



# Unit 15: Introduction to stand-alone PV systems

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## Table of contents

1. About this document .....	3
1.1 Degree of difficulty.....	3
1.2 information about the icons.....	3
1.3 Acknowledgments and intellectual propertyz.....	3
2. Introduction.....	4
3. The photovoltaic system.....	4
3.1 The photovoltaic generator or solar panels array.....	6
3.2 The battery or accumulator.....	6
3.3 The regulator.....	7
3.4 The converter.....	8
3.5 The equipment or the consumption loads .....	9
4. The solar panel.....	9
4.1 Solar Panel Parameters.....	11
4.2 Panel parameters for system sizing.....	13
4.3 Interconnection of panels.....	13
4.4 How to choose a good panel.....	14
5. The battery.....	14
5.1 Types of batteries.....	15
5.1.1 Adaptation of traction batteries.....	16
5.2 States of charge.....	16
5.2.1 Overcharge .....	16
5.2.2 Overdischarge.....	17
5.3 Battery Parameters.....	17
5.3.1 Measuring the state of charge of the battery.....	18
5.3.1 Battery and regulator protection.....	19
5.4 Temperature effects.....	20
5.5 How to choose a good battery.....	20
5.6 Life expectancy versus number of cycle .....	21
6. The power charge regulator.....	21
6.1 Regulator Parameters.....	22
6.2 Regulators for communication systems.....	22

7. Converters.....	23
7.1 DC/DC Converters.....	23
7.2 DC/AC Converter or Inverter.....	23
8. Equipments or loads.....	24
8.1 Home Appliances.....	24
8.2 Wireless telecommunications equipment.....	25
8.3 Election of the voltage.....	26
8.4 Wiring.....	27
9. Economy of a solar installation.....	28
10. Reference Links.....	29
11. Intellectual Property Rights .....	29
12. Stipulations of intellectual property for this unit.....	29

# 1. About this document

This material is part of the course package created for TRICALCAR project. For information on TRICALCAR, please consult the introductory module or, [www.wilac.net/tricalcar/](http://www.wilac.net/tricalcar/). This material was originally developed in Spanish for the TRICALCAR project.

## 1.1 Degree of difficulty

The degree of difficulty of this unit is "basic".

## 1.2 information about the icons

In this unit you will find 5 types of icons whose meaning is described below:

Central concept	Important practice recommended	Exercise	Intellectual property	Intellectual property
				

## 1.3 Acknowledgments and intellectual property

In 1998, the organization Engineering without Borders (Spanish Federation) published the first version of a handbook titled "Manual de Energía Solar Fotovoltaica y Cooperación al Desarrollo". The handbook was written and published by members of the NGO and experts of the Institute of Energy Solar of the Polytechnical University of Madrid. By curiosities of life, none of the members of the editorial team kept the document in electronic format and more editions were never made. They have passed almost ten years from that very first edition and this document is an effort to rescue and to extend the handbook.

As part of this rescue operation I want to thank to the coordinators of the first original edition and my mentors in my years at University: Miguel Ángel Eguido Aguilera, Mercedes Montero Bartolomé y Julio Amador. This new work is licensed under Creative Commons Attribution Share Alike 3.0. We hope that this material becomes a new departure point for new editions including new contributions by the community.

This second and extended edition of the guide has received valuable input from Frédéric Renet and Louise Berthilson.

## 2. Introduction

This thematic unit serves as an introduction to the components of a *stand alone photovoltaic system* (i.e. isolated, not connected to the grid). The objective of this document is to show the basic concepts of photovoltaic solar energy, and to serve as base knowledge to *size* solar systems that take into consideration the information and resources available in the region.

In order to avoid possible confusions, let us start by mentioning that we are going to discuss the use of solar energy for the production of electrical energy (photovoltaic solar energy). The solar energy can also be used to warm up fluids (thermal solar energy) which can in turn be used to produce electricity.

The first part of the document provides a general overview of the components that forms a photovoltaic system, the second part discusses in detail each one of the components of the system.

## 3. The photovoltaic system



*A photovoltaic system is based on the property of certain materials to turn the radiant energy of the sun into electrical energy.*

The total radiant energy that hits a certain area is measured by a quantity known as *Irradiance* (G) and it is measured in watt per square meter ( $W/m^2$ ). The instantaneous values are normally averaged during a certain period of time, so it is common to talk about total irradiance per hour, day or month.

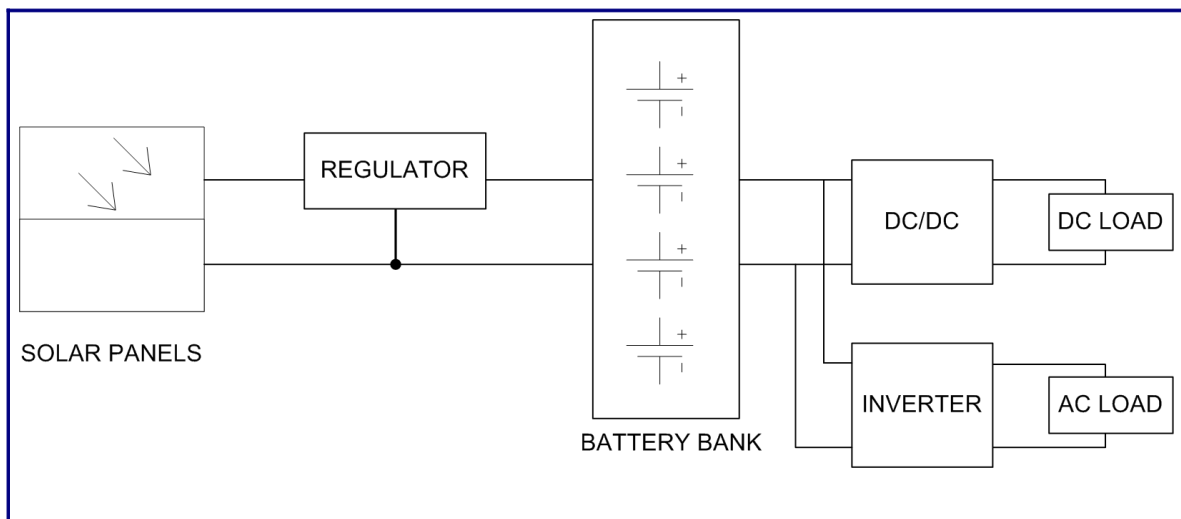
Due to the random nature of the solar energy, the radiation that arrives at the surface of the Earth cannot be predicted with high precision. It is necessary to work with statistical data based on the "solar history" of the place, data that is normally gathered in weather station. When available these values can be retrieved from databases or data tables with digested values. In most of the cases, you will find difficult to find detailed information and you will be forced to work with approximate values.

