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Bachelor's Degree in Energy Engineering
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*Bachelor's Thesis*

# "Charging tests on a photovoltaic panel for solar cookers"

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# Acknowledgements

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# TABLE OF CONTENTS

# FIGURES INDEX

## TABLES INDEX

# 1. Abstract

This research project focuses on the process, development and outcome of collecting and storing energy through photovoltaic panels connected to batteries. The main aims of the project are: to find out if the batteries can be used to store energy while simultaneously having a load connected to the photovoltaic panel; to carry out an experimental campaign for a realistic device; to learn how the charge controller works; to experiment first-hand with real material in a laboratory and outdoors; and to see if this system could be economically feasible especially as an alternative energy source for cooking in developing countries. This system would allow the user to consume electricity during the day, for example for cooking, while the batteries are being charged so that when there is no sunlight, like at night, electricity supply would still be available. The implementation of photovoltaic panels along with storage batteries could solve many electrical supply problems worldwide. For instance, in developing countries where there is less and less firewood and its use is unhealthy due to poor ventilation of houses, in places where electricity is unaffordable or non-existent and where poorer populations of the world cannot find other means of fuel for cooking or to provide for their minimal energy needs.

Throughout this project the main components of a photovoltaic system will be explained as well as some basic concepts related to solar energy. An in depth analysis of the experimental results obtained will also be made. In order to show the positive impact these kinds of systems could have in certain areas of the world, the energy access situation in developing countries is analysed and a specific case study is applied for Nigeria. In the conclusions of this project the objectives achieved are mentioned, such as being able to decipher the functioning of the charge controller of the device used or being able to carry out an experimental characterization campaign of a realistic device.

# 2. Introduction

In today’s modern society energy plays a key role in most fields. Its use goes from covering basic needs, like lighting streets and houses, to powering more complex industrial machines. With such an increase in the demand for energy, the need for more renewable, reliable and cleaner sources of energy is urgent. We are already noticing the effects of releasing excessive amounts of polluting gases into the atmosphere and with the rise in energy demand we cannot continue to build so many power stations that burn fossil fuels. Some major reasons for this are that fossil fuels are not sustainable due to the fact that they are near depletion, and secondly because we cannot keep emitting polluting gases into the atmosphere without expecting detrimental consequences on our health and on our environment.

Amongst the renewable sources of energy a very interesting option is solar energy. The short set up time of a photovoltaic solar field compared to other types of power plants, the non-emission of gases, the low maintenance cost and its year by year growing competitiveness due to the decreasing price of photovoltaic panels, make solar energy a very attractive alternative for investors. The use of this technology combined with industrial scale batteries could become one of the main sources of electricity generation in the future. However, the technological advances needed for such an approach have not yet reached perfection stage in the field of batteries.

Even though the technology for the use of photovoltaic panels combined with a storage system is not yet totally developed for use at an industrial scale, it is viable on a smaller scale. A photovoltaic panel along with a storage system can be used by an individual in a house to carry out daily activities that need electricity and at night, when there is no sunlight, the storage system can supply the electricity that the photovoltaic panels no longer provide. Furthermore, the use of this technology, if focused on individual consumers, could be used in developing countries where many people have no access to electricity due to a lack of electrification or to the excessive price of electricity. African governments from these countries are starting to recognise the advantages that solar energy has and are starting to legislate in its favour.

The implementation of photovoltaic panels with a storage system would not only allow people in developing countries to cover their basic electrical needs like cooking, but it would also solve a health issue related to the inadequate ventilation of homes when biomass or fossil fuels are being used for cooking or heating houses.

In this project a photovoltaic panel was tested to see if it could provide enough energy to a load while simultaneously charging a pair of batteries. The results obtained from this project could be very useful because if it shows that a load can be used while charging the batteries this could be implemented in developing countries with a solar cooker as the load. This could enable people without access to electricity to cook during the day and also at night time as a consequence of the batteries. During the measurements a follow-up check was carried out on the charge and discharge of the batteries to observe their progression minute by minute. A study on the functioning of the charge controller was also done in order to have a better overall understanding on its effects on the entire system.

# 3. History of Solar Energy

## 3.1 A Short History of Solar Energy

It is known that in ancient times sunlight was used to dehydrate and preserve food. This basic use of sunlight was the first step towards future developments in the field of solar energy.

In the Siege of Syracuse (214–212 B.C.) legend has it that Archimedes invented, amongst several other defensive war machines, a giant mirror formed by hexagons to concentrate sunlight and burn from the distance the sails from the ships attacking the city.

Around the 16th century there is evidence that Leonardo Da Vinci concentrated the sun's rays in order to melt metal for the construction of architectural domes. Another known project of his was the creation of an industrial scale solar concentrator which was kilometers in diameter.

In 1767 the Swiss scientist Horace Bénédict De Saussure invented the heliothermometer, an instrument capable of measuring solar radiation. The later development of his device gave way to the present measuring instruments for solar radiation that we use today. In fact Saussure invented the first solar collector which was made of wood and glass and was used to trap solar energy.

The first material that was used in the attempts of cooking by means of the sun was glass. Solar radiation can penetrate glass, but the heat is then retained and accumulated if the space is closed. So, if a glass box is left under the sun and heated, high enough temperatures can be reached in order to cook food inside it. In 1865, the French inventor Auguste Mouchout was able to create the first machine capable of transforming solar energy into mechanical energy. This mechanism basically generated vapour through a solar collector which caused a motor to move due to the effects of its pressure. He also designed solar cookers for the French army and wrote a book on solar energy explaining how it worked and discussing possible industrial applications.

The biggest boost to the solar cooker technology was given in the 60's when The United Nations promoted its diffusion to end cooking fuel problems in the poorest regions of the world. Nowadays a lot of information on solar cookers can be found in libraries or on the internet, but it is curious to see that the technology on solar cookers has not emerged on a bigger scale in the places where it is most needed, given the fact that these places are usually the ones with more solar radiation.

## 3.2 The Discovery of Photovoltaic Energy

In 1839 Alexandre Edmond Becquerel, a French researcher, discovered the photovoltaic effect for the first time. He was experimenting with an electrolytic battery with platinum electrodes and realised that when he exposed them to the sun the current increased. This discovery introduced the beginning of the study and use of solar photovoltaic energy.

The next step in the study of photovoltaic energy was taken in 1873 when the British electrical engineer Willoughby Smith discovered the photovoltaic effect in solids, specifically in Selenium. Not long after, in 1877, Professor William Grylls Adams, with the help of his student Richard Evans Day, created the first selenium photovoltaic cell.

Further advancement occurred in 1953, when Calvin Fuller, Gerald Pearson and Daryl Chapin, while experimenting with the applications of silicon in electronics, created a solar silicon based cell, which proved to be much more efficient than those of selenium. As of that moment, improvements were made on this invention, making it capable of supplying enough energy to make small electrical devices work.

The solar energy industry kept growing until the 1950's, when the cost of natural gas descended and the extraction of coal was improved, making solar energy seem more expensive than it was and causing it to be abandoned for industrial purposes. The first commercial cells did not appear until 1956; however, they were too expensive for most people to buy until around the 1970's, when the price of solar cells fell by about 80%. In the late 1950's, solar cells were used in satellites launched by the USA and the Soviet Union.

The abandoning of solar energy for practical uses lasted until the 1970's, when the price of petroleum and gas increased. Another less important factor involved in the retake of solar energy was the danger of using gas and coal boilers, since a bad combustion could easily generate toxic gases (Carbon monoxide). Later in the 1990's, due to the Gulf War, there was a bigger interest in developing solar energy in order to depend less on petroleum.

# 4. Photovoltaic systems

Photovoltaic solar energy is used in many applications where electricity generation is needed, and can be very useful especially in areas where there is no electrical network. In order to generate and supply this energy, photovoltaic systems are used. One of the main aspects that distinguish photovoltaic systems from other renewable energy sources is that they generate electricity when they receive sunlight. However, energy consumption in many applications occurs regardless of the sun's availability, for example during the night. Therefore, depending on whether the photovoltaic system is connected to the electrical network or not, energy storage systems may be needed.

## 4.1 The functioning of photovoltaic Technology

The photovoltaic conversion consists in the direct transformation of sunlight into electricity. Most of the photovoltaic cells employed for this conversion use two or more layers of semiconductive material, typically silicon, in the form of pn-junction. Some of the advantages of these devices are that they do not have any mechanical or moving parts (this does not apply to PV panels with solar tracking technology), they do not generate pollution (except during the fabrication process), they have a long life expectancy and each year their efficiency increases while their price decreases.

In order to understand how a photovoltaic cell works we must first know some basic concepts to be able to understand the process.

- Atom: It is composed of a nucleus and electrons that orbit around the nucleus. The closer an electron is to the nucleus the more energy is required to overcome the attraction to the nucleus and become free.
- Energy Bands: A grouping of the energy levels that occurs when atoms are together.
- Valence Band: It is the outermost electron orbital (or shell) of an atom where if enough energy is gained the electrons can escape their bonds and move into the conduction band (In the conduction band electrons can move freely creating electric current).
- Band Gap: It is the distance between the valence band and the conduction band. The band gap represents the minimum energy required for an electron to move into the conduction band. By looking at the size of the band gap in figure 1 we can see the difference between conductors, semiconductors and insulators.
- Hole: It is the space left behind by an electron when it leaves an atom. This absence leaves a positive charge in the hole’s location.
- Behaviour of the carriers (electrons/holes): When an electric field is present electrons will move in the opposite direction of the electric field while the holes will move in the same direction as the electric field. However, when there is no electric field the carriers (electrons/holes) move randomly.

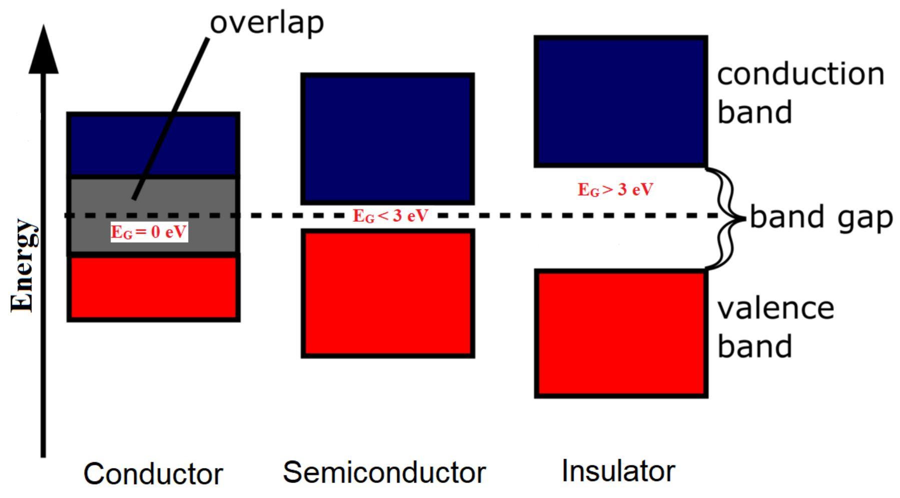

**Figure 1. Band gap diagram for conductors, semiconductors, and insulators [1]**

When light strikes a semiconductor three things can happen. It can be reflected, absorbed or transmitted through the pure semiconductors. In our case, the desired option is that the light is absorbed by the photovoltaic cell since reflection and transmission are loss mechanisms.

When a photon is absorbed by the cell if it has enough energy an electron will be excited into the conduction band. There are three possible scenarios depending on the amount of energy the photon has:

- If $E_{ph} < E_G$ the photons will interact weakly and pass through the semiconductor as if they were transparent.
- If $E_{ph} = E_G$ photons will be efficiently absorbed.
- If $E_{ph} > E_G$ photons will be strongly absorbed but the excess of energy will be wasted (Inefficient).

$E_{ph} = h \times \upsilon$; Where h is Planck's constant: $h = 6.626 \times 10^{-34}$ [J · s]

Semiconductors can be intrinsic or extrinsic. Intrinsic semiconductors have no impurities and the number of carriers they have depends on the material itself. On the other hand, extrinsic semiconductors are doped with small amounts of impurities.

As said before, most photovoltaic cells use two layers of silicon in the form of pn-junction. This pn-junction form basically consists of joining together an n-type silicon layer with a p-type silicon layer. The terms n-type and p-type are used to refer to the charge of the semiconductor. In the case of an n-type semiconductor the term refers to the negative charge of the electron since there are more electrons than holes, while in a p-type semiconductor the term refers to the positive charge of the holes since in this case they are more abundant.

In n-type silicon semiconductors silicon atoms can be replaced by atoms with 5 valence electrons, leaving the extra electron free to participate in the conduction band. Phosphorus is a commonly used dopant for n-type silicon.

In p-type silicon semiconductors the silicon atoms can be replaced by atoms with 3 valence electrons, leaving a hole free to participate in the conduction band. For p-type silicon a commonly used dopant is Boron.

If we had a close look at a photovoltaic cell we could see that the silicon layer that is on top (where the light will hit first) is the n-type.

In a photovoltaic cell when the n-type and the p-type silicon semiconductors are joined the excess electrons from the n-type side feel attracted by the holes of the p-type side and migrate towards the p-type side. In the same way, the excess holes from the p-type side feel attracted by the electrons and diffuse to the n-type side. The movement of electrons towards the p-type side leaves positive charges in the n-type side and the movement of the holes towards the n-type side leaves negative charges in the p-type side, creating an electric field that can be seen in figure 2. The more electrons move towards the p-type side the stronger the electric field gets and the more it slows down the migration of electrons towards the p-type side (electrons naturally move in the opposite direction to the electric field). As a result of the electric field, a potential difference is set up.

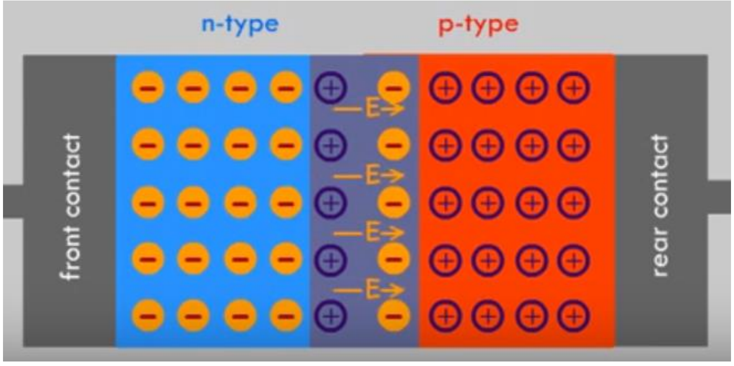

**Figure 2. Electric field formed in a pn-junction from a PV cell [2]**

When sunlight shines on the cell the photoelectric effect takes place. The photoelectric effect consists in photons striking the semiconductor and exciting the silicon atoms causing the electrons to mobilize and break free (this happens as long as the photon’s energy is equal or higher than the band gap energy). Due to the electric field the excess electrons stay on the n-type side while the excess holes are swept over to the p-type side. This creates an extra negative charge on the n-type side and an extra positive charge on the p-type side. If a load is connected to both sides, as in figure 3, the electrons will be attracted to the p-type side and travel through the circuit in order to get there since the electric field prevents the passage of electrons. As a result an electric current will flow through the circuit.

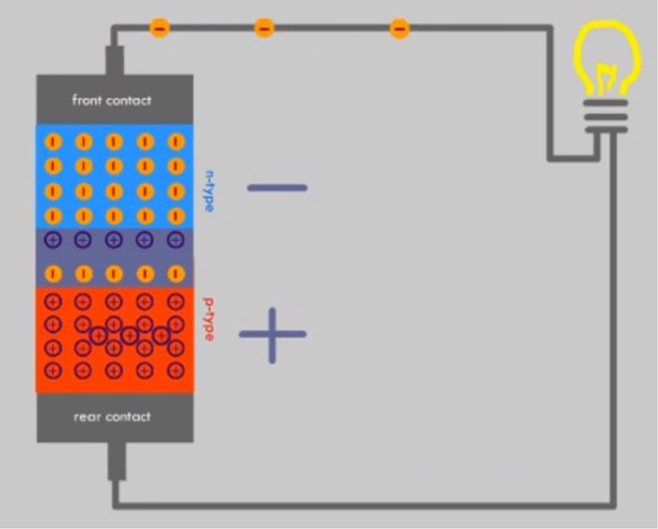

**Figure 3. Flow of electric current in a circuit connected to a PV cell [2]**

In the absence of light the solar cell does not produce any current or voltage. The solar cell works as a diode, when we connect it to a large external voltage supply it generates a current called the diode or dark current ($I_D$).

When sunlight hits the solar cell and the positive and negative sides are connected forming a circuit, the resulting current obtained is called photocurrent ($I_{ph}$). In order to obtain the net current the normal diode current ($I_D$) must be subtracted from the photocurrent ($I_{ph}$). The net current is expressed with the following formula:

$$I = I_{ph} - I_0(\exp\left(\frac{e\times V}{k\times T_C}\right) - 1)$$

$I_0$ = Dark saturation current (A)
$T_C$ = Absolute temperature of the cell (K)
k = Boltzmann's gas constant = 1.381 x$10^{-23}$ (J/K)
e = Electronic charge = 1.602 x$10^{-19}$ (J/V)
V = Voltage imposed across the cell (V)

There are three types of solar cells monocrystalline silicon cells, multicrystalline silicon cells and amorphous silicon cells. Monocrystalline silicon cells are made of pure monocrystalline silicon, they have an ordered crystal structure, they have no impurities and they have an efficiency between 15% and 18%. The drawback of these types of solar cells is that their manufacturing cost is quite high. Multicrystalline cells have numerous grains and are easier to manufacture but they have a lower efficiency (12% to 14%). Finally, amorphous silicon cells are very thin cells whose substrate can be rigid or flexible and they have silicon atoms in a thin homogeneous layer. The problem with these types of solar cells is that their efficiency is very low (6%) [3].

The efficiency values of solar cells might seem low due to several factors. Firstly, we must take into account the thermodynamic efficiency limit, which is the absolute maximum theoretical efficiency when converting sunlight into electricity. For photovoltaic cells that do not concentrate the sun’s radiation, like the ones we use in this project, the theoretical maximum efficiency is around 43%. For photovoltaic cells that concentrate the sun’s radiation this value goes up to around 83%. Secondly, the Shockley-Queisser limit must also be taken into account. This limit refers to the maximum amount of energy a photovoltaic cell can collect from the sun with a single p-n junction, which is around 30% [4]. The reason for this is that photovoltaic cells only react with certain frequencies of the light spectrum. Most panels work with light with a wavelength between 400 and around 1100 nm [5], not being able to use a big part of the light spectrum. Moreover, in order for an electron to be excited into the conduction band a photon with energy equal or higher to the band gap energy is needed, so photons with less than that energy are wasted. The excess energy from photons with higher energy than the band gap one will also be wasted. These are some of the main reasons why the efficiency of solar cells is relatively so low.

