End of Degree Project

Bachelor's degree in Industrial Technology Engineering

Can Carbassa: An Off-Grid Solution for a Rural Home

Project Report

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ETSEIB

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Abstract

This project aims to design an off-grid electrical installation based on renewable sources that can successfully solve the energy requirements of Can Carbassa, a rural home in the Alt Empordà.

To do so the project is divided into four main chapters. In the first chapter the residence is described, along with its geographical location and climate. In the following chapter off-grid electrical installations are studied from a theoretical point of view, looking at the components that make up the system and what role they play in it, as well as the different technological solutions available on the market today.

In the third chapter the current electrical installation is analysed to determine the current consumption and production and determining the weak points of the system. The conclusions of this analysis will be used in the following chapter to design the new installation, sizing all the components and defining the connections between them.

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1. Introduction

1.1. Problem to be solved

Can Carbassa is an old farmhouse located in the middle of the forest in the Alt Empordà, with no connection to the electricity grid. The current electrical installation is based on solar power and a backup generator and has been upgraded several times to keep up with the needs of the residents. However it is insufficient to meet the current power demand, and often proves unreliable, with some devices not being able to function when the backup generator is working. In this project the current installation is analysed to determine its weak points and a new installation is sized according to current requirements.

1.2. Objectives

The main objective of this project is to design a new electrical installation based on solar and wind power sources, that meets the current power demands and allows for future growth. It must prove to be reliable and robust, being able to operate and respond under all kinds of conditions.

The usage of the backup generator in the new installation must be reduced to zero, except in exceptional circumstances, to reduce fuel costs and pollution.

The new installation must include network connectivity, to allow the owners to monitor the system when they are not in the residence.

1.3. Scope

This project includes the study of the current electrical installation, along with the design and sizing of the new system. The consumption requirements of the residence will not be modified, as they are fixed by the residents.

The functioning of the different components of the system along with the technological solutions available in the market is also studied.

2. Description of the residence

Can Carbassa is an old Catalan farmhouse – a *masia* – dating back at least 300 years. It was constructed in several phases, with two distinct parts being clearly visible. Up until the 1960s it served as residence for cherry farmers, which was very common in the area, as it presents optimal climatic conditions for this kind of crop. After that the house was abandoned for 30 years, and it fell into disrepair, until it was bought by the current owners in 1992.

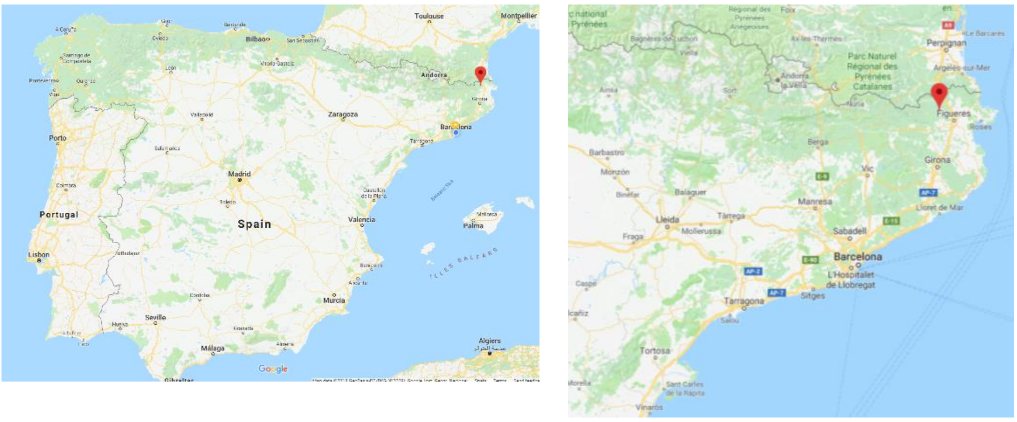
2.1. Construction

When the house was bought by the current owners it was in ruins, with only a few walls standing and no roof. A first restoration was carried out on one half of the house, in what is now known as the old part of the house. Years later in 2012 a second restoration was carried out, to rebuild the other half of the ruins, and the new part of the house was built.

The residence has stone and clay walls (about 50 cm thick) in the old part and brick walls with a stone finish in the new part. There are four bedrooms, kitchen, dining room, living room, study and bathroom.

2.2. Geographical Location

Can Carbassa is located in the *Serra dels Avalls,* a mountainous area in the municipality of Terrades, in the *comarca* of the Alt Empordà, north-eastern Catalunya (Spain).



42°19'15.7"N 2°51'35.5"E

Figure 2.1 Location of the residence within Spain and Catalunya (Google Maps)

This region is located between the Pyrenees and the coast and is dominated by steep hills of up to 500 metres, growing higher towards the west and flattening out towards the east. Can Carbassa is located at 245 m, on the southern side of a 250 m hill, within a valley oriented from east to west.

The house itself faces south-east, specifically at an angle of 150º with respect to the North, as can be seen in Figure 2.2.

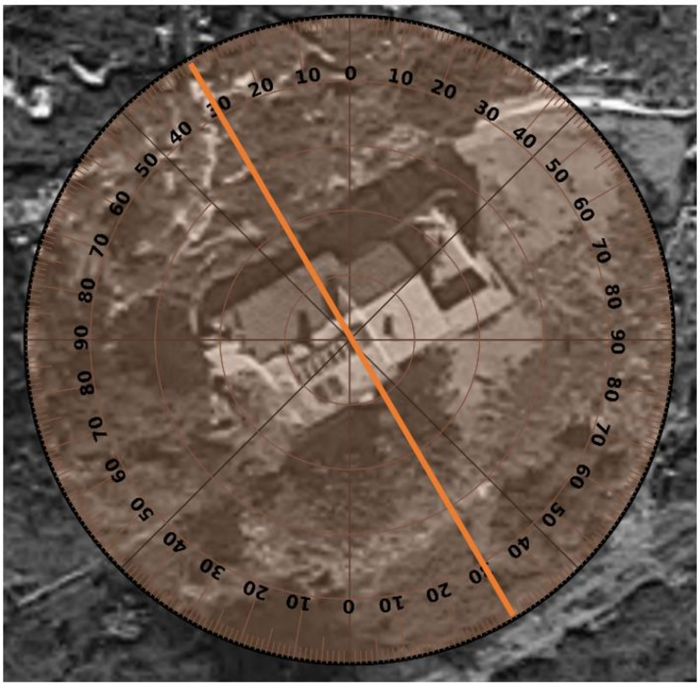


Figure 2.2 Orientation of the house in degrees

2.3. Climate

The area in which Can Carbassa is located is characterised by a Hot-summer Mediterranean climate, *Csa* according to the Köppen classification, with hot summers and mild winters. A more detailed classification is offered by the (*Atles climàtic de Catalunya : període 1961-1990 . - 2a ed. . - Barcelona: Institut Cartogràfic de Catalunya - Servei Meteorològic de Catalunya, 2008*), which states that the climate in the area is *Mediterrani Prelitoral Nord*, which translates to Northern Precoast Mediterranean climate. According to the authors this climate has hot summers and mild winters, with an irregular distribution of rainfall throughout the year.

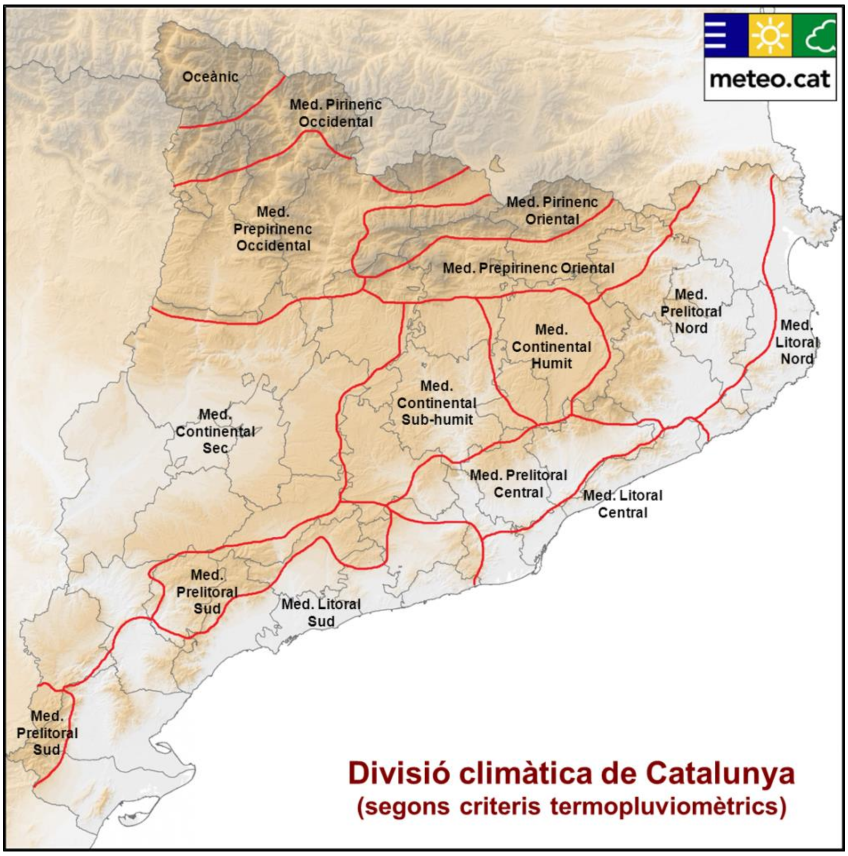


Figure 2.3 Types of climate present in Catalunya (meteocat)

The Alt Empordà, *comarca* in which the house stands, has its own climatological singularities, especially when it comes to wind. Due to its location between the Pyrenees and the Alps, in the Gulf of Lion, when northern winds blow they are funnelled down through the Gulf, creating strong wind gusts over the *comarca*. This wind is known locally as the *Tramuntana* (from the Italian name *Tramontana*, meaning between mountains), and can blow for days with gusts of up to 120 km/h. This wind is quite common during the winter months, between October and March. In the summer months the dominant wind is a sea breeze from the SE, created by the temperature difference between the warm land and the cool sea. This wind is not as strong as the *Tramuntana*, and is less gusty, reaching maximum speeds of 45 km/h.

