CASE STUDIES

Photovoltaics electrification in off-grid areas

Daniel Masa Bote

PHOTO: Practical Action.

GDEE GLOBAL DIMENSION IN ENGINEERING EDUCATION

CASE STUDIES **Photovoltaics electrification in off-grid areas**

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PHOTOVOLTAICS ELECTRIFICATION IN OFF-GRID AREAS

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1. INTRODUCTION

Energy is one of the most important available resources and, in any of its forms – mechanical, thermal, electricity– it is crucial for most human activities. However, access to energy is not universal. In 2014, according to the International Energy Agency[1], 1,300 million people, which is 18% of global population, lacked access to electricity and 2,700 million people, 40% of global population, relied on the combustion of biomass for cooking.

In recent years, the use of renewable power worldwide has been increasing steadily. The share of electricity generated by non-hydroelectric renewable energy sources has increased from 1.7% in 2000 to 5.0% in 2012. Investment in renewable energy has been motivated by the increasing awareness of global warming caused by greenhouse emissions, the inevitable exhaustion of traditional energy sources (fossil fuels) in the future and the need for countries to assure energy self-sufficiency. The growth in electricity generation from renewable sources is almost exclusive to developed countries. This does not imply, however, that renewable energy sources are exclusive to developed countries or only suited to their needs. In fact, some of the main features of renewable energies are often overlooked and only those related to the factors that have motivated the aforementioned increase in use are considered. These neglected features are those that make renewable energies an appropriate energy source for rural areas of developing regions.

on Renewable energy generation via photovoltaics (PV), in particular, offers major advantages for rural electrification in developing regions: modularity, autonomy, low maintenance costs and absence of pollution. Modularity means that the efficiency of a PV system is not penalized by small system sizes. For example, a small solar home system of 50 watts performs similarly to a microgrid of several kilowatts. PV systems rely on sunlight to generate electricity, a renewable resource widely available and often abundant in the underdeveloped regions of the world. It must be noted that other renewable resources for the generation of electricity, like wind or flowing water, are less widely applicable as they depend more on site-specific factors than PV systems. Maintenance costs of PVs are usually low due to the high reliability of components, the absence of moving parts that may wear out and the fact that neither fuel nor supplies are needed on a regular basis. For example, PV crystalline modules, the more widely extended type of modules, are guaranteed by manufacturers to lose only as much as 10% of their nominal power after 20 years of operation and remain fully operational even after this time period. As a clean technology, PVs also have minimal impact on the environment and is a safer and healthier option compared to many traditional energy sources, such as burning kerosene for indoor

[1] http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/#d.en.8609

lighting. Nonetheless, it must also be noted that the major drawback of PVs, in comparison to other technologies, may be their higher initial investment cost.

The above advantages of PV electricity make this technology one of the most suitable electricity sources for rural areas of developing regions, unrivalled by traditional electricity sources and providing electricity to remote areas not reached by the traditional electric grid. Therefore, PV systems are a useful tool that contributes to human development and the well-being of inhabitants in such areas. Though it is difficult to account for the number of PV systems in use in developing countries, it is estimated that are currently more than three million of solar home systems.

This case study is aimed to provide knowledge on PV systems used in rural electrification in developing regions.

1.1. Disciplines covered

This case study is suitable for courses on electrical engineering and energy systems, particularly those focused on renewable energies. Students will learn how to design a PV system and to estimate its output. Students will also have to extract relevant information from datasheets, manufacturers' catalogues and irradiation databases.

This case study is intended to be included in courses that cover energy in general or renewable energy generation as main topics, and complement course syllabuses by providing a broader perspective in these areas. This case study is self-contained and students are not required to possess extensive previous knowledge of energy generation or electrical systems. In this regard, the case study includes explanation of all theoretical aspects involved. These explanations can be omitted if the students are familiar with the topics studied. However, some basic understanding of physical and electrical principles (like difference between energy and power, or between AC and DC) is required. Therefore, this case study can also be included in any engineering or technical course dealing with human development.

1.2. Learning outcomes

Students are expected to achieve the following learning outcomes:

- Know the basic typologies of PV systems available for rural electrification and criteria for choosing the most appropriate depending on the intended application.

- Be able to develop a basic model to estimate the output of PV systems and required size according to a given expected electricity demand.

1.3. Activities

This case study is divided in two activities than can be modified and adapted at the discretion of the lecturer:

- Activity 1: **introduction to theoretical aspects** that students will need for this case study. This phase can be omitted if the case study is included in a course dealing with renewable energies and the topic has been previously addressed in class. This is a class activity, with an estimated duration of two hours.
- Activity 2: based upon the knowledge acquired in the previous activity, the students will have to **design a solar home system for a rural developing area**. The students will have to calculate the energy demand associated to the given loads and the size of a PV system able to provide enough electricity to meet this demand. The size of the system will be dependent on the irradiation of the solar home system location. This is a homework activity and its estimated duration is four hours.

2. Class activity

2.1. Stand-alone PV systems

This activity provides the necessary theoretical background that will be necessary to complete the other activities. This activity can be skipped or shortened if the students already possess knowledge of PV systems. The contents of this activity include a brief introduction to PV systems, methods for sizing a stand-alone system, estimating the irradiation received by a PV generator, and estimating the energy generated by a PV system.