A few organizations that have produced maps that include average values of daily global irradiation for different regions. These values are known as "peak sun hours" or PSHs, the PSH that are posted in global solar power maps are a mechanism to simplify your calculations.



A “peak sun” corresponds to a radiation of  $1000 \text{ W/m}^2$  so when we find that certain area has 4 PSH in the worse of the months, it means that in that month we should not expect a daily irradiation bigger than  $4000 \text{ W/m}^2(\text{.day})$ . The peak sun hours are an easy way to represent the worse monthly average of irradiation per day.

A photovoltaic system consists of three main components, the panel or array of panels, the regulator and the batteries. The panels are responsible of collecting the energy of the sun and generate electricity, the battery of storing it and the regulator of ensuring that panel and battery are working together in an optimal fashion. It is important that you do not forget that the panels and the batteries of a photovoltaic system work in DC. When the range of operational voltage of your equipment does not fit the voltage supplied by your battery, it will be necessary to include some type of “converter”. If the equipment that you want to feed uses a different DC voltage than the one supplied by the battery you will need to use a DC/DC converter and if some of your equipment (loads) requires AC you will need to use a DC/AC converter, also known as inverter.



**Figure 1:** General diagram of a solar installation with DC and AC loads

Other important elements in your photovoltaic system (although they are not described in detail in this introduction) are the thermomagnetic circuit breakers that need to be included to protect different electrical circuits, surge protectors, fuses, proper size wiring, ground rods, lighting arrestors, etc.

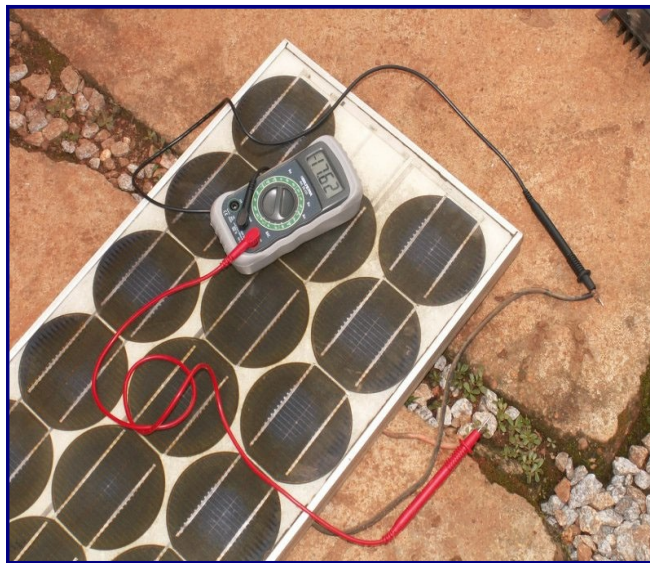
### **3.1 The photovoltaic generator or solar panels array**



*The solar panel or module is composed of solar cells that are responsible of collecting solar radiation and transforming it into electrical energy. The solar panel arrays are formed by a set of panels connected in series and/or parallel so as to provide the necessary energy for the load.*

The electrical current supplied by an array of solar panels varies proportionally to the solar radiation. As the solar energy changes in time due to the climatological conditions, the hour of the day, etcetera, we must count with an energy storage to supply energy when the sunlight is lacking: the batteries.

Several technologies exist to build solar cells. The most used actually is crystalline silicon, either monocrystalline or polycrystalline. A less efficient is the amorphous silicon. With a reduced life expectancy and a 6 to 8% transformation efficiency amorphous silicon is only used for low power equipments as portable calculators. New technology as silicon ribbon or thin films are developed but are actually marginal.



**Figure 2:** Solar Panel

### **3.2 The battery or accumulator**

The battery or batteries are in charge of storing the energy produced by the panels that is not consumed immediately to use it during the periods of low or null solar irradiation. The storage is in form

of chemical energy and the most common type in solar applications are the maintenance-free lead-acid batteries also called recombinant or VRLA (*valve regulated lead acid*).



*Apart from storing energy, the sealed lead-acid batteries have also two important missions:*

- *To be able to provide an instantaneous power superior to which the array of panels can generate. This instantaneous power is needed to start some appliances as the motor of a refrigerator or a pump.*
- *To determine the voltage of operation of your installation.*



**Figure 3:** Lead-Acid 200 Ah battery. Detail of the effect of the weight on the terminals during transportation

For small power installation and where space constraints are important other type of batteries like NiCd, or NiMh (used in cellular phone) can be used. This type of batteries needs a specialized charger/regulator and cannot directly replace lead-acid batteries.

### **3.3 The regulator**



*The regulator or solar power charge regulator assures that the battery works in appropriate conditions, avoiding the overcharging and undercharging, situations that are very detrimental for the life of the battery.*

The mechanism to ensure a correct charging and discharging of the battery requires the knowledge of the state of charge (SoC) of the battery. The SoC is obtained based on the voltage of the battery. Using the battery voltage as an indicator and knowing the type of technology of the battery, allows the

regulators to know the exact voltage points where the battery is getting overcharged or excessively discharged.

The regulator can include other elements that, although are not essential, add valuable information and security control to the equipment: ammeters, voltmeters, measurement of ampere-hour, timers, alarms, etc.



**Figure 4:** Solar charge controller or regulator of 30 A

### 3.4 The converter

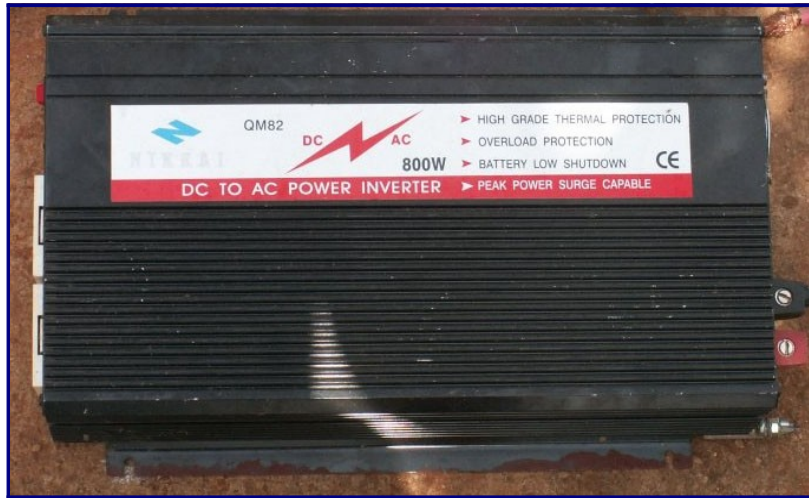
The electricity that provides the panel array-battery is DC and forces the loads to work to a certain voltage level, which might not be the same level that your loads need.