3. Off-Grid Residential Power Systems

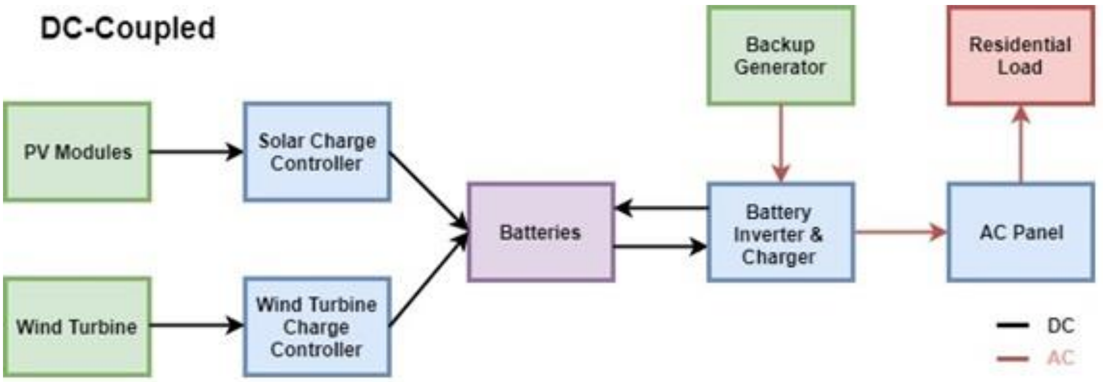
Off-grid residential power systems based on renewable energy sources have been around for decades and are a fast-developing mature technology. In this section the different components which will make up the power system are described, as well as the different technological solutions available on the market.

Off-grid solar installations are made up of different components, interconnected in such a way so power generated by the PV modules and the wind turbine can be stored in the batteries and supplied to the residence. In these systems some components work with DC while others work in AC, and these are listed in the following table:

Table 3.1

AC Components	DC Components
Residential Load Backup Generator	PV Modules Batteries Wind Turbine

Depending on how these components are connected, off-grid solar installations can be classified in two types: AC-Coupled systems and DC-Couples systems. The difference between the two lies in the power conversion chain. While DC-Coupled systems feed the DC supply from the PV modules and wind turbine into the batteries to charge them, AC-Coupled systems first convert the DC from the PV modules to AC with an inverter, feeding it directly into the system. AC-Coupled systems with a wind turbine normally maintain the configuration the same as in DC-Coupled systems for this component, however other layouts are possible. In this project only this alternative will be considered.



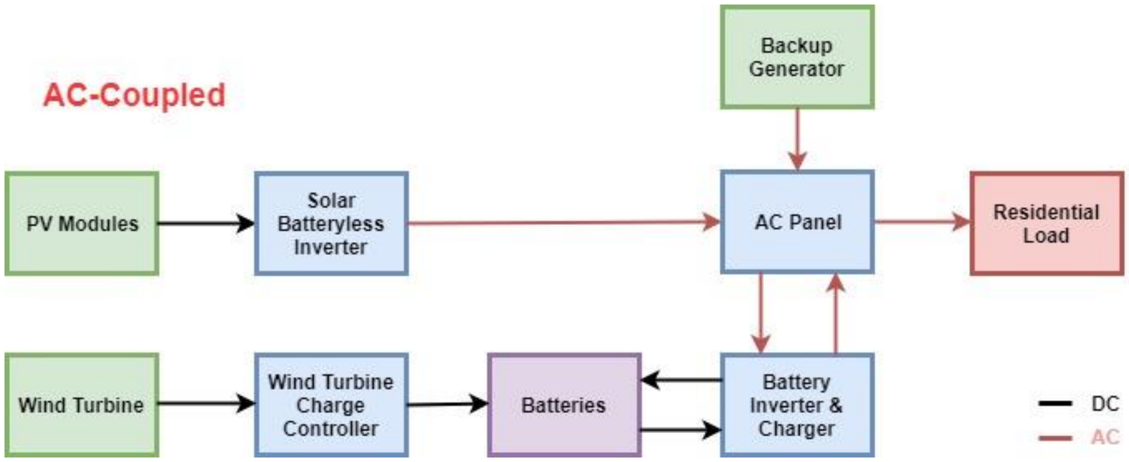


Figure 3.1 Schematic of a DC-Coupled (top) and a AC-Coupled (bottom) off-grid solar installation, including power generation (green), management (blue), storage (purple) and consumption (red).

AC-Coupled systems perform well in installations where the PV modules are far from the residence, high power installations and sites with multiple solar production sites. Otherwise DC-Coupling is a cheaper, more efficient solution, as only one inverter is required.

3.1. Photovoltaic Modules

Photovoltaic Modules, sometimes abbreviated as PV modules, convert solar radiation into electric current. PV modules are composed of multiple solar cells, which produce electrical current thanks to the photovoltaic effect.

3.1.1. Functioning Principle: The Photovoltaic Effect

The photovoltaic effect is the creation of voltage and electrical current in a material when exposed to light. Solar cells are based on the properties of the p-n junction, seen in Figure 3.2, to create electrical power from solar radiation.

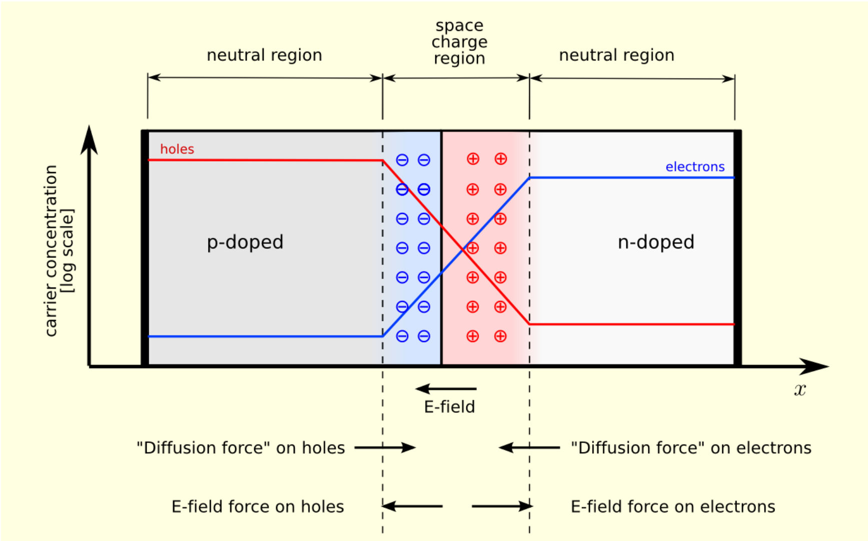


Figure 3.2 Schematic of a p-n junction with no voltage applied (TheNoise)

A p-n junction is created by joining two pieces of semiconductor material, each doped with different elements. The p region is doped with elements with fewer valence electrons, creating ‘holes’, and the n region is doped with elements with more valence electrons, giving this region an excess of electrons. When joined there is a diffusion flow of holes toward the n region and of electrons to the p region, creating an electrical field, which eventually grows strong enough to impede any further flow of holes or electrons, creating the *depletion region*.

When a p-n junction is exposed to solar radiation the atoms in the depletion zone are bombarded by photons. When a photon hits an atom it is absorbed and creates a free electron and a hole, which each flow toward the n region and p region respectively, due to the electric field. The higher concentration of electrons in the n region with respect to the p region creates an electric potential (voltage). By connecting both regions to a load a direct electric current is formed due to the difference in potential, as shown in Figure 3.3.

