7
Solar Power

This chapter provides an introduction to the components of a ***standalone photovoltaic system***. The word standalone refers to the fact that the system works without any connection to an established power grid. In this chapter, we will present the basic concepts of the generation and storage of photovoltaic solar energy. We will also provide a method for designing a functional solar system with limited access to information and resources.

This chapter only discusses the use of solar energy for the direct production of electricity (***photovoltaic solar energy***). Solar energy can also be used to heat fluids (***thermal solar energy***) which can then be used as a heat source or to turn a turbine to generate electricity. Thermal solar energy systems are beyond the scope of this chapter.

Solar energy

A photovoltaic system is based on the ability of certain materials to convert the radiant energy of the sun into electrical energy. The total amount of solar energy that lights a given area is known as ***irradiance*** (***G***) and it is measured in ***watts per square meter*** (***W/m***^{2}). The instantaneous values are normally averaged over a period of time, so it is common to talk about total irradiance per hour, day or month.

Of course, the precise amount of radiation that arrives at the surface of the Earth cannot be predicted with high precision, due to natural weather variations. Therefore it is necessary to work with statistical data based on the "solar history" of a particular place. This data is gathered by a weather station over a long period and is available from a number of sources, as tables or databases. In most cases, it can be difficult to find detailed information about a specific area, and you will need to work with approximate values.

A few organizations have produced maps that include average values of daily global irradiation for different regions. These values are known as ***peak sun hours*** or ***PSH***s. You can use the PSH value for your region to simplify your calculations. One unit of "peak sun" corresponds to a radiation of 1000 Watts per square meter. If we find that certain area has 4 PSH in the worst of the months, it means that in that month we should not expect a daily irradiation bigger than 4000 W/m^2 (day). The peak sun hours are an easy way to represent the worst case average of irradiation per day.

Low resolution PSH maps are available from a number of online sources, such as *http://www.solar4power.com/solar-power-global-maps.html*. For more detailed information, consult a local solar energy vendor or weather station.

What about wind power?

It is possible to use a wind generator in place of solar panels when an autonomous system is being designed for installation on a hill or mountain. To be effective, the average wind speed over the year should be at least 3 to 4 meter per second, and the wind generator should be 6 meters higher than other objects within a distance of 100 meters. A location far away from the coast usually lacks sufficient wind energy to support a wind powered system.

Generally speaking, photovoltaic systems are more reliable than wind generators, as sunlight is more available than consistent wind in most places. On the other hand, wind generators are able to charge batteries even at night, as long as there is sufficient wind. It is of course possible to use wind in conjunction with solar power to help cover times when there is extended cloud cover, or when there is insufficient wind.

For most locations, the cost of a good wind generator is not justified by the meager amount of power it will add to the overall system. This chapter will therefore focus on the use of solar panels for generating electricity.

Photovoltaic system components

A basic photovoltaic system consists of four main components: the ***solar panel***, the ***batteries***, the ***regulator***, and the ***load***. The panels are responsible for collecting the energy of the sun and generating electricity. The battery stores the electrical energy for later use. The regulator ensures that panel and battery are working together in an optimal fashion. The load refers to any device that requires electrical power, and is the sum of the consumption of all electrical equipment connected to the system. It is important to remember that solar panels and batteries use ***direct current*** (***DC***).

If the range of operational voltage of your equipment does not fit the voltage supplied by your battery, it will also be necessary to include some type of ***converter***. If the equipment that you want to power uses a different DC voltage than the one supplied by the battery, you will need to use a ***DC/DC converter***. If some of your equipment requires AC power, you will need to use a ***DC/AC converter***, also known as an ***inverter***.

Every electrical system should also incorporate various safety devices in the event that something goes wrong. These devices include proper wiring, circuit breakers, surge protectors, fuses, ground rods, lighting arrestors, etc.

The solar panel

The ***solar panel*** is composed of solar cells that collect solar radiation and transform it into electrical energy. This part of the system is sometimes referred to as a ***solar module*** or ***photovoltaic generator***. ***Solar panel arrays*** can be made by connecting a set of panels in series and/or parallel in order to provide the necessary energy for a given load. The electrical current supplied by a solar panel varies proportionally to the solar radiation. This will vary according to climatological conditions, the hour of the day, and the time of the year.