2.1.1. Introduction to PV systems

PV systems can be divided in two main categories:

- **Grid-connected systems**. These systems are connected to electricity distribution grids. Their design is usually optimized to maximize energy production. Grid-connected PV systems are subdivided into utility-scale solar power stations and building-integrated PV systems, usually referred as BIPV. Solar power stations are large in size, by PV system standards, with power ranging from hundreds of kilowatts to hundreds of megawatts. They are mounted on the ground and typically connect to transmission lines. All electricity produced by these systems is fed into the grid. Building-integrated systems are smaller in size, from several kilowatts to a few megawatts, and they are mounted on or nearby buildings. These systems are connected to distribution lines and the electricity produced can be fed into the grid or consumed locally at the building itself. Sometimes, their design does not optimize energy production, but rather satisfies other purposes such as architectural design or aesthetics.

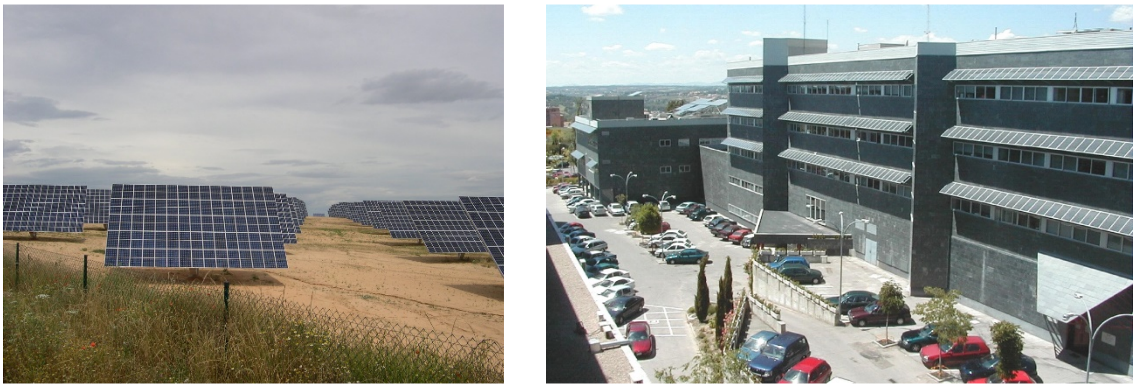

Figure 1 *Grid connected systems: large PV plant at Milagro, Spain (left image) and building integrated system in the premises of the Technical University of Madrid (right image).*

- **Stand-alone systems**. These systems are not connected to electrical grids. Instead, they are used to power electric loads in remote areas that are not connected to electric grids. The advantages mentioned in the introduction – modularity, autonomy, low maintenance costs and absence of pollution – make stand-alone systems an ideal solution to provide electricity in remote areas. Instead of maximizing yearly electricity generation, stand-alone systems are designed to provide electricity to a set amount of loads all year round. These systems usually include a battery, so surplus electricity is stored and available when there is no solar radiation (during the night), or insufficient solar radiation (days with fully overcast sky).

Figure 2 *Stand-alone system: PV generator (left) and battery bank (right). This PV system belongs to a mini-grid located in San Lorenzo, Ecuador.*

This case study focuses on stand-alone systems, as they are the PV application that can best provide electricity to rural areas of developing regions. The main components of a stand-alone system are: the PV generator, which is made from the connection of PV modules and converts solar irradiation into DC current; the energy storage (usually batteries), which store any surplus electricity produced by the modules for later use; and the power conditioning units, which are electronic devices that adapt the electricity produced by the PV modules to the requirements of the loads and available storage. The components of a stand-alone system can be arranged in different configurations. The two most common configurations are the following:

- **DC bus configuration**. The main components of the system are connected in DC. The charge regulator, or DC/DC converter, may possess two different outputs for the loads and the battery, or only one output to which both the loads and battery are wired. In the last case, the charge regulator usually operates a relay in the battery line to prevent excessive discharge or overcharge that may damage the battery. This configuration is typical of small systems. If AC loads are present in the system, they are powered by a DC/AC inverter connected to the DC bus.

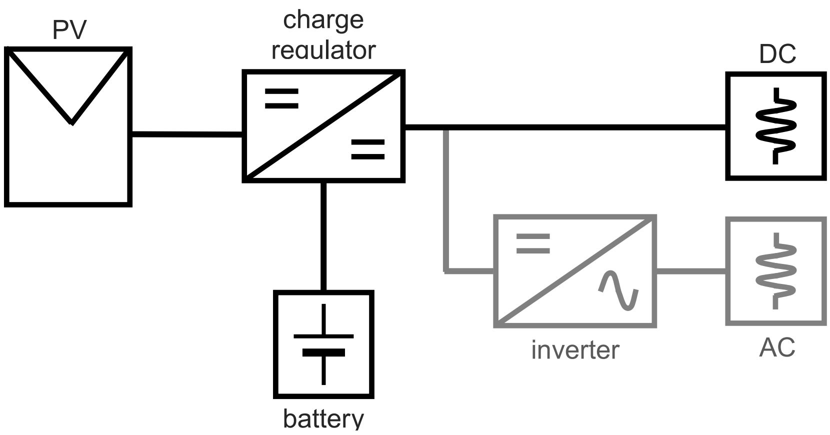

Figure 3 *Stand-alone system with DC bus configuration.*

- **AC bus configuration**. The main components of the system are connected to an AC bus. The use of an AC bus allows the use of AC loads and inverters for grid-connected systems, which are usually cheaper and offer more variety than DC equipment. The configuration also simplifies the connection of other energy sources like wind turbines, diesel generators, or even the electrical grid if the latter is extended to the location of the stand-alone system. These additional energy sources can be connected to the AC bus. Systems based on an AC bus configuration are usually large. It is possible to power DC loads through a DC/DC converter connected to the battery line.