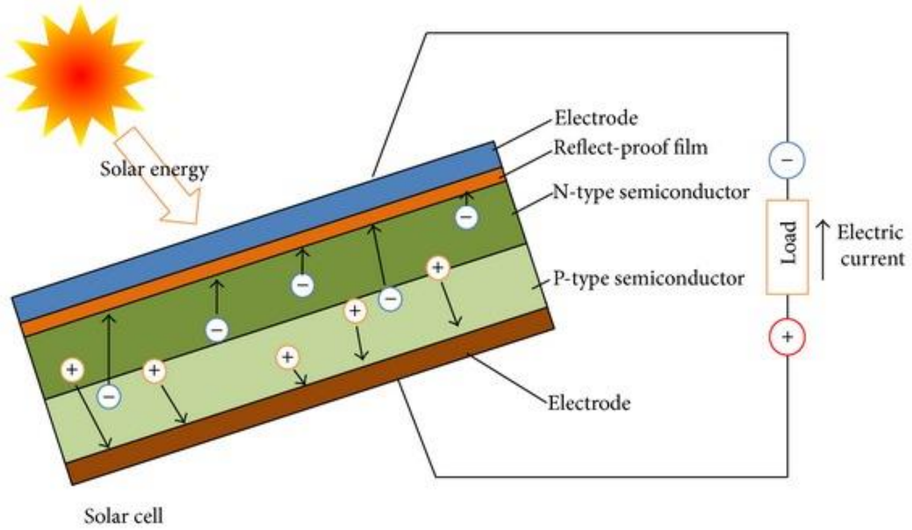


Figure 3.3 Schematic of a solar cell connected to a load (Tom van Gerven)

Due to the higher surface quality of the n-doped material it is placed at the light-receiving end of the cell. By making this layer as thin as possible (<1 μm) the amount of light absorbed in the p-n junction is maximised.

In order for the solar cell to produce electricity several other components must be added (Figure 3.4.):

- **Front contact (metallic fingers and busbar):** Metallic fingers provide a path for the electrons emitted by the p-n junction, since the resistance of the semiconductor is quite high. As they shade the cell from incoming light they must be adequately spaced to strike a balance between light collection and cell resistivity. They are typically 20-200 μm wide and are placed 1-5 mm apart.
- **Rear contact:** Allows electrons to return to the positive electrode. Its design is not as important as the front contact as no light must pass through it, however it is made as thin as possible to optimise thickness.
- **Reflect-proof coating:** It maximises the light absorbed by the cell, minimising the fraction of light reflected.

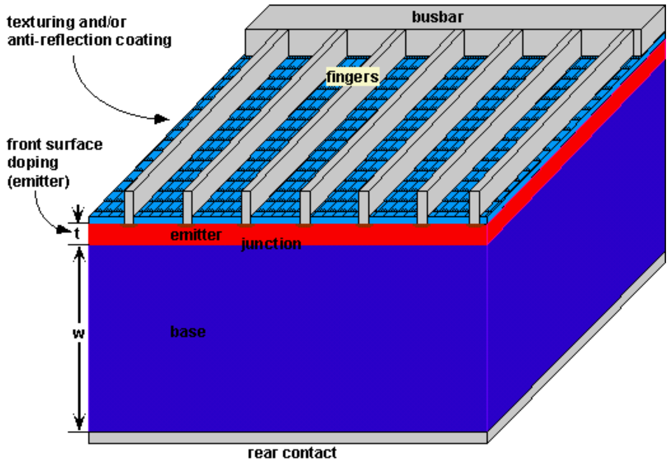


Figure 3.4 Parts of a solar cell (pveducation.org)

3.1.2. Parameters

In order to determine the performance quality of a solar several parameters must be measured and obtained by performing a flash test. A flash test is carried out by exposing a solar panel to a short burst (1 to 30 ms) of high intensity light (1000 W/m^2) from a xenon arc lamp, which has an output spectrum very similar to that of the sun. The following output parameters are measured:

- **Open Circuit Voltage (VOC):** Voltage with no load connected to the output.
- **Voltage at Maximum Power (VMP):** Voltage at which the solar panel outputs the most power.
- **Short-Circuit Current (ISC):** Current output when the panel output is shorted (V=0 V).
- **Maximum Power Current (Imp):** Current output at the maximum power point.
- **Maximum Power (Pm):** Maximum value of the product of the output voltage and the output current. Each solar panel's power output is rated to this point.
- **Fill Factor (FF):** It is obtained by dividing the maximum power Pm by the product of VOC and ISC. It is a measure of the solar panel's quality.

The overall maximum efficiency of a solar panel can be obtained by dividing the incident light power by the maximum output power:

$$\eta = \frac{Maximum\ Power}{Area * Light\ Intensity} \qquad \text{Eq 3.1}$$

3.1.3. Technological Solutions

The photovoltaic effect was discovered in the 1950s. Since then several different technologies have been developed, using different materials, trying to strike a balance between efficiency and manufacturing cost.

In this section we will be examining different technological solutions for residential solar cells according to their efficiency (Figure 3.5), area required and cost, specifically crystalline silicon and thin film technology. It must be noted that other technologies do exist but will not be included as they are not aimed at residential applications.

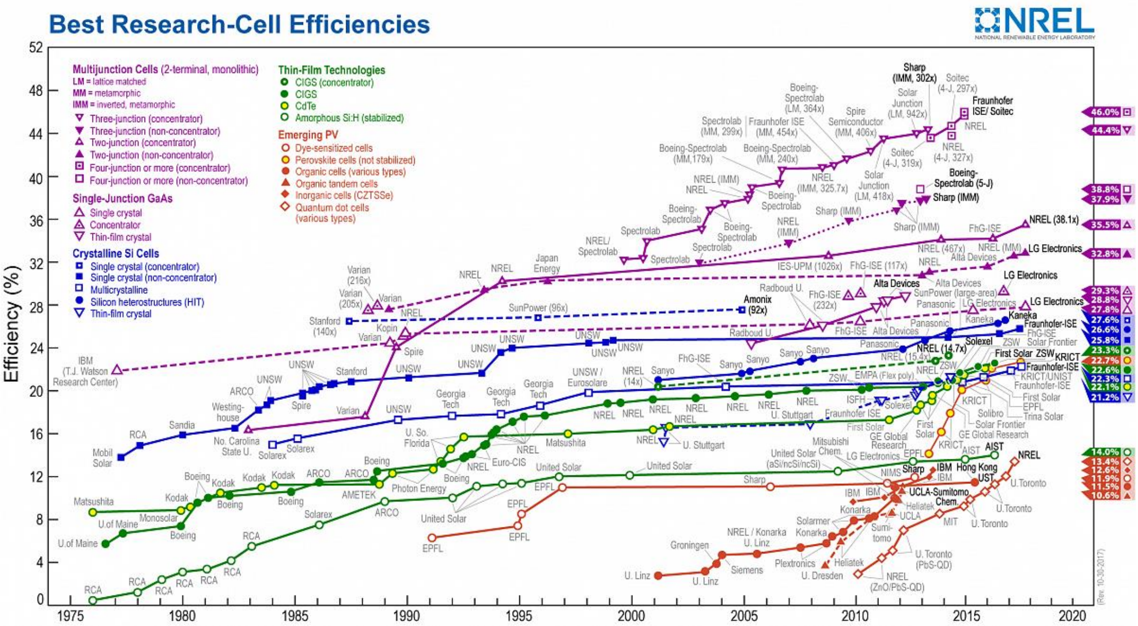


Figure 3.5 Evolution of solar cell technology efficiency (NREL)

3.1.3.1. Crystalline Silicon

Nowadays solar cell technology is mostly based on silicon, accounting for 94% of the global production in 2016 (Ise, 2018). It is the most mature and developed solar cell technology, partly due to the usage of silicon in electronic and computing, and the abundance of silicon in the Earth's crust.

However, crystalline silicon is not an ideal material for light absorption, as it presents an indirect band gap (Figure 3.6). This means a photon must coincide with a phonon for an electron to transition to the conduction band, making the solar cell thicker and more temperature dependent.

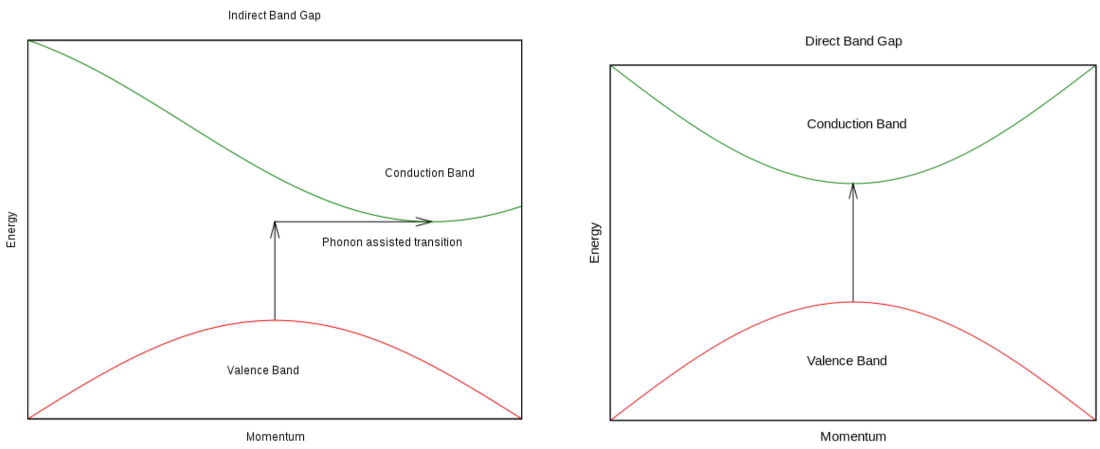


Figure 3.6 Indirect (left) and direct (right) semiconductor band gaps (Profjohn)

Two types of crystalline silicon are currently used to manufacture solar cells:

- **Monocrystalline silicon:** The base material is a single, continuous crystal of silicon, with no grain edges. Manufactured using the *Czochralski* process.
- **Polycrystalline silicon:** The base material is composed of small crystals (crystallites).

