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PV System Design

In Chapter 15, we thoroughly discussed PV modules . Further, in Chapter 18 we discussed how to estimate the irradiance on a PV module in dependence of the position of the Sun and partial absorption and diffusion in the atmosphere. Finally, we introduced all the other components of PV Systems in Chapter 19.

In this chapter, we will combine the knowledge gained so far in order to design complete PV systems. We can design PV systems at different levels of complexity. For a first approximation, the performances of the PV modules and the the other components (like the inverter) at standard test conditions (STC) and the number of *Equivalent Sun Hours* (ESH) at the location of the PV system are sufficient. The concept of STC (AM1.5 illumination with a total irradiance of 1000 W/m^2 and a module temperature of 25°C) was already introduced in Chapter 9; the notion of ESH will be discussed below. In a more detailed approach, performance changes of the different components due to changing irradiance and weather conditions are taken into account. Since these performance changes can be quite high, they can alter the optimal system design considerably.

There are two main paradigms for designing PV systems. First, the system can be designed such that the generated energy and the loads, *i.e.* the consumed energy, match. Hence, an *energy balance* must be done Secondly, the design of a PV system can be based on economics. We must distinguish between *grid-connected* and *stand-alone* systems. As we will see, grid-connected systems have very different demands than stand-alone systems.

This chapter is organised as follows: First, as an example, we will discuss a design of a simple stand-alone system in Section 20.1. After that we will take a more detailed look on *load profiles* in Section 20.2. In Section 20.3 and on how weather and irradiance conditions affect the performance of PV modules and BOS components, mainly inverters. Finally, in Sections 20.4 and 20.5 we learn how to design grid-connected and stand-alone systems, respectively.

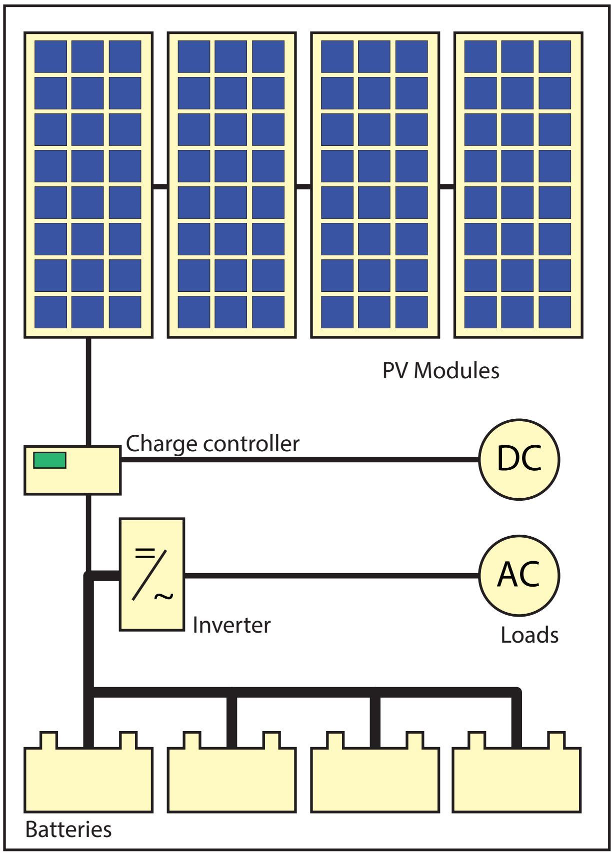

Figure 20.1: Illustrating a simple off-grid PV system with AC and DC loads (see also Fig. 17.2).