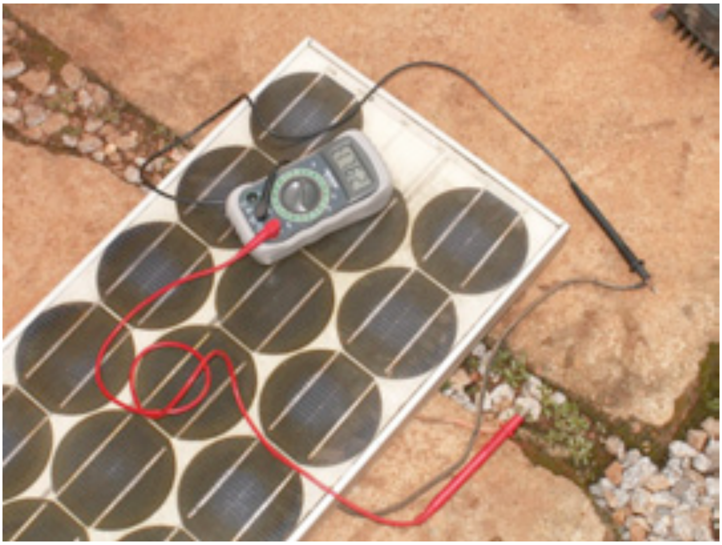

Figure 7.1: A solar panel

Several technologies are used in the manufacturing of solar cells. The most common is crystalline silicon, and can be either monocrystalline or polycrystalline. Amorphous silicon can be cheaper but is less efficient at converting solar energy to electricity. With a reduced life expectancy and a 6 to 8% transformation efficiency, amorphous silicon is typically used for low power equipment, such as portable calculators. New solar technologies, such as silicon ribbon and thin film photovoltaics, are currently under development. These technologies promise higher efficiencies but are not yet widely available.

The battery

The ***battery*** stores the energy produced by the panels that is not immediately consumed by the load. This stored energy can then be used during periods of low solar irradiation. The battery component is also sometimes called the ***accumulator***. Batteries store electricity in the form of chemical energy. The most common type of batteries used in solar applications are ***maintenance-free lead-acid batteries***, also called ***recombinant*** or ***VRLA*** (***valve regulated lead acid***) batteries.

Figure 7.2: A 200 Ah lead-acid battery. The negative terminal was broken due to weight on the terminals during transportation.

Aside from storing energy, sealed lead-acid batteries also serve two important functions:

- They are able to provide an instantaneous power superior to what the array of panels can generate. This instantaneous power is needed to start some appliances, such as the motor of a refrigerator or a pump.
- They determine the operating voltage of your installation.

For a small power installation and where space constraints are important, other type of batteries (such as NiCd, NiMh, or Li-ion) can be used. These types of batteries need a specialized charger/regulator and cannot directly replace lead-acid batteries.

The regulator

The ***regulator*** (or more formally, the ***solar power charge regulator***) assures that the battery is working in appropriate conditions. It avoids ***overcharging*** or ***overdischarging*** the battery, both of which are very detrimental to the life of the battery. To ensure proper charging and discharging of the battery, the regulator maintains knowledge of the ***state of charge*** (***SoC***) of the battery. The SoC is estimated based on the actual voltage of the battery. By measuring the battery voltage and being programmed with the type of storage technology used by the battery, the regulator can know the precise points where the battery would be overcharged or excessively discharged.

Figure 7.3: A 30 Amp solar charge controller

The regulator can include other features that add valuable information and security control to the equipment. These features include ammeters, voltmeters, measurement of ampere-hour, timers, alarms, etc. While convenient, none of these features are required for a working photovoltaic system.

The converter

The electricity provided by the panel array and battery is DC at a fixed voltage. The voltage provided might not match what is required by your load. A ***direct/alternating (DC/AC) converter***, also known as ***inverter***, converts the DC current from your batteries into AC. This comes at the price of losing some energy during the conversion. If necessary, you can also use converters to obtain DC at voltage level other than what is supplied by the batteries. ***DC/DC converters*** also lose some energy during the conversion. For optimal operation, you should design your solar-powered system to match the generated DC voltage to match the load.