Each type of crystalline structure presents its own advantages and drawbacks:

Table 3.2. Mono and polycrystalline solar panel comparison

Monocrystalline silicon		**Polycrystalline silicon**	
Advantages	Disadvantages	Advantages	Disadvantages
• High efficiency (26,7% lab) • Space required • Lifespan (≈25 years) • Low-light performance	• High cost • Dependence on temperature • Inefficient manufacturing process	• Lower cost • More efficient manufacturing process • Less temperature dependence	• Lower efficiency (22,3% lab) • Space required • Aesthetic appearance

3.1.3.2. Thin Film

Thin film solar cells, as the name indicates, are significantly thinner than their crystalline counterparts (about 350 times). These thicknesses are achievable thanks to the use of direct bandgap semiconductor materials, such as:

- Cadmium Telluride (CdTe)
- Amorphous silicon (a-S)
- Copper Indium Gallium Selenide (CIGS)
- Gallium Arsenide (GaAs)

Table 3.3 Thin Film solar cell materials

Material	Efficiency (lab)	Cost	Space	Comments
CdTe	22,1 %	Low	High	Toxic materials used
a-S	14 %	Low	High	Only for small loads
CIGS	22,6 %	Low	High	
GaAs	28,8 %	Prohibitive	High	Used in aerospace applications

Thin film solar is a developing technology, compared to the well-established crystalline silicon industry. This means that availability may be somewhat limited.

Thanks to the properties of the materials used, as well as the thickness of the solar cells, thin film solar modules are flexible, and are also very easy to install.

3.2. Wind Turbine

A wind turbine produces electrical power by harvesting the mechanical power of the wind, a renewable energy source.

3.2.1. Functioning Principle

Wind is caused by the irregular heating of the earth's surface by the sun, which causes pressure differences and therefore air circulation. The orography and the presence of bodies of water condition the flow of air, channelling wind through certain areas and blocking air flow in others.

As the incoming airflow arrives at the turbine it is deflected by the blades, which in turn causes a force in the opposite direction of the deflection, making the blade spin around the turbine's axis. The rotating axis is connected to a generator through a gearbox, which converts the slow rotation speeds of the blades (5 to 20 rpm) to the faster angular velocities required by the generator to generate electricity (750 to 3600 rpm).

The generator outputs AC current, which is then fed either to a transformer, to set the voltage at the required level for domestic use or storage. Some wind turbines include a rectifier, so the turbine outputs DC current, which can be used to charge the batteries of an off-grid installation.

The theoretical maximum extractable wind power is given by the Betz law, which states that maximum turbine efficiency is 59,3%:

$$P = \frac{16}{27} * P_{wind} = \frac{8}{27} \rho v^3 A \qquad \text{Eq 3.2}$$

Where ρ is the air density [kg/m^3], v is the wind speed [m/s] and A is the effective area of the disk. As can be seen in the equation the harvestable power has a cubic dependence on wind speed, meaning that small variations in wind speed can cause substantial variations in the power produced.

3.2.2. Parameters

In order to study and compare the working of different turbines we must consider the power curve of each turbine. As can be seen in Figure 3.7, the power output of a wind turbine is a function of the wind speed and increases in a non-linear way up until a certain speed, from which point on it stays constant.

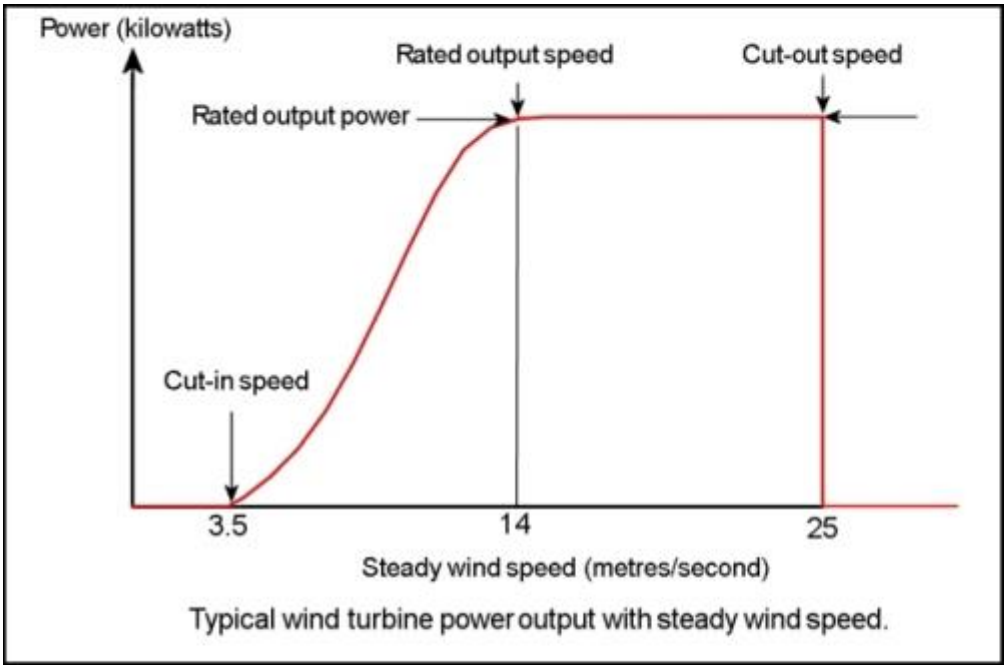


Figure 3.7 Wind turbine power output curve (wind power program)

Several characteristic points can be identified on the power curve:

- **Cut-in speed:** Speed at which the turbine blades start spinning and power is produced.
- **Rated output speed:** Speed at which the power output stops increasing.
- **Rated output power:** Maximum power that the turbine can produce, at speeds between the rated output speed and the cut-out speed.
- **Cut-out speed:** Above the cut-out speed the turbine's operation is no longer safe, and a braking system stops the blades from spinning.

Other important parameters include:

- **Tip speed ratio (TSR):** It is defined as the speed of the blade tip divided by the wind speed:

$$\lambda = \frac{\omega R}{v} \qquad \text{Eq 3.3}$$

Where v is the wind speed [m/s], ω is the angular velocity of the blade [rad/s] and R is the rotor radius. High values of TSR are desirable for efficient generator operation, but they also induce vibrations and erosion.

- **Wind turbulence:** Due to the interaction between the airflow and the ground wind at low levels tends to be turbulent. However, at higher altitudes the effect of the ground on the wind speed decreases, and the airflow becomes steadier.
- **Power Coefficient (C_p):** It is defined as the quotient of the effective power harvested by the turbine over the wind power. The maximum theoretical value is the Betz ratio.

3.2.3. Technological Solutions

Two basic families of wind turbines can be found on the market today: horizontal axis wind turbines and vertical axis wind turbines.

3.2.3.1. Horizontal Axis Wind Turbine (HAWT)

HAWTs have a horizontal main rotor shaft and blades which face into the wind mounted at the top of a tower. The blades are designed to be lift inducing, with the lift force in turn creating a rotation torque around the rotor axis, and must always be upwind of the tower, in order to avoid wake turbulence. This requires an orientation system for the rotor axis, so the blades are always facing into the wind. The turbine must be placed at the top of a freestanding tower in order to reduce turbulence and changes in wind direction, which reduce the efficiency of a HAWT.