20.1 A simple approach for designing stand-alone systems

In this section, we will design a simple stand-alone system, as depicted in Fig. 20.1. The design presented here is based on very simple assumptions and does not take any weather-dependent performance changes into account. Nonetheless, we will see the major steps that are necessary for designing a system. Such a simple design can be performed in a six step plan:

1. Determine the total load current[1] and operational time
2. Add system losses
3. Determine the solar irradiation in daily equivalent sun hours (ESH)
4. Determine total solar array current requirements
5. Determine optimum module arrangement for solar array
6. Determine battery size for recommended reserve time
7. Choose a suitable charge controller

1. Determine the total load current and operational time

Before we can determine the current requirements of loads of our PV system, we have to decide on the nominal operational voltage of the PV system. Usual nominal voltages are 12 V, 24 V or 48 V. 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: $15\,\mathrm{W} \cdot 6\,\mathrm{h} = 90\,\mathrm{Wh}$

Device B: $20\,\mathrm{W} \cdot 3\,\mathrm{h} = 60\,\mathrm{Wh}$
Total: $90\,\mathrm{Wh} + 60\,\mathrm{Wh} = 150\,\mathrm{Wh}$

$150\,\mathrm{Wh}/12\,\mathrm{V} = 12.5\,\mathrm{Ah}$

In case of AC loads the energy use has to be expressed as a 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 the inverter, which

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[1] If in a very simple PV system a charge controller without MPPT is used, we need to determine the current; not the power.

can be assumed to be 95% for a good inverter. 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 40 W*, runs 2 hours per day and the TV set with rated power* 70 W *is 3 hours per day in operation. The daily energy requirements of the devices expressed in DC Ah are calculated as follows:*

Device C: $40\,\mathrm{W} \cdot 2\,\mathrm{h} = \quad 80\,\mathrm{Wh}$

Device D: $70\,\mathrm{W} \cdot 3\,\mathrm{h} = 210\,\mathrm{Wh}$

Total: $80\,\mathrm{Wh} + 210\,\mathrm{Wh} = 290\,\mathrm{Wh}$

DC requirement: $290\,\mathrm{Wh}/0.95 = 305\,\mathrm{Wh}$

$305\,\mathrm{Wh}/12\,\mathrm{V} = 25.5\,\mathrm{Ah}$

2. Add system losses

Some components of the PV system, such as charge regulators and batteries require 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 with 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:*

$(12.5\,\mathrm{Ah} + 25.5\,\mathrm{Ah}) \cdot 1.2 = 45.6\,\mathrm{Ah}$

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

How much energy a PV module delivers depends on several factors, such as local weather conditions, seasonal changes, and installation of modules. As we already discussed in Chapter 18, PV modules should be installed under the optimal *tilt angle* in order to achieve best year-round performance. However, if the PV system is only used during a specific period, the tilt angle needs to be optimised for that specific period. In fact the power output during winter is much less than the annual average and in the summer months the power output will be above the average. Figure 20.2 shows the the average global horizontal irradiance of the World in $\mathrm{kWh/m^2/day}$, which is equivalent to the daily equivalent sun hours (ESH). We mainly see that the insolation decreases with latitude. However, also other variations are visible because of regional climates.

As we already discussed in Chapter 5, solar cells are usually characterised with the AM1.5 spectrum, which is normalised such that it has a total irradiance of $1000\ \mathrm{W/m^2}$. Hence 1 equivalent sun means a solar irradiance of $1000\ \mathrm{W/m^2}$. When solar irradiation