Figure 7.4: An 800 Watt DC/AC converter (power inverter)

The load

The ***load*** is the equipment that consumes the power generated by your energy system. The load may include wireless communications equipment, routers, workstations, lamps, TV sets, VSAT modems, etc. Although it is not possible to precisely calculate the exact total consumption of your equipment, it is vital to be able to make a good estimate. In this type of system it is absolutely necessary to use efficient and low power equipment to avoid wasting energy.

Putting it all together

The complete photovoltaic system incorporates all of these components. The solar panels generate power when solar energy is available. The regulator ensures the most efficient operation of the panels and prevents damage to the batteries. The battery bank stores collected energy for later use. Converters and inverters adapt the stored energy to match the requirements of your load. Finally, the load consumes the stored energy to do work. When all of the components are in balance and are properly maintained, the system will support itself for years.

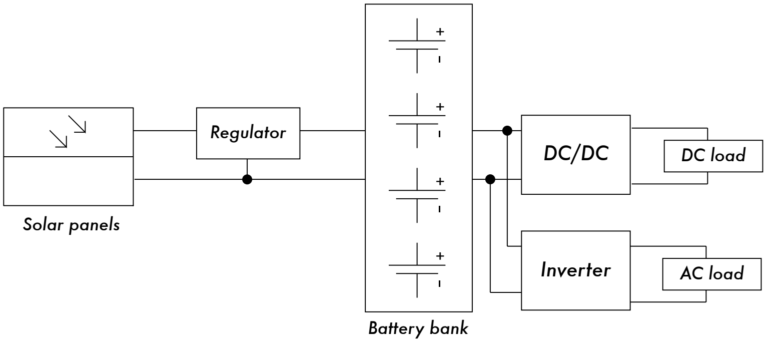

Figure 7.5: A solar installation with DC and AC loads

We will now examine each of the individual components of the photovoltaic system in greater detail.

The solar panel

An individual solar panel is made of many solar cells. The cells are electrically connected to provide a particular value of current and voltage. The individual cells are properly encapsulated to provide isolation and protection from humidity and corrosion.

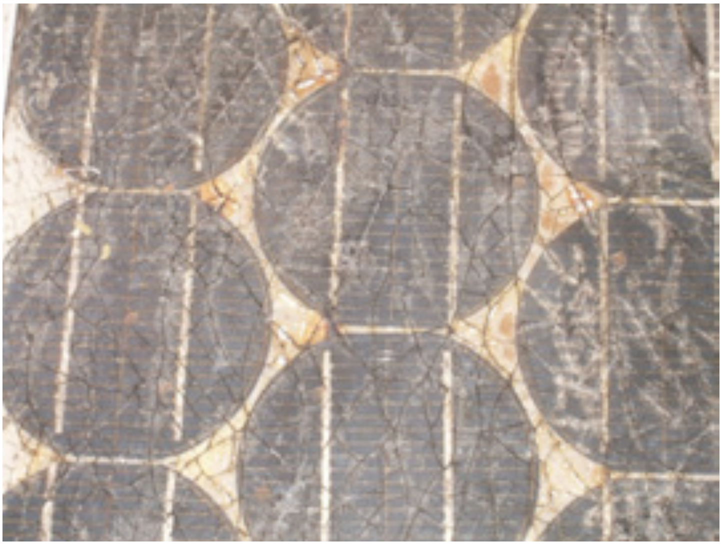

Figure 7.6: The effect of water and corrosion in a solar panel

There are different types of modules available on the market, depending on the power demands of your application. The most common modules are composed of 32 or 36 solar cells of crystalline silicon. These cells are all of equal size, wired in series, and encapsulated between glass and plastic material, using a polymer resin (EVA) as a thermal insulator. The surface area of the module is typically between 0.1 and 0.5 m^2. Solar panels usually have two electrical contacts, one positive and one negative.