*A direct/alternating (DC/AC) converter, also known as inverter, allows to convert the DC current from your batteries into AC at the price of losing some energy during the conversion.*



*If necessary, you can also use converters to obtain DC at another voltage level that the supplied by the batteries, these DC converters from direct to direct current (DC/DC) also imply energy losses so at the time of designing your solar-powered (communication) system it is advisable to avoid them by making sure that all your loads work to the same voltage provided by the batteries.*



**Figure 5:** The DC/AC Converter or power inverter. Maximum power 800 W

### **3.5 The equipment or the consumption loads**



*The loads are the equipment that is connected to your energy system and will consume the generated energy and stored energy (wireless communications equipment, routers, workstations, lamps, TV sets, VSAT modems, etc).*

Although it is not possible to have an absolute certainty of what is going to be the exact total consumption of your equipment, it is vital to make a good estimate. In this type of systems it is absolutely necessary to take into consideration the need of efficient and low power equipment to avoid wasting energy. For example, if you are going to use communication equipment that is going to operate 24/7 you must consider those that are based on computer architectures specially designed for low power consumption.

## **4. The solar panel**



*The panel, module or photovoltaic generator are formed by a set of solar cells. The cells are associated electrically to provide the values of necessary current and voltage for a determined application, and properly encapsulated to provide isolation and protection from the humidity and the corrosion.*



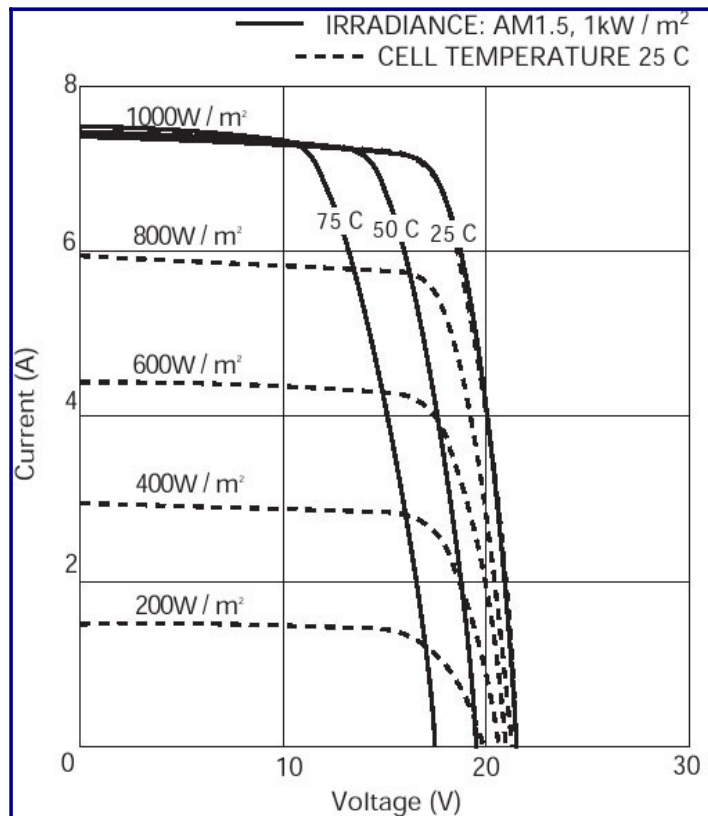
**Figure 6:** The effect of water and corrosion in a solar panel



*The market offers different types from modules depending on the type of power demands. The most common ones are the ones composed of 32 and 36 solar cells of crystalline silicon, all of equal size, associated in series and encapsulated between glass and a plastic material and a polymeric resin (EVA) as a thermal insulator.*

Based on the size of the cells, the area of the module varies between 0'1 and 0'5 m<sup>2</sup>. Panels have two electrical contacts, one positive and one negative, although sometimes you will find some extra contacts to allow the installation of bypass diodes. The object of these bypass diodes is to protect the panel against a phenomenon that is known as "hot-spot". The hot-spot takes place when some of the cells are in shadow and they start to behave as a load that dissipates energy. In those situations the solar cell can increase its temperature to values between 85 and 100°C.

The electrical performance of a solar module its represented by the IV characteristic curve, that represents the current that it provides based on the voltage that "sees" for a certain solar radiation.



**Figure 7:** Different IV Curves. The current (A) changes with the irradiance, the voltage (V) changes with the temperature

The curve represents all the possible values of voltage-current. The curves depend on two main factors: the temperature and the solar radiation received by the cells. For a given solar cell area, the current generated is directly proportional to solar irradiance (G) and the voltage reduces slightly with an increase of temperature. The point of operation of solar panel is determined by the “load” that is present between its electrical contacts. A good regulator will try to maximize the amount of energy that a panel provides by tracking the point that provides maximum power (VxI). The maximum power corresponds to the knee of the IV curve.

## 4.1 Solar Panel Parameters

The main parameters that characterize a photovoltaic panel are:

1. **SHORT CIRCUIT CURRENT  $I_{sc}$ :** It is the maximum current that the panel provides, and corresponds to the current produced when connectors are short circuited.