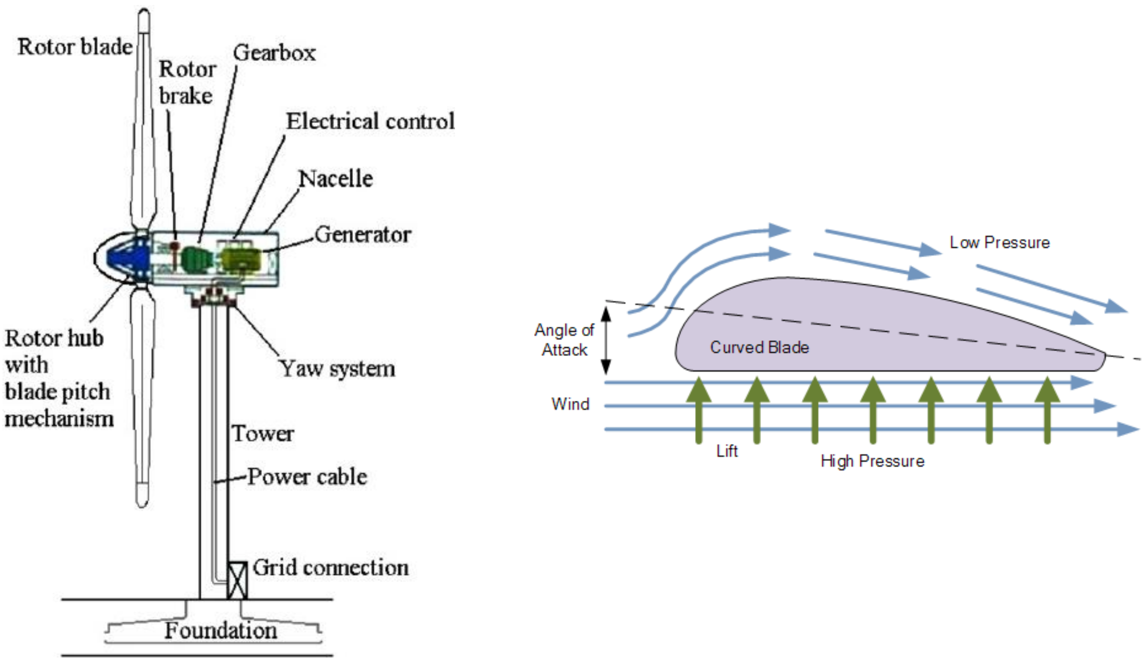


Figure 3.8 Horizontal axis wind turbine (left) and a HAWT blade profile (right) (Jung-Ryul Lee)

HAWT are the most common type of wind turbine and is used in residential applications (<1 kW) as well as large-scale wind farms (up to 8 MW).

3.2.3.2. Vertical Axis Wind Turbine (VAWT)

VAWTs have a vertically oriented rotor shaft, which allows the turbine to generate power with wind coming from any direction, and therefore not needing a blade-orientation system. Two main types of VAWT can be identified according to how wind power is harvested (Figure 3.9):

- **Darrieus wind turbine:** The blades are designed with the profile of an aerofoil, which creates a lift force perpendicular to the rotor axis, making the axis rotate at high speeds. Due to their design Darrieus turbines are not self-starting, and the blades can spin at many times the wind speed, making it a good option for electricity generation.

- **H-Darrenius wind turbine:** An improved versin of the Darrenius turbine, it offers higher efficiency and easy manufacturing.
- **Savonius wind turbine:** The blades on this kind of turbine resemble anemometer cups, which when hit by wind induce a drag force perpendicular to the motor axis. The Savonius turbine is self-starting and is used in applications where reliability is of more importance than high efficiency.

The biggest disadvantage of the Darrieus turbine is its lack of self-starting capabilities, but by combining it with the Savonius turbine this problem is easily overcome. This new device is called the Self Starting Darrieus Wind Turbine and is composed by a Darrieus turbine and a small Savonius turbine attached to the base of the rotor, allowing it to be self-starting.

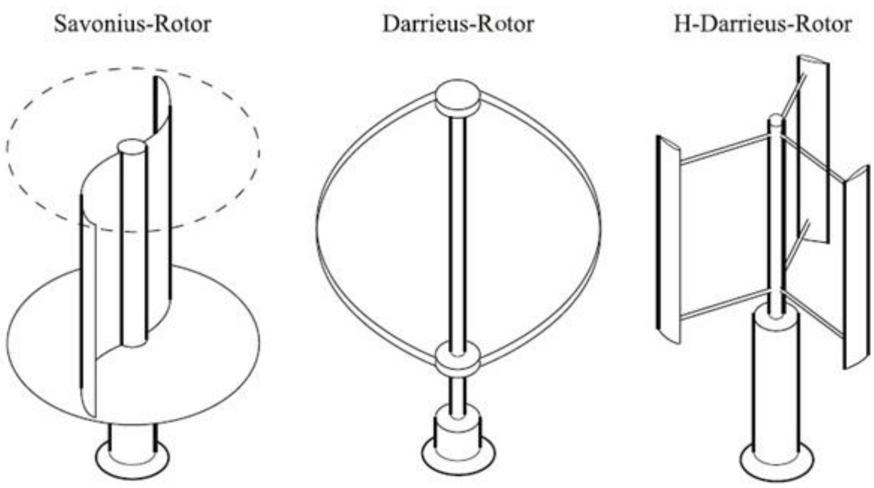


Figure 3.9 Savonius and Darrieus wind turbines (Jung-Ryul Lee)

VAWTs operate close to the ground, and perform well in turbulent environments, with sudden changes in the wind direction.

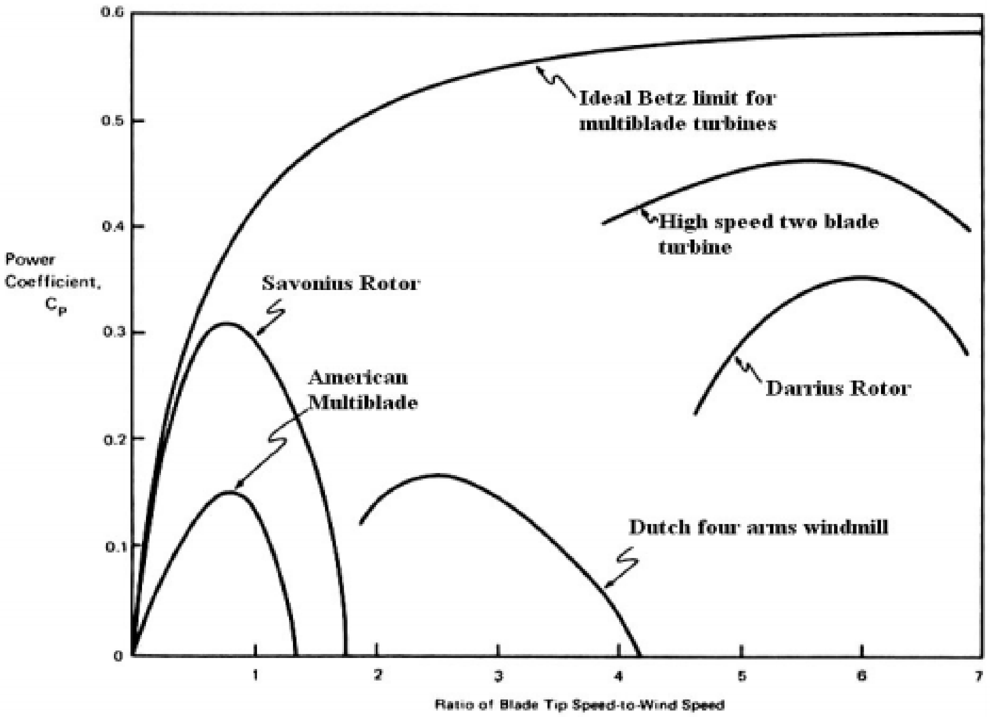


Figure 3.10 Power coefficient in function of the TSR for different types of turbine (Jung-Ryul Lee)

As can be seen in Figure 3.10 both the HAWT and the Darrenius turbines can operate in approximately the same range of TSR, but the HAWT is more efficient. The Savonius rotor is only viable at low speeds.

Table 3.4 Wind turbine type pros and cons			
HAWT		VAWT	
Advantages	Disadvantages	Advantages	Disadvantages
High generating capacity High efficiency	Noise Land use Tall tower Sensitive to wind direction	Accepts wind from any direction Easy maintenance Good in turbulent environments	Low starting torque Limited to low speed environments Tendency to stall in gusty conditions

3.3. Batteries

Electricity is notoriously difficult to store, requiring a transformation to another form of energy. Batteries store electrical energy by converting it to chemical energy when charging, allowing it to be converted back to electricity when required.