Some panels also include extra contacts to allow the installation of ***bypass diodes*** across individual cells. Bypass diodes protect the panel against a phenomenon known as "hot-spots". A hot-spot occurs when some of the cells are in shadow while the rest of the panel is in full sun. Rather than producing energy, shaded cells behave as a load that dissipates energy. In this situation, shaded cells can see a significant increase in temperature (about 85 to 100ºC.) Bypass diodes will prevent hot-spots on shaded cells, but reduce the maximum voltage of the panel. They should only be used when shading is unavoidable. It is a much better solution to expose the entire panel to full sun whenever possible.

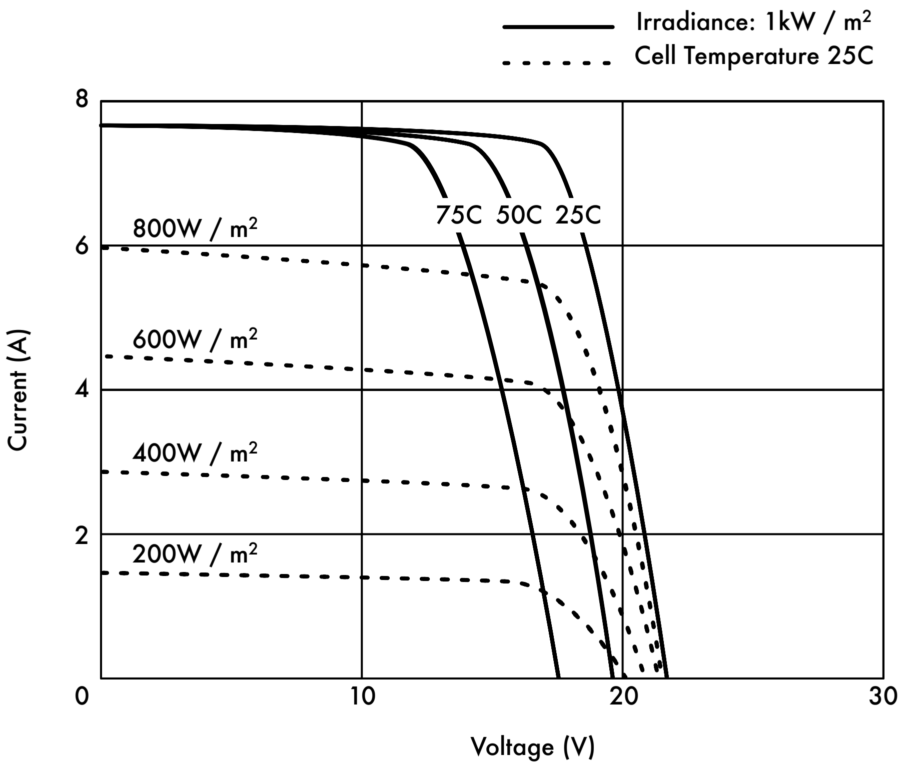

Figure 7.7: Different IV Curves. The current (A) changes with the irradiance, and the voltage (V) changes with the temperature.

The electrical performance of a solar module its represented by the ***IV characteristic curve***, which represents the current that is provided based on the voltage generated for a certain solar radiation.

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), while the voltage reduces slightly with an increase of temperature. A good regulator will try to maximize the amount of energy that a panel provides by tracking the point that provides maximum power (V x I). The maximum power corresponds to the knee of the IV curve.

Solar Panel Parameters

The main parameters that characterize a photovoltaic panel are:

1. **SHORT CIRCUIT CURRENT** (I_{SC}): the maximum current provided by the panel when the connectors are short circuited.
2. **OPEN CIRCUIT VOLTAGE** (V_{OC}): the maximum voltage that the panel provides when the terminals are not connected to any load (an open circuit). 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 cells connected in series.
3. **MAXIMUM POWER POINT** (P_{max}): the point where the power supplied by the panel is at maximum, where $P_{max} = I_{max} \times V_{max}$. 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 load or the regulator. Typical values of V_{max} and I_{max} should be a bit smaller than the I_{SC} and V_{OC}
4. **FILL FACTOR** (FF): the relation between the maximum power that the panel can actually provide and the product $I_{SC} \cdot V_{OC}$. This gives you an idea of the quality of the panel because it is an indication of the type of IV characteristic curve. The closer FF is to 1, the more power a panel can provide. Common values usually are between 0.7 and 0.8.
5. **EFFICIENCY** (h): the 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. This is normally around 10-12%, 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 see that:

$$h = P_{max} / P_L = FF \cdot I_{SC} \cdot V_{OC} / P_L$$

The values of I_{SC}, V_{OC}, I_{Pmax} and V_{Pmax} are provided by the manufacturer and refer to standard conditions of measurement with irradiance G = 1000 W/m^2, at sea-level, for a temperature of cells of T_c = 25ºC.