2. **OPEN CIRCUIT VOLTAGE  $V_{oc}$** : It is the maximum voltage that provides the panel, it corresponds to the case where the terminals are not connected to any load or the circuit is open. This value is normally 22 V for panels that are going to work in 12 V systems, and is directly proportional to the number of series connected cells
3. **MAXIMUM POWER POINT**: There is an operation point where the power supplied by the panel is maximum ( $I_{Pmax}$ ,  $V_{Pmax}$ ) as  $P_{max} = I_{pmax} \cdot V_{pmax}$ . The maximum power point of a panel is measured in Watts (W) or peak Watts ( $W_p$ ). It is important not to forget that in normal conditions the panel will not work at peak conditions as the voltage of operation is fixed by the "loads" or the regulator. The typical values of  $V_{Pmax}$  and  $I_{Pmax}$  should be a bit smaller than the  $I_{sc}$  and  $V_{oc}$
4. **FILL FACTOR FF**: The fill factor is the relation between the maximum power that the panel can give and the product  $I_{sc} \cdot V_{oc}$ . It gives an idea of the quality of the panel because it is an indication of the type of IV characteristic curve. The closer the FF is to 1, the greater the power a panel can provide. The common values usually are between 0'7 and 0'8.
5. **EFFICIENCY  $\eta$** : : It is ratio between the maximum electrical power that the panel can give to the load and the power of the solar radiation ( $P_L$ ) incident on the panel, normally around 10-12%, but depending on the type of cells (monocrystalline, polycrystalline, amorphous or thin film).

Considering the definitions of point of maximum power and the fill factor we have that:

$$\eta = PM / PL = FF \cdot ISC \cdot VOC / PL$$

The values of  $I_{sc}$ ,  $V_{oc}$ ,  $I_{Pmax}$  and  $V_{Pmax}$  are provided by the manufacturer and they refer to a standard conditions of measurement of:

- Irradiance  $G = 1000 \text{ W/m}^2$ .
- At sea-level.
- For a temperature of cells of  $T_c = 25^\circ\text{C}$ .



*The panel parameters values change for other conditions of Irradiance  $G$  and temperature  $T$ . Sometimes, the manufacturer includes graphs or tables with values for conditions different from the standard. Depending on the place you are going to install your solar system you might be interested to check the performance values at different panel temperatures.*

Be aware that two panels can have the same  $W_p$  but very different behavior in operational conditions. When acquiring a panel, it is important to verify, if possible, that their parameters (at least,  $I_{SC}$  and  $V_{OC}$ ) match with the values promised by the manufacturer.

## **4.2 Panel parameters for system sizing**

For the calculation of the number of panels that we are going to need to cover our energy needs you just need to know the current and voltage at the point of maximum power:  $I_{Pmax}$  and  $V_{Pmax}$ .

You should always be aware that the panel is not going to work in the perfect conditions as the “loads” or regulation system are not going to work always at the point of maximum power of the panel. In any case, you can assume a loss of efficiency of 5% in your calculations to compensate this assumption.

## **4.3 Interconnection of panels**

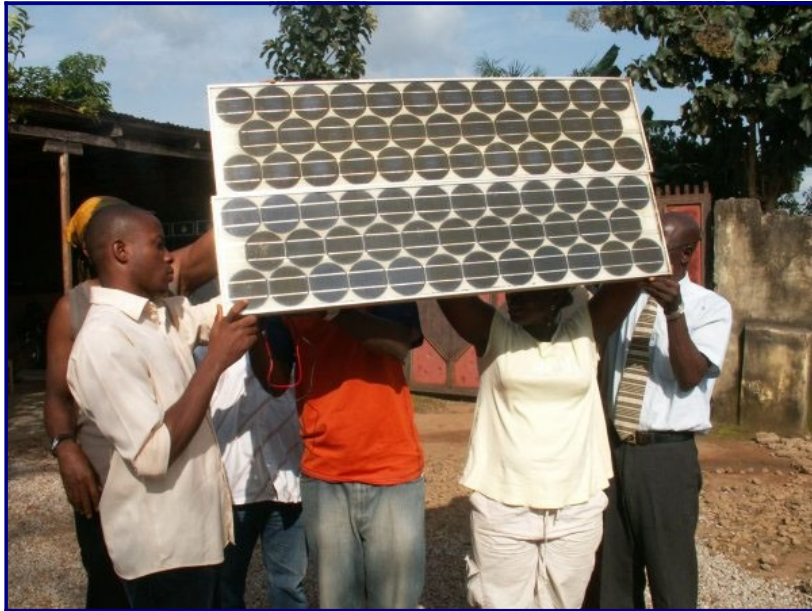
The array of solar panels is composed by the number of necessary panels interconnected electrically, and installed with the help of some type of support structure.

It is very important that all the panels of your array are identical (same brand and same characteristics), because any dispersion in their operation values have a big impact in the operation and performance of your system. Even in case the panels are nominally equal, they will display some dispersion in their characteristics due to the very same process of manufacturing (normally  $\pm 10\%$ ).



*The objective that we want to achieve by interconnecting the panels is double, first we want to obtain a level of voltage that is near (but greater) than the level of voltage of the batteries and secondly we must be able to supply a level of current big enough to feed our equipment and to load the batteries.*

The process of interconnection takes place by associating panels in a series, until the suitable voltage level is reached and by grouping several associated series until we can reach the level of desired current.



**Figure 8:** Interconnection of panels in parallel. The voltage remains constant while the current duplicates. (Photo: *Fantsuam Foundation, Nigeria*)

#### ***4.4 How to choose a good panel***

If you are going to install solar panels in low soiling geographical areas consider panels with low affinity for soil retention.

Check the mechanical construction of the panel and verify the glass is hardened and the aluminum frame robust and well built. Solar cells inside the panel can last more than 20 years, but they are very fragile and the panel must protect them from mechanical hazards.

Be sure that the manufacture provides you not only with the nominal peak power of the panel (Wp) but the variation of the power with the irradiation and temperature.

Look for the manufactures quality guarantees in terms of expected power output and mechanical construction.

A quick calculation when buying panel if to compare the ratio Watt/Price.

### **5. The battery**

The battery “hosts” a certain reversible chemical reaction that make possible that electrical energy can be stored and later retrieved when needed. Electrical energy is transformed into chemical energy and vice versa.



*A battery is formed by a set of “elements” or “cells” arranged in series. Lead-acid batteries consist of two submerged lead electrodes in an electrolytic dissolution of water and sulfuric acid. Between the electrodes a potential difference of in the range of 2 volts takes place depending on the instantaneous value of the load state of the battery.*

The most common batteries in photovoltaic solar applications have a nominal tension of 12 or 24. A battery of 12 V will contain 6 cells in series.

The fundamental mission of the battery is the supply of electrical energy to the system when this energy is not supplied by the array of solar panels. The battery experiments a cyclical process of charging and discharging of energy depending on the presence or absence of sun light.