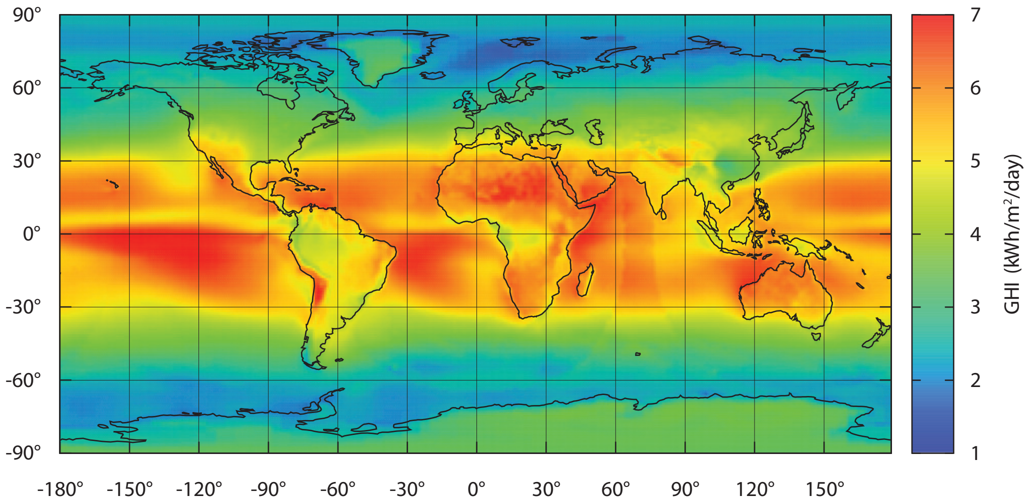

Figure 20.2: The average global horizontal irradiance of the World given in kWh/m^2/day, which is equivalent to the daily equivalent sun hours (ESH). (Data taken from [157]).

data are available for a particular location, the equivalent sun hours can be determined. Figure 20.3 shows the annual irradiation for the Netherlands at an optimally tilted plane with a tilt of 36°. For example, in Delft (Netherlands) the average annual solar irradiation at a horizontal plane is 999 kWh/m^2 [158]. For optimally tilted modules the annual solar irradiation is a bit higher with 1146 kWh/m^2 [158]. With the value from the AM1.5 spectrum, we hence find 999 equivalent sun hours at a horizontal plane and 1146 equivalent sun hours at optimal tilt. When we take the length of the year (365.25 days) into account, we calculate the *average number of daily sun hours* to be 2.7 h and 3.1 h for horizontal and optimal tilt, respectively. For the rest of the discussion, we will use a value of 3 h of sun per day.

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 45.6 Ah*. The daily ESH for the Netherlands is about 3 hours. The required total current generated by the solar array is* 45.6 Ah / 3 h = 15.2 A*.*

Figure 20.3: Yearly insolation at optimal tilt (36°) in the Netherlands in kWh/m^2 (Source: PVGIS [158–160]).

5. Determine optimum module arrangement for solar array

Usually, PV manufacturers produce modules in a whole series of different output powers. In the optimum arrangement of modules the required total solar array current (as determined in step 4) is obtained with the minimum number of modules. Modules can be either connected in series or 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.

The output voltage of PV modules should fit to the battery voltage for optimal operation. If the modules are based on crystalline silicon technology, they usually contain 36 or 72 cells connected in series for systems based on 12 V or 24 V, respectively. The open-circuit voltage (V_{oc}) of the cells used for the module is typically 0.6 V, therefore, the open-circuit voltage of the module is 21.6 V or 43.2 V, respectively. As we have seen in Section 19.1, the optimal operation voltage of a solar cell is at around 70%-80% of the V_{oc}, hence 16.2 V or 32.4 V for modules with 36 and 72 cells, respectively. These voltages are very well suited for charging batteries with a nominal voltage of 12 V or 24 V, respectively.

The required 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 maximum power. The number of modules in series is determined by dividing the nominal PV system voltage with the voltage at maximum power. Both this voltage and current are given in the datasheet. 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 15.2 A. *We have* Kyocera KD140 *modules with a nominal power of 140 W available, which consist of 36 cells connected in series. At the maximum power point, these modules have a voltage of* $V_{\text{mpp}} = 17.7$ *V and a current of* $I_{\text{mpp}} = 7.9$ *A. The number of modules in parallel is* 15.2 A / 7.9 A $= 1.9 < 2$ *modules. The nominal voltage of the PV system is* 12 V. *The required number of modules in series thus is* 12 V / 17.7 V $= 0.67 < 1$ *module. Therefore, the total number of modules in the array is* $2 \times 1 = 2$ *modules.*

6. Determine battery size for recommended reserve time

Batteries are a major component of 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. Because of this reserve, the PV system is not dependent on energy generated by PV modules for a certain period of time, called *days of autonomy*. The required days of autonomy depend on the type of the loads. For critical loads such as components for telecommunications systems the autonomy can be 10 days and more, for residential use it is usually 5 days or less. This depends also on the weather of the PV system location.