3.3.1. Working Principle

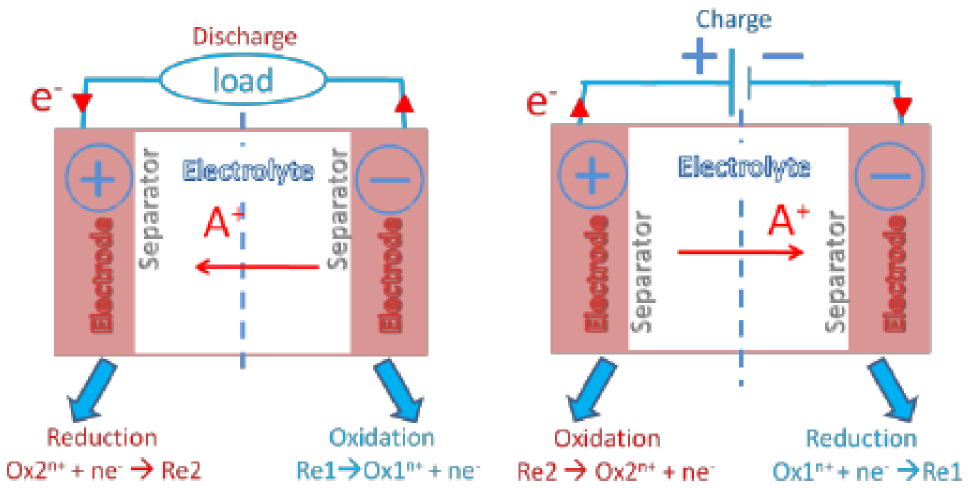


Figure 3.11 Illustration of the workings of a voltaic cell during charging and discharging. (Rudolf Metkemeijer)

Batteries work by storing electric energy in the form of chemical energy in several voltaic cells (Figure 3.11). Voltaic cells consist of two electrodes, one positive and one negative, immersed in an electrolyte.

Two processes can be carried out in a voltaic cell: charging and discharging. During a charge cycle an external DC power source applies a voltage across the cell's terminals, forcing an oxidation reaction (release of free electrons) on the positive electrode and a reduction reaction (capture of free electrons) on the negative electrode. During a discharge cycle the reduction reaction occurs on the positive electrode and the oxidation on the negative electrode, producing a voltage difference between the electrodes, and a flow of direct current when connected to a load.

Depending on the reversibility of the chemical reactions used, batteries are classified as rechargeable or non-rechargeable. Rechargeable batteries can be recharged after a discharge, while non-rechargeable batteries can only be discharged once.

3.3.2. Parameters

In order to be able to study and compare different types of batteries the following parameters are defined:

- **Capacity:** The total amount of electricity a battery can store, measured in kWh or Ah. A volumetric energy density [kWh/m^3] and gravimetric energy density [kWh/kg] can also be defined.
- **Power:** Maximum instantaneous electric power a battery can supply at a given moment in time, measured in kW or A. A volumetric power density [kW/m^3] and gravimetric power density [kW/kg] can also be defined.
- **Cell Voltage:** Nominal voltage a single battery cell can provide, measured in V.
- **Depth of discharge (DoD):** Due to their chemical composition batteries need to retain a certain amount of charge at all times, to avoid causing irreversible reactions which would lower the battery’s capacity. It is measured in a percentage of the total capacity, that is, of a battery has a capacity of 100 kWh and a DoD of 70%, only 70kWh should be used before recharge.
- **Round-trip efficiency:** Fraction of the energy put into storage which can later be retrieved for use. It takes into account the charge efficiency as well as the storage discharge efficiency.
- **Cycle life:** A battery cycle is a process of charging a battery and discharging it as required by the load which it supplies. The useful life of a battery is defined by the number of cycles it can function retaining 80% of its capacity.

3.3.3. Technological Solutions

Several kinds of batteries are available on the market, depending on the buyer's needs. Two types of rechargeable batteries will be analysed: the lead-acid battery and the lithium-ion battery.

3.3.3.1. Lead-Acid Battery

Lead-acid batteries were invented in 1859 and are the oldest type of rechargeable battery. Despite their age they are still very present in the market today.

The electrodes are made of pure lead (Pb) reinforced with other metals such antimony (Sb) and calcium (Ca). The electrolyte solution is sulphuric acid ($H_2SO_{4\,(aq)}$). Due to the materials used in its construction lead-acid batteries need to be transported with care and require special treatment for recycling at the end of their useful life.

3.3.3.1.1. Charge/Discharge Cycle

In a fully discharged state both plates are made up of lead sulphate ($PbSO_4$), and the electrolyte has a low concentration of H_2SO_4. During charging an oxidation reaction is produced on the negative electrode and a reduction reaction on the positive plate, and when fully charged the positive electrode is composed of PbO_2 and the negative electrode of pure lead Pb.

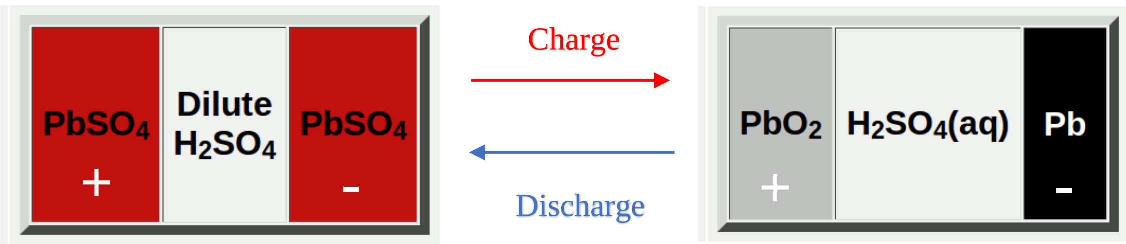


Figure 3.12 Chemical composition of a lead-acid battery in its fully drained state (left) and when fully charged (right). (Jeff Evarts)

Lead-acid batteries are charged in a three-phase constant-current/constant-voltage (CC/CV) process:

- **Constant Current Charge:** The battery is charged at constant current up to 70% of its capacity during 5 to 8 hours.

- **Equalising Charge:** When a set voltage is reached the charging is switched to a constant voltage method for the remaining 30% of its capacity during 7 to 10 hours.
- **Float Charge:** When the charge current drops below 3 to 5% of the Ah rating a full charge is reached, and the voltage is reduced. The charging during this phase compensates for battery self-discharge.

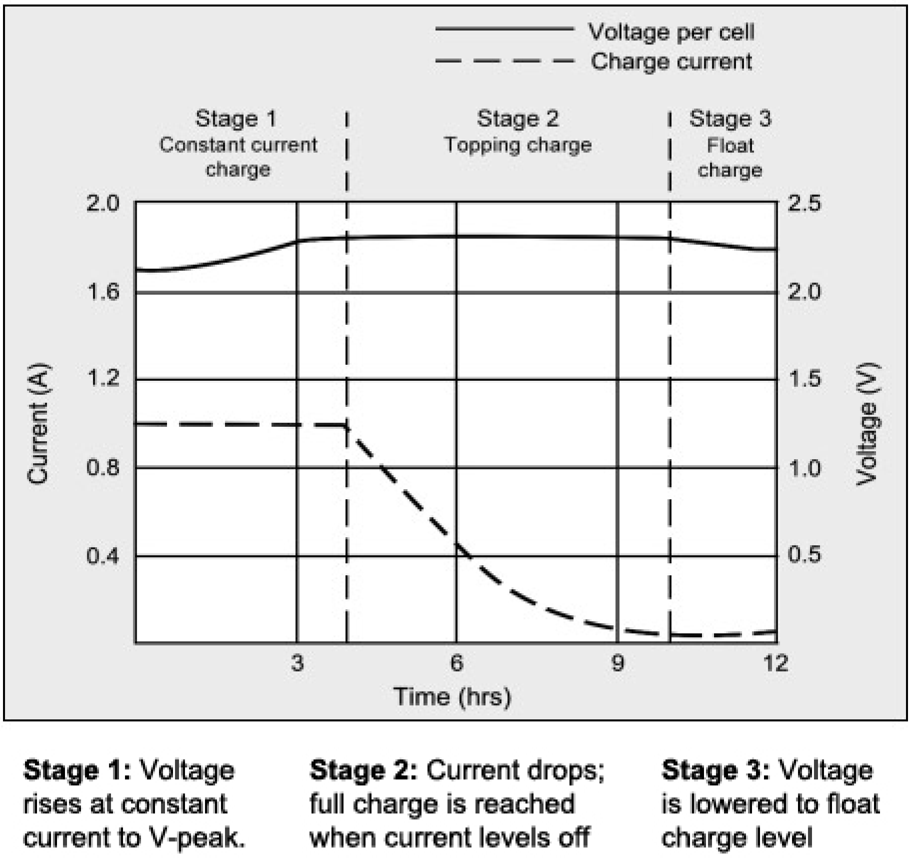


Figure 3.13 Evolution of the charge voltage and current during the three charging phases. (Cadex)

Lead-acid batteries must be fully-charged periodically to avoid performance losses due to the build-up of lead sulphate ($PbSO_4$) crystals on the electrodes, a phenomenon known as sulfation.

As for the discharge cycle lead-acid batteries are classified in two categories according to their maximum output current and capacity: deep-cycle batteries and starting batteries. The first type is designed for high DoD applications with thick plate electrodes, while the second has a higher number of thin electrodes, that provide maximum surface area and minimum resistance, and can only be used in low DoD applications. Deep-cycle batteries have high capacity with low power rating, while starter batteries have a low capacity and high power rating.