- During the hours that there is sun, the array of panels produces electrical energy. The energy that is not consumed immediately it is used to charge the battery.
- During the hours of absence of sun, any demand of electrical energy is taken care of by the battery, that, therefore, discharges.

These cycles of charge and discharge of the battery go in parallel with three different cycles that affect the irradiation of the place: the one due to the differences between day and the night, the stations and the (pseudo-)random variation of the climatological conditions (clouds, dust, pollution, etc).

If the battery does not store enough energy so as to face the demand during the periods without sun, the system will exhaust and become unavailable for the consumption. On the contrary, the system oversizing is expensive and inefficient. When designing stand-alone system we need to reach a compromise between cost and availability of the system. To be able to do that we introduce the concept of *number of days of autonomy*. If we take the case of a telecommunications system the number of days of autonomy depends on its critical function within your network design. If the equipment is going to serve as repeater and is part of the backbone of your network, you must design your photovoltaic system with an autonomy of up to 5-7 days. If on the contrary the solar system is responsible of a providing energy to a client equipment you can probably reduce by half the number of days of autonomy. In any case, you will always have to look for a commitment between cost and reliability.

## **5.1 Types of batteries**

There are several types of models (technologies) of batteries destined for different type of usages. The most suitable type for photovoltaic applications are the stationary batteries, designed to have a fixed location (fix station) and for in scenarios where the power consumption is more or less irregular. The "stationary" batteries do not need to produce high currents in brief periods of time but should accommodate deep discharge cycles.

The stationary batteries can have alkaline electrolyte (as Nickel-Cadmium) or an acid one (known as Lead-Acid, being the lead the element used in its electrodes). Stationary batteries based on Nickel-Cadmium are recommended for their high reliability and resistance, but due to their elevated price the balance inclines in favor of the sealed lead-acid batteries.



*In many cases when it is difficult to find local, good and cheap stationary batteries (importing batteries is not cheap), you will be forced to use batteries targeted to the automobile market.*

### **5.1.1 Adaptation of traction batteries**

The car batteries are not very recommendable for photovoltaic applications as they are designed to provide a great intensity during few seconds (when starting) rather than low intensity for long period of time. This design characteristic of traction batteries implies a shortening of their life when integrated in photovoltaic systems. Traction batteries can be used in small applications, where it is important to have low costs, or when there are not other batteries in the market. Distilled water can be used to extend their life. Adding water and lowering the density from 1,2 instead of 1,28, reduces the anode's corrosion. In order to measure the density of the dissolution it is necessary to use a densimeter or hydrometer.



*The traction batteries are designed for vehicles and electrical wheelbarrows, they are cheaper than the stationary ones and can serve in a photovoltaic installation if you do not forget that they need very frequent maintenance. Never forget that these batteries are not designed for deep discharging. A truck battery should not discharged more than the 70% of its total capacity (yes, that means that you can only use a maximum of 30% of their nominal capacity)*

## **5.2 States of charge**

There are two special state of charge that can take place during the cyclic charge and discharge of the battery

### **5.2.1 Overcharge**

It takes place when the battery arrives at the limit of its capacity. If the panels via the regulator continue injecting energy the water of the sulfuric acid dissolution begins to break, producing oxygen and

hydrogen. This process is known as *gasification* and has the negative effect of the loss of water in the dissolution and the oxidation the positive electrode.

On the other hand, the presence of gas has the advantage that avoids the stratification of the acid. Due to the continuous cycles charge and discharge that the battery undergoes the acid tends to concentrate itself at the bottom of the battery reducing the effective capacity. The process of gasification “moves” the dissolution and avoids the stratification.

Again, it is needed to find a compromise between the advantages (avoid stratification) and the disadvantages (losing water). The solution is to allow light overcharges every certain time (that translates to a voltage between 2'35 and 2'4 Volts for each element of the battery, at 25°C). The regulator should ensure the periodical and controlled overcharges. Latest development include the use of a technique known as pulse wave modulation (PWM) during the overcharging period.

### 5.2.2 Overdischarge

In the same way that there is a upper limit, there is also a lower limit in a battery state of charge. Discharging over that limit implies the deterioration of the battery. The regulator acts also in this case, preventing that more energy is extracted from the battery. When the voltage of the battery reaches the minimum limit of 1'85 Volts at 25°C per cell, the regulator disconnects the loads (your equipment) from the battery.

If the discharge of the battery is very deep and the battery remains long time discharged, three effects take place: formation of hard sulfation (crystallized sulfate), loosening of battery plate active material, and plate buckling. The hard sulfation is specially negative as it generates big crystals that do not take part in any chemical reaction and can make your battery unusable.

## 5.3 Battery Parameters

The main parameters that characterize a battery are:

1. **NOMINAL VOLTAGE  $V_{NBat}$** : being the most common value 12 V.
2. **NOMINAL CAPACITY  $C_{NBat}$** : Maximum amount of energy that can be extracted from the battery. It is expressed in Ampere-hour (Ah) or Watt-hour(Wh). The amount of energy that can be obtained from a battery depends on the time in which the extraction process takes place (the more it lasts the process, the more amount of energy we will be able to obtain). The capacity of a battery should be specified based on different discharging times. For photovoltaic applications, this time must be bigger than 100 hours (C100).
3. **MAXIMUM DEPTH OF DISCHARGE  $DoD_{max}$** : The depth of discharge (%) is the perceptual value of energy extracted from a battery in a discharge. The regulators limit this depth, and they are calibrated habitually to allow a maximum depths of discharge of the battery around 70%. The life expectancy of a battery depends on how deep we discharge it in every cycle. The

manufacturer must provide graphs that relate the number of charge-discharge cycles to the life of the battery. As a general rule you should avoid that your deep cycle battery discharges more than 50% and as little as 30% for traction batteries.

4. **USEFUL CAPACITY  $C_{UBat}$ :** It is the real (as in usable) capacity of a battery. It is equal to the product of the nominal capacity by the maximum DoD. For example a stationary battery of nominal capacity ( $C_{100}$ ) of 120 Ah and depth of discharge of 70%, has a useful capacity of 84 Ah.