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

Table 20.1: Worksheet for designing a simple off-grid PV system based on rough assumptions.

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	=	

expressed in Ah) by the number of days of recommended reserve time. In order to prolong the life of lead-acid batteries, which are most commonly used, it is recommended to discharge the battery maximally by 80%. If this value is decreased, also the battery lifetime is prolonged, but the system becomes more expensive. In the end, a cost evaluation has to be made in order to choose the optimal configuration.

Example

The total DC requirements of loads plus the system losses are $45.6\,\mathrm{Ah}$*. The recommended reserve time capacity for the installation side in the Netherlands is 5 days. Battery capacity required by the system is* $45.6\,\mathrm{Ah}\cdot 5 = 228\,\mathrm{Ah}$*. The minimal battery capacity for a safe operation therefore is* $228\,\mathrm{Ah}/0.8 = 285\,\mathrm{Ah}$.

Designing a simple PV system as described in this section can be carried out using a worksheet as in Table 20.1, where the PV system design rules are summarised.

Remark

In the example discussed above we sized the PV array according by using the daily equivalent sun hours. This approach will work very well in regions that have small changes in irradiation throughout the year, *i.e.* regions that are in the proximity of the Equator. If we move further away from the equator, the differences between the length of the day in summer and winter become larger. As a consequence, also the difference between the daily sun hours in winter and summer becomes larger. To account for this effect, the system can be

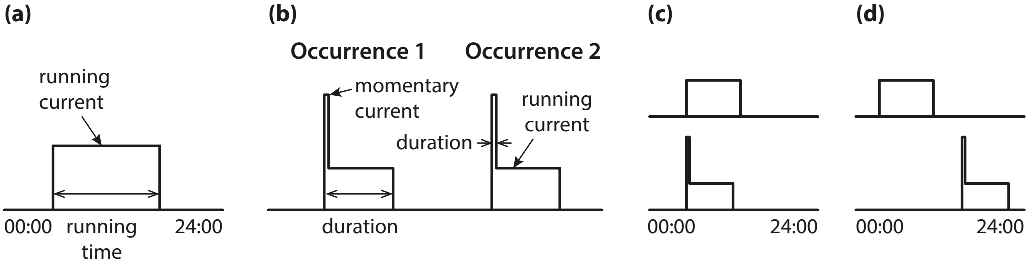

Figure 20.4: Illustrating different load profiles.

sized such that it delivers sufficiently energy in the *worst* month, *i.e.* December or January on the Northern hemisphere. However, this may make the systems very large and significantly oversized during the summer months, which makes the system less economical. In general we can say that designing off-grid systems becomes more difficult the further we are away from the Equator.

20.2 Load profiles

Now we take a look at the load profile. Figure 20.4 illustrates different shapes that loads can have. (a) A simple load draws a constant amount of power for a certain time. (b) However, the consumed power does not need to be constant but can also show peaks that correspond to switching electrical appliances on or off. A household of course has several different loads that (c) can be switched on at the same time (coincident) or (d) at different times (non-coincident).

Analysing load profiles can be performed with increasing complexity — and hence accuracy. The simplest method is to determine the loads on a 24-hour basis. To do this, an arbitrary day can be taken and the electricity consumption can be monitored. However, several loads do not fit in such a scheme. Several examples for this already were treated in Section 20.1. For example, washing machines and dishwashers do not fit in a 24-hour scheme because typically they are only used several times in a week. Additionally, several loads are seasonal in nature, for example, air conditioning or heating, in case this is performed with a heat pump. Therefore it is advisable to look at load profiles for a whole year.

The total energy consumed in a year is given by

$$E_L^Y = \int_{\text{year}} P_L(t)\,\mathrm{d}t, \tag{20.1}$$

where $P_L(t)$ is the power of the load at a time t. E_L^Y is expressed in kWh/year.

20.3 Meteorological effects

Standard Test Conditions (STC) of Photovoltaic (PV) modules are generally not representative of the real working conditions of a solar module. For example, high levels of irradi-