Solar cells are connected together to increase their output power, forming a photovoltaic module. Most modules consist of a transparent top surface, that is hermetic to water and vapour, has a low reflectivity and has a high impact resistance, an encapsulant, to provide adhesion between the solar cells, the top and the rear surfaces of the photovoltaic module, a rear layer and a frame. These parts can be seen in figure 4. Modules can be connected in series or in parallel to form arrays and produce even more output power.

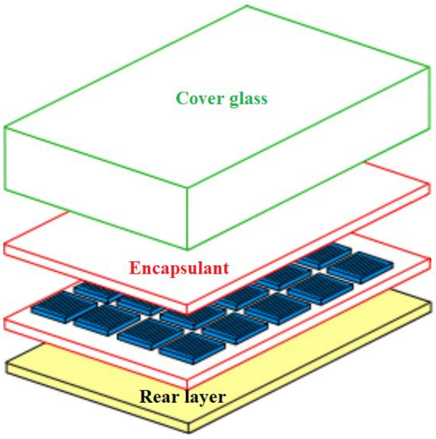

**Figure 4. Parts of a PV module [3]**

## 4.2 Types of photovoltaic systems

There are two main types of photovoltaic systems, those that are not connected to the electrical network and are called autonomous photovoltaic systems and those that are directly connected to the electrical network.

### 4.2.1 Autonomous photovoltaic systems

The electricity produced in the photovoltaic conversion is used to cover a certain electrical demand in remote places isolated from the electrical network, where they are competitive (in financial terms and in reliability of supply) with conventional systems.

There are different possible configurations for the autonomous photovoltaic systems depending on the level of complexity that the owner wants. The simplest configuration of the system consists of a photovoltaic generator that operates a DC load. Other more complex configurations can include, apart from the photovoltaic generator, storage batteries and DC loads or DC+AC loads. The usage of a power inverter in the photovoltaic system to allow the provision of service to AC loads reduces the system’s operating performance if the power consumed is much less than the rated power from the inverter. This is due to the typical efficiency curve that autonomous power inverters have. For example, in an autonomous photovoltaic system in which all the loads are in AC with a power inverter of 1kW of rated power, the usage of an only lamp with a consumption of 18W of power would make the power inverter work with a very low efficiency. This is why illumination is normally designed with DC loads and the rest of the loads are designed in AC.

We can distinguish different autonomous photovoltaic systems depending on their applications: electrification systems, professional systems and agricultural systems.

- Electrification systems: One of the markets with more present demand is power supply for houses, mainly for illumination and home appliances, that are isolated from the electrical network both in developing and developed countries. Isolated houses (distributed electrification) or entire towns (centralized electrification) can generate their own electricity without the need for a sophisticated maintenance or regular fuel supplies. These autonomous photovoltaic systems can also be used for exterior lighting in smaller sizes. Each illumination point can have its own generator, battery and charge controller to provide maximum reliability and flexibility. Some examples of systems in exterior lightning are road signs, illumination in gardens and public street lighting.

- Professional systems: Telecommunications and professional applications are another of the traditional markets in which photovoltaic solar energy is used. Most of these devices work with direct current, making the coupling to the direct current from the photovoltaic system simple and cheap. Reliability is critical in these devices, since a fault can be extremely expensive. On the other hand, modularity and flexibility in the photovoltaic systems allow powering from the smallest to the largest devices that are sometimes in remote and inaccessible locations. Some examples are radio and TV repeaters and telemetry stations.

### 4.2.2 Photovoltaic systems connected to the electrical network

Photovoltaic systems connected to the electrical network are mainly found in photovoltaic power plants, where electricity is produced at an industrial scale and injected to the network, and on house roofs, where electricity is produced for private consumption.

When installing a photovoltaic system some factors like the losses due to shading, the optimum angle to maximize electricity generation (if the panels are fixed) or the architectural and environmental integration must be taken into account. Once the system is connected to the grid we must ensure the absence of disturbing effects on the electrical network.

Typically, the nominal power of the installations in single family homes or buildings is related to the available useful surface for the photovoltaic generation system. An approximate size from 8 to 10 $m^2$ is needed to obtain 1 kWp depending on the performance of the photovoltaic generator. The typical power value in most installations stands at around 5 kWp in single family homes and up to 100 kWp in other buildings. The connection to the electrical network in this kind of systems can be directly done through the low voltage network in single-phase mode if the input is less than or equal to 5 kW and in three phase mode if it is above 5kW.

Other types of photovoltaic systems connected to the electrical network are the photovoltaic solar plants, with nominal power values above 100 kWp. These power plants normally have access to the electrical network through a medium or high voltage connection but before doing so the electricity passes through a transformer that raises the output voltage from the power inverter adapting it to the network voltage. A great advantage photovoltaic solar plants have is that they can be set up much faster than other conventional power plants due to the ease in installing and connecting the photovoltaic generator. Photovoltaic solar plants can also be used to laminate the consumption demand peaks that often take place during the peak generation hours of photovoltaic solar plants at midday.

## 4.3 Components of a Photovoltaic system

In general, a photovoltaic system is composed by a photovoltaic generator, a storage battery, a charge controller and a power inverter. An example of a photovoltaic system can be seen in figure 5.

- ***Photovoltaic Generator:*** Its function is to transform the suns energy into electricity. It is composed of many photovoltaic modules connected in series or/and in parallel, and at the same time each photovoltaic module is composed of basic components called photovoltaic cells. The power that a typical photovoltaic cell can produce is normally of the order of 3W. Since this value is quite low, producers normally group them together connecting them in series and in parallel to end up forming a photovoltaic module, which is what people normally buy. The power that a photovoltaic module can provide depends on the number of cells it has. A typical value for modules composed of 36 cells connected in series ranges between 50 and 100W. If more power is needed, further modules will have to be connected in series and in parallel until the desired power is attained.

- ***Storage battery:*** If needed (systems connected to the electrical network do not need storage), the energy produced by the photovoltaic generator is stored in this component. By storing in this way, the energy produced during the hours in which there is sunlight can be used during the night or during the moments in which the amount of solar radiation is not sufficient to cover the power demand. The storage battery will therefore be charging and discharging itself cyclically, and to control these processes a charge controller will be needed.

- ***Charge Controller:*** This device is in charge of protecting the storage battery against excessive overloads or discharges that could damage the battery and reduce its useful lifespan. The operating mode is quite simple, when the device detects that the battery is being overcharged it disconnects the photovoltaic generator and when the device detects that the battery is being over-discharged it disconnects the load.

- ***Power inverter:*** The purpose of this component is to transform direct current (DC) into alternating current (AC) with the maximum efficiency possible. Photovoltaic modules produce direct current that can be directly stored in batteries and when power is drawn from them it is also in the form of direct current. If the need arises to provide service to certain loads that work with alternating current, which is the most common scenario, a power inverter would be put in place to transform direct current into alternating current. Nevertheless, there are also DC/DC power inverters that are used when the intention is to modify the relation between voltage and current of a DC power source. Loads are an essential part in a photovoltaic system because they determine the size of the system. The loads that must be satisfied can be in AC or DC, but normally photovoltaic systems that supply energy to the electrical network always need to do so with alternating current.

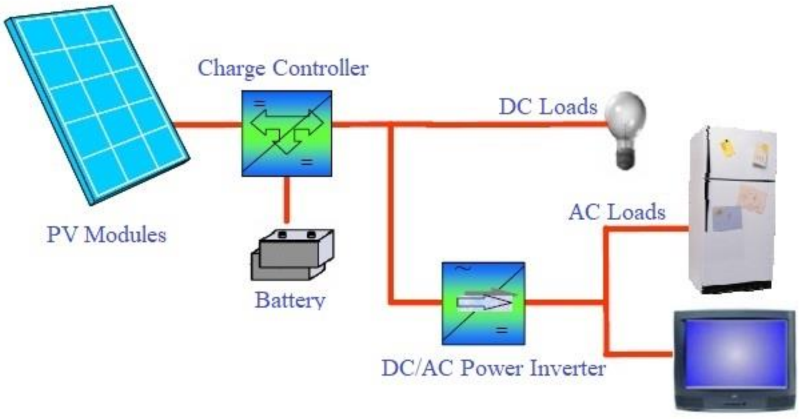

**Figure 5. Basic structure of an autonomous photovoltaic system**

Large Photovoltaic systems are usually far from urban areas, so in order to transport electricity in an efficient way the use of substations is necessary. To begin with, the direct current coming from the photovoltaic system must be transformed into alternating current by means of a power inverter if it has not already been done. Then a transformer raises the voltage level through electromagnetic induction and electricity flows through the electrical lines towards urban areas where the voltage level is then reduced again by another transformer and distributed throughout the area. The conversion of direct current into alternating current and the voltage raise are done in order to reduce losses during the transportation process.

# 5. Batteries

In photovoltaic systems batteries are used mainly as an energy storage system, due to the temporary displacement that may exist between the generation and consumption periods. Nevertheless, they can also be used for other purposes such as voltage stabilizers and to supply a surge of high current (for example: engine start-ups). Batteries are commonly used in autonomous photovoltaic systems but not in photovoltaic systems connected to the electrical network.

The vast majority of batteries in the market are lead-acid (Pb-a) which work well in photovoltaic systems as long as an adequate maintenance is carried out. Other types of batteries are Lead-Calcium (Pb-Ca) and Lead-Antimony (Pb-Sb). The first type mentioned (Pb-Ca) needs less maintenance and has a lower self-discharge, while the Lead-Antimony (PB-Sb) battery deteriorates less during the daily cycle and delivers enhanced performance at low load levels.

The most common batteries used in photovoltaic applications are Lead-Acid and Nickel-Cadmium. Due to cost the use of Lead-Acid batteries is more frequent although sometimes Nickel-Cadmium batteries are used in professional applications where cost is not a definitive factor. The Nickel-Cadmium batteries have many advantages respect to the Lead-Acid ones, like the possibility of undergoing deep discharges or being able to remain long periods in low load levels without deteriorating. Other qualities that can be highlighted are its lower self-discharge and a lower requirement for maintenance. There are also other types of batteries (Ni-Fe, Ni-Zn, $Zn\text{-}Cl_2$…), but their characteristics are not adequate for their use in photovoltaic applications.

## 5.1 Common components of a battery

Batteries are normally composed of elements of 2 volts that connected in series supply the operating voltages of 12 V, 24 V, 48 V, etc. The capacity (Ah) of a group of batteries connected in series is equal to the capacity of each one of the elements that compose the group. On the other hand, if that group of batteries is connected in parallel, the capacity of their elements is added together. The required capacity from the batteries in a photovoltaic system is estimated taking into account the loads and the days of autonomy of the system. An appropriate dimensioning of the batteries is important, since an excess of capacity would lead to difficulties in being able to fully charge and a lack of capacity would lead to little autonomy and the risk of running out of energy supply if there is no solar radiation.

Lead-Acid batteries are electrochemical cells in which the reactions in the electrodes are reversible and therefore can be used to accumulate energy and release it afterwards when connected to a circuit with an external load. Electrochemical cells are essentially composed of plates, active matter and electrolyte.

- The cell: Basic electrochemical element of a battery. It consists of a set of positive and negative plates divided by insulating separators, immersed in an electrolyte solution, all inside a container. In a typical Lead-Acid (Pb-a) battery each cell has a nominal voltage of around 2V, that can be associated in series to give voltages of 12V (6 cells in series) or 24V (12 cells in series).

- The plates: They consist of a grid with active matter, often called electrode. Positive and negative electrodes allow the entrance and exit of electric current by the effects of the charging and discharging processes. The electrodes undergo oxidation/reduction reactions and depending on the process they work as an anode or as a cathode. Commonly, in each cell there are a number of plates connected in parallel to a bus that is located on the top part of the plates, both positive and negative. The depth of the cycling of a battery depends on the thickness of the plates. In starter batteries many thin plates are used, resulting in a large reaction surface for the supply of high currents in a short period of time, but making them not very resistant to deep and prolonged discharges. On the other hand, the use of thicker plates allows deep discharges over long periods of time maintaining a good adherence of the active matter to the grid (this will result in a longer useful life for the battery).

- They form the positive and negative electrodes that allow the entrance and exit of the electric current that circulates inside each element of the battery by the effects of the charging or discharging processes.

- Active material: they are a part of each cell and are involved in the electrochemical reaction of charging and discharging. In some types of plates, grids are used to retain the active material and improve the distribution of the current on the plate.

- Electrolyte: It is a diluted solution of sulfuric acid, in the case of Lead-Acid batteries, that works as a means of transport of electric charges between the positive and negative plates and also intervenes in the charging and discharging reaction.

- Grid: It serves as a support for active matter and in Lead-Acid (Pb-a) batteries it’s formed by a lead alloy. Antimony or Calcium are normally used as alloy elements in order to strengthen the grid and therefore define the different characteristics from the battery (like the cycling capacity and the battery gassing). Depending on the shape of the grid the plates of the batteries can be tubular or flat.

- Separators: They are porous (rubber, plastic,…) and insulating materials that separate the positive and negative plates avoiding a short circuit and allowing the flow of electrolyte and ions in between the plates.

- Element: The set of positive and negative plates and separators, assembled together with buses that interconnect positive and negative plates.

- Terminals: They are the external electrical connections (positive and negative).

- Filler plugs: During the charging process some gases are produced and escape to the exterior through the filler plugs.
- Battery casing: Commonly made of plastic or hard rubber. It contains all the elements of the battery. Transparent battery cases make it easier to control visually the level of electrolyte.

## 5.2 Types of batteries

Batteries are normally divided into two categories: primary and secondary. Primary batteries are non-rechargeable and are not used in photovoltaic systems. Secondary batteries are the ones that are used in photovoltaic systems since they are rechargeable.

Some of the most commonly used secondary batteries are shown in table 1 and their characteristics will now be further analysed.

**Table 1. Secondary battery types and characteristics [25]**

| Type | Cost | Deep cycling | Maintenance |
|---|---|---|---|
| ***Lead-Acid*** | | | |
| Lead-Antimony | Low | Good | High |
| Lead-Calcium Open | Low | Poor | Medium |
| Lead-Calcium Sealed | Low | Poor | Low |
| Hybrid (Antimony/Calcium) | Medium | Good | Medium |
| ***Immobilized Electrolyte*** | | | |
| Gel | Medium | Very good | Low |
| AGM | Medium | Very good | Low |
| ***Nickel-Cadmium*** | | | |
| “Sintered” plates | High | Good | None |
| “Pocked” plates | High | Good | Medium |

***Lead-Acid batteries***

They are the most used in photovoltaic applications due to their low cost compared with other type of batteries.

The types of Lead-Acid (Pb-a) batteries can be classified in the following way:

- Starter batteries: They are designed for very shallow cycles. They are mainly used in the start-up of engines from the automotive sector to provide high levels of current in a short period of time.

- Traction batteries: They are designed for very deep cycles. They are mainly used in electric vehicles. These batteries are built to last longer and therefore have thicker and less plates than other types of batteries. Grids with high lead-antimony content are used in order to improve the deep cycling.

- Stationary batteries: They are commonly used in uninterrupted power systems (computer systems or telecommunications). They are designed for very sporadic operations and they rarely get discharged. They are normally in a continuous floating charge status.

Some of the main characteristics of the different types of Lead-Acid batteries will now be further explained:

- Lead-Antimony batteries: They use Antimony as the main element in the Lead alloy in the grids, providing greater mechanical strength and high discharge rates with a very good cycle depth. They also reduce the loss of active matter and have a longer life expectancy than Lead-Calcium batteries when operating at high temperatures. On the other hand, they have a high self-discharge and therefore require a frequent addition of water. Most of these batteries are open with recombination vent caps to decrease maintenance.

- Lead-Calcium batteries: They use Calcium as the main element in the Lead alloy in the grids. They have a lower self-discharge and a lower gassing (therefore a lower maintenance) than the Lead-Antimony batteries. However, they have a worse acceptance of the load after deep discharges and have a shorter life time under repetitive discharges that are over 25%. Generally, they do not tolerate well overcharges, very deep discharges and operation under high temperatures. These batteries can be of two types: open or sealed. Sealed batteries do not need maintenance and have enough electrolyte for their time life without adding water.

- Hybrid batteries: They are normally open type with capacities of around 200 Ah. The most common design uses tubular positive plates made of calcium and flat negative plates made of antimony, combining the advantages of both elements. Nevertheless, special care must be taken with possible stratification and sulfation problems.

The chemical reactions in a Lead-Acid battery are:

- In the positive plate:

$$\boldsymbol{PbO_2 + 4H^+ + 2e^- \Leftrightarrow Pb^{2+} + 2H_2O} \tag{1}$$

$$Pb^{2+} + SO_4^{2-} \Leftrightarrow PbSO_4 \tag{2}$$

- In the negative plate:

$$\boldsymbol{Pb \Leftrightarrow Pb^{2+} + 2e^-} \tag{3}$$

$$Pb^{2+} + SO_4^{2-} \Leftrightarrow PbSO_4 \tag{4}$$

- In the global reaction:

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O \tag{5}$$

## ***Immobilized Electrolyte batteries***

They are another type of Lead-Acid battery with the difference that in them the electrolyte is immobilized in some way. These batteries are very sensible to the charging methods, voltage regulations and operation under high temperatures. The most common types of these batteries are the gel and AGM (Absorbed Glass Mat) batteries.

Gel batteries normally use Lead-Acid grids. The addition of silicon dioxide “gels” the electrolyte. These batteries use an internal mechanism of recombination to minimize the escape of gases and reduce the water losses. Some have a small amount of phosphoric acid added to the electrolyte in order to improve the depth of discharge in the cycling, minimizing the corrosion of the grid at low charge states.

In AGM batteries the electrolyte is in crystalline form creating layers in between plates. They are specially designed to minimize water losses during an overcharge.

## ***Nickel-Cadmium Batteries***

The main characteristics of the Nickel-Cadmium batteries are their long life expectancy, low maintenance, they are not affected by excessive overcharges and voltage regulations are not critical parameters. However, the price of these types of batteries is much higher than the price of Lead-Acid batteries.

In a cell from a typical Nickel-Cadmium battery the positive electrodes are made of Nickel hydroxide (NiO(OH)) and the negative electrodes are made of Cadmium (Cd). Both electrodes are immersed in a potassium hydroxide (KOH) solution. During the discharge process Nickel hydroxide turns into Nickel Hydroxide (II) ($Ni(OH)_2$,) and Cadmium turns into Cadmium hydroxide ($Cd(OH)_2$). The concentration of electrolyte does not change during the reaction.

The two main types of Nickel-Cadmium batteries are those with “sintered” plates and those with “pocked” plates. In the Nickel-Cadmium batteries with “sintered” plates the electrolyte is immobilised and presents the so called “memory effect” by which a battery that is discharged several times to a percentage of its capacity will memorize this cycle and will limit greater discharges giving as a result a loss of capacity. The Nickel-Cadmium batteries with “pocked” plates require water addition periodically but do not present the memory effect.