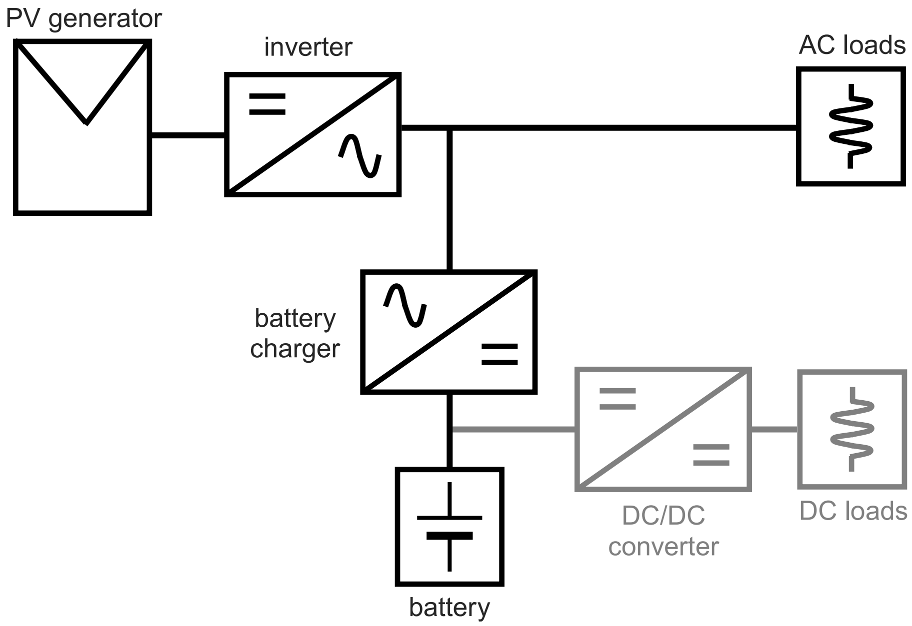

Figure 4 *Stand-alone system with AC bus configuration.*

Variations of the above configurations and even a mix configurations (AC/DC bus) are possible.

2.1.2. PV GENERATOR

The PV generator is the core of any PV system. The generator converts light into electric energy, the so called photovoltaic effect. In small stand-alone systems, which generate between 5 and 50 watts, the PV generator is composed of only one PV module. In larger systems that generate greater power, the PV generator is formed by the electrical connection of several PV modules. The PV module is, therefore, the minimal unit capable of generating electric energy from sunlight. Figure 4 shows the current-voltage characteristic or I-V curve of a PV module. When the PV module is shorted it delivers its maximum current, this is called short-circuit current (ISC). If the PV module is left in open-circuit, it provides its maximum voltage, or open-circuit voltage (VOC). Although the PV module may operate at any point of the current-voltage characteristic, there is only one point that maximizes energy generation. This point is called the maximum power point (MPP) and is characterized by its current IM and voltage VM.

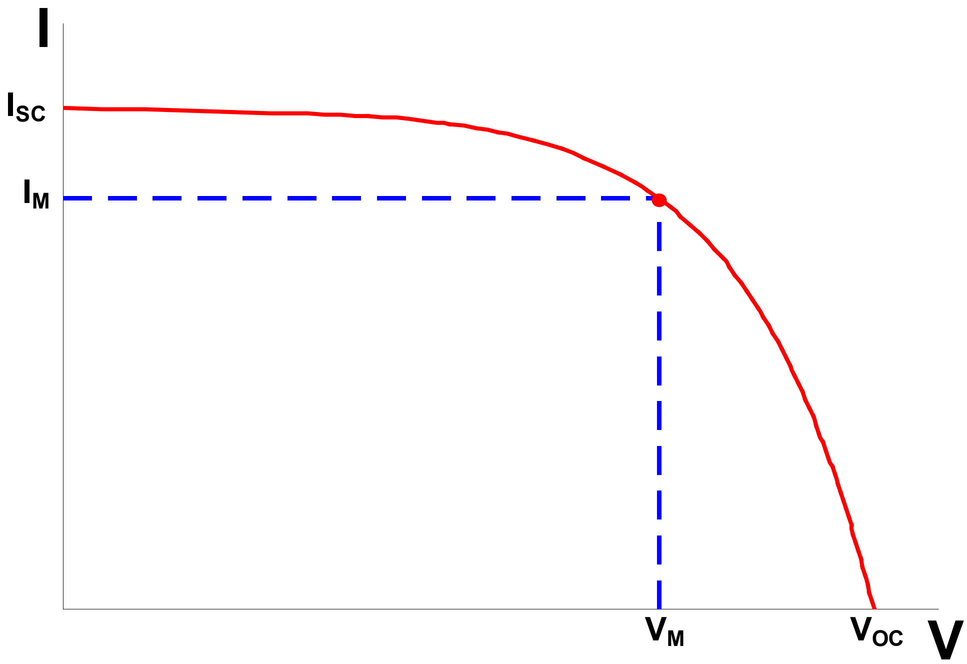

Figure 5 *Current-Voltage (I-V) curve of a PV module.*

The current-voltage characteristic of a PV module is not static, it changes with the operating environment of the module. As the solar radiation increases, the current delivered by the PV module increases. On the contrary, as the temperature of the module increases, the voltage decreases. These effects are shown in Figure 5.