### 5.3.1 Measuring the state of charge of the battery

A sealed lead-acid battery of 12 V provides different voltages depending on its the state of charge. When the battery is fully loaded the output voltage is of 12,8 V. The output voltage lowers quickly to 12,6 V when loads are attached. As the battery is giving constant current during operation, the battery voltage reduces linearly from 12,6 to 11,6 V depending on the state of charge. A sealed lead-acid batteries gives 95% of its energy within this voltage range. If we make the broad assumption that a fully loaded battery has a voltage of 12,6 V and 11,6 V when empty, we can estimate that a battery has discharged 70% when it reaches a voltage of 11,9 V. Unfortunately these values are approximated since they depend on the life of the battery and its quality, the temperature, etc.

State of Charge	12 Volt battery	Volts to per Cell
100%	12.7	2.12
90%	12.5	2.08
80%	12.42	2.07
70%	12.32	2.05
60%	12.20	2.03
50%	12.06	2.01
40%	11.9	1.98
30%	11.75	1.96
20%	11.58	1.93
10%	11.31	1.89
0%	10.5	1.75

**Table 1:** State of charge based on open-circuit voltage

Considering the previous table and that a truck battery should not discharged more than 20% or 30% we can determine that the useful capacity of a battery of 170 Ah is 34 Ah (20%) and 51 Ah (30%). Using the same table we can instruct our regulator not to let the battery go under a voltage of 12,3 V.

### 5.3.1 Battery and regulator protection

Thermomagnetic circuit breakers or one time fuses must be used to protect the batteries and the installation from short circuit and malfunctions.

There are two types of fuses: slow blow, and quick blow. The slow blow fuses should be used with inductive or capacitive loads where a high current can occur at the power up. Slow blow fuses will let pass a higher current than their rating for a short time, but quick blow fuses will immediately blow if the current going through them is higher than their rating.

The regulator is connected to the battery and the loads and two different protections need to be considered. One fuse should be placed to protect the battery from short-circuit in case of regulator failure. A second fuse is needed to protect the regulator from excessive load current. This second fuse is normally integrated in the regulator.

Every fuse has rated with a maximum current and a maximum usable voltage. The maximum current should be 20% bigger than the maximum current expected.

Even if the batteries carry a low voltage a short circuit can lead to a very high current which can reach several hundred amperes. Large currents can cause fire, damage the equipments and the batteries and provoke electric shock on human body

If the fuse breaks, do never replace a fuse with a wire or a higher rating fuse. Always replace the fuse with another one which has the same characteristics.



**Figure 9:** A battery bank of 3600 Ah, currents reach levels of 45 A during charging

## 5.4 Temperature effects

The effects of temperature are specially important in the characteristics of a battery:

- On the one hand, the nominal capacity of a battery (that the manufacturer usually gives for 25°C) increases with the temperature at the rate of 1%/°C, approximately. But in the case of too high temperature, the chemical reaction that takes place in the battery accelerates, which can cause the same type of oxidation that takes place during *overcharging* and hence reducing the life expectancy of battery. This problem can be compensated partially in car batteries by having low densities of dissolution (1,25 when the battery is totally charged).
- If the temperature is low, the useful life increases, but the risk of freezing increases. The freezing temperature depends on the density of the solution, that is directly related as well to the state of charge of the battery. The bigger the density the smaller the risk of freezing. In areas of low temperatures we should avoid having the batteries discharged having a smaller DoD<sub>max</sub>.
- The temperature also changes the relation between voltage and charge, it's preferable to use a regulator which compensate the low voltage disconnect and low voltage reconnect parameters. The temperature sensor of the regulator must be fixed to the battery. A simple scotch tape is enough.
- In hot areas it's important to keep the batteries as cool as possible. The batteries must be in a covered place and never get direct sunlight. It's possible to place the batteries on a small support to allow air to flow under them and increase the cooling.

## 5.5 How to choose a good battery

Choosing a good battery can be very challenging in developing regions. High capacity batteries are heavy, bulky and expensive to import. A 200 Ah battery weights around 50 kgs (120 lb) and it can not be transported as hand luggage. If you want long-life (as in > 5 years) and maintenance free batteries be ready to pay the price.



*A good battery should always come with its technical specifications including the capacity at different discharge rates (C20, C100), operating temperature, cut-off voltage points and requirements for chargers.*

The batteries must be free of cracks, liquid spillage or any sign of damage and battery terminals should be free of corrosion. As laboratory tests are necessary to obtain complete data about real capacity and ageing, expect lots of low quality batteries (including fakes) in the local markets. A typical price (not including transport and import tax) is 3-4 USD per Ah in 12 V lead-acid batteries.

## 5.6 Life expectancy versus number of cycle

Batteries are the only component of a solar system you need to amortize in a short period and replace regularly. Even for deep cycle batteries if you reduce the number of deep discharge (>30%) cycles, you can increase dramatically the life of a battery.

If you discharge the battery every day you will have to change it after less than one year. If you use only 1/3 of the capacity the battery can last more than 3 years. It can be cheaper to buy a 3 times bigger capacity than to change the battery every year.

## 6. The power charge regulator

The power charge regulator is also known as charge controller, voltage regulator, charge-discharge controller or charge-discharge and load controller. The regulator sits between the array of panels and the batteries and the battery and your equipment or loads.



*Remember that the voltage of a battery, although always next to 2 V by cell, varies according to its state of charge. By measuring with sufficient precision the voltage, the regulator prevents the overcharging or overdischarging of the battery.*

The regulators that are used in solar applications should be connected in series: they disconnect the array of panels from the battery, to avoid the overcharging, and the battery from the load, to avoid overdischarging. The connection and disconnection is done by means of switches who can be of two types: electromechanical (relays) or solid state (bipolar transistor, MOSFET). Remember that regulators should not be connected in parallel.



*In order to protect the battery from gasification the switch opens the charging circuit when the tension in the battery reaches its high voltage of disconnect (HVD) or cut-off set point.*

The low voltage disconnect (LVD) prevents the battery from overdischarging by disconnecting or shedding the load. To prevent continuous connections and disconnections the regulator will not connect back the loads until the battery reaches a *low reconnect voltage* (LRV). Typical values for a 12 V lead-acid flooded battery are:

Voltage Point	V
LVD	11.5
LRV	12.6
Constant Voltage Regulated	14.3
Equalization	14.6
HVD	15.

**Table 2:** Typical voltage values for lead-acid flooded battery

The most modern regulators are also able to automatically disconnect the panels during the night to avoid discharging of the battery, overcharge the battery periodically (equalization) to improve their life and use a mechanism known as *pulse width modulation* (PWM) to prevent excessive gassing.