The panel parameters values change for other conditions of irradiance and temperature. Manufacturers will sometimes include graphs or tables with values for conditions different from the standard. You should check the performance values at the panel temperatures that are likely to match your particular installation.

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

Panel parameters for system sizing

To calculate the number of panels required to cover a given load, 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 perform under perfect conditions as the load or regulation system is not always going to work at the point of maximum power of the panel. You should assume a loss of efficiency of 5% in your calculations to compensate for this.

Interconnection of panels

A ***solar panel array*** is a collection of solar panels that are electrically interconnected and installed on some type of support structure. Using a solar panel array allows you to generate greater voltage and current than is possible with a single solar panel. The panels are interconnected in such a way that the voltage generated is close to (but greater than) the level of voltage of the batteries, and that the current generated is sufficient to feed the equipment and to charge the batteries.

Connecting solar panels in series increases the generated voltage. Connecting panels in parallel increases the current. The number of panels used should be increased until the amount of power generated slightly exceeds the demands of your load.

It is very important that all of the panels in your array are as identical as possible. In an array, you should use panels of the same brand and characteristics because any difference in their operating conditions will have a big impact on the health and performance of your system. Even panels that have identical performance ratings will usually display some variance in their characteristics due to manufacturing processes. The actual operating characteristics of two panels from the same manufacturer can vary by as much as ±10%.

Whenever possible, it is a good idea to test the real-world performance of individual panels to verify their operating characteristics before assembling them into an array.

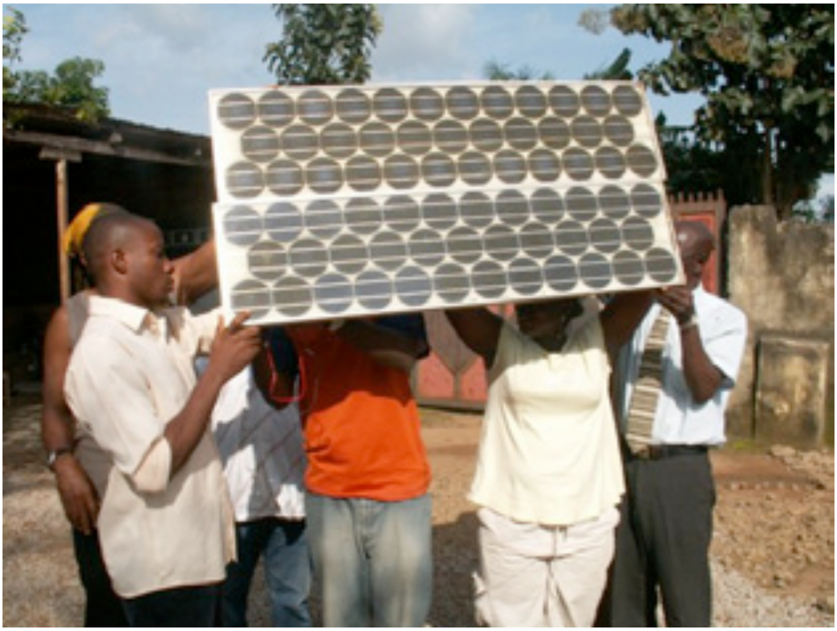

Figure 7.8: Interconnection of panels in parallel. The voltage remains constant while the current duplicates. (Photo: Fantsuam Foundation, Nigeria)

How to choose a good panel

One obvious metric to use when shopping for solar panels is to compare the ratio of the nominal peak power (W_p) to the price. This will give you a rough idea of the cost per Watt for different panels. But there are a number of other considerations to keep in mind as well.

If you are going to install solar panels in geographical areas where soiling (from dust, sand, or grit) will likely be a problem, consider purchasing panels with a low affinity for soil retention. These panels are made of materials that increase the likelihood that the panel will be automatically cleaned by wind and rain.

Always check the mechanical construction of each panel. Verify that the glass is hardened and the aluminum frame is robust and well built. The solar cells inside the panel can last for more than 20 years, but they are very fragile and the panel must protect them from mechanical hazards. Look for the manufacturer's quality guarantee in terms of expected power output and mechanical construction.

Finally, be sure that the manufacturer provides not only the nominal peak power of the panel (W_p) but also the variation of the power with irradiation and temperature. This is particularly important when panels are used in arrays, as variations in the operating parameters can have a big impact on the quality of power generated and the useful lifetime of the panels.

The battery

The battery “hosts” a certain reversible chemical reaction that stores electrical energy that can later be retrieved when needed. Electrical energy is transformed into chemical energy when the battery is being charged, and the reverse happens when the battery is discharged.

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 solution of water and sulfuric acid. A potential difference of about 2 volts takes place between the electrodes, depending on the instantaneous value of the charge state of the battery. The most common batteries in photovoltaic solar applications have a nominal voltage of 12 or 24 volts. A 12 V battery therefore contains 6 cells in series.

The battery serves two important purposes in a photovoltaic system: to provide electrical energy to the system when energy is not supplied by the array of solar panels, and to store excess energy generated by the panels whenever that energy exceeds the load. The battery experiences a cyclical process of charging and discharging, depending on the presence or absence of sunlight. 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 supplied by the battery, thereby discharging it.

These cycles of charge and discharge occur whenever the energy produced by the panels does not match the energy required to support the load. When there is sufficient sun and the load is light, the batteries will charge. Obviously, the batteries will discharge at night whenever any amount of power is required. The batteries will also discharge when the irradiance is insufficient to cover the requirements of the load (due to the natural variation of climatological conditions, clouds, dust, etc.)

If the battery does not store enough energy to meet the demand during periods without sun, the system will be exhausted and will be unavailable for consumption. On the other hand, the oversizing the system (by adding far too many panels and batteries) is expensive and inefficient. When designing a stand-alone system we need to reach a compromise between the cost of components and the availability of power from the system. One way to do this is to estimate the required ***number of days of autonomy***. In 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 will likely want to design your photovoltaic system with an autonomy of up to 5-7 days. On the other hand, if the solar system is responsible for a providing energy to client equipment you can probably reduce number of days of autonomy to two or three. In areas with low irradiance, this value may need to be increased even more. In any case, you will always have to find the proper balance between cost and reliability.

Types of batteries

Many different battery technologies exist, and are intended for use in a variety of different applications. The most suitable type for photovoltaic applications is the ***stationary battery***, designed to have a fixed location and for scenarios where the power consumption is more or less irregular. "Stationary" batteries can accommodate deep discharge cycles, but they are not designed to produce high currents in brief periods of time.

Stationary batteries can use an electrolyte that is alkaline (such as Nickel-Cadmium) or acidic (such as Lead-Acid). Stationary batteries based on Nickel-Cadmium are recommended for their high reliability and resistance whenever possible. Unfortunately, they tend to be much more expensive and difficult to obtain than 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.

Using car batteries

Automobile batteries are not well suited for photovoltaic applications as they are designed to provide a substantial current for just few seconds (when starting then engine) rather than sustaining a low current for long period of time. This design characteristic of car batteries (also called ***traction batteries***) results in an shortened effective life when used in photovoltaic systems. Traction batteries can be used in small applications where low cost is the most important consideration, or when other batteries are not available.

Traction batteries are designed for vehicles and electric wheelbarrows. They are cheaper than stationary batteries and can serve in a photovoltaic installation, although they require very frequent maintenance. These batteries should never be deeply discharged, because doing so will greatly reduce their ability to hold a charge. A truck battery should not discharged by more than 70% of its total capacity. This means that you can only use a maximum of 30% of a lead-acid battery's nominal capacity before it must be recharged.

You can extend the life of a lead-acid battery by using distilled water. By using a densimeter or hydrometer, you can measure the density of the battery's electrolyte. A typical battery has specific gravity of 1.28. Adding distilled water and lowering the density to 1.2 can help reduce the anode's corrosion, at a cost of reducing the overall capacity of the battery. If you adjust the density of battery electrolyte, you **must** use distilled water, as tap water or well water will permanently damage the battery.

States of charge

There are two special state of charge that can take place during the cyclic charge and discharge of the battery. They should both be avoided in order to preserve the useful life of the battery.

Overcharge

Overcharge takes place when the battery arrives at the limit of its capacity. If energy is applied to a battery beyond its point of maximum charge, the electrolyte begins to break down. This produces bubbles of oxygen and hydrogen, in a process is known as ***gasification***. This results in a loss of water, oxidation on the positive electrode, and in extreme cases, a danger of explosion.

On the other hand, the presence of gas avoids the stratification of the acid. After several continuous cycles of charge and discharge, the acid tends to concentrate itself at the bottom of the battery thereby reducing the effective capacity. The process of gasification agitates the electrolyte and avoids stratification.

Again, it is necessary to find a compromise between the advantages (avoiding electrolyte stratification) and the disadvantages (losing water and production of hydrogen). One solution is to allow a slight overcharge condition every so often. One typical method is to allow a voltage of 2.35 to 2.4 Volts for each element of the battery every few days, at 25ºC. The regulator should ensure a periodical and controlled overcharges.

Overdischarge

In the same way that there is a upper limit, there is also a lower limit to a battery's state of charge. Discharging beyond that limit will result in deterioration of the battery. When the effective battery supply is exhausted, the regulator prevents any more energy from being extracted from the battery. When the voltage of the battery reaches the minimum limit of 1.85 Volts per cell at 25°C, the regulator disconnects the load from the battery.

If the discharge of the battery is very deep and the battery remains discharged for a long time, three effects take place: the formation of crystallized sulfate on the battery plates, the loosening of the active material on the battery plate, and plate buckling. The process of forming stable sulfate crystals is called hard sulfation. This is particularly negative as it generates big crystals that do not take part in any chemical reaction and can make your battery unusable.

Battery Parameters

The main parameters that characterize a battery are:

- ***Nominal Voltage***, V_{NBat}. the most common value being 12 V.
- ***Nominal Capacity***, C_{NBat}: the maximum amount of energy that can be extracted from a fully charged battery. It is expressed in Ampere-hours (Ah) or Watt-hours (Wh). The amount of energy that can be obtained from a battery depends on the time in which the extraction process takes place. Discharging a battery over a long period will yield more energy compared to discharging the same battery over a short period. The capacity of a battery is therefore specified at different discharging times. For photovoltaic applications, this time should be longer than 100 hours (C100).
- ***Maximum Depth of Discharge***, DoD_{max}: The depth of discharge is the amount of energy extracted from a battery in a single discharge cycle, expressed as a percentage. The life expectancy of a battery depends on how deeply it is discharged in each cycle. The manufacturer should provide graphs that relate the number of charge-discharge cycles to the life of the battery. As a general rule you should avoid discharging a deep cycle battery beyond 50%. Traction batteries should only be discharged by as little as 30%.
- ***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 and the maximum DoD. For example, a stationary battery of nominal capacity (C100) of 120 Ah and depth of discharge of 70% has a useful capacity of (120 x 0.7) 84 Ah.

Measuring the state of charge of the battery

A sealed lead-acid battery of 12 V provides different voltages depending on its state of charge. When the battery is fully charged in an open circuit, the output voltage is about 12.8 V. The output voltage lowers quickly to 12.6 V when loads are attached. As the battery is providing 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 provides 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 when "full" and 11.6 V when "empty", we can estimate that a battery has discharged 70% when it reaches a voltage of 11.9 V. These values are only a rough approximation since they depend on the life and quality of the battery, the temperature, etc.

State of Charge	12V Battery Voltage	Volts per Cell
100%	12.7	2.12
90%	12.5	2.08
80%	12.42	2.07
70%	12.32	2.05
60%	12.2	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

According to this table, and considering that a truck battery should not be discharged more than 20% to 30%, we can determine that the useful capacity of a truck 170 Ah truck battery is 34 Ah (20%) to 51 Ah (30%). Using the same table, we find that we should program the regulator to prevent the battery from discharging below 12.3 V.

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***. Slow blow fuses should be used with inductive or capacitive loads where a high current can occur at power up. Slow blow fuses will allow a higher current than their rating to pass for a short time. Quick blow fuses will immediately blow if the current flowing through them is higher than their rating.

The regulator is connected to the battery and the loads, so two different kinds of protection needs to be considered. One fuse should be placed between the battery and the regulator, 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 into the regulator itself.

Figure 7.9: A battery bank of 3600 Ah, currents reach levels of 45 A during charging

Every fuse is rated with a maximum current and a maximum usable voltage. The maximum current of the fuse 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 easily reach several hundred amperes. Large currents can cause fire, damage the equipment and batteries, and possibly cause electric shock to a human body

If a fuse breaks, never replace a fuse with a wire or a higher rated fuse. First determine the cause of the problem, then replace the fuse with another one which has the same characteristics.

Temperature effects

The ambient temperature has several important effects on the characteristics of a battery:

- The nominal capacity of a battery (that the manufacturer usually gives for 25°C) increases with temperature at the rate of about 1%/°C. But if the temperature is too high, the chemical reaction that takes place in the battery accelerates, which can cause the same type of oxidation that takes places during overcharging. This will obviously reduce the life expectancy of battery. This problem can be compensated partially in car batteries by using a low density of dissolution (a specific gravity of 1.25 when the battery is totally charged).
- As the temperature is reduced, the useful life of the battery increases. But if the temperature is too low, you run the the risk of freezing the electrolyte. The freezing temperature depends on the density of the solution, which is also related to the state of charge of the battery. The lower the density, the greater the risk of freezing. In areas of low temperatures, you should avoid deeply discharging the batteries (that is, DoD_{max} is effectively reduced.)
- The temperature also changes the relation between voltage and charge. It is preferable to use a regulator which adjusts the low voltage disconnect and reconnect parameters according to temperature. The temperature sensor of the regulator should be fixed to the battery using tape or some other simple method.
- In hot areas it is important to keep the batteries as cool as possible. The batteries must be stored in a shaded area and never get direct sunlight. It's also desirable to place the batteries on a small support to allow air to flow under them, thus increase the cooling.

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 kg (120 pounds) 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 aging, 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 for 12 V lead-acid batteries.

Life expectancy versus number of cycles

Batteries are the only component of a solar system that should be amortized over a short period and regularly replaced. You can increase the useful lifetime of a battery by reducing the depth of discharge per cycle. Even deep cycle batteries will have an increased battery life if the the number of deep discharge (>30%) cycles is reduced.

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

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, the batteries, and your equipment or loads.

Remember that the voltage of a battery, although always close to 2 V per cell, varies according to its state of charge. By monitoring the voltage of the battery, the regulator prevents overcharging or overdischarging.

Regulators used in solar applications should be connected in series: they disconnect the array of panels from the battery to avoid overcharging, and they disconnect the battery from the load to avoid overdischarging. The connection and disconnection is done by means of switches which can be of two types: electromechanical (relays) or solid state (bipolar transistor, MOSFET). Regulators should never be connected in parallel.

In order to protect the battery from gasification, the switch opens the charging circuit when the voltage in the battery reaches its high voltage 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 battery are:

Voltage Point	Voltage
LVD	11.5
LRV	12.6
Constant Voltage Regulated	14.3
Equalization	14.6
HVD	15.5

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

As 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).

Regulator Parameters

When selecting a regulator for your system, you should at least know the ***operating voltage*** and the ***maximum current*** that the regulator can handle. The operating Voltage will be 12, 24, or 48 V. The maximum current must be 20% bigger than the current provided by the array of panels connected to the regulator.

Other features and data of interest include:

- Specific values for LVD, LRV and HVD.
- Support for temperature compensation. The voltage that indicates the state of charge of the battery vary with temperature. For that reason some regulators are able to measure the battery temperature and correct the different cut-off and reconnection values.
- 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, LVD or HVD has been reached, etc.