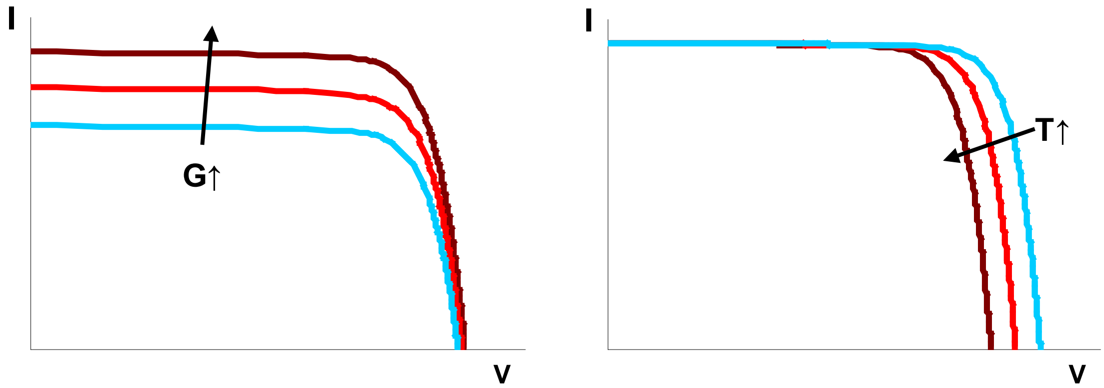

Figure 6 *Effect of the environmental conditions on the current-voltage characteristic of a PV module: current increases with solar irradiation (left image) and voltage decreases with temperature (right image).*

Since the current-voltage characteristic of a PV module depends on both irradiation and temperature, the maximum power that it can deliver varies accordingly. As a result, a uniform set of conditions has been established so that modules can be rated and compared to each other. These conditions are called the Standard Test Conditions (STC): irradiation of 1000 W/m^2 and module temperature of 25 ºC (among other characteristics). Hence, the nominal power of a PV module is the maximum power point of its current-voltage characteristic at STC; that is, the maximum power delivered by the module at 1000 W/m^2 and 25 ºC. It is common practice to express the nominal power of a PV module in watts-peak (W_P), which is the same power unit as watts but implies that power was measured at STC.

If the PV generator is made up of several modules, these are connected in series, parallel, or both, inside the generator. The nominal power of the generator is the sum of the nominal powers of the individual modules, the voltage of the generator is the sum of the voltages of the modules that are connected in series and the current is the sum of the currents of the modules that are connected in parallel.

$$P_{gen} = N_s N_p P_{\text{mod}}$$
$$V_{gen} = N_s V_{\text{mod}}$$
$$I_{gen} = N_p I_{\text{mod}}$$

where P_{gen} is the nominal power of the generator, N_s is the number of modules in series, N_p is the number of modules in parallel, P_{mod} is the power of one module, V_{gen} is the voltage of the generator, V_{mod} is the voltage of one module, I_{gen} is the current of the generator and I_{mod} is the current of one module.

2.1.3. Power conditioning

The role of the power conditioning elements in a PV system is to adjust the electric energy delivered by the power generator (whose output is always in DC) to voltage and current levels suitable for the loads and batteries. A range of different power conditioning units can be found in stand-alone PV systems, according to its needs and configuration (DC or AC bus).

- **Charge regulator**. Charge regulators are used in systems with a DC bus configuration. This element is a DC/DC converter that provides electricity to DC loads and regulates the charge or discharge of the battery (hence its name). The main function of the charge regulator is to preserve the battery by avoiding overcharge or deep discharge situations. Charge regulators for smaller systems do not significantly change the voltage output of the PV generator and, therefore, the PV generator, loads and battery operate at the same voltage (12, 24 or 48 V). In larger systems, the voltage of the PV generator is usually higher than the voltage of DC bus and the charge regulator reduces this voltage to a level suitable for the loads and battery.

- **Solar inverter**. Solar inverters are found in systems with either DC or AC bus configuration. An inverter converts DC current into AC current, an operation called inversion. In a system with a DC bus configuration, the inverter is connected to the output of the charge regulator. If an AC bus is used, the inverter is connected directly to the output of the PV generator. In a DC bus configuration, the DC levels accepted by the inverter at its input are larger than in an AC configuration.
- **Bidirectional inverter**. A bidirectional inverter or battery inverter is used in stand-alone systems with AC bus configuration. This element charges and discharges the battery from, or to, the AC bus when needed. Therefore, this element operates bi-directionally, converting from AC to DC and vice versa. The battery inverter also preservers the life of the battery by avoiding overcharging or deep discharging.