The peak power operating point of the array of panels will vary with temperature and solar illumination, new regulators are capable of constantly tracking the maximum point of power of the solar array. This feature is known as *maximum power point tracking* (MPPT).

## 6.1 Regulator Parameters

The minimum values that you need to know of a regulator for your system sizing are:

- Maximum current that the regulator can handle. It must be 20% bigger than the array of panels that is connected to.
- Operational Voltage: 12, 24, or 48 V.

Other data of interest, that they must be provided by the manufacturer are:

- Values of LVD, LRV and HVD.
- Support for temperature compensation. The voltage that indicates the state of charge of the battery vary with the temperature, for that reason some regulators are able to take into consideration the temperature and correct the different cut-off and reconnection points.
- Instrumentation and gauges. The most common instruments measure the voltage of the panels and batteries, the state of charge (SoC) or Depth of Discharge (DoD). Some regulators include special alarms to indicate that the panels or loads have been disconnected, etc.

## 6.2 Regulators for communication systems

There are several efforts to build low cost and efficient charge controllers for wireless (WiFi) communication systems. Apart from efficient charging, the projects seek to monitor the state of charge of the battery and inform the devices of the energy available that can make smart decisions as lowering

the transmission power or a nice shutdown. Some of this efforts includes the Green WiFi initiative and the TIER group work.

## 7. Converters



*The converters or inverters where referring to AC/DC are equipment that transforms the voltage level provided by the solar array to a different one suitable for your equipment.*

### 7.1 DC/DC Converters



*DC/DC converters transform a continuous voltage to another continuous voltage with a different value. They are used to power the equipment that do not accept directly the output voltage of the solar installation. There are two conversion methods which can be used to adapt the voltage from the batteries: linear and switching conversion.*

***Linear conversion** lowers the voltage from the batteries by burning in the regulator the rest of the energy. This method is very simple but inefficient.*

***Switching conversion** generally use a magnetic component to temporally store the energy and transform it to another voltage. The resulting voltage can be superior, inferior or inverse (negative) from the input voltage.*

The efficiency of a linear regulator decreases when the difference between the input voltage and the output voltage increase. For example, if we want to convert from 12 V to 6 V, the linear regulator will have an efficiency of only 50%. A standard switching regulator has an efficiency of at least 80%.

### 7.2 DC/AC Converter or Inverter

They are used when your equipment needs AC power . The inverters chop and invert the DC current to generate a *square wave* that is later filtered to eliminate the undesired harmonics. In fact, there are very few inverters that supply a pure sine wave as output. Most of the models available in the market are known as "modified sine wave" as their voltage output is not a pure sinusoid. When it comes to efficiency, modified sine wave inverters perform better than pure sinusoidal inverters.



*Be aware that not all the equipments accept a modified sine wave as voltage input.*

For example, it is common that some laser printers do not work, that the power supplies of DC warm up more and that amplifiers can emit a buzzing sound.

Aside from the type of waveform, some of the features that inverters can have include:

1. **Reliability in the presence of surges:** that is the capability of knowing when a high current is the result of starting a motor or a short circuit that requires a circuit cut-off.
2. **Conversion Efficiency:** something that depends a lot of the instantaneous power demanded at each time. As converters show a greater efficiency working near their nominal power, it is advisable to select a model that will operate most of the times close to its nominal power. The manufacturer usually provides the performance of the inverter at 70% of its nominal power.
3. **Battery charging:** many inverters can also incorporate the inverse function: the possibility of charging batteries in the presence of an alternative source of current (grid, generator, etc). This type of inverters are known as charger/inverter.
4. **Automatic fall-over:** the capability to switch automatically between different sources of power (grid, generator, solar).



*When using telecommunication equipments avoid the use of DC/AC converters and feed them directly from a DC source. Most communications equipments can accept a wide range of input voltage but this something that you have to check carefully to ensure optimal performance and avoid burning a few capacitors.*

## 8. Equipments or loads

Obviously the greater the consumption, the more expensive is the installation. Therefore, we must insist on two fundamental aspects: In the first place, in doing a realistic estimate, of the maximum consumption. Secondly, once the installation is in place, it is necessary to respect this established maximum consumption to avoid frequent failures in the provision.

### 8.1 Home Appliances

The use of photovoltaic solar energy is not recommended for heat-exchange type of applications (electrical heating, refrigerators, etcetera). In fact, photovoltaic energy needs to be deployed with lots of care and looking into low power appliances.

Some hints follows:

- The photovoltaic solar energy is suitable for illumination. In this case, the use of halogen light bulbs or fluorescent lamps is mandatory. Although these lamps are more expensive they have much better energy efficiency than incandescent light bulbs. Nowadays LED lamps which are very efficient and are DC fed are the best choice.

- It is possible to be use it for low and constant consumption house appliances (the most typical case, the TV). You should choose them small size and take into consideration that a B/W TV consumes half that a color one.
- The photovoltaic solar energy is not recommended for any application that transform energy into heat (thermal energy). Use solar heating or butane as alternative.
- In the case of installation of washing machines, it is recommended to use conventional automatic washing machines avoiding the use of any washing programs that include centrifuged water heating.
- The refrigerators must be of low consumption. There are specialized refrigerators that work in DC although their consumption is high (around 1000 Wh/day).

The estimation of the total consumption is a fundamental step in the sizing of you solar system. As a reference we include a table that gives you an idea of the power consumptions that you could expect from difference appliances.

Equipment	Consumption (Watts)
Portable Computer	30-50
Low power Lamp	6-10
WRAP (one radio)	4-10
VSAT Modem	15-30
PC (without LCD)	20-30
PC (with LCD)	200-300
Switch (16 ports)	6-8

**Table 3:** Average power consumption of equipment

## ***8.2 Wireless telecommunications equipment***

In those locations where grid power is available it is normal to feed the communications equipment via Power-over-Ether (PoE) according to the standard 802.af. By using PoE you will be able to use a single cable to transport both power and data.

In many cases we are going to need energy for our wireless telecommunications equipment in a place where electrical provision does not exist. The best locations for a repeater usually are at the top of mountains in windy and remote unpopulated areas. It is very important to ensure that all the equipment uses the minimum amount of power to reduce the size of your solar panels and batteries. In addition, you might be interested in enclosing most of the elements of your communication unit in a watertight box at the top of a tower. A compromise between, cost, reliability, and weight is always needed.

