrays when some cells or modules become shaded.

PV system requires regular maintenance to ensure proper operation and the full life of components. Some of the most important maintenance tasks are:

- cleaning of modules front,
- removal obstacles, tree branches, etc. which cause shadowing of the modules,
- battery charge check, if it remains very low the system should be re-designed,
- topping of battery electrolyte.

The rest of components of PV systems require little or no maintenance.

References

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[9.3] www.firstsolar.com/index.html