The power conditioning elements for a stand-alone PV system must be chosen according to the following criteria:

- **Configuration of the system**. A DC bus only requires a charge regulator and an inverter if AC loads are to be powered. Contrastingly, an AC bus always requires both solar inverters and a battery inverter.
- **Maximum power of the system**. The maximum operating power of the power conditioning element must be appropriate to the nominal power of the PV generator, as well as the maximum power that is expected to be demanded by the loads. It is not convenient to oversize these components because they work more efficiently when the power delivered by them is closer to its maximum.
- **Voltage and current levels**. For both voltage and current, the input range that is accepted by charge regulators or solar inverters must match the expected output range of the PV generator. The fact that the voltage and current of a PV generator depend on operating conditions must be taken into account. The voltage output of a charge regulator must match the nominal voltage of the battery and the DC loads. The output of a solar inverter, as well as the AC connection of the battery inverter, must match the voltage and phase of the AC bus.

2.1.4. Energy storage: batteries

A PV system only generates electricity during daytime and this electricity depends on the irradiation level. In order to have access to electricity at night (for instance, for lighting purposes) or when irradiation levels are low, stand-alone PV systems include energy storage to store for later use any surplus electricity that is generated by the system. The energy storage may be replaced, or its size reduced by the used of secondary generators like wind or diesel generators. Hybrid systems with two or more generators are outside the scope of this case study.

The most common form of storage found in stand-alone systems is electrochemical accumulation or batteries. Of the different types of batteries that are available, lead-acid batteries are used in almost 100% of stand-alone systems. In solar pump applications, where the load of the system is a water pump, energy is usually stored as potential energy by means of filling an elevated water tank.

There are several different types of lead-acid batteries:

- **Automotive batteries**. These batteries (also called Starting, Lightning and Ignition (SLI) batteries) are designed for use in vehicles. Their main advantages are low cost, wide availabilty, possibility of local production and easy ability to recycle. Their main drawback is their shortened lifetime, as they are not optimized for use in stand-alone systems.
- **Deep cycle batteries**. These batteries are designed to sustain deeper discharges than SLI batteries, and are therefore more suitable for stand-alone systems. The main advantage of deep cycle batteries is their longer lifetime. Their primary drawbacks are high cost and low availability in developing countries. Deep cycle batteries are divided into Flooded Acid Batteries (FLA) and Valve Regulated Lead Acid batteries (VRLA), or sealed batteries. FLA batteries are more reliable than VRLA batteries, but they may require maintenance once or twice a year. VRLA batteries require less maintenance but this is at the cost of reduced reliability.

The main parameter of a battery, besides its nominal voltage, is its capacity. The capacity of a battery is the amount of energy that can be stored in it and retrieved at a later time. The energy stored in a battery is usually expressed as a percentage of its capacity , or the State Of Charge (SOC), and ranges from 100% to 0%. However, a state of charge of zero is never achieved in practice because low levels of charge damage the battery and reduce its lifetime. In general, the SOC may never be below 50% for SLI batteries and 20% for deep cycle batteries. However, higher values are recommended in both cases to extend lifetime (60% and 45% respectively). With this in mind, when sizing the battery of stand-alone system, the minimum SOC must be considered. For example, if a storage capacity of 150 Wh is estimated and a SLI battery is chosen, the nominal capacity of the battery must be 300 Wh to assure that a SOC lower than 50% is not reached.

2.2. Design of stand-alone PV systems

The design of a stand-alone system must assure that the loads powered by the system receive enough electricity throughout the year. To fulfil this condition, the system is designed for the month of the year with lowest levels of solar irradiation. Taking into account the electricity that is demanded by the loads and the average daily irradiation in the month with the lowest average solar irradiation, the size of the PV generator is estimated so that the electricity generated exceeds the demand of the loads. This process is divided in the following steps:

- Determining the optimal orientation and tilt angles of the PV generator.
- Estimating the energy generated by the PV system.
- Determining the size of the PV system.

2.2.1. Optimal orientation and tilt angles

The first step in determining the size of the PV generator is choosing the tilt and orientation angles. Tilt is the angle between the surface of the PV generator and the horizontal. It is represented by the Greek letter *β*. Orientation is the angle between the projection of a line that is perpendicular to the generator and the direction of South. It is represented by the letter *α*. It must be noted that the orientation angle is sometimes measured against North in systems located in the Southern Hemisphere. These angles are shown in Figure 4. In the figure, ns is the normal to the surface of the PV generator.

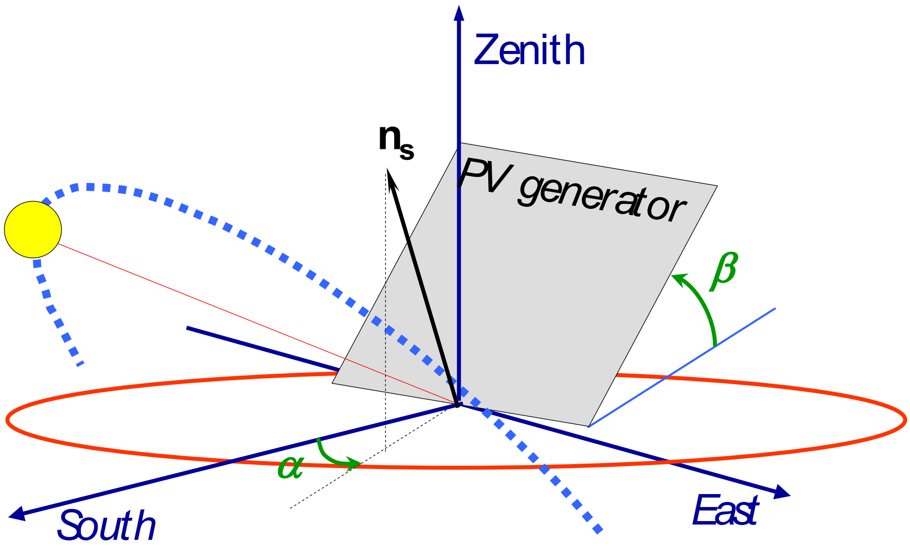

Figure 7 *Angles defining the surface of a PV generator.*

The solar irradiation captured by the PV generator is maximized when its surface its perpendicular to the solar rays. The optimal tilt angle is the complementary angle of the Sun's elevation at noon during the central day of the worst month (i.e., the month with the lowest irradiation). The optimal orientation is facing due South in the Northern Hemisphere and due North in the Southern Hemisphere.