Overdimensioning does not necessary lead to the best solutions as the size of your components needs to be enclosed. Hosting a 50 Kgs battery at the top of tower is challenging!



*One of the first things that you must consider is the type of wireless (IEEE 80211) routers that you are using. Equipment based on traditional Intel x86 are power hungry in comparison with RISC-based architectures as ARM or MIPS. One of the boards with lowest power consumptions is the Soekris platform that uses an AMD ElanSC520 processor.*

Another alternative to AMD (ElanSC or Geode SC1100) is the use of equipment with MIPS processors. MIPS processors have a better performance than an AMD Geode at the price of consuming between 20-30% of more energy.

Equipment	Consumption (Watts)
Linksys WRT54G (radio BCM2050)	6
Linksys WAP54 (radio BCM2050)	3
Orinoco/WavePoint II ROR (radio 30 mW)	15
Soekris net4511 (not radio/radio)	1.8 / 4.8
WRAP.1E-1 (nonradio)	2.04 / 5.04
Routerboard 532 (nonradio)	2.3 / 5.3
Inhand ELF3 (nonradio)	1.53 / 4.53
Senao 250 mW Radio	3
Ubiquity 400 mW Radio	6

**Table 4:** Average power consumption of equipment

Measuring power consumption of wireless equipment is not simple because they depend not only on the architecture but on the number of network interfaces, radios, types of memories/storage and traffic. As a general rule we can say that a wireless board of low consumption consumes in the range of 2-3 W and a 200 mW radio card consumes as much as 3 W. High power cards as the Ubiquity of 400 mW consume around 6 W. A repeating station with two radios can range between 8 and 10 W.



*Although the standard IEEE 802.11 incorporates a Powersaving mode (PS) mechanism, its benefit is not as good as expected.*

The main mechanism for energy saving is to allow the stations to put to sleep its wireless cards periodically by means of a timing circuit. When the wireless card wakes up it verifies if a beacon exists

indicating pending traffic. The energy saving only takes place in the client side as the access point needs to remain always awake transmitting periodical beacons and storing their clients pending traffic.

### **8.3 Election of the voltage**

Most of low power stand-alone systems use 12 V battery power as that is the most common operational voltage in sealed lead-acid batteries today. When designing a wireless communication system you need to take into consideration the most efficient voltage of operation of your equipment. While the input voltage can accept a wide range of values, you need to ensure that the overall power consumption of the system is minimum.

### **8.4 Wiring**

An important component of the installation is the wiring. A proper wiring ensures efficient energy transfer. Some of the good practices that you should consider include:

- Use a screw to fasten the cable to the battery terminal
- Spread Vaseline or mineral jelly on the battery terminals. Corroded connection will have an increased resistance and will result in loss.
- For low currents (<10 A) you can consider the use of *Faston connectors*. For bigger currents use metallic ring lugs.

The wire size is normally given in American Wire Gauge (AWG). During your calculations you will need to use a conversion table between AWG and mm<sup>2</sup> and cable resistance<sup>1</sup>. For example a AWG #6 cable has 4.11 mm of diameter and can handle 55 A. The current carrying capacity varies depending on the type of insulation, current and use. Always, consult the manufacture for more detailed information.

AWG gauge	Diameter mm	Ohms per km	Max Amp
0000	11.684	0.16072	302
000	10.40384	0.202704	239
00	9.26592	0.255512	190
0	8.25246	0.322424	150
1	7.34822	0.406392	119
2	6.54304	0.512664	94
3	5.82676	0.64616	75
4	5.18922	0.81508	60
5	4.62026	1.027624	47

1. [http://en.wikipedia.org/wiki/American\\_wire\\_gauge](http://en.wikipedia.org/wiki/American_wire_gauge)

6	4.1148	1.295928	37
7	3.66522	1.634096	30
8	3.2639	2.060496	24
9	2.90576	2.598088	19
10	2.58826	3.276392	15

**Table 5:** AWG Conversion Table. Reference values for maximum amperes

## 9. Economy of a solar installation

Contrary to what we could believe the solar energy is not free. You have to buy equipment to transform the solar energy in electricity, but you also have to replace the components of the system and maintain them. Often the problem of equipment replacement is overlooked and a solar system is implemented without a proper maintenance training.

In order to calculate the *real* cost of your installation, we include a illustrative example. The first thing to do it is to collect the information of the first investment costs.

Description	Number	Unitary Cost	Sub Total
Solar panel 60Wp (@ aprox. 4 USD/Wp)	4	\$300	\$1,200
Regulator 30A	1	\$100	\$100
Wiring (meters)	25	\$1	\$25
Deep cycle batteries (50 Ah)	6	\$150	\$900
Total			\$2,225

**Table 6:** Initial investment budget

The calculation of our investment cost is relatively easy once the system has been dimensioned. You just need to add the price for each equipment and the labor cost to install and wire the equipments together. For simplicity, we do not include the costs of transport and installation but you should not overlooked them.

To figure out how much a system will really cost to operate we must estimate how long each part will last and how often you must replace it. In accounting terminology this is known as *amortization*. Our new table will look like this:

Description	Number	Unitary Cost	Sub Total	Life time	Yearly cost
<b>Solar panel 60W</b>	4	\$300	\$1,200	20	\$60

<b>Regulator 30A</b>	1	\$100	\$100	5	\$20
<b>Wiring (meters)</b>	25	\$1	\$25	10	\$2.50
<b>Deep cycle batteries</b>	6	\$150	\$900	5	\$180
<b>Total</b>			<b>\$2,225</b>	<b>Annual cost:</b>	<b>\$262.5</b>

**Table 7:** Calculation of annual costs due to replacement and maintenance

As you see, once the first investment has been done, an annual cost of \$262.5 is expected. The annual cost is an estimation of the required capital per year to replace the system components once they reach the end of their life time.

## 10. Reference Links

- Introduction to batteries  
<http://homepages.which.net/~paul.hills/Batteries/BatteriesBody.html>
- Batteries FAQ  
[http://www.windsun.com/Batteries/Battery\\_FAQ.htm](http://www.windsun.com/Batteries/Battery_FAQ.htm)
- Power Comparison of different wireless boards  
<http://tier.cs.berkeley.edu/wiki/SBC:Choices>

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