3.3.3.1.2. Types

Lead-acid batteries fall into two categories when we consider the electrolyte solution:

- **Flooded:** The electrolyte solution is aqueous H_2SO_4. They are the cheapest type of lead-acid battery but require regular maintenance (checking electrolyte specific gravity and adding water).
- **Absorbed Glass Matt:** The electrolyte (H_2SO_4) is suspended in a fine fiberglass mesh. They have a low internal resistance, can provide high currents, charge up to five times faster than the flooded version and can offer high DoD.

3.3.3.2. Lithium-Ion Battery

Lithium-ion batteries are a relatively recent technology, first being patented by Sony in 1991. As the name indicates they are based on the movement of Lithium (Li^+) between the positive and negative electrodes, which are made of Lithium Cobalt Oxide in the case of the positive electrode and carbon (in the form of graphite) in the case of the negative electrode.

3.3.3.2.1. Charge/Discharge Cycle

During charging lithium ions are released from the negative electrode, made of carbon in the form of graphite, releasing an electron. They then travel through a separator to the positive electrode, combining with the cobalt oxide (CoO_2) and absorbing an electron.

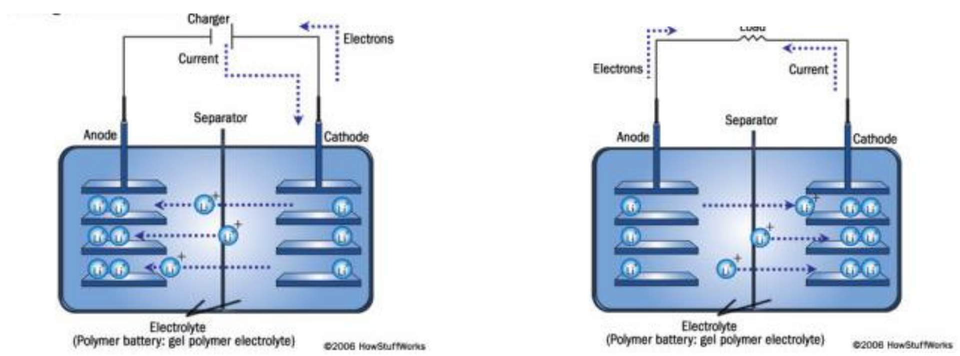


Figure 3.14 Lithium-ion battery charge (left) and discharge (right) mechanisms. (HowStuffWorks)

The charge cycle for lithium-ion batteries has three main stages, with the first two being similar to the first two phases of the lead-acid battery charging cycle:

- **Constant Current Charge:** The battery is charged at constant current up to 70% of its capacity during 1 to 2 hours.
- **Saturation Charge:** When a set voltage is reached the charging is switched to a constant voltage method, until the current drops below 3-5% of the rated current, when the charging terminates. This phase lasts approximately 2 to 3 hours.
- **Topping Charge:** When the charging is terminated the battery voltage starts to drop dues to self-discharge. In order to keep the battery fully charged a topping charge is applied when the voltage drops below a set limit.

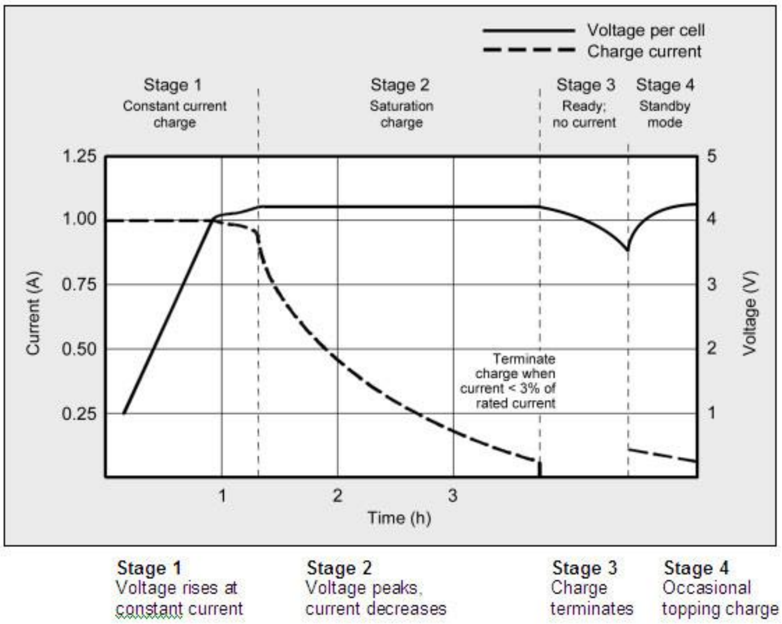


Figure 3.15 Lithium-ion battery charging cycle phases. (Cadex)

The discharge cycle of the lithium-ion battery is optimised depending on whether a high capacity or a high instantaneous power is required. Energy cells provide maximum capacity for long runtimes, while power cells provide high power capabilities with moderate capacity.

3.3.3.3. Comparison

In the following table the parameters of lead-acid and lithium-ion batteries are compared:

Table 3.5 Comparison of the different types of battery technology

Property	Lead-Acid		Lithium-Ion
	Flooded	AGM	
Volumetric Energy Density [kWh/m^3]	80	100	250
Specific Power [kW/kg]	180	180	250-340
Cell Voltage [V]	2	2	3,7
Rated DoD [%]	50	50	80
Time to Full Charge [h]	12-16	5-7	2-3
Cycle Life	1200 @ 50% DoD	1000 @ 50% DoD	1900 @ 80% DoD

3.4. Backup Generator

A backup generator provides power to the installation when its needs are not covered by the PV module and wind turbine production or the energy stored in the batteries.

3.4.1. Standby Generator

Standby generators are permanent installations, providing backup for several days. They run off propane or natural gas, which must be stored in controlled underground tanks. In a situation where backup power is needed they power up automatically, and produce pure sinewave AC current.

Figure 3.16 Standby generator installed outside a residence. (Generac)

Standby generators start at a power of about 5 kW and require a professional to carry out the installation.

3.4.2. Portable Generator

Portable generators combine a combustion engine with an alternator into a single piece of equipment, with the rotational torque being transferred via a shaft.

In order to produce alternating current at a frequency of 50 Hz the alternator must rotate at a constant speed of 3000 or 1500 rpm (depending on the alternator). However the loads to which the generator is connected are not normally constant and can present sharp variations. The combustion engine cannot adapt to brusque changes in power demand very well, and is unable to maintain a constant rotation speed, meaning that the output current varies in frequency. For this reason portable generators output low quality sinewave AC current, which causes lights to flicker and is bad for devices that incorporate electronic circuits.

3.4.3. Inverter Generator

The inverter generator is a relatively modern solution to the problem of varying power demand. They are composed of a combustion engine connected to a three-phase alternator, which produces three-phase AC current. The AC current is then converted to DC current using a rectifier, and then to single-phase AC current via an inverter. The alternator produces a clean distortion-free AC current sinewave, regardless of the load to which it is connected.

Unlike the portable generator, the speed at which the alternator spins is variable depending on the load, with high loads inducing high speeds, and is controlled by the inverter. This makes the inverter generator much more efficient than the portable generator, as the speed of the motor varies in function of the demand at any given time.

3.5. Power Management System

The Power Management System (PMS) includes the components of the off-grid system which convert control the flow of electrical power from one part of the circuit to another, and do not produce, store or consume[1] power.

The PMS is different in DC-Coupled and AC-Coupled systems, but both share three components: the wind turbine charge controller, the battery inverter/charger and the AC panel.

3.5.1. DC-Coupled Systems

As explained at the beginning of the section, DC-Coupled systems use the power produced by both the PV modules and the wind turbine to charge the batteries, which are connected to the residential load via an inverter.

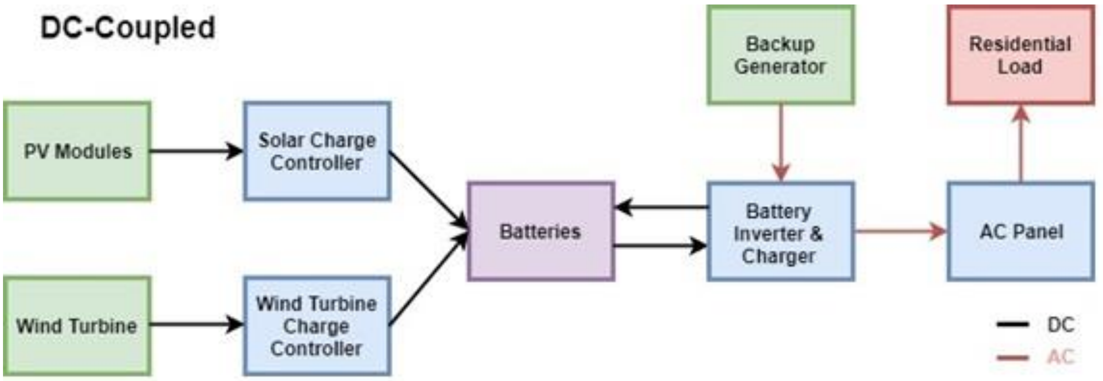


Figure 3.17 Schematic of a DC-Coupled off-grid solar installation, including power generation (green), management (blue), storage (purple) and consumption (red).