The Sun's elevation at midday on any given day can be estimated by the following equation:

$$\sin \gamma_s = \sin \delta \sin \phi + \cos \delta \cos \phi$$

where γ_s is the Sun's elevation, δ is solar declination and ϕ is latitude.

Solar declination is the angle between Earth's equator and the ecliptic plane. It can be estimated by the following equation:

$$\delta(^{\circ}) = 23{,}45 \sin\left[\frac{360}{365}(d_n + 284)\right]$$

where d_n is the number of the middle day of the worst month in the year (1-365).

2.2.2. Energy generated by a PV system

The energy generated by a PV system is obtained by first estimating the maximum electricity that the system would generate according to the solar irradiation received by the PV generator. The different losses that are present in a PV system are subtracted from the maximum electricity. The following losses are present in a PV system:

- **Thermal losses (*L_{TH}*)**. These losses occur when the PV modules work at a temperature different to the temperature of Standard Test Conditions. It must be noted that module temperature, or cell temperature, is generally higher than ambient temperature and they are not interchangeable.
- **Shading losses (*L_{SH}*)**. These losses are due to shadows cast on the PV generator by nearby obstacles. Usual obstacles include houses, trees or poles.
- **Optical losses (*L_O*)**. These losses account the reflection of the sunlight on the surface of the PV generator. Dirtiness on the surface of the PV generator enhances optical losses.
- **System losses (*L_S*)**. These are the conversion losses of the power conditioning equipment present in the PV system: inverters, charge regulators, etc.
- **Electrical losses (*L_E*)**. Miscellaneous loss mechanisms are included in electrical losses like the dispersion of the actual values of the actual equipment used in the system from datasheet values and voltage drops in the wiring.

Therefore, a PV system output is estimated as follows:

$$E_{PV} = \frac{G_t(\alpha, \beta)}{G^*} P_{nG}(1 - L_{TH})(1 - L_{SH})(1 - L_O)(1 - L_s)(1 - L_E)$$

where E_{PV} is the electricity produced by the PV system, $G_t(\alpha,\beta)$ is the solar irradiation over the surface of the PV generator during the time interval *t*, G^* is the irradiance at STC and P_{nG} is the nominal peak power of the PV generator at STC.

The exact procedure to estimate the solar irradiation over an arbitrary surface at a given location for arbitrary values of α and β, as well as the different losses, is too complex and exceeds the purposes of this case study. The irradiation over the surface of the PV generator will be provided to the students in the activities. A simplified method to estimate losses is proposed. This method is based on the performance ratio, PR, a parameter that measures the overall efficiency of a PV system and comprises all loss mechanisms. Therefore, the energy produced by a system is:

$$E_{PV} = \frac{G_t(\alpha, \beta)}{G^*} P_{nG} PR(1 - L_{SH})$$

The performance ratio being:

$$PR = (1 - L_{TH})(1 - L_O)(1 - L_s)(1 - L_E)$$

To obtain the electricity generated in watts, irradiation (G_t) must be expressed in watts per square meter and the nominal power of the PV generator expressed in watts. The shading losses have been kept out of the performance ratio as it is common practice to account for them separately. An appropriate value for the performance ratio of a stand-alone system is in the range of 0.6 to 0.7 while for shading losses it is 0.2-0.25.

2.2.3. Sizing of the stand-alone PV system

In the design of a stand-alone PV system it is necessary to determine the nominal power of the PV generator and the capacity of the battery. The nominal power of the PV generator must assure that the electricity generated by the PV system during one day during the least sunny month is larger than the electricity needed by the loads:

$$E_{PV} > E_L$$

where E_L is the electricity demanded by the loads.

E_L is estimated from the power of each load and its time of operation:

$$E_L = \sum_i t_i P_i$$

where t_i is the time of operation of each load and P_i is its power.

Example: During the design phase of a stand-alone PV system the loads in Table 1 have been identified. It is known that the average daily irradiation during the worst (least sunny) month is 2780 Wh/m^2. We want to estimate the minimum size of the generator that assures that the loads receive enough electricity throughout the year. The PR of the system is 0.7 and the shading losses are 0.25.