The chemical reactions in a Nickel-Cadmium battery are:

- In the positive plate:

$$\mathbf{2NiO\,(OH) + 2H_2O + 2e^- \Leftrightarrow 2Ni\,(OH)_2 + 2OH^-} \tag{6}$$

- In the negative plate:

$$\mathbf{Cd + 2OH^- \Leftrightarrow Cd\,(OH)_2 + 2e^-} \tag{7}$$

- In the global reaction:

$$\mathbf{Cd + 2NiO\,(OH) + 2H_2O \Leftrightarrow Cd\,(OH)_2 + 2Ni\,(OH)_2} \tag{8}$$

## 5.3 Battery Performance characteristics

The performance of a battery depends on many factors, like the material used in it. Therefore if a person is to use a battery for a specific task the following aspects must be taken into account.

*Causes of the aging of a battery*:

- Degradation of the positive plates: The continuous cycles of charge and discharge cause regular dilation and contraction of the materials from the positive plates reducing the adhesion of the active material to the grid and causing its detachment.

- Degradation of the negative plates/sulfation: When a battery remains long periods of time discharged or normally receives insufficient recharges, it loses irreversibly active matter. This is due to the recrystallization of the fine crystals of lead sulphate formed during the discharge, turning into large crystals that have greater difficulty in transforming during the next charge of the battery and reduce the active area. This will inevitably involve an increase in the inner resistance, a higher heat generation and a reduction of the capacity. The deeper the discharge, the more active material is turned into lead sulphate. During the charging process lead sulphate is reconverted into lead dioxide. This reconversion is inhibited if the battery remains discharged for extended periods of time.

- Stratification: It occurs as a consequence of gravity and long periods of inactivity of the battery. A density gradient is established between the top and the bottom of the battery, having electrolyte with higher density at the bottom and electrolyte with lower density at the top. In order to counteract the electrolyte stratification an overcharge voltage can be applied to stimulate the homogenization of the electrolyte due to the agitation produced by the bubbles of the gassing effect.

- Self-discharge: It is a loss of capacity that normally occurs when the battery is in an open circuit. The self-discharge of a battery increases with higher operating temperatures.

*Battery cycling*

The cycling of a battery refers to the processes of charge and discharge that occur within the battery. The discharge process occurs when the battery supplies a certain amount of current for a period of time (discharge rate). During the charging process the battery receives a certain amount of current for a period of time (charging rate). When we talk about a cycle we are referring to a discharge followed by a recharge.

Depending on the depth of the discharge the useful life of the battery can be affected. With deeper discharges the number of cycles of a battery decreases. Generally, a battery is said to have ended its useful life when 20% of its initial capacity has been lost. Moreover, the lifetime of a battery does not only depend on the number of cycles, but also on the operating conditions.

*Battery Capacity*

The capacity is a measure of the power of a battery to store or supply electrical energy and is commonly expressed in ampere-hours (Ah). It can also be expressed in watt-hours (Wh) multiplying the ampere-hours (Ah) by the rated voltage of the battery.

The capacity is specified for a certain rate of discharge and depends on multiple design and operational factors. Amongst the design factors are the quantity of active matter, the number, design and dimensions of the plates and the density of the electrolyte. On the other hand, the operational factors consist of the discharge rate, the depth of discharge, the cut-off and restart voltage, the operating temperature and the cycling of the battery.

Low temperatures reduce the available capacity of the batteries (For every 10ºC decrease in temperature, taking as the initial temperature the operating temperature of each battery, the capacity is reduced around 10%). At low temperatures the resistivity and viscosity of the acid increase and therefore during the discharge of the battery the electrolyte does not penetrate so deeply into the active matter of the plates and the cut-off voltages are reached sooner. If the inner temperature of the battery was to reach the electrolyte freezing point (In fully charged batteries the freezing point of the electrolyte is around -60ºC, but as the battery gets discharged the freezing point approaches 0ºC) the battery would suffer an irreversible damage. In order to avoid reaching the freezing point of the electrolyte a more concentrated acid is used in batteries that normally operate at temperatures below zero. On the other hand, high temperatures increase the capacity of the battery but the downside is that the life expectancy of the battery is significantly reduced (For every 10ºC increase in temperature, taking as the initial temperature the operating temperature of each battery, the life expectancy of the battery is reduced by half). Most manufacturers recommend operating temperatures between 20ºC and 30ºC.

### *State of charge*

The state of charge is defined as the quantity of energy available in the battery and is expressed as a percentage of the available energy respect to the fully charged battery. Therefore, a fully charged battery is said to be at 100% of the state of charge (SOC) and a fully discharged battery is at 0% of the state of charge (SOC). Changes in the state of charge are reflected in the density of the electrolyte and in the voltage of the battery.

The classical methods to determine the state of charge are measuring the open circuit voltage, determining the internal resistance, measuring the density of the electrolyte and calculating the ampere-hours of charge/discharge.

### *Density of the electrolyte*

The density of the electrolyte is directly related to the state of charge (SOC) of the battery depending on the concentration of the electrolyte in the design and the temperature. Therefore, by measuring the density of the electrolyte we can obtain the state of charge of the battery (SOC). However, sometimes low or inconsistent values of the density can indicate sulfation, stratification or lack of equalization between cells and in some cases, if the values of the density are very low, an internal failure or an internal short-circuit.

In a lead-acid battery the electrolyte is a solution of sulfuric acid and water. In a totally charged battery the solution of the electrolyte has sulfuric acid at 36% weight or at 25% volume. If we take into account an operating temperature of 27ºC, values between 1,250 and 1,280 g/cm$^3$ (depending on the density of the acid used) indicate that the battery is 100% SOC, while values close to 1 g/cm$^3$ indicate that the battery is fully discharged (0% SOC). When a battery is discharged, hydrogen ions ($H^+$) and sulphate ions ($SO_4^{2-}$) from sulfuric acid combine with the active matter from the positive and negative plates to form lead sulphate ($PbSO_4$), reducing the density of the electrolyte. When a battery is being discharged the acid solution dilutes more and more until there are no ions left in the solution and the density of the electrolyte is near to that of the water.

The density of the electrolyte also affects its freezing point. As seen in table 2, when the battery is discharged its density decreases and its freezing point increases.

**Table 2. Freezing points of the electrolyte depending on its density. [25]**

| Density (g/cm$^3$) | Weight concentration (%) | Volume concentration (%) | Freezing point (ºC) |
|---|---|---|---|
| 1,000 | 0,0 | 0,0 | 0 |
| 1,050 | 7,3 | 4,2 | -3,3 |
| 1,100 | 14,3 | 8,5 | -7,8 |
| 1,150 | 20,9 | 13,0 | -15 |
| 1,200 | 27,2 | 17,1 | -27 |
| 1,250 | 33,4 | 22,6 | -52 |
| 1,300 | 39,1 | 27,6 | -71 |

In very cold climates the density of the electrolyte adjusts in a range of 1,250 to 1,280 g/cm$^3$, while in tropical climates the range is 1,210 to 1,230 g/cm$^3$. The low concentration of electrolyte contributes to increasing the battery's life expectancy by reducing the degradation effect of the grids and separators. However, these low concentrations of electrolyte decrease the capacity of the battery.

### *Depth of discharge (DOD)*

The depth of discharge (DOD) of a battery is the percentage of capacity that has been extracted respect to the capacity when the battery is fully charged. Therefore, when adding the state of charge (SOC) and the depth of discharge (DOD) we must get 100%.

In Lead-acid batteries (Pb-a), the lower the depth of discharge (DOD) the longer the useful life of the battery. The maximum depth of discharge (DOD) recommended for a battery (in order not to lose life expectancy) is normally given by the cut-off voltage and the discharge rate. For deep-cycle batteries the depth of discharge (DOD) can reach up to 80% while for starter batteries it only reaches up to 15-20%.

In photovoltaic systems the DOD is an indicator of the autonomy when no energy is received from the photovoltaic generator during a period of days and energy must be supplied for consumption. If the system has a low DOD this translates into a short period of autonomy.

### *Different cycle type batteries*

- *Shallow cycle batteries:*

Shallow cycle batteries are normally used as starter batteries. Their grids are made of lead-calcium and they must not be discharged (DOD) more than 15% per day. The total charge of these type of batteries must never be under 50% of their capacity, since it would be very difficult to recharge them after (especially when using low cost batteries). They are designed to provide large currents in a short period of time and do not stand deep discharges.

- *Deep cycle batteries:*

Deep cycle batteries can withstand large discharges for long periods of time but, in spite of that, they should not be discharged 100%. Most manufacturers recommend not discharging over 80% of the battery’s nominal capacity.

### Battery charge

While the battery is being charged current flows in the opposite direction from when the battery is being discharged, restoring the active matter in the plates. This increases the voltage, the density of the electrolyte and the state of charge.

There are four charging phases (these can be seen in figure 6) when charging a battery with a charge regulator:

- Bulk phase: This first stage takes place when a battery is discharged. All the current produced by the photovoltaic panels is injected into the battery, increasing its voltage until a state of charge between 80% and 90% is reached. After this point the absorption phase takes place. In this project two batteries of 12V each connected in series (24V in total) reached a maximum voltage value of 28V approximately during the bulk phase, while the current value was near to 2A.
- Absorption phase: Once the absorption voltage (voltage reached at the end of the bulk phase) is reached the charge regulator maintains it constant and slowly begins to decrease the current inflow until the battery is fully charged. The purpose of this phase is to recover the electrolyte that might have been altered during deep discharge processes. In the case of the batteries used in this project the voltage value during the absorption phase was around 28V and the minimum value of the current during this phase was around 0.7A.
- Floating phase: When the battery is fully charged a low current value is maintained in order to compensate the self-discharge of the battery. At the beginning of this phase there is a small drop in the voltage value after which it remains constant. In this research the voltage value was near to 27V during the floating phase and the value of the current was around 0.1A.
- Equalization phase: Here the battery is basically being overcharged to maintain the consistence between the different cells that form the battery (for example, when some cells have a different density than others). This type of charge is used periodically in order to reverse the stratification and eliminate sulfation. The voltage value in this phase can rise slightly above the voltage value in the absorption phase and the value of the current can also increase above the value of the current in the floating phase.

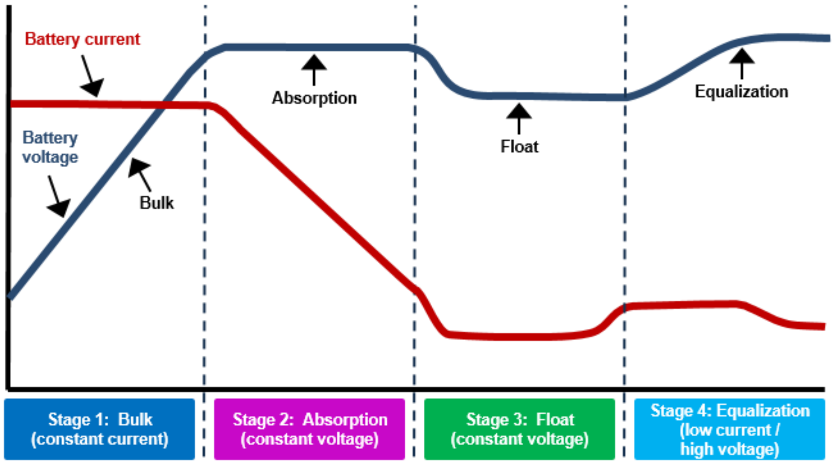

**Figure 6. Charging stages of a battery**

*The gassing effect*

The gassing effect occurs when the battery is near its complete charge. Generally, the gassing effect is irreversible resulting in a loss of water and therefore decreasing the level of electrolyte and increasing its concentration (in sealed batteries the gas recombination process allows the formation of water from the hydrogen and oxygen generated during the normal operation). The gassing effect consumes a part of the charge current that cannot be supplied in the next discharge and therefore reduces the battery’s charging performance. In lead-acid and nickel-cadmium batteries gassing results in the formation of hydrogen in the negative plate and oxygen in the positive plate. Charge controllers are normally used to allow the charge until the gassing voltage is reached and then disconnect the power generator in order to avoid an overcharge. Batteries that need maintenance must be replenished with water frequently to avoid the exposure and damage of the plates. The gassing voltage depends on the temperature and on the current rate, since an increase in temperature reduces the gassing voltage and a gain in the charging rate increases it.

*Efficiency of a battery*

The efficiency of a battery is given by the type of battery, charging method, rates of charge and discharge, depth of discharge and temperature. The efficiency is typically much higher when the state of charge (SOC) is low and as the battery reaches its full charge the efficiency lowers. In order to determine the total efficiency of a battery we must first obtain its voltage efficiency and its charging efficiency.

- Voltage efficiency: It is influenced by the rates of charge and discharge and the temperature. The way to calculate the value of the voltage efficiency is by dividing the discharge voltage of a battery by the charge voltage of the battery. For example, if we assume that a battery charges on average at 20V and is discharged at 18V, the efficiency would then be 90%.

- Charge efficiency: It is also called coulombic efficiency and is calculated by dividing the ampere hours delivered by the battery during the discharge by the ampere hours received by the battery during the charge. Due to the gassing effect and other internal mechanisms the battery cannot supply all the current that is given to the battery when charging. At low stages of charge (SOC) the battery accepts the charge very well, since there is not much gassing and the charging efficiency is high. On the other hand, when the state of charge (SOC) is almost 100%, the gassing and the internal heating reduce the charging efficiency.

Once the voltage and the charge efficiency are obtained the total efficiency of the battery is calculated by multiplying them.

# 6. Solar energy concepts

Some of the basic concepts related to solar energy and the use of photovoltaic panels will be explained bellow for clearer understanding of section 7 and the overall project.

## 6.1 Solar radiation

Planet Earth receives uniform and constant sunlight, except during solar storms. But this value can slightly change when the Earth gets closer or farther from the sun during its elliptical orbit, represented in figure 7, having its maximum value during the winter solstice of the northern hemisphere and its minimum value during the summer solstice of the northern hemisphere.

However, the irradiance[1] perceived during winter is lower than in summer causing the characteristic low temperatures of this season. This is due to the tilt of the pivot axis of the Earth around itself with respect to its trajectory around the sun, which has a permanent value of about 23.45º, causing a deviation of the sun’s rays with respect to the optimum (vertical) during the winter (figure 7). As a result of this the sun rises more over the horizon in summer than in winter (the maximum elevation of the sun over the horizon takes place during the summer solstice), making the days last longer than the nights.

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[1] Magnitude used to describe the incident power per unit area of all types of electromagnetic radiation

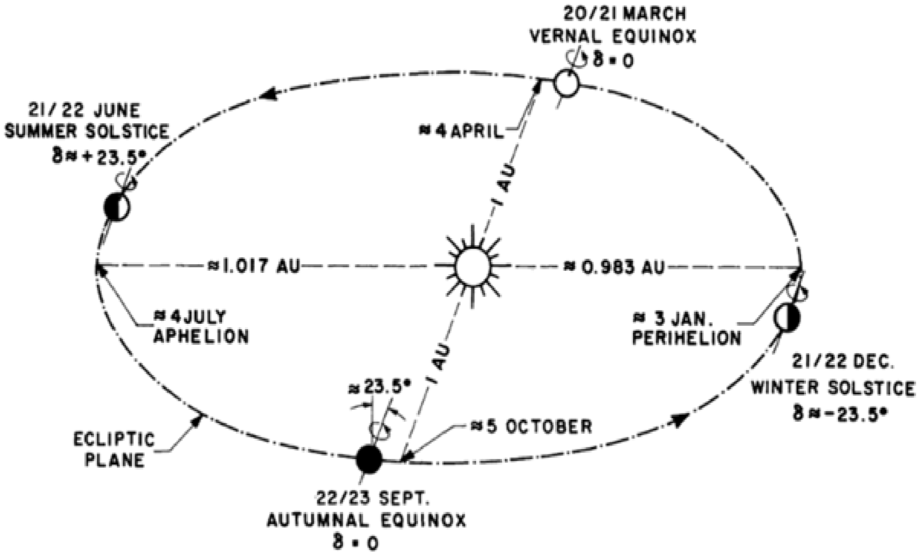


**Figure 7. Earth motion around the sun and declination angles [22]**

Sunlight is composed of a wide range of different colours that correspond to different wavelengths of the light wave. The whole is called the spectrum, which goes from infrared (long wavelength and invisible to the human eye) to ultraviolet (small wavelength and also invisible to the human eye). The visible spectrum is in between them. The sum of all those visible colours gives what is known as white colour.

Due to absorption and dispersion of the atmosphere, dust, clouds and the air molecules, the irradiance decreases when passing through the atmosphere. The natural solar irradiance in the Earth’s surface has an approximate maximum value of 1000 or 1100 $W/m^2$ [12]. This amount of irradiance applied directly on the food is normally insufficient to cook as fast as with combustion or electric cookers. Therefore, in order to solve this problem, solar rays are concentrated by using lenses or mirrors to have a greater intensity.

## 6.2 Direct and diffuse radiation

The global radiation of the sun can be decomposed into two, direct and diffuse radiation. Direct radiation comes directly from the sun and has quasi-parallel rays while diffuse radiation comes from the dispersion (elastic interaction) of direct radiation in the atmosphere due to the presence of air molecules, dust, water droplets and water crystals. Also, when solar rays hit the Earth’s surface part of the radiation is reflected generally in a diffuse form (except in smooth surfaces). During a clear sunny day the diffuse radiation only represents a small portion of the total radiation, while during cloudy or foggy day the diffuse radiation can represent most of the total radiation. However, when direct radiation reaches the Earth’s atmosphere part of it is absorbed and therefore turned into thermal energy (inelastic interaction).

## 6.3 Solar Angles

The Earth is constantly moving around the sun although seen from the Earth’s surface the sun has an apparent movement through the sky, rising in the east and setting in the west. The sun travels 360º in 24 hours oriented towards the equator during its movement through the Earth’s sky.

Depending on the period of the year the height of the sun with respect to the horizon (the horizon is perpendicular to the zenith) changes, having its maximum height during the summer solstice and its minimum height during the winter solstice, as seen in figure 9. Those heights can be calculated by adding (summer solstice) or subtracting (winter solstice) the inclination of the equatorial plane with respect to the plane of the ecliptic (figure 8), which is approximately 23.45º, to the latitude. In the winter and summer equinoxes the axis of the Earth is perpendicular to the solar rays and therefore its declination does not affect when calculating the sun’s position in the sky, which is the absolute value of the latitude.