[1] The real consumption is not zero but is considered negligible.

3.5.1.1. Solar Charge Controller

In DC-Coupled systems the DC current generated by the solar panels is used to charge the batteries. In order to regulate this process (to charge the batteries following their charging curve) a battery charger is required.

3.5.1.1.1. Working Principle

The voltage produced by the solar panels is variable, depending on weather conditions. To be charged correctly batteries (regardless of their chemistry) have a charging curve with a constant current and constant voltage phase. If the batteries were connected directly to the solar panels and wind turbine the charge curve would not be followed, and the batteries would not charge correctly, resulting in a reduced lifespan.

A battery charger regulates the current produced by the sources and modulates it to the battery charging curve. It also avoids battery overcharging, by regulating the battery voltage. During the constant current phase it allows as much current as the sources can produce to flow into the batteries (as long as it does not go over the device's rated current). When the constant voltage phase is reached the charger keeps the battery voltage constant, regulating the current flow.

3.5.1.1.2. Parameters

Battery chargers can be characterised by the following parameters:

- **Battery Voltage:** Nominal voltage of the battery or battery bank, measured in V. It corresponds to the output voltage of the charger.
- **Solar Panel Open Circuit Voltage:** Open circuit voltage reached when the solar panels are not connected to a load, measured in V. It depends on the layout (parallel or series) of the different PV modules.
- **Charging Current:** Maximum current at which the charger can charge the batteries during the bulk phase, measured in A.

3.5.1.1.3. Technological Solutions

Two types of battery chargers are available on the market today: PWM and MPPT chargers.

3.5.1.1.3.1. Pulse-Width Modulation (PWM)

Pulse-Width Modulation or PWM battery chargers get their name from the way the constant voltage phase is managed. In order to maintain a constant battery voltage, the charger acts as a switch, sending pulses of current modulated in length according to the battery's and solar panels' voltage.

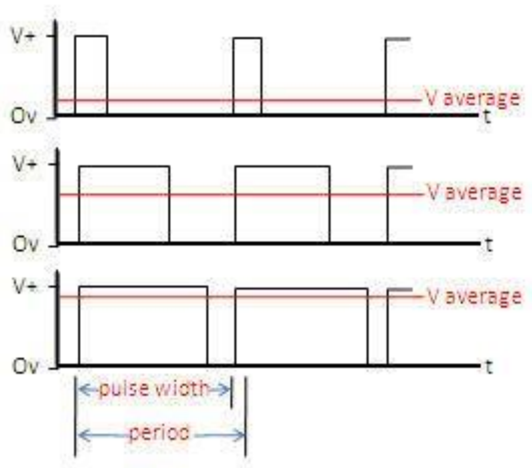


Figure 3.18 Voltage pulses with different in lengths, showing the change in the average voltage value (e-bluelight).

To use a PWM battery charger the solar panel and battery nominal voltages must be equal, even though in bright conditions the solar panels work at a higher voltage.

3.5.1.1.3.2. Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking or MPPT battery chargers are based on the existence of a Maximum Power Point (MPP, see section 2.1.2), that is a voltage and current at which the power output by the solar panel is at its maximum.

The charger constantly adjusts the voltage at which the solar panels produce in order to operate at the MPP, while maintaining the battery voltage constant at its charging value, using a DC/DC converter. This allows the solar panels to operate at different voltage than the battery bank, which theoretically allows 100% of the power produced by the panels to be used to charge the batteries. In reality this depends on the efficiency of the charger, which is normally around 94-97%.

3.5.2. AC-Coupled Systems

AC-Coupled systems differ from DC-Coupled systems in the connection between the solar array and the rest of the system. In AC systems the DC current produced by the solar panels is converted to AC by a batteryless inverter, and the battery bank is charged exclusively by the inverter/charger (Figure 3.19).

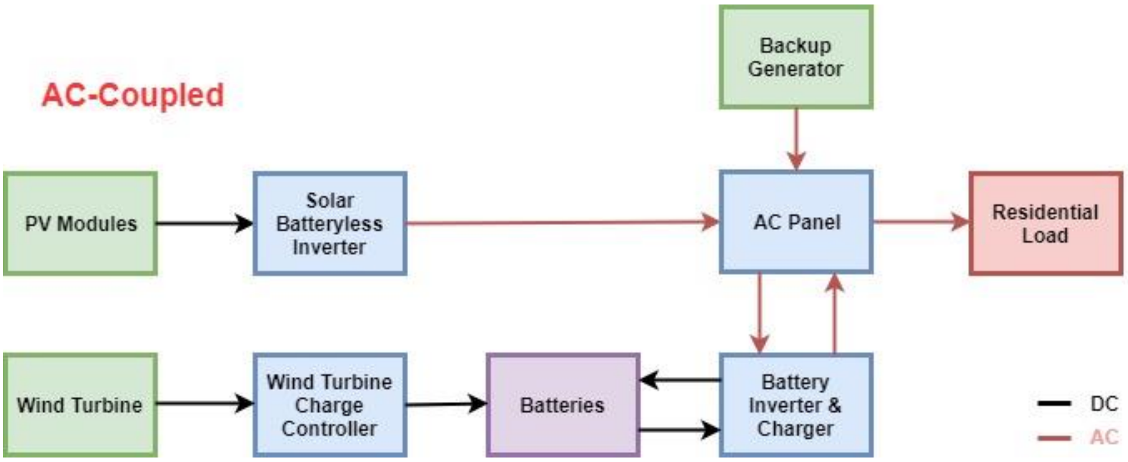


Figure 3.19 Schematic of an AC-Coupled off-grid solar installation, including power generation (green), management (blue), storage (purple) and consumption (red).

3.5.2.1. Solar Batteryless Inverter

The solar batteryless inverter transforms the DC current produced by the PV modules into AC power, which is fed straight to the AC panel, ready for residential use.

Most batteryless inverters incorporate MPPT technology (explained in section 2.5.1.1.3.2), and therefore have a double function: to convert DC current to AC current and to track the MPP by adapting the voltage at which the PV modules work.

3.5.2.1.1. Solar Micro-Inverter

Solar micro-inverters convert the DC current from a single solar panel into AC current. Having the inverter work with only one panel means that each panel can work at its own MPP. This is especially advantageous when the PV modules are partly shaded, or are facing in different directions, as the light conditions may vary drastically from panel to panel.

3.5.3. Common Components

3.5.3.1. Wind Turbine Charge Controller

The wind turbine charge controller manages the power flow between the wind turbine and the battery bank.

The charge controller for the wind turbine works in exactly the same way as the DC-Coupled solar charge controller, charging the batteries according to their charge curve and avoiding overcharging. However it must also ensure that the turbine is under a constant load to avoid uncontrolled blade spinning (*overspeeding*). This occurs when the batteries enter the float stage, and when the set float voltage is reached the controller turns on a dump load, normally a resistive heating element, to dissipate power, along with a fan to keep the element from overheating.

3.5.3.2. Battery Inverter & Charger

The battery inverter and charger, as its name indicates, has two functions: converts DC current from the batteries to AC current to be used by the residential load and also to charge the batteries when required.

In DC-Coupled systems it is the only inverter in the installation, and is normally operating as an inverter, only charging the batteries when the backup generator is producing power. However in AC-Coupled systems it is used to charge the batteries with solar power, and the charge function is used more often.

These devices typically have a built-in transfer switch, which detect when an external AC power source such as a backup generator is connected the device and rapidly change mode to act as a pass through to the residential load. If the connected load does not exceed the nominal output power of the generator excess power is used to charge the batteries. However if the load demands more power than the external source can provide the device acts as an inverter, providing additional power from the batteries.

3.5.3.2.1. Parameters

A battery inverter and charger is defined by the following parameters:

- **Rated Output Power:** Maximum power the device can feed into the AC grid. Both the apparent power [kVA] and the active power [kW] limits are given.
- **Output Power Factor:** It is the part of the output apparent power [kVA] that is given in the form of real power [kW].
- **Output Voltage:** AC voltage at which the load functions, in the case of Spain at 230 VAC at 50 Hz.
- **Battery Voltage:** DC voltage at which the batteries work, measured in V.

3.5.3.3. AC Panel

The AC panel divides the different loads into sub circuits, according to their nature and location within the residence. Each circuit is governed by a circuit breaker, which protects against short-circuits by opening a switch when excessive current flows through the device.

The panel must also include a residual current devices (RCDs), which cuts the power supply when a current leak is detected. Current leaks are caused by devices with faulty connections and protect against electrocutions. A circuit breaker at the entrance of the AC Panel to allow power to be cut to the system, necessary for carrying out maintenance.

4. Current Installation

In this section the current electrical installation will be examined, along with the consumption needs of the residents. The system components are connected to form a DC-Coupled setup, and consists of solar panels, a battery bank, a battery charger (fed from the solar panels), an inverter/charger and a backup generator. The detailed calculations can be found in