Table 1 *Loads powered by the PV system.*

Type	Quantity -	Power W	Hours of operation h
Lamp	3	11	2
TV set	1	75	1

Solution: *First, we have to calculate the electricity demanded daily by the loads. We use the information in Table 1: the system must power three lamps of 11 watts during 2 hours daily and a TV set of 75 watts during 1 hour. The demanded electricity is:*

$$E_L = lamp\ demand + TV\ demand = 3 \times 2h \times 11W + 1 \times 1h \times 75W = 141Wh$$

The electricity generated by a PV system is:

$$E_{PV} = \frac{G_t(\alpha,\beta)}{G^*} P_{nG} PR(1 - L_{SH})$$

In the former equation, if we substitute E_{PV} *by* E_L *and* $G_t(\alpha,\beta)$ *by the average daily irradiation during the worst month, we can calculate the nominal power of the PV generator* P_{nG} *that assures that the loads will receive enough electricity all year round:*

$$P_{nG} = \frac{G^*}{G_t(\alpha,\beta)} \frac{E_L}{PR(1 - L_{SH})} = \frac{1000\,W/m^2}{2780\,Wh/m^2} \times \frac{141Wh}{0{,}70 \times (1 - 0{,}25)} = 96W \approx 100W$$

A PV generator of 96 watts or larger is enough provide sufficient electricity to the loads.

As stated before, the capacity of a battery should take into account not only the energetic needs that the stand-alone PV system must satisfy but also the minimum state of charge of the battery, which is dependent on the type of battery. The electricity that the battery must store can be given in watt-hours or in terms of system autonomy, i.e. the number of days that the battery, if fully charged, can power the loads.

Example: It has been decided to provide the system in the previous example with an autonomy of 1.5 days. Determine the minimum battery capacity of the battery that assures this autonomy. The manufacturer of the battery assures that the state of charge must be above 60% at all times to avoid excessive damage.

Solution: *An autonomy of 1.5 days implies that the battery must store enough electricity to power the loads during one and a half days. The daily demand of the system is 141 Wh. Therefore, the maximum electricity that will be extracted from the battery is:*

$$E = 1{,}5 \times 141Wh = 211{,}5Wh$$

Taking into account that the SOC of the battery cannot be lower than 60%, the capacity C of the battery is:

$$C = \frac{211{,}Wh}{1 - 0{,}6} = 528{,}75Wh \approx 530Wh$$

Note: The capacity of a battery is usually expressed in ampere-hours (Ah), which is a unit of electric charge. The capacity in watt-hours is obtained by multiplying the capacity in ampere-hours by the voltage of the battery (typically 12, 24 or 48 V).

3. Homework activity

One homework activity is proposed for the students in this case study. The objective of this task is for students to design a stand-alone PV system using the methods described in the preceding section. The students can work together on this activity in groups of two to four people, depending on class size.

The students will perform the following tasks during this activity:

- Estimate the electricity needs of the PV system from the information provided.
- Estimate the optimal tilt and orientation angles of the PV generator.

- Determine the minimum acceptable sizes of the PV generator and the battery.
- Adapt the design of the PV system to fulfil new requirements.

3.1. Proposed activity

The purpose of this activity is to design a stand-alone system. The system will be located in a remote village in the province of Cajamarca (Peru), where the main economic activity is sugarcane cultivation. The stand-alone system will provide electricity to the local sugarcane mil and a new tele-centre that will be built in the village to provide communication and office services. The loads of both applications are described in Table 2. The monthly averages of daily irradiation are given in Table 3.

1) Estimate how much electricity will be demanded daily by the tele-centre and the sugarcane mill.

2) Estimate the optimal inclination and orientation angles of the PV generator if the latitude of the village is 7.5º South.

3) Estimate the minimum size of the PV generator needed in order to provide enough electricity to supply all the loads. The performance ratio of the system is 0.7 and the shading losses are 0.2.

4) The PV system will be based on an AC bus configuration. In this configuration, a solar inverter and a battery inverter are necessary. Propose a suitable configuration for the PV generator (number of modules and electrical connection) using one of the modules from Table 4. Select an appropriate inverter from Table 5. A factor of 1.2 must be applied to the short-circuit current of the PV generator to account for an irradiation level higher than the irradiation at standard test conditions. Accordingly, a factor of 1.25 must be applied to the open-circuit voltage.

5) The stand-alone PV system will incorporate flooded lead-acid batteries as backup. Estimate the minimum capacity of the batteries needed to provide an autonomy of two days. It is recommended that the batteries do not discharge below a state of charge of 30%.

6) After one year of operation of the PV system the results are satisfactory. The villagers plan to extend the functionalities of the system in order to overcome the lack of available water during the dry season, from May to September. A water pump is purchased and connected to the PV system. Estimate how much water will be pumped daily during the month of August if all the surplus electricity not

consumed by the tele-centre and mill is allocated for this purpose. Consider that the pump and the pipes are lossless and that all surplus electricity is transformed into potential energy. The well has a depth of 20 metres and the water tank is placed 15 metres above ground.

Table 2 *Loads in the telecentre and mill that will be powered by the PV system.*

Load	Quantity -	Power W	Hours of operation h
Telecentre			
Telephone	2	10	24
Printer/fax	1	25	2
Computer (+screen)	2	175	8
Recharge stations	2	5	8
Sugarcane mill			
Mill	1	2000	2
Various machinery	1	1200	3

Table 3 *Monthly averages of daily irradiation in Cajamarca.*

Month	$G_{dm}(\alpha,\beta)$ Wh/m^2
January	4430
February	4360
March	4360
April	4350
May	4200
June	4250
July	4750
August	5070
September	5150
October	5030
November	4740
December	4590

Table 4 *PV modules parameters at Standard Test Conditions.*

Model	Nominal power W	V_{OC} V	I_{SC} A
ModA	50	22,5	3,0
ModB	75	17,8	4,2
ModC	150	22,6	8,7
ModD	240	37,1	8,7

Table 5 *Solar inverter parameters.*

Model	Nominal power W	Max DC voltage V	Max DC current A
Inv1	5000	500	24
Inv2	5000	750	15
Inv3	6000	600	15
Inv4	9000	800	27

3.2. Solution and Evaluation Criteria

1) The electricity demanded by every load is estimated by multiplying the power of the load by its operation time. The sum of all the individual demands gives the overall electricity demand.