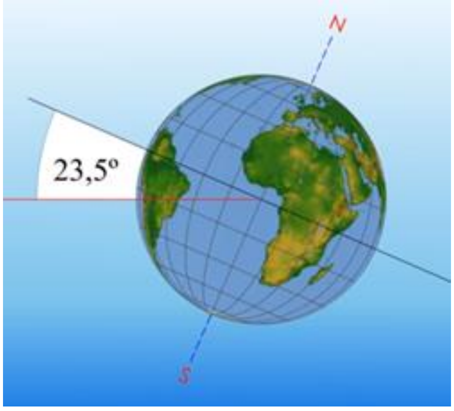


**Figure 8. Tilt of the equatorial plane with respect to the ecliptic plane**

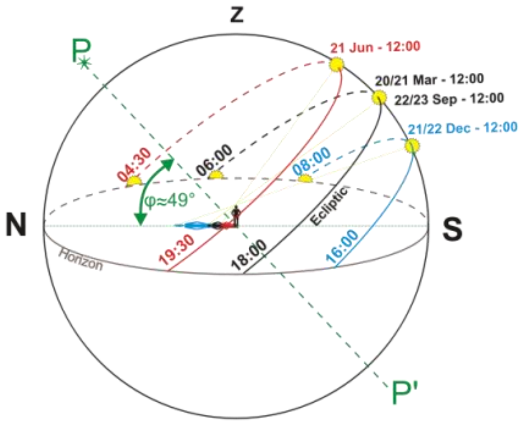


**Figure 9. Apparent movement of the sun**

An overview of the main angles involved in the calculation of the solar radiation received by solar collectors will now be made using the local horizontal plane and the zenith (vertical to the horizontal plane):

- **Sun declination angle (δ)**: It is defined as the angle formed between the solar rays and the equatorial plane. This angle can be seen in figure 10. Because the axis of rotation of the Earth remains parallel to itself while travelling around the sun, this angle varies between +23.45º and -23.45º being positive in the northern hemisphere and negative in the southern hemisphere. On equinoxes the declination angle is 0º.

$$\delta = 23.45^{\circ} \times \sin(360^{\circ} \times \frac{284 + d}{365})$$

*d is the day of the year (from 1 to 365)*

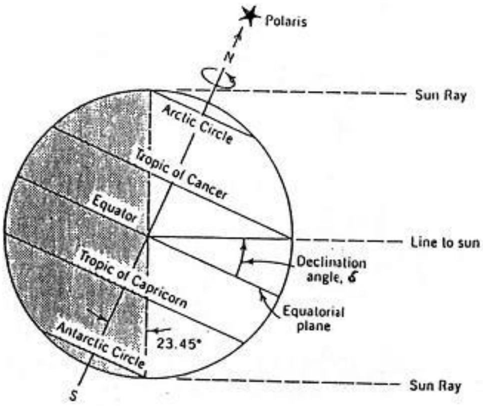


**Figure 10. Solar declination**

- **Hour angle (ω)**: As represented in figure 11, the hour angle indicates the angular distance between the observer's meridian and the meridian whose plane contains the sun. Solar noon (when the sun reaches its highest point in the sky) is taken as the origin of the angle, increasing approximately 15º per hour in the sense of the sun's movement.

$$\omega = 360^{\circ} \times \frac{Solar\ Time - 12h}{24h}$$

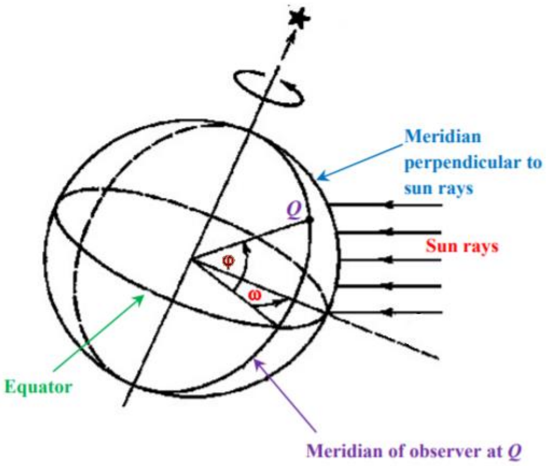


**Figure 11. Hour angle**

- **Latitude (ϕ)**: It is the angular distance between the equator and a certain point on the Earth, measured along a meridian (from 0º to 90º). A graphic example is seen in figure 12. Depending on the hemisphere the point is at the angle can be positive (northern latitude) or negative (southern latitude).

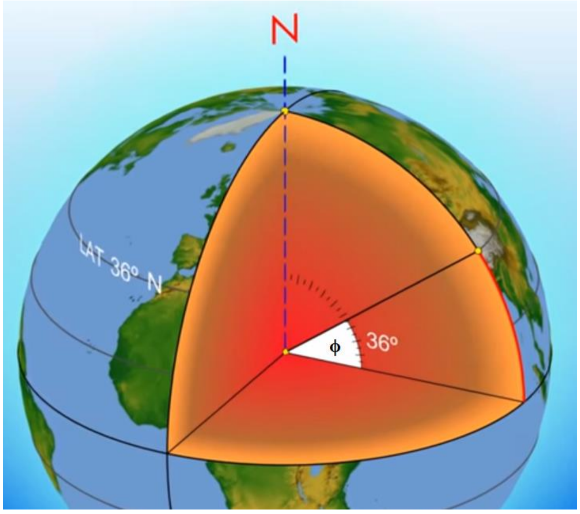


**Figure 12. Latitude**

- **Solar altitude angle (γs)**: It is the angle formed between the sun's rays and the horizontal plane. The sum of the solar zenith angle and the solar altitude angle gives 90º.

$$\gamma_S + \theta_{zS} = \frac{\pi}{2}$$

- **Solar zenith angle (θzs)**: It is the angle formed between the sun's rays and the vertical at a certain point (zenith). The zenith angle is expressed as a function of the time, the day, the year and the latitude.

$$\sin(\gamma_S) = \cos(\theta_{zS}) = \sin(\phi) \times \sin(\delta) + \cos(\phi) \times \cos(\delta) \times \cos(\omega)$$

- **Solar azimuth angle (Ψs)**: It is the angle formed by the projection of the sun's rays in the horizontal plane and the south direction. At solar noon its value is 0º. This angle is represented in figure 13.

$$\Psi_S = sign(\omega) \left| \cos^{-1}\left(\frac{\cos(\theta_{zS}) \times \sin(\phi) - \sin(\delta)}{\sin(\theta_{zS}) \times \cos(\phi)}\right) \right|$$

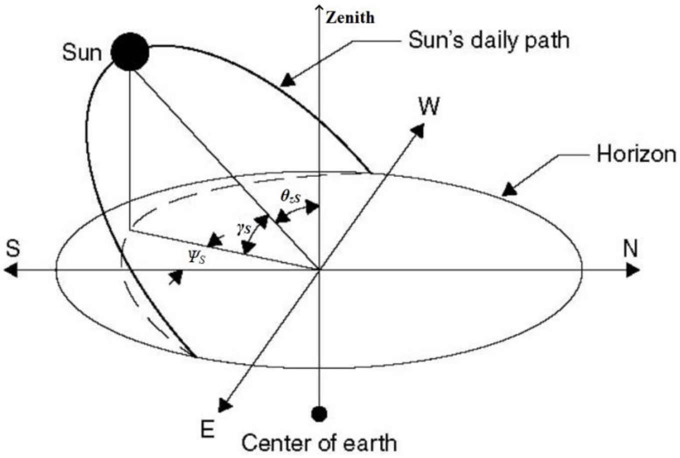


**Figure 13. Solar coordinates**

Supposing a solar collector with a flat area $A_a$:

- **Collector slope (β)**: It is the angle between the solar collector and the horizontal plane.
- **Surface azimuth angle (α)**: It is the angle formed by the projection of the perpendicular line to the collection area in the horizontal plane and the south direction. It is represented in figure 14.

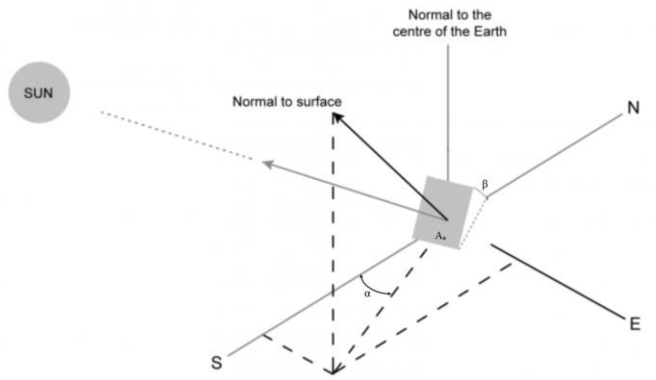


**Figure 14. Surface azimuth angle**

- Incidence angle ($\theta_S$): It is the angle between the sun's rays and the normal to the collection surface (Figure 15).
$$\cos(\theta_S) = \sin(\delta) \times (\sin(\phi) \times \cos(\beta) - \cos(\phi) \times \sin(\beta) \times \cos(\alpha)) + \cos(\delta) \times [\cos(\phi) \times \cos(\beta) \times \cos(\omega) + \sin(\beta) \times (\sin(\phi) \times \cos(\alpha) \times \cos(\omega) + \sin(\alpha) \times \sin(\omega)]$$

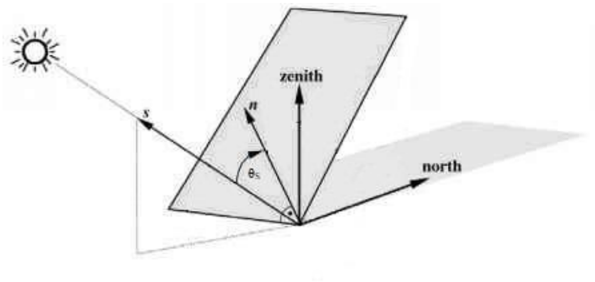


**Figure 15. Incidence angle**

## 6.4 Solar trackers

In order to obtain a low or zero value for the incidence angle automatic or manual solar trackers with single or dual axis can be used. Single-axis solar trackers are less complicated than dual-axis ones and can only pivot in one plane when following the sun’s daily path, either horizontally or vertically. On the other hand, dual-axis trackers have two degrees of freedom and can use azimuthal and elevation movements. In order to have the correct values of the sun’s position at any given moment dual-axis trackers can use three different electronic methods: astronomical coordinates, a solar sensor (with clouds or during the night it can become disoriented) or a hybrid of the two previous options. When using astronomical coordinates a microprocessor calculates the sun’s position in the sky based on the time, the coordinates of the location and the orientation of the device.

# 7. Experimental phase

## 7.1 Materials and Methods

In this project the photovoltaic system used was composed of:

- A photovoltaic panel with 72 solar cells and a power of 300 W.
- 2 gel batteries of 12V and 100Ah each, connected in series in order to have a nominal voltage of 24V.
- A 20A regulator.
- Two resistances of approximately 2.5 ohms each

All these components can be seen in figures 16, 17 and 18. The solar irradiance values were measured with a device called MacSolar that can be seen in figure 19.

In order to obtain the measurements needed, a simple process was followed. First, the photovoltaic panel along with its structure were taken outside and put under the sun. Next, a pot was filled with cool water and the two resistances were connected to the system and put inside the pot in order to avoid overheating. Once the computer was plugged into the charge controller the system could be connected and the computer was able to read the measured values in real time.

**Figure 17. Photovoltaic system seen from the front.**

**Figure 16. Photovoltaic system seen from the side.**

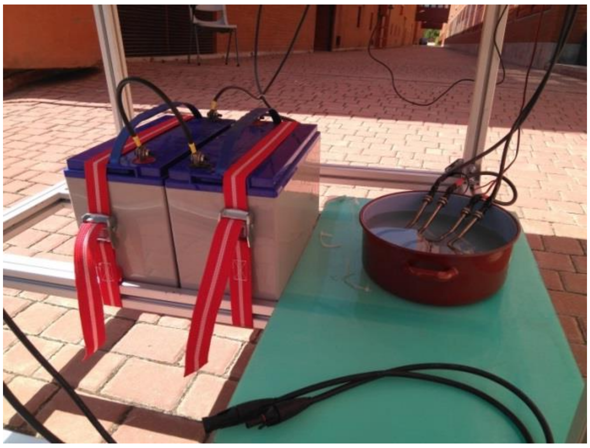


**Figure 18. Batteries and resistances.**

**Figure 19. MacSolar**

## 7.2 Experimental results

The purpose of the measurements carried out for this project were to analyse whether a photovoltaic panel of 300W could provide enough electricity for cooking and at the same time storing the remaining electricity in a battery. The resulting information could be very useful, because if the photovoltaic panel produces more electricity than is needed for cooking, a battery could be charged in the daytime while it simultaneously uses part of the electricity produced for cooking or for other purposes. Enough electricity could be stored to use when there is no sunlight, like at night or on cloudy days. This could provide an innovative and clean source of energy in developing countries where many people have no access to electricity to cover their basic needs.

### 7.2.1 Power, voltage and current analysis

During the measurements it was confirmed that the panel could provide enough electricity to a load of 5 ohms approximately while charging the batteries simultaneously. Below are the graphs of the measurements taken in the research and comments on the findings.

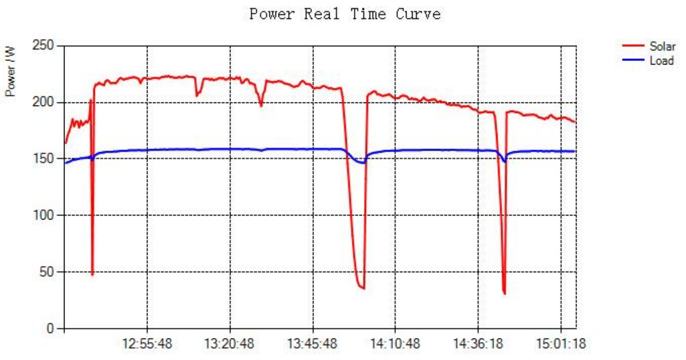


Figure 22. Power during the charge of the batteries and the use of a load. 24/08/2017

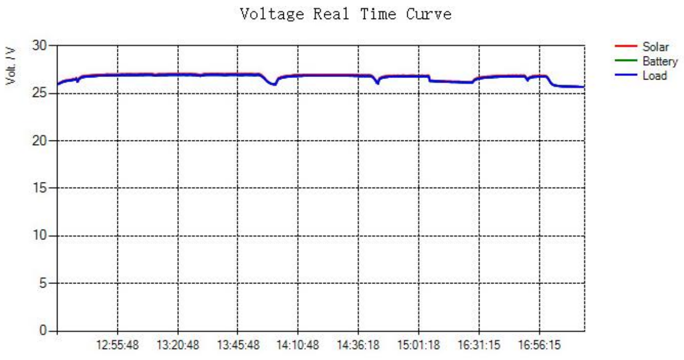


Figure 23. Voltage during the charge of the batteries and the use of a load. 24/08/2017

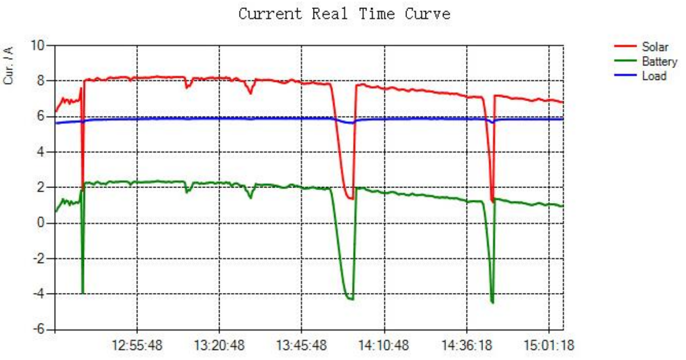


Figure 21. Current during the charge of the batteries and the use of a load. 24/08/2017

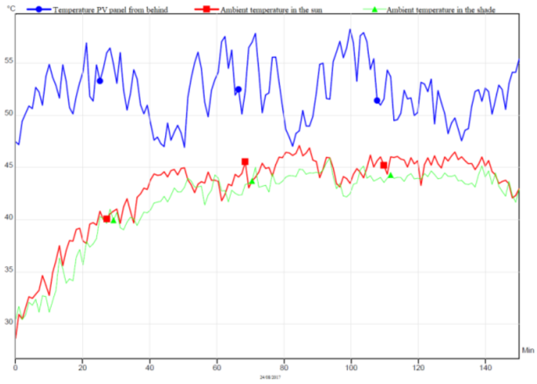


Figure 20. Temperature graph. 24/08/2017

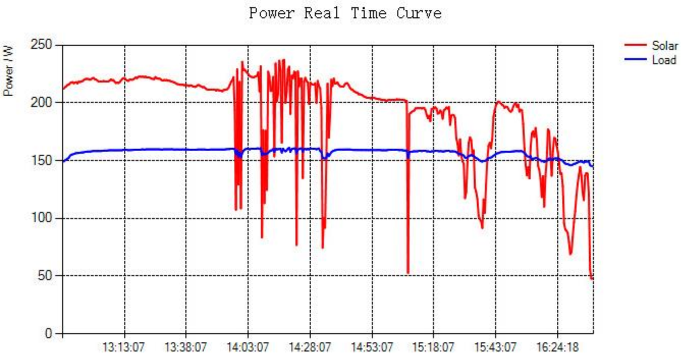


Figure 25. Power during the charge of the batteries and the use of a load. 25/08/2017

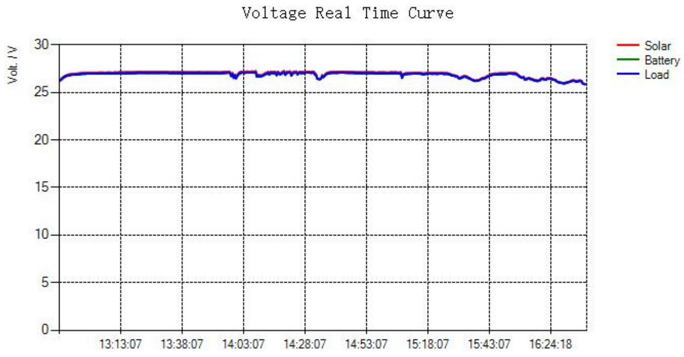


Figure 24. Voltage during the charge of the batteries and the use of a load. 25/08/2017

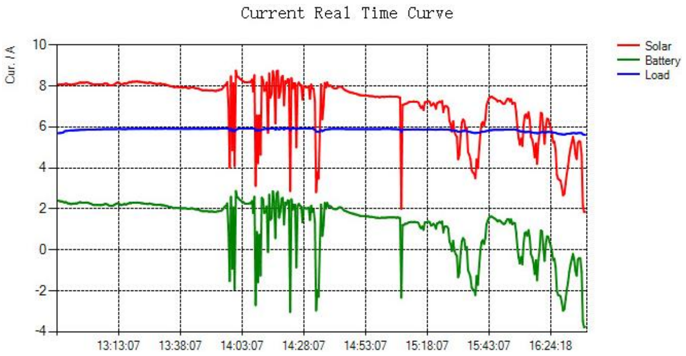


Figure 26. Current during the charge of the batteries and the use of a load. 25/08/2017

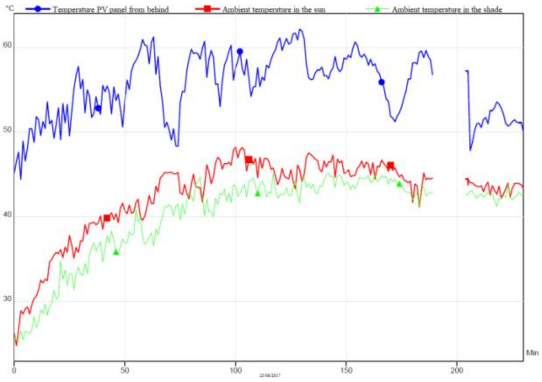


Figure 27. Temperature graph. 25/08/2017

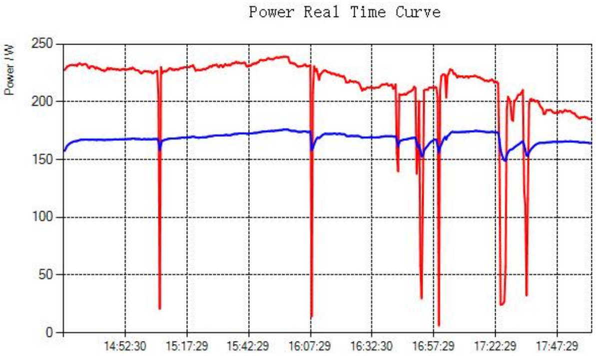


Figure 29. Power during the charge of the batteries and the use of a load. 30/08/2017

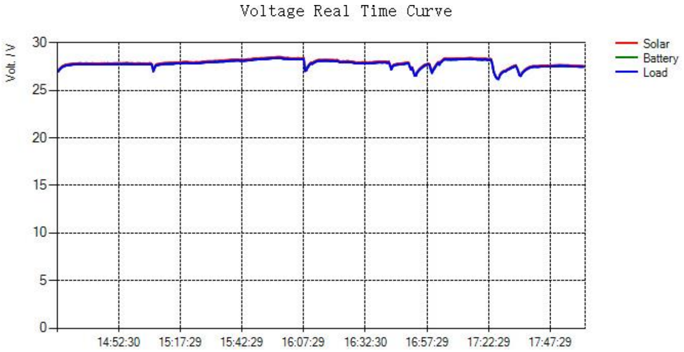


Figure 30. Voltage during the charge of the batteries and the use of a load. 30/08/2017

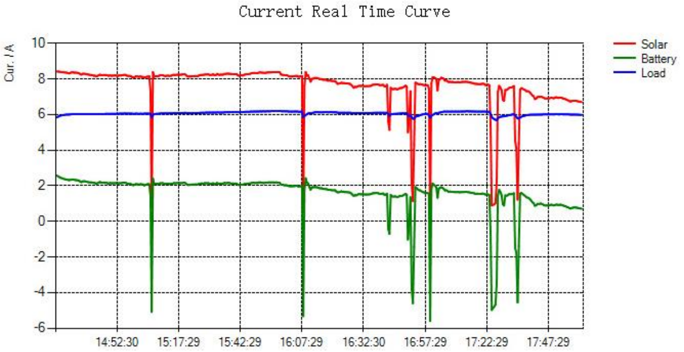


Figure 28. Current during the charge of the batteries and the use of a load. 30/08/2017

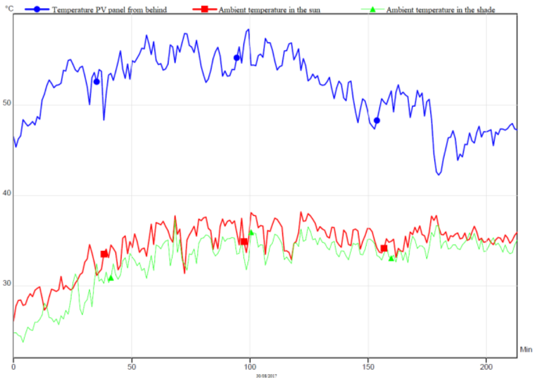


Figure 31. Temperature graph. 30/08/2017

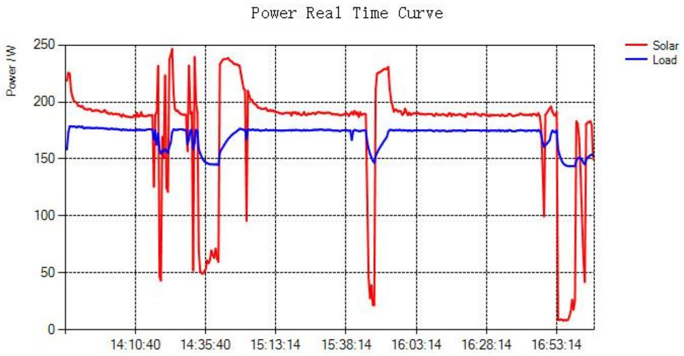


**Figure 33. Power during the charge of the batteries and the use of a load. 31/08/2017**

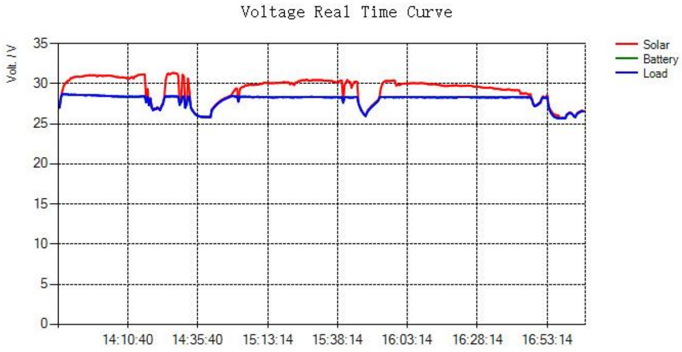


**Figure 32. Voltage during the charge of the batteries and the use of a load. 31/08/2017**

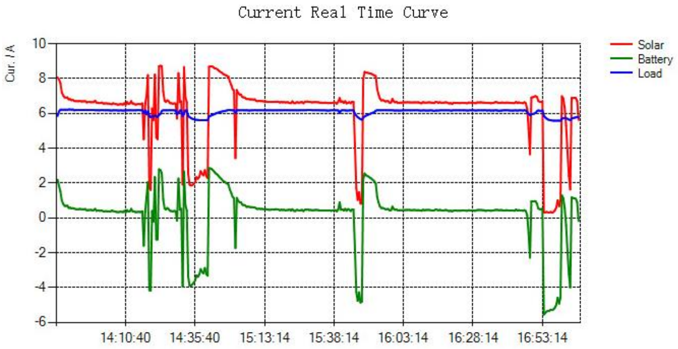


**Figure 35. Current during the charge of the batteries and the use of a load. 31/08/2017**

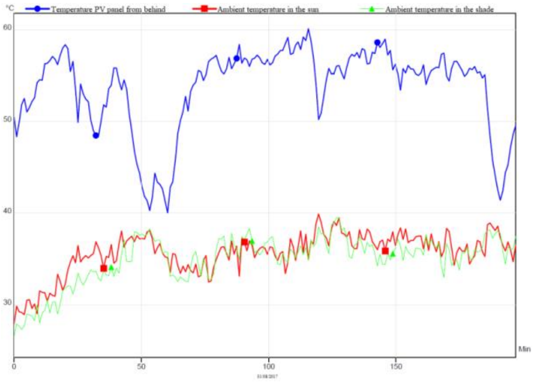


**Figure 36. Temperature graph. 31/08/2017**

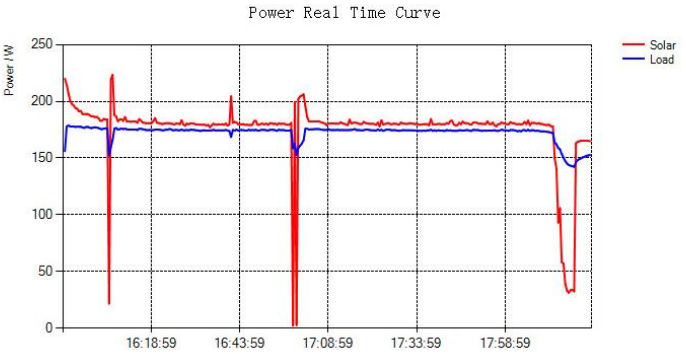


**Figure 34. Power during the charge of the batteries and the use of a load. 04/09/2017**

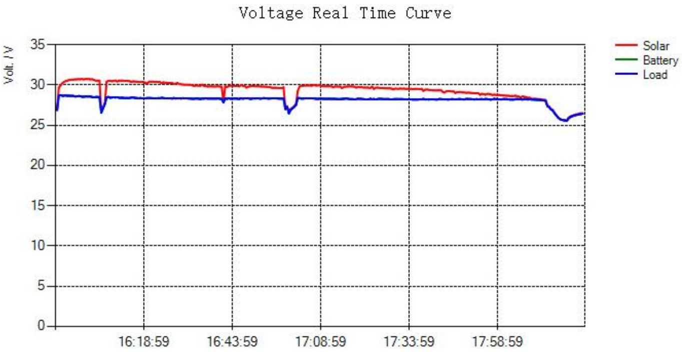


**Figure 37. Voltage during the charge of the batteries and the use of a load. 04/09/2017**

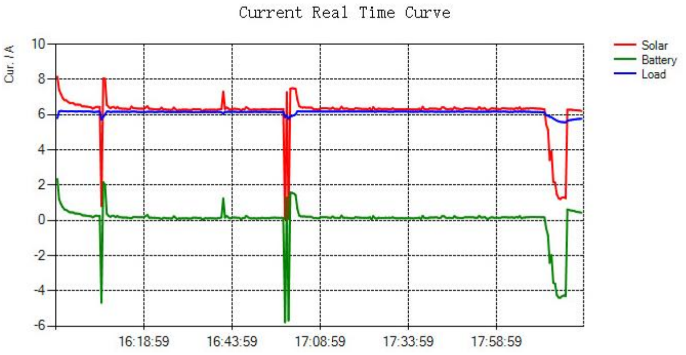


**Figure 39. Current during the charge of the batteries and the use of a load. 04/09/2017**

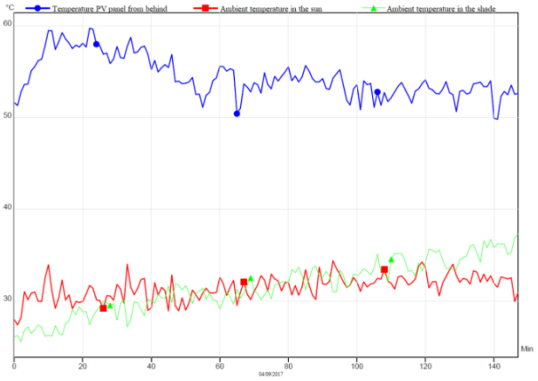


**Figure 38. Temperature graph. 04/09/2017**

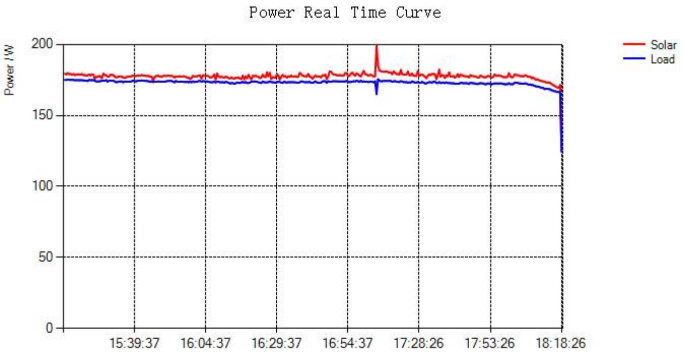


**Figure 40. Power during the charge of the batteries and the use of a load. 05/09/2017**

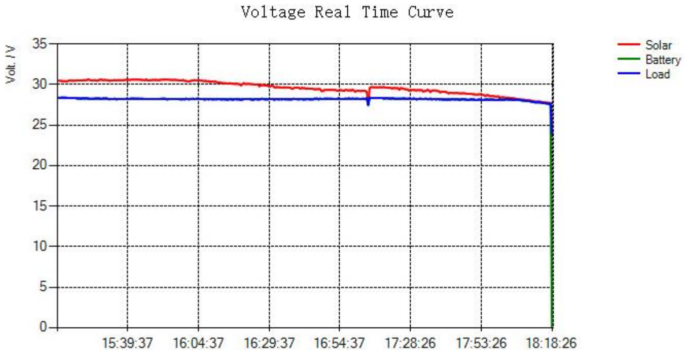


**Figure 41. Voltage during the charge of the batteries and the use of a load. 05/09/2017**

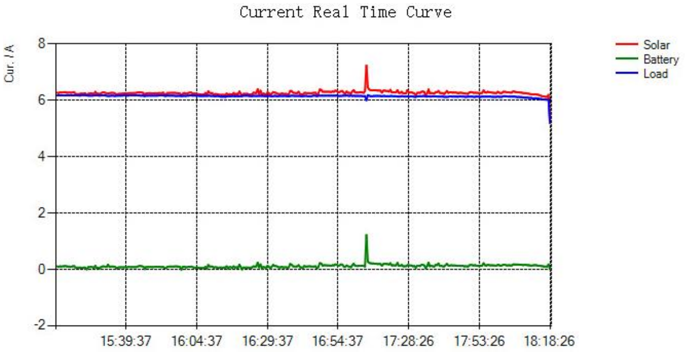


**Figure 43. Current during the charge of the batteries and the use of a load. 05/09/2017**

**Figure 42. Temperature graph. 05/09/2017**

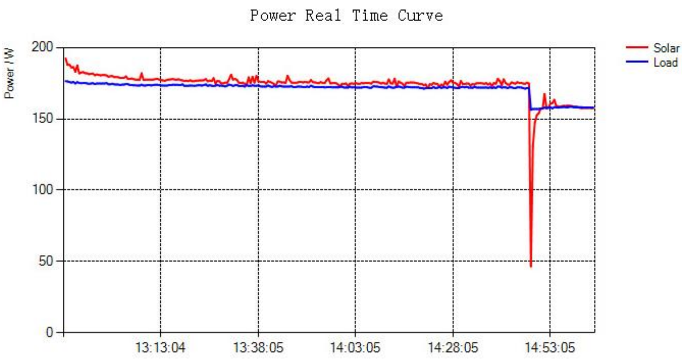


Figure 45. Power during the charge of the batteries and the use of a load. 06/09/2017

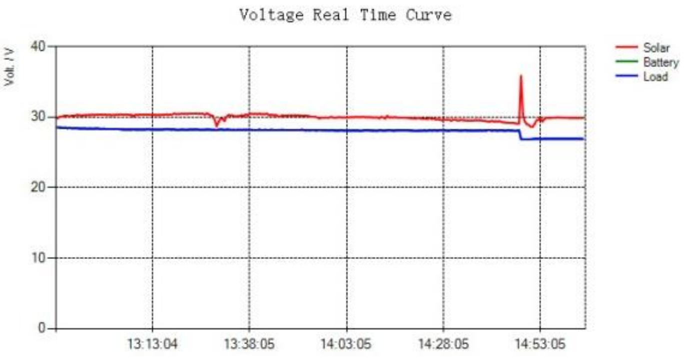


Figure 44. Voltage during the charge of the batteries and the use of a load. 06/09/2017

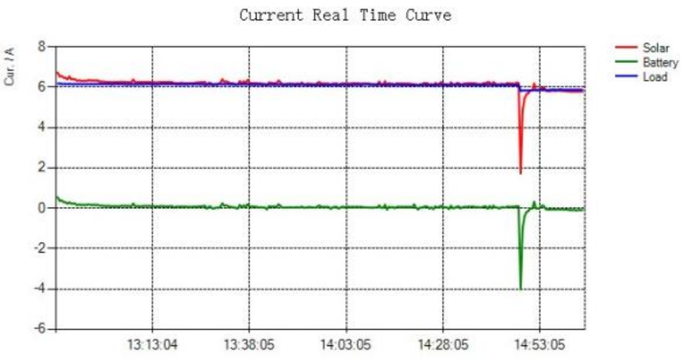


Figure 47. Current during the charge of the batteries and the use of a load. 06/09/2017

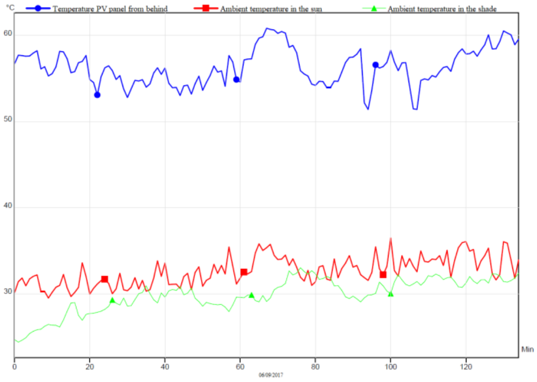


Figure 46. Temperature graph. 06/09/2017

In the graphs above we can see the measured values for the power, the voltage, the current and the temperature during the months of August and September. In the case of these graphs, the photovoltaic panel was being used to charge the two batteries (total nominal voltage of 24V) while also having a load of approximately 5 ohms connected. In the first graph of each day we can observe the power values. The solar power values normally kept increasing until around midday, when they reached their maximum value, and after that point they started decreasing. This can easily be seen in the power graph measured on the 24th of August (figure 20). In the graphs we can observe that there are some sudden drops. The main cause for these drops was the appearance of clouds that blocked the sun and therefore less radiation was perceived. By having an overall look we can say that the 25th, the 30th and the 31st of August (figures 24, 28 and 32) were the days with more clouds while the rest were more clear and sunnier. The power values during the month of September tend to be somewhat lower than the ones of August, since less solar radiation is perceived during September.

If we look at the current graphs we see that normally the values given by the photovoltaic panel are approximately the sum of the load and the battery currents. This occurs because the load is connected in parallel with respect to the batteries and therefore the batteries voltage and the load’s voltage are the same and the current provided by the photovoltaic panel has to be the sum of their currents. When the absorption phase takes place in the charging process of a battery the charge regulator maintains the voltage reached at the end of the bulk phase constant and reduces the current provided to the battery gradually until it is fully charged. On the 4th, 5th and 6th of September (figures 38, 42 and 46) the batteries where almost fully charged and therefore the battery’s current was near to 0 Amps.

One of the main problems during the project was that the initial depth of discharge (DOD) was low. This was due to the fact that the 4 hours used to discharge the batteries were not sufficient to give a low initial depth of discharge, since the capacity of the batteries was such that in 4 hours the nearly 5 ohms we used for the load were not able to discharge the battery a lot. It must be added here that the photovoltaic panel was not always available for use since other students were using it for other projects throughout the research period. Therefore, fully discharging the batteries was complicated if in between discharges another student had to use the photovoltaic system for other purposes.

Finally, if we take a look at the voltage graphs we can see that during the charge of the batteries the voltage provided by the photovoltaic panel is very similar to the battery’s voltage (and the load’s voltage since the value is the same as for the battery). This occurs because the charge regulator, during the bulk phase of the charging of the batteries, forces the photovoltaic panel to have a voltage value equal to the batteries voltage that slowly increases until the absorption phase is reached. When the absorption phase is reached the regulator maintains the batteries voltage reached during the bulk phase constant and starts decreasing the current provided to the batteries. When the absorption phase is reached the photovoltaic panel’s voltage no longer matches the batteries voltage as we can see in the graphs. Once the absorption phase has finished, the floating phase takes place. During this phase the voltage is reduced a bit (normally the reduction is seen in the graph as a sudden drop) and a very low current value is maintained in order to compensate for the self-discharge of the battery. This last phase can be seen very well on the 6th of September (figures 45 and 46), when the initial state of charge (SOC) was 90% and after 2 hours and a half approximately, it reached 100%.

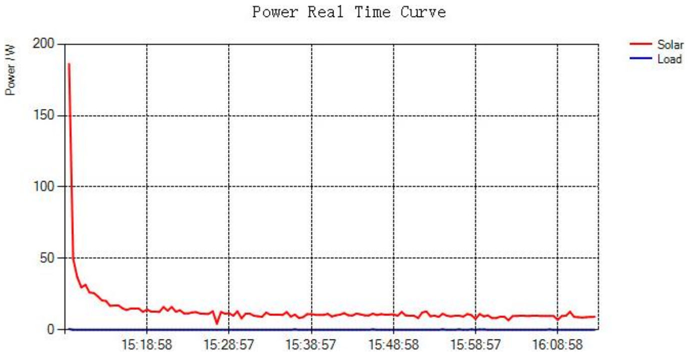


Figure 48. Power during the charge of the batteries without a load. 01/09/2017

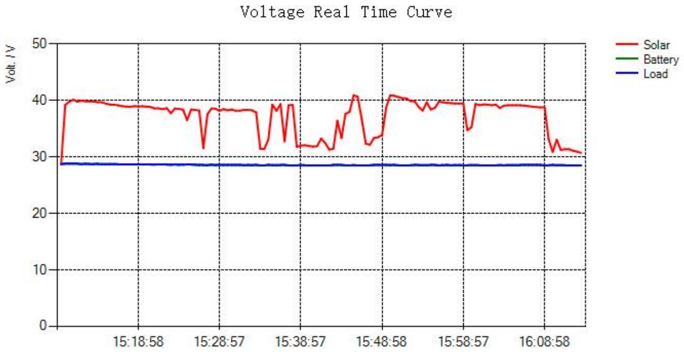


Figure 49. Voltage during the charge of the batteries without a load. 01/09/2017

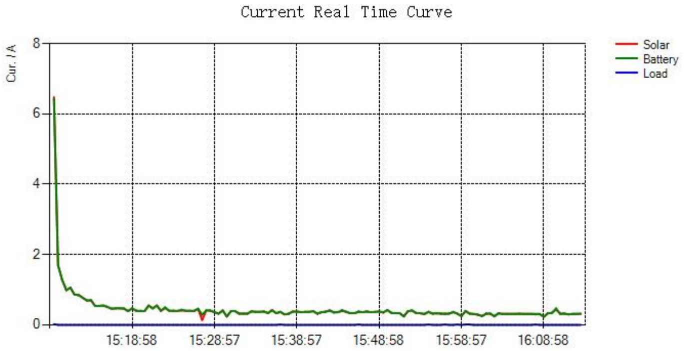


Figure 51. Current during the charge of the batteries without a load. 01/09/2017

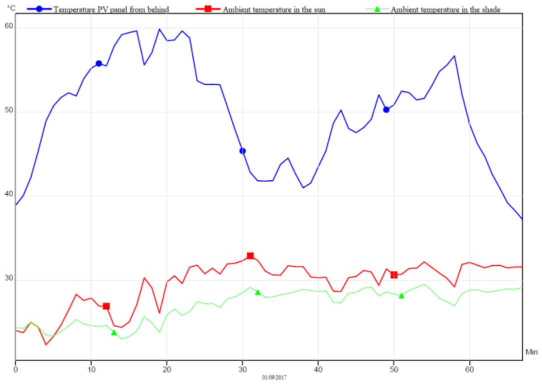


Figure 50. Temperature graph. 01/09/2017

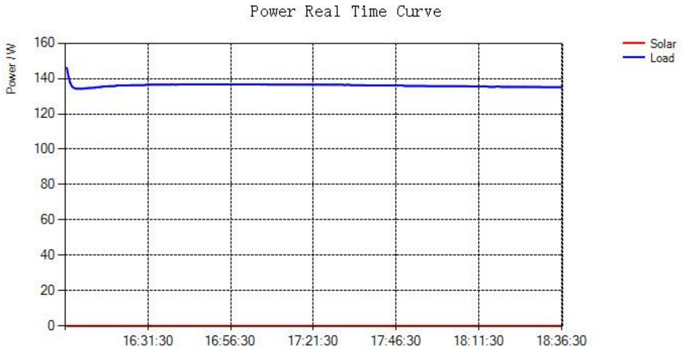


Figure 53. Power during the discharge of the batteries. 20/09/2017

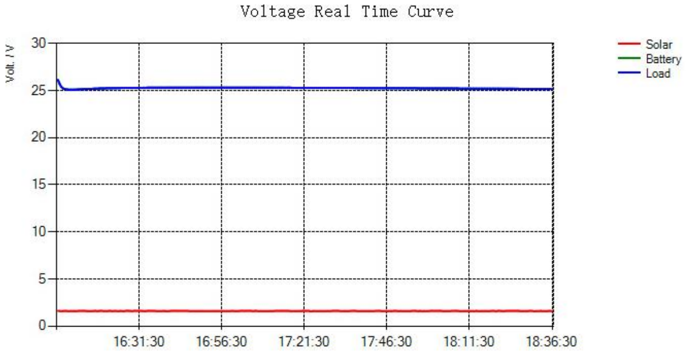


Figure 52. Voltage during the discharge of the batteries. 20/09/2017

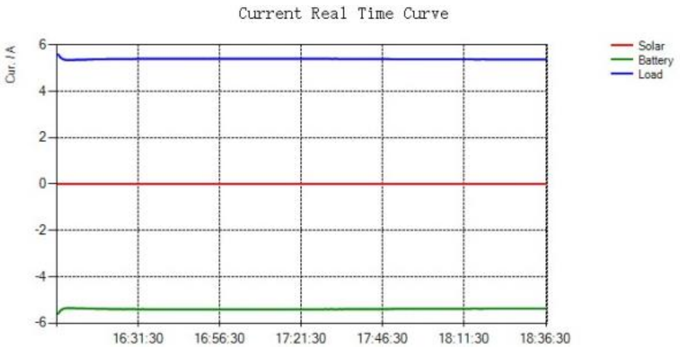


**Figure 55. Current during the discharge of the batteries. 20/09/2017**

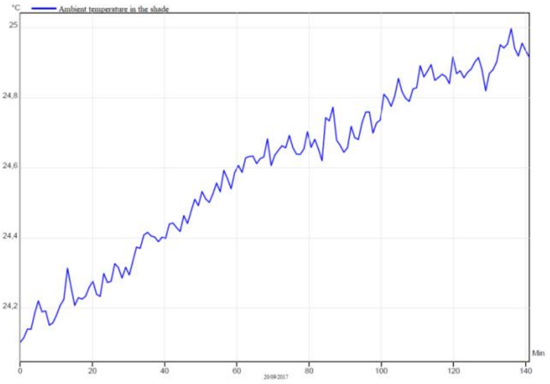


**Figure 54. Temperature graph. 20/09/2017**

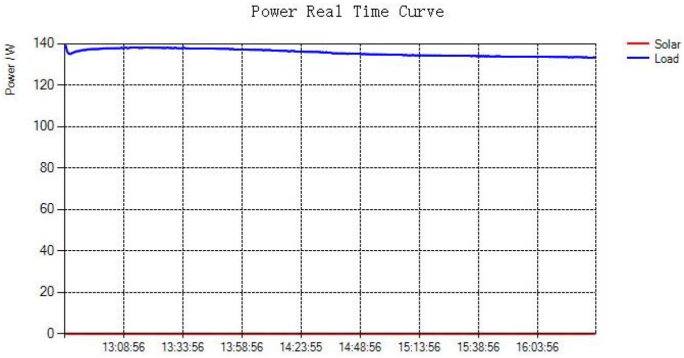


**Figure 57. Power during the discharge of the batteries. 26/09/2017**

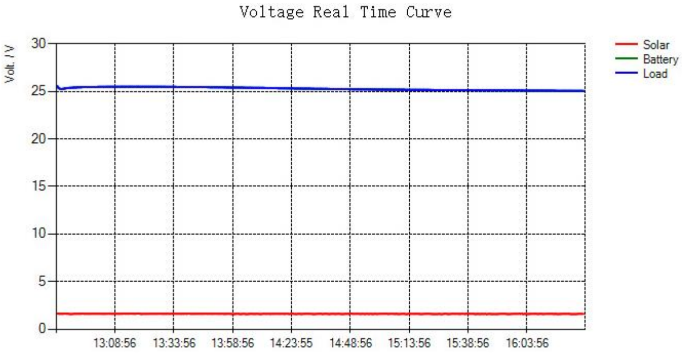


**Figure 56. Voltage during the discharge of the batteries. 26/09/2017**

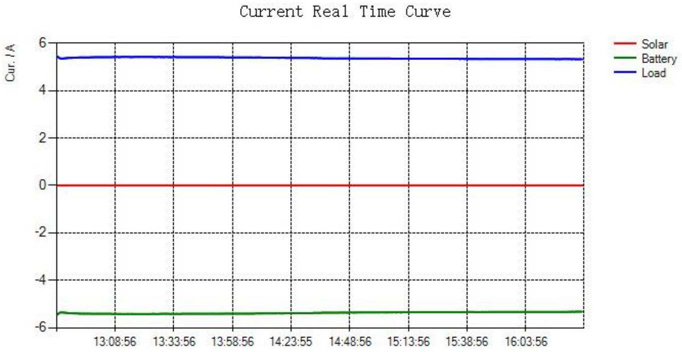


**Figure 58. Current during the discharge of the batteries. 26/09/2017**

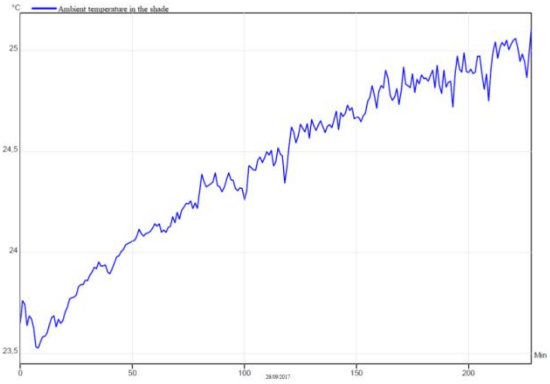


**Figure 59. Temperature graph. 26/09/2017**

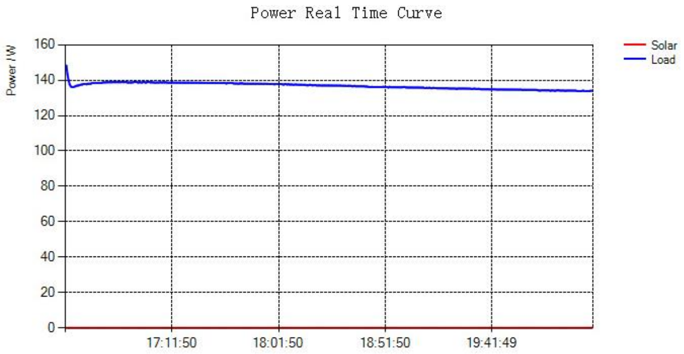


**Figure 60. Power during the discharge of the batteries. 04/10/2017**

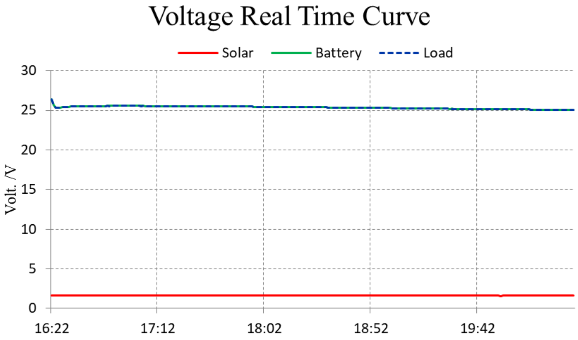


**Figure 61. Voltage during the discharge of the batteries. 04/10/2017**

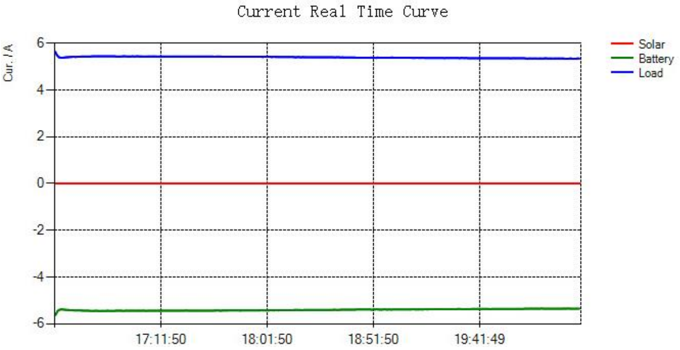


**Figure 63. Current during the discharge of the batteries. 04/10/2017**

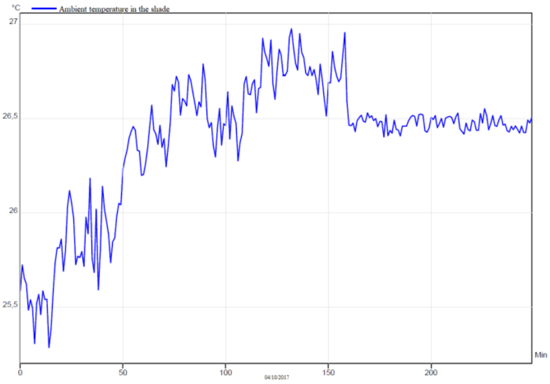


**Figure 62. Temperature graph. 04/10/2017**

In the above graphs we can observe the charge of the batteries (absorption phase) without a load on the 1st of September and the discharge of the batteries when the photovoltaic panel is not connected on the 20th and the 26th of September and on the 4th of October. During the discharge of the batteries, when the photovoltaic panel is not connected and when the battery provides the load with the current that the PV panel no longer gives, we hardly notice a variation in the voltage of the batteries, even though measurements were taken in a period of approximately 4 hours. This result shows that the batteries can supply electricity over long periods of time, making them very reliable. In order to have a better view of the decrease in the voltage of the batteries when being discharged, a longer period of measurement time would be needed.

The charge controller provides an adequate amperage to the battery depending on the state of charge (SOC), reducing the amount of current provided as the state of charge increases. In a way this process is controlled by the voltage due to the fact that as the voltage from the batteries increases to reach its maximum value the amperage received by the batteries decreases. For example, in figures 29 and 30, when the batteries are not fully charged and the voltage value is around 27V the current provided to the batteries is around 2A. However, when the voltage value is higher, like in figures 37 and 38 where it is slightly above 28V, the current provided to the batteries is lower, around 0.15A. In this project, a load is connected in parallel to the batteries making the charging process of the batteries occur slower. This happens because the charge controller used does not give priority to the charging of the batteries and therefore does not disconnect the load, having to distribute the amperage between both. As the batteries reach their full state of charge the amperage they receive will decrease and the charge controller will take less current from the photovoltaic panel. This occurs because the load has to have the same amount of voltage as the batteries and cannot accept all the remaining current that the batteries no longer accept because if it did the voltage would change.

In addition, if a smaller load was to be connected in parallel to the batteries it would receive more current. This would occur because the load's voltage has to be the same as the voltage in the batteries and since the value of the resistance is smaller and the only value that is not fixed is the current, the load has to receive more current in order to maintain the voltage value equal to the one in the batteries. This increase would be limited by the maximum current of the photovoltaic panel, the maximum current from the charge controller and the load's resistance.

If the system had no load connected to it and the battery was fully charged, thus receiving very low current to compensate for the self-discharge, the voltage in the photovoltaic panel would be greater than the maximum power voltage. This would cause the output power from the photovoltaic panel to have a low value.

On closer examination of the measurements collected in August and September, we can observe that the measurements taken on the first days showed that the voltage value of the photovoltaic panel was close to 27V. However, from the 30th of August onwards, the measured voltage values on the photovoltaic panel were near to 30V. Taking into account that the maximum efficiency is obtained with a voltage value of 37.52V, these values were not high enough to reach the maximum efficiency the photovoltaic panel can produce. On the other hand, if we take a closer look at the current on the 24th, 25th and 30th of August, we can see that the current of the photovoltaic panel was around 8A, which is very close to the maximum power current of 8.27A. Nonetheless, since the maximum power voltage was not attained, maximum voltage was not obtained either. As a result, the maximum efficiency of the photovoltaic panel was not achieved. On the rest of the days that measurements were taken the current value was near 6A due to the fact that the batteries were practically charged and did not accept much current.

In addition, when the batteries were being charged without a load on the 1st of September (figures 48,49,50 and 51), it was observed that the voltage value on the photovoltaic panel was near to 40V. This surpassed the maximum power voltage of 37.52V, which therefore caused the output power to decrease. Furthermore, we noticed that since the batteries were almost fully charged the current received was very low, near 0.4A, in order to compensate for the self-discharge. Consequently, since there was no load, the charge controller forced the photovoltaic panel to supply only the amount of current required by the batteries.

By using formula 9, an approximation of the efficiency of the photovoltaic panel can be obtained.

$$\eta = \frac{P}{A_t * G_t} \quad (9)$$

$P$ = Generated power
$A_t$ = Total area of the photovoltaic panel
$G_t$ = Normal irradiance to the tilted plane

In the following table we can see the maximum efficiency of the photovoltaic panel that was reached at a certain moment during the days in which measurements were taken.

| Date | Maximum power reached [W] | $G_n$ [W/m$^2$] | $G_T$ [W/m$^2$] | Maximum efficiency reached |
|---|---|---|---|---|
| 24-ago | 224.01 | 1037 | 1032.81 | 0.11 |
| 25-ago | 237.27 | 1023 | 1018.87 | 0.12 |
| 30-ago | 239.40 | 1051 | 1046.76 | 0.12 |
| 31-ago | 247.13 | 1049 | 1044.77 | 0.12 |
| 04-sep | 224.10 | 1052 | 1047.75 | 0.11 |
| 05-sep | 199.10 | 1053 | 1048.75 | 0.10 |
| 06-sep | 182.80 | 1003 | 998.95 | 0.09 |

| | |
|---|---|
| $\theta_S$ [degrees] | 5.15 |
| $A_t$ [m$^2$] | 1.94 |

As seen in the table above, the maximum efficiency of the photovoltaic panel reached during the measurements was of 12%. This value is a bit far from the maximum efficiency of 18.4% of the photovoltaic panel. One reason why the efficiency obtained during the measurements is lower than the maximum efficiency is that the voltage from the batteries and the load was not sufficiently high to reach the maximum power voltage value of 37.52V. This forced the photovoltaic panel to attain a lower voltage value, thus preventing it from obtaining the maximum efficiency.

### 7.2.2 Analysis of solar angles and irradiance values

Irradiance values and the incidence angle where also measured while carrying out the experimental part of the project. The incidence angle was directly measured on site, but in order to check that the value was correct it was also calculated in a more theoretical way.

*Incidence angle*

| Initial values | |
|---|---|
| Geographical Latitude (Universidad Carlos III, Leganés) | L = 40.334º |
| Day number (6th of September) | N= 249 |

In order to calculate the solar altitude one of the values we need to calculate first is the solar declination:

$$\delta = 23.45^{\circ} \times \sin\left[\frac{360\times(284+\mathrm{N})}{365}\right] = 23.45^{\circ} \times \sin\left[\frac{360\times(284+249)}{365}\right] = 5.793^{\circ}$$

Once we have obtained the value for the solar declination the next step is to calculate the Equation of Time.

$$\mathrm{EoT} = 9.87 \times \sin(2\mathrm{B}) - 7.53 \times \cos(\mathrm{B}) - 1.5 \times \sin(\mathrm{B}) = 9.87 \times \sin(2 \times 166.15) - 7.53 \times \cos(166.15) - 1.5 \times \sin(166.15) = 2.3654 \text{ [minutes]}$$

Where B is obtained from this equation

$$\mathrm{B} = \frac{(\mathrm{N}-81)\times360}{364} = \frac{(249-81)\times360}{364} = 166.153846^{\circ}$$

With the Equation of Time calculated we now proceed to obtain the Time difference value

$$\mathrm{TD} = \mathrm{EoT} + 4 \times (\mathrm{LL} - \mathrm{SL}) - \mathrm{DS} = 2.36 + 4 \times (-3.76 - 15) - 60 = -132.6946 \text{ [minutes]} = -2.2116 \text{ [hours]}$$

| | |
|---|---|
| Local Longitude (LL) | -3.764989º (Universidad Carlos III, Leganés) |
| Standard Longitude (SL) | 15º |
| Daylight Saving (DS) | 60 minutes (for the period between the end of March and the end of October) |
| | 0 minutes (for the rest) |

With the value for the time difference we now calculate the solar time

$$\mathrm{ST} = \mathrm{LST} + \mathrm{TD} = 15\mathrm{h} - 2.2116\mathrm{h} = 12\mathrm{h}\ 47\mathrm{min} = 12.79\mathrm{h} = 767.3 \text{ min}$$

Local Standard Time (LST) = 15h

After all this has been done the next step will be to calculate the hour angle

$$\mathrm{h} = (ST - 12) \times 15^{\circ} = (12.79 - 12) \times 15^{\circ} = 11.85^{\circ}$$

With all the values obtained and knowing that the Slope of the PV panel (β) is equal to 30°, the solar altitude can now be calculated

$$\sin(\alpha) = \sin(\mathrm{L}) \times \sin(\delta) + \cos(\mathrm{L}) \times \cos(\delta) \times \cos(\mathrm{h}) = \sin(40.33) \times \sin(5.79) + \cos(40.33) \times \cos(5.79) \times \cos(11.85) = 0.807$$

$\alpha = 53.864^{\circ}$

On site, the angle between the solar rays and the photovoltaic panel was 84.85°. By subtracting that angle to 90° we would get the angle of incidence (angle between the sun's rays and the normal to the collection surface).

$$\theta_s = 90^{\circ} - 84.85^{\circ} = 5.15^{\circ}$$

If we subtract the slope of the PV panel to the measured angle between the solar rays and the PV panel we should obtain the solar altitude.

$$\alpha_2 = 84.85^{\circ} - 30^{\circ} = 54.85^{\circ}$$

The value obtained is very similar to the one calculated before ($\alpha \approx \alpha_2$) therefore we can assume that the value measured is correct.

*Irradiance values*

During the experimental part of the project the values for the normal total irradiance, for the diffuse irradiance and an approximation of the total irradiance on the horizontal plane were calculated. Because the values measured for the diffuse irradiance made no logical sense, probably due to a human error while measuring, a mean value was taken for the month of August (2017) from the Agencia Estatal de Meteorología (AEMET). The total irradiance on the horizontal plane will be calculated in a more precise way with the help of the other measured values. In order to simplify the problem mean values will be used.

The formula used to calculate the normal irradiance to the tilted plane using a sky model is the following

$$G_T = G_b \times \frac{\cos(\theta_s)}{\cos(\theta_{zs})} + G_d \times \left(\frac{1+\cos(\beta)}{2}\right) + (G_b + G_d) \times \rho_g \times \left(\frac{1-\cos(\beta)}{2}\right)$$

But since we want to calculate the total irradiance on the horizontal plane we will have to calculate the direct irradiance on the horizontal plane first

$$G_b = \frac{G_T - G_d \times \left(\frac{1+\cos(\beta)}{2} + \rho_g \times \frac{1-\cos(\beta)}{2}\right)}{\frac{\cos(\theta_s)}{\cos(\theta_{zs})} + \rho_g \times \frac{1-\cos(\beta)}{2}}$$

Once the direct irradiance on the horizontal plane has been obtained we can calculate the total irradiance on the horizontal plane by adding the direct and diffuse irradiance

$$G_{hor} = G_b + G_d$$

The numerical values for what has just been seen are in the following table

| | |
|---|---|
| $G_n$ [W/m$^2$] | 1012.76 |
| $\theta_{zS}$ [degrees] | 36.136 |
| $\theta_{zS}$ [radians] | 0.63 |
| $\theta_S$ [degrees] | 5.15 |
| $\theta_S$ [radians] | 0.09 |
| $G_d$ [W/m$^2$] | 135.7 |
| $G_T$ [W/m$^2$] | 1008.68 |
| β [degrees] | 30 |
| β [radians] | 0.52 |
| $\rho_g$ | 0.2 |
| $G_{b,hor}$ [W/m$^2$] | 706.12 |
| $G_{hor}$ [W/m$^2$] | 841.8161152 |

$G_n$ Mean total irradiance normal to the sun’s rays
$\theta_{zS}$ Solar zenith angle
$\theta_S$ Incidence angle
$G_d$ Mean diffuse irradiance [27]
$G_T$ Mean total irradiance normal to the tilted plane
β Slope of the PV panel
$\rho_g$ Soil reflectivity
$G_{b,hor}$ Mean direct irradiance on the horizontal plane
$G_{hor}$ Mean total irradiance on the horizontal plane

# 8. Energy access in developing countries

Energy can be divided into two categories, primary energy and secondary energy. Primary energy is the type that is directly harvested from natural resources such as coal, oil, natural gas, wind power, solar power, biomass, etc. On the other hand, secondary energy is derived from primary energy which has been transformed in order to meet consumer demand, like electricity.

In developed countries, the use of energy is taken for granted in daily life. However, the case in most developing and underdeveloped countries is generally different, as a very high percentage of the population in these areas do not have any access to modern supplies of energy for daily use. In today’s world about 1.1 billion people have no access to electricity and 2.8 billion people rely on biomass, coal or kerosene for cooking [6]. The countries that suffer this lack of electrification have been making an effort to turn their situation around and between 2000 and 2012 an approximate rate of 62 million people per year have gained access to electricity [8]. In addition, as of 2012, this rate has increased to more than 100 million people per year with access to electricity. However, despite the electrification efforts which surpassed population growth in 2014, sub-Saharan Africa's electrification rate is only 43% [7]. Urban areas in this region are the places that have experienced these developments the most, so there is still a long way to go before many rural areas receive access to electricity services.

In addition, those who have access to electricity in this region many times have to face high prices for a supply that is unreliable. This fact added to the non-electrified areas cause many people to rely on biomass, coal or kerosene for cooking. Due to the use of these sources, household air pollution causes 2.8 million premature deaths per year worldwide [6], and 600000 of those premature deaths take place in Africa according to a study in 2014 [8]. About 2.8 billion people worldwide still have no access to clean cooking [7] that would prevent household air pollution, although there have been awareness campaigns on these risks. Unfortunately, one third of the world's population (2.5 billion people), continues to cook with solid biomass (mainly fuelwood), 120 million people cook with kerosene and 170 million people cook with coal [7]. Among the populations without clean cooking, 1.9 billion live in developing Asia and 850 million live in sub-Saharan Africa [7]. This information shows that in developing countries where there is a lack of electrification, population growth is high and household income is low, many people are not able to afford modern energy services, if they are available, and have no other option but to use these other sources due to their low cost and availability.

## 8.1 The firewood crisis

The ease of using firewood and its high heat capacity make it an attractive alternative for cooking and heating in developing countries where people cannot afford or do not have electricity services. However, the use of firewood has several negative effects.

The use of this fuel creates several health problems, amongst other effects. During the combustion of the firewood $CO_2$ and water vapour are mainly released, but a small quantity of oxides are also formed with the nitrogen contained in the air ($NO_x$), which turns out to be toxic. Moreover, an imperfect or incomplete combustion produces unburned hydrocarbons (HCs) which are also toxic and can produce cancer. In the case of imperfect combustion, carbon monoxide (CO) is also produced which is again toxic, and at high levels of concentration can leave a person unconscious or can even cause death. Even if the combustion is very good coal particles are formed, these are seen as black smoke, and can also create health problems. In order to avoid the formation of CO, black smoke and HCs an intimate mix of the fuel with the air (burning solid fuels cannot achieve an intimate mix between the fuel and the air), high temperatures and an excess of air are needed. However, these conditions favour the formation of NOx so a very technically elaborated combustion is needed, which is not met by most simple kitchens.

In poor regions wood is burned in houses without a chimney, contaminating the air inside. Being exposed to this smoke constantly can generate a pulmonary emphysema and eye, throat and lung cancers [13][14][15].

Apart from the health issues generated by the burning of firewood, deforestation is devastating entire natural environments leaving very few forest area per inhabitant, especially in Asia and Africa. The amount of trees being cut down to obtain firewood has overpassed the regenerative capacity of nature and if nothing is done, very soon there will be a rapid decrease in the number of forests left. The reduction of forests can generate many problems, since forests protect soil and water resources (they reduce salinity, filter pollutants, control floods and enhance precipitations), control desertification, mitigate the climate, filter air pollution and conserve ecosystems with their natural flora and fauna.

In addition, people have to make long journeys to get firewood. The average amount of hours spent collecting fuelwood each week is 6 hours and to collect this fuelwood the average distance they have to travel is 4.6 kilometres per trip [16]. Taking into account that the average number of trips a person makes to collect firewood is around 3 trips per week [16], this would mean travelling around 13.8 kilometres each week for firewood collection alone. In addition, many of those who travel to collect firewood belong to a very low-income household and most likely will have to make the journey on foot. Furthermore, this burden principally falls on women and children, creating a risk of injury and violence for the first and reducing the education time for the second [16].

The consumption of wood per capita depends on the season (the consumption is not the same in a cold season as in a hot season) and the family size (the bigger the size, the less consumption per capita each member has) among other things. The typical values of wood consumption per person go from 1kg to 8 kg. Figure 60 shows the mean consumption per capita in some sub-Saharan countries. If we assume the values of ash wood with 15% of humidity our calorific value (PCI) will be around $4.11\frac{kWh}{kg}$, as seen in table 3. In the case of Nigeria the mean fuelwood consumption is of $4\frac{kg}{day}$, therefore a person would need approximately $16.44\frac{kWh}{day}$.

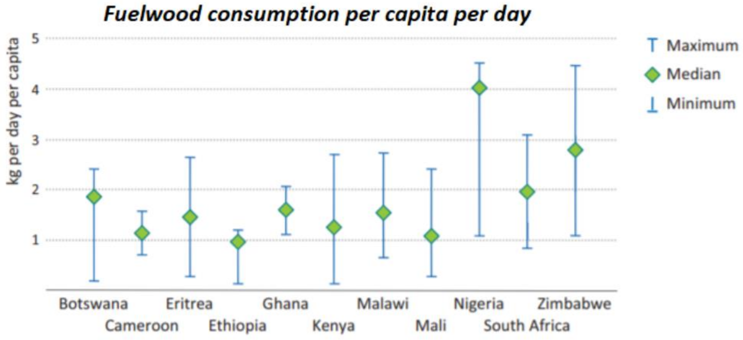
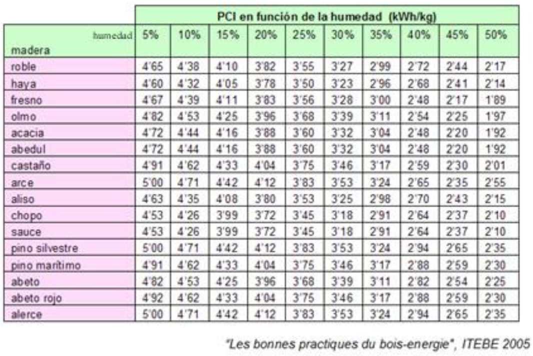


**Figure 64. Fuelwood consumption per capita per day [8]**

**Table 3. Calorific value as a function of humidity**



| | PCI en función de la humedad (kWh/kg) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| humedad<br>madera | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% |
| roble | 4'65 | 4'38 | 4'10 | 3'82 | 3'55 | 3'27 | 2'99 | 2'72 | 2'44 | 2'17 |
| haya | 4'60 | 4'32 | 4'05 | 3'78 | 3'50 | 3'23 | 2'96 | 2'68 | 2'41 | 2'14 |
| fresno | 4'67 | 4'39 | 4'11 | 3'83 | 3'56 | 3'28 | 3'00 | 2'48 | 2'17 | 1'89 |
| olmo | 4'82 | 4'53 | 4'25 | 3'96 | 3'68 | 3'39 | 3'11 | 2'54 | 2'25 | 1'97 |
| acacia | 4'72 | 4'44 | 4'16 | 3'88 | 3'60 | 3'32 | 3'04 | 2'48 | 2'20 | 1'92 |
| abedul | 4'72 | 4'44 | 4'16 | 3'88 | 3'60 | 3'32 | 3'04 | 2'48 | 2'20 | 1'92 |
| castaño | 4'91 | 4'62 | 4'33 | 4'04 | 3'75 | 3'46 | 3'17 | 2'59 | 2'30 | 2'01 |
| arce | 5'00 | 4'71 | 4'42 | 4'12 | 3'83 | 3'53 | 3'24 | 2'65 | 2'35 | 2'55 |
| aliso | 4'63 | 4'35 | 4'08 | 3'80 | 3'53 | 3'25 | 2'98 | 2'70 | 2'43 | 2'15 |
| chopo | 4'53 | 4'26 | 3'99 | 3'72 | 3'45 | 3'18 | 2'91 | 2'64 | 2'37 | 2'10 |
| sauce | 4'53 | 4'26 | 3'99 | 3'72 | 3'45 | 3'18 | 2'91 | 2'64 | 2'37 | 2'10 |
| pino silvestre | 5'00 | 4'71 | 4'42 | 4'12 | 3'83 | 3'53 | 3'24 | 2'94 | 2'65 | 2'35 |
| pino marítimo | 4'91 | 4'62 | 4'33 | 4'04 | 3'75 | 3'46 | 3'17 | 2'88 | 2'59 | 2'30 |
| abeto | 4'82 | 4'53 | 4'25 | 3'96 | 3'68 | 3'39 | 3'11 | 2'82 | 2'54 | 2'25 |
| abeto rojo | 4'92 | 4'62 | 4'33 | 4'04 | 3'75 | 3'46 | 3'17 | 2'88 | 2'59 | 2'30 |
| alerce | 5'00 | 4'71 | 4'42 | 4'12 | 3'83 | 3'53 | 3'24 | 2'94 | 2'65 | 2'35 |

*"Les bonnes practiques du bois-energie", ITEBE 2005*

## 8.2 Electricity cost in the Nigerian case

In this section the price of electricity services in Nigeria will be analysed in order to see the cost that an average person in a developing country has to face. Taking into account that an average person in Nigeria needs around 16.44 $\frac{kWh}{day}$, the energy needed for a month (30 days) would be approximately 493.2 kWh. Depending on the area the person lives in, electricity services will be cheaper or more expensive, since, as seen in figure 61, there are 11 electricity distribution companies in Nigeria and depending on the region a person lives in they can get service from one company or another.

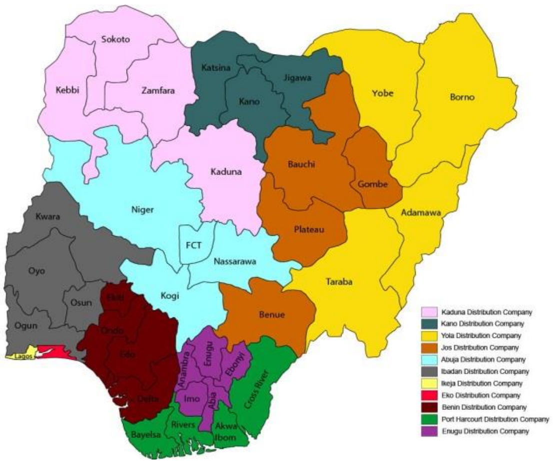


**Figure 65. Nigerian electricity supply industry (NESI) [23]**

In order to get the energy needed, the customer tariff class would have to be R2 Single Phase. Depending on the company, people pay the same for single phase as for three phase, which is the cheapest tariff that gives the energy needed. For those who cannot pay so much for an electricity service (normally those in rural areas), companies have a special life line tariff (R1) that provides 50 Kwh maximum for 4 N/Kwh (N= Naira, the Nigerian currency; 1€=442.127 N in April 2018). The problem is that this quantity does not cover all the basic electricity needs a person has.

The most expensive electricity tariff (R2S) for 2018 costs 31.26 N/Kwh and is provided by Benin Electricity Distribution PLC [9]. The cheapest tariff (R2S) for 2018 costs 21.3 N/Kwh and is provided by Ikeja Electric [10].

So, if a person consumes 493.2 kWh in 30 days these will be the costs of the electricity service:

- R1:
  Consumption charge: 50kWh $* \, 4\frac{N}{Kwh}$ = 200N
  Fixed charges: 0N
  Sub-total: 200N
  5% VAT (Value Added Tax): 200N$*$0.05 = 10N
  Total: 200N +10N = 210N

  (The problem with this tariff is that the total amount of a person's basic Kwh would not be covered)

- R2S (Benin Electricity Distribution PLC):
  Consumption charge: 493.2kWh $* \, 31.26\frac{N}{Kwh}$ = 15417.43N
  Fixed charges: 0N
  Sub-total: 15417.43N
  5% VAT (Value Added Tax): 15417.43N$*$0.05 = 770.87N
  Total: 15417.43N + 770.87N = 16188.3N

- R2S (Ikeja Electric):
  Consumption charge: 493.2kWh $* \, 21.3 \frac{N}{Kwh}$ = 10505.16N
  Fixed charges: 0N
  Sub-total: 15417.43N
  5% VAT (Value Added Tax): 10505.16N$*$0.05 = 525.26N
  Total: 10505.16N + 525.26N = 11030.42N

The minimum wage in 2015 was 18000N [11] exclusive of all deductions except those specified by the law (income tax and pension contribution). This is not enough money to live with, since apart from electricity (which costs more than half of that minimum salary) you also have to take into account other costs such as food, clothes and transport. For this reason, many people turn to wood as their means of heating and cooking because it is what they can afford. In some parts of the world firewood is sold at a retail price as low as 0.04€/kg [12], which results in a monthly cost of 4.8€/month in Nigeria (the mean fuelwood consumption in Nigeria is of $4\frac{kg}{day}$).

If the photovoltaic system used in this research project was to be installed in a house in Nigeria, the costs would be the following:

**Table 4. Table of costs for the photovoltaic system used**

| Material | Cost [€] |
|---|---|
| 2 Batteries Gel Ultracell Ugc100 | 327.98 |
| Holding structure | 99.99 |
| 300W Panel with 72 cells | 244.99 |
| Regulator | 33 |
| Pv stick mc4 weidmuller m | 14.52 |
| Pv stick mc4 weidmuller h | 14.52 |
| Fuse and fuse holder | 8.47 |
| Total | 743.47 |

If we convert the total cost from € to NGN (Nigerian Naira) with an exchange rate of 1 EUR = 442.127 NGN (08/04/2018), the total cost would rise to 328721.93 NGN.

The initial cost of installing the photovoltaic panel and the batteries is high, and an extra cost would have to be added for the shipment and for a cooking pot that can be connected to the photovoltaic system, if the user does not have one. If we estimate that this extra cost is around 60€ the final cost to set up everything would be around 355347.54 NGN.

For a person that had the most expensive tariff contracted in order to cover his basic needs before installing the PV panel, his yearly savings in electricity would be 194259.60 NGN if he decided to be completely disconnected from the electrical grid. Taking this into account, the payback period would be of around 2 years. If the person decided to have the life line tariff contracted in addition to the solar panel, the yearly savings would be 194259.6 NGN and the payback period would practically be the same.

The use of a photovoltaic system would eliminate the health risks involved in the use of firewood for cooking and would allow the user to save a lot of money in the long term. However, the main problem some people would have is the initial cost since such a high initial cost might make photovoltaic systems an unattractive option. But it is the long term savings and benefits that should be taken into account and marketed. Nonetheless, for those who cannot afford the initial cost and are willing to install a photovoltaic system, the Nigerian government is starting to give incentives.

## 8.3 Alternatives to firewood and fossil fuels

Other alternatives that are attractive to families and communities, apart from fuelwood, are the use of biogas and solar cookers (although they have limited effects). Biogas is a clean and sustainable energy that comes from the wet fermentation of organic waste, like animal and human dung. It can be used for cooking purposes after being conveniently stored and distributed through pipes. However, the production of biogas has a few negative aspects that must be taken into account. The production of biogas requires a large space and produces unpleasant odours. There must also be a manure availability that is not always possible and even if there was, its use as a fertilizer competes with its use to produce biogas. Also, in order build, maintain and use the biogas production facilities technical training is needed. Finally, one of the biggest drawbacks is the great initial investment needed due to the fermentation tank and the pipe network needed for the biogas distribution.

Solar cookers are another interesting alternative. The main positive aspect regarding health issues is that they do not produce smoke. There are two types of solar cookers, thermal and electric. Thermal solar cookers optically concentrate solar radiation and a black surface absorbs it in order to heat the food. In order to reduce the heat losses that appear in the cooking-pot when the temperature increases, a thermal insulator can be used. On the other hand, electric solar cookers obtain electricity from the sun through a photovoltaic panel and heat the food by using an internal resistance. A combination of thermal and electric solar cookers along with a storage system and high heat retention could be an interesting option to cook with. The problem with solar cookers is their relatively high initial investment for households, although the maintenance costs are very low. In (Saxena, Varun, Pandey, & Srivastav, 2011) a calculation of the net present value (NPV) and the payback period of a solar cooker is made, taking into account the purchase and maintenance costs and the interest rates. The amount of fuel saved was taken into account as virtual income, with an estimated yearly growth. The payback period goes from something more than a year up to four years approximately according to different authors cited in the text mentioned before. In the case of the PRINCE-40 (40 $m^2$ of aperture area) panelled concentrating solar cooker for communities the payback period is of the order of 1 year [18].

Many people in developing countries find it difficult to believe that a solar cooker can raise the temperature enough to be able to cook, so several activists of solar cookers, cook in the presence of those that are interested in order to show that it is possible. Solar cookers do not contaminate or consume any fuel, so they are sustainable and suitable for energy poverty situations. The set-up, use and maintenance of a solar cooker are quite simple and can be taught in a few sessions. Furthermore, the implementation of solar cookers would not only be beneficial for the aspects already mentioned, but also would reduce deforestation since there would no longer be a need for using firewood. However, a negative aspect of solar cookers is that due to the intermittence of the sun they cannot be considered as a unique cooking medium, since there are times at which they cannot be used (if there is no storage system installed).

The following table summarizes different cooker characteristics.

**Table 5. Characteristics of the different cooking options [12]**

| | **Acquisition [€]** | **Efficiency [%]** | **Daily hours spent cooking [h]** | **Household consumption [toe/year][nn-1]** |
|---|---|---|---|---|
| **Conventional cookers** | | | | |
| **Charcoal** | 2.5 to 5 | 20 | 2 to 4 | 0.5 to 1.9 |
| **Firewood or straw** | 0 to 1.5 | 11 | 2 to 4 | 1.0 to 3.7 |
| **Modern cookers** | | | | |
| **Kerosene** | 25 | 45 | 1 to 3 | 0.1 to 0.2 |
| **LPG[nn]** | 50 | 55 | 1 to 3 | 0.08 to 0.15 |
| **Electricity** | 250 | 75 | 1.2 to 2.4 | 0.07 to 0.13 |
| **Digester biogas** | 500 to 1200 | | 1 to 3 | 0.07 to 0.13 |
| **Improved cookers** | | | | |
| **Coal** | 11 | 26 | 1.5 to 3 | 0.4 to 1.5 |
| **Firewood** | 15 | 25 | 2 to 4 | 0.5 to 1.6 |
| **Solar cooker** | 1 to 100 | - | 1 to 8[nn+1] | 0 |

[nn-1] toe (tonne of oil equivalent) is a unit of energy defined as the amount of energy released when burning 1 tonne of crude oil. It equals 41.868 GJ (gigajoules) or 11.630 MWh (megawatt-hours).

[nn] Liquefied petroleum gas: propane and butane.

[nn+1] Slow solar cookers, like the panel ones or solar box ovens, they do not need much attention and are the ones with the longest cooking time due to their low power. Quick solar cookers, like concentrating ones, are able to cook within the same time as modern cookers if the day allows it.

## 8.4 Nigeria’s regulatory framework on solar energy

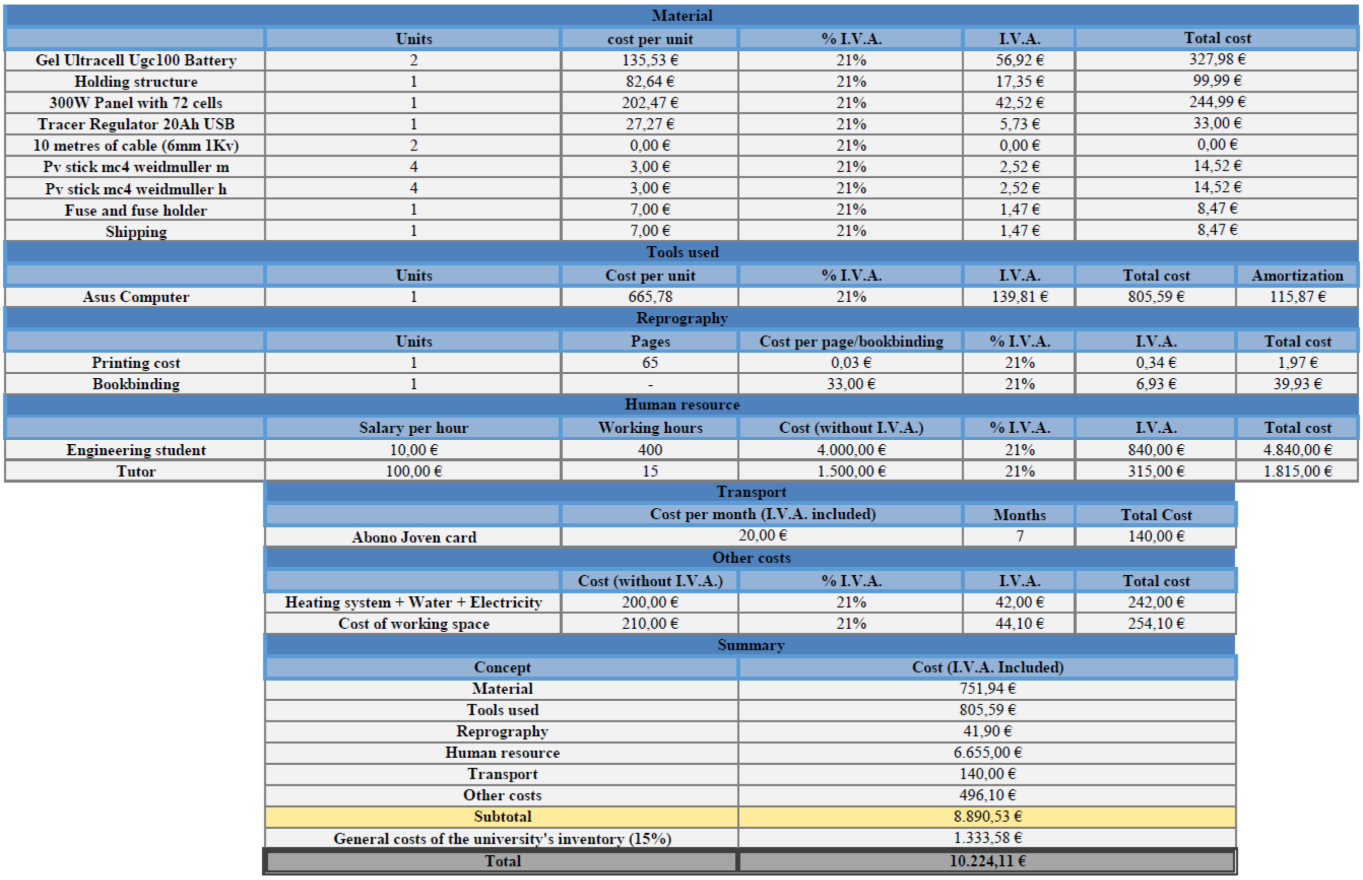
In the ECOWAS (Economic Community of West African States) region, in which Nigeria is included, the institutional, regulatory, legal and tariff structures and frameworks are mostly non-existent or not firmly implemented [19]. In 2015 there were very few incentives for private capital to invest in renewable energies and most of the projects carried out were funded by ODA (Official Development Assistance). Therefore one of the priority goals the ECOWAS region has set for the upcoming years is to improve this situation by starting to implement some short-term and long-term policies. These policies, among others, include incentives like tax exemptions to attract investors and campaigns to popularize the use of renewable energies. The ECOWAS region is aiming to increase the share of renewable energies in the energy mix in its member countries.

In Nigeria some of the main short-term strategies that are being followed in order to improve the country’s situation with respect to solar energy are [20]:

- An intensification of the research and development in solar energy technology.
- Providing adequate incentives to suppliers of solar energy products and services.
- Providing adequate incentives to local manufacturers for the production of solar energy systems and accessories.
- Setting up measures to accelerate the emergence of local solar energy industries.
- Setting up campaigns in order to popularize solar energy and present it as a solution for the lack of energy supply in rural and peri-urban areas.
- Providing fiscal incentives for the installation of solar energy systems.
- Developing and enforcing standards for solar energy technologies, products, services and processes.

The ECOWAS’s aim (so as Nigeria’s) is to locally manufacture part of the photovoltaic panels that are being installed in its member countries and increase the share of locally manufactured PV panels annually. In fact, the ECOWAS region has launched a programme to train and obtain qualified solar installers and develop a regional renewable energy standard [21]. In order to develop those standards the ECREEE (ECOWAS Centre for Renewable Energy and Energy Efficiency) is planning to work with some European countries that already have a developed solar technology. With all the efforts that are being put out it is likely that in a few years a more solid regulatory framework will be established.

# 9. Budget



**Material**

| | Units | cost per unit | % I.V.A. | I.V.A. | Total cost |
|---|---|---|---|---|---|
| Gel Ultracell Ugc100 Battery | 2 | 135,53 € | 21% | 56,92 € | 327,98 € |
| Holding structure | 1 | 82,64 € | 21% | 17,35 € | 99,99 € |
| 300W Panel with 72 cells | 1 | 202,47 € | 21% | 42,52 € | 244,99 € |
| Tracer Regulator 20Ah USB | 1 | 27,27 € | 21% | 5,73 € | 33,00 € |
| 10 metres of cable (6mm 1Kv) | 2 | 0,00 € | 21% | 0,00 € | 0,00 € |
| Pv stick mc4 weidmuller m | 4 | 3,00 € | 21% | 2,52 € | 14,52 € |
| Pv stick mc4 weidmuller h | 4 | 3,00 € | 21% | 2,52 € | 14,52 € |
| Fuse and fuse holder | 1 | 7,00 € | 21% | 1,47 € | 8,47 € |
| Shipping | 1 | 7,00 € | 21% | 1,47 € | 8,47 € |

**Tools used**

| | Units | Cost per unit | % I.V.A. | I.V.A. | Total cost | Amortization |
|---|---|---|---|---|---|---|
| Asus Computer | 1 | 665,78 | 21% | 139,81 € | 805,59 € | 115,87 € |

**Reprography**

| | Units | Pages | Cost per page/bookbinding | % I.V.A. | I.V.A. | Total cost |
|---|---|---|---|---|---|---|
| Printing cost | 1 | 65 | 0,03 € | 21% | 0,34 € | 1,97 € |
| Bookbinding | 1 | - | 33,00 € | 21% | 6,93 € | 39,93 € |

**Human resource**

| | Salary per hour | Working hours | Cost (without I.V.A.) | % I.V.A. | I.V.A. | Total cost |
|---|---|---|---|---|---|---|
| Engineering student | 10,00 € | 400 | 4.000,00 € | 21% | 840,00 € | 4.840,00 € |
| Tutor | 100,00 € | 15 | 1.500,00 € | 21% | 315,00 € | 1.815,00 € |

**Transport**

| | Cost per month (I.V.A. included) | Months | Total Cost |
|---|---|---|---|
| Abono Joven card | 20,00 € | 7 | 140,00 € |

**Other costs**

| | Cost (without I.V.A.) | % I.V.A. | I.V.A. | Total cost |
|---|---|---|---|---|
| Heating system + Water + Electricity | 200,00 € | 21% | 42,00 € | 242,00 € |
| Cost of working space | 210,00 € | 21% | 44,10 € | 254,10 € |

**Summary**

| Concept | Cost (I.V.A. Included) |
|---|---|
| Material | 751,94 € |
| Tools used | 805,59 € |
| Reprography | 41,90 € |
| Human resource | 6.655,00 € |
| Transport | 140,00 € |
| Other costs | 496,10 € |
| Subtotal | 8.890,53 € |
| General costs of the university's inventory (15%) | 1.333,58 € |
| **Total** | **10.224,11 €** |

$$Amortization = 805.59€ * \frac{210\ days}{4 \times 365\ useful\ life\ days} = 115.87€$$

# 10. Conclusion & future works

Throughout this research project the main objectives that were initially proposed at the beginning have been achieved, such as partially deciphering the functioning of the charge controller and carrying out an experimental characterization campaign of a realistic device.

- This project has demonstrated that a small photovoltaic system can provide enough energy to perform two activities at the same time, both to cook and to charge a pair of batteries. During the experimental phase we observed that if a smaller load was to be connected instead of the one used (5 ohms), the voltage would remain constant but the current received would increase. Another interesting observation made during the experiment was that when the voltage of the photovoltaic panel surpasses the maximum power voltage the output power was reduced, as seen also in the theory on this subject matter. As the experiment developed it was noticed that the direct radiation had values close to 1000 W/m$^2$, a factor that can contribute to the possibility of having higher efficiencies. However, since other factors like high temperatures or a low depth of discharge (DOD) in the batteries on some days contributed to lowering the efficiency of the photovoltaic panel, the maximum efficiency was not attained.

- The knowledge gained from the research process reveals that on a larger scale these types of systems could be installed in places where there is a shortage of electricity, overuse of firewood or where electricity is very expensive and unreliable. The insight obtained has not only provided deeper understanding in the way photovoltaic systems function, but it has also presented evidence of a functional system, which could be implemented on a larger scale for solar cooking in the near future. It also suggests that improved storage capacity of batteries, charged by solar energy through photovoltaic panels, have the potential of storing and supplying the growing demand for a clean, sustainable and cost efficient source of energy for cooking. In this thesis, the main areas related to photovoltaic systems have been described and theoretical research in the following fields of knowledge has also been presented:

  - Photovoltaic panels
  - Components of a photovoltaic system
  - Batteries
  - Solar radiation
  - Solar angles
  - Advantages of solar energy above other traditional energy sources

- The main practical part of the thesis has looked at the functioning of a photovoltaic system based on solar energy collected through solar panels and stored in batteries. The data collected was carefully recorded and analysed to find out if it could be stored and used later when there was no sunlight. In order to observe and study the variables and outcomes of this part of the thesis, the following strategies were implemented:

- Identifying and understanding the components to be used
- Setting up the photovoltaic system
- Recording data on a daily basis
- Calculating an approximation of the performance of the panels each day
- Studying and re-evaluating areas of challenge
- Identifying and describing issues to be taken into account on a daily basis

It can be deduced from both the practical and theoretical parts of this project that it has been very useful as a learning tool as well as providing a base for ongoing research in the future. If the findings of this, and similar researches, were to be supported by companies interested in clean solar energy, by governments, or by NGOs who are working in the field of alternative energy, especially in developing countries, it could be put to greater use in areas of the world where this type of knowledge is lacking.

Thanks to continued research, better and more efficient solar cells are being developed annually. New materials are being tested and some solutions like stacking together different semiconductors with different energy gaps are being studied for the Shockley-Queisser limit. Additionally, a multi-junction solar cell with an efficiency of 46% was recently created in a laboratory where French and German scientists were working together [24]. Solar energy is a clean and sustainable alternative that can reduce the detrimental impact of global pollution, and researches like this offer the possibility of implementing functional low cost and efficient appliances for daily household use that can help this situation. The results of this research portray a development that can make a contribution to sustainable energy practices in the world.

To conclude, the type of technology that has been tested in this project could have a more promising future if new types of batteries are developed that can last longer and deteriorate at a slower pace. This could also allow photovoltaic systems to be more cost-effective and functionally practical. Similarly, an interesting area for future research would be to test the maximum number of batteries that can be connected to a panel like the one used in this project, so that they can be charged while simultaneously being connected to a load. Finding out such data would allow the user to calculate the maximum time that the system mentioned in this project would function without sunlight.

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