Table 6 *Electricity demanded by the loads connected to the PV system.*

Load	Quantity -	Power W	Hours of operation h	Electricity Wh
Telecentre				
Telephone	2	10	24	480
Printer/fax	1	25	2	50
Computer (+screen)	2	175	8	2800

Recharge stations	2	5	8	80
Sugarcane mill				
Mill	1	2000	2	4000
Various machinery	1	1200	3	3600

The overall electricity demand is 11,010 Wh.

2) May is the worst month in terms of solar irradiation. Therefore, the students have to calculate the elevation of the Sun at midday in the 15th of May, which is the 135th day of the year:

$$\delta = 23{,}45 \sin\left[\frac{360}{365}(135+284)\right] = 18{,}8^{o}$$
$$\sin\gamma_s = \sin(18{,}8^{o})\sin(-7{,}5^{o}) + \cos(18{,}8^{o})\cos(7{,}5^{o}) = 0{,}8965$$
$$\gamma_s = \arcsin(0{,}8965) = 63{,}7^{o}$$

The optimal inclination for the PV generator is then:

$$\beta = 90^{o} - 63{,}7^{o} = 26{,}3^{o}$$

Since the PV system is in the southern hemisphere, the optimal orientation is due north.

3) $$P_{nG} = \frac{1000\,W/m^2}{4220\,Wh/m^2} \times \frac{11010Wh}{0{,}70\times(1-0{,}2)} = 4681W$$

4) The result of this section is not unique as different combinations of modules and inverter are possible. The quotient between the result of section 3 and the nominal power of each module provides the number of modules in the generator. The quotient must be rounded to the next highest integer. The number of modules for every model in Table 4 and suitable values for N_p and N_s are given in the following table. The nominal power of every possible generator is given. It must be noted that the exact result for ModA is 94 modules but it has been increased to 96 modules because a configuration of 24x4 modules is more suitable than a configuration of 47x2.

Table 7 *PV generator configuration for every model of PV module.*

Model	Number of modules -	Power W	N_P -	N_S -
ModA	96	4800	7	24
ModB	63	4725	3	21
ModC	32	4800	2	16
ModD	20	4800	2	10

In order to select and inverter, the maximum voltage $V_{max,g}$ and current $I_{max,g}$ of the PV generator have to be estimated first. The process is shown only for ModA modules:

$$V_{\max,G} = 1{,}25 \times V_{OC,\text{mod}} \times N_s = 1{,}25 \times 22{,}5 \times 24 = 675V$$
$$I_{\max,G} = 1{,}2 \times I_{SC,\text{mod}} \times N_p = 1{,}2 \times 3 \times 4 = 14{,}4A$$

If the students have chosen the ModA module, the Inv2 inverter suits the PV generator. Inv1 suits the other three models. Inv3 does not suit any of the configurations in Table 7. Although Inv4 satisfies the voltage and current requisites for all the options, is inappropriate due to its excessive nominal power.

5) Two days of autonomy require a storage system that can deliver 22020 Wh of electricity (11010Wh/day by 2 days). Since the minimum SOC is 30%, the capacity of the battery is:

$$C = \frac{22020Wh}{1-0{,}3} = 31457{,}1Wh \approx 31500Wh$$

6) In first place, the students have to estimate the daily generation of the PV system in August.

$$E_{PV} = \frac{G_t(\alpha,\beta)}{G^*} P_{nG} PR(1-L_{SH}) = \frac{5070\,Wh/m^2}{1000\,W/m^2} \times 4800W \times 0{,}7 \times 0{,}8 = 13628Wh$$

A value of 4800 W for the PV generator has been used here. However, different values such as 4,725 W or 4,681 W from section 3 are also acceptable.

The daily surplus electricity is then:

$$E_{left} = 13628Wh - 11010Wh = 2618Wh$$

All of this electricity is transformed into gravitational potential energy. The students must remember that this potential energy is calculated with the equation:

$$E = mgh$$

where *E* is the gravitational potential energy, *m* is the mass, *g* is the acceleration of Earth's gravity at its surface and *h* is the height. If mass is measured in kilograms, *g* in metres per square second and *h* in metres, energy must be measured in joules.

Since one joule is one watt per second, surplus electricity is easily converted into joules.

$$E_{left} = 2618Wh = 2618Wh \times \frac{3600s}{1h} = 9424800Ws = 9424800J$$

The water is raised by the pump to a height of 35 metres, 20 metres of the well plus 15 metres of the deposit. Therefore, the water pumped by the PV system is:

$$m = \frac{E}{gh} = \frac{9424800J}{9{,}8\, m/s^2 \times 35m} = 27477{,}55kg \approx 27477kg$$

Since one litre of water weighs one kilogram, the PV system will pump 27,477 litres of water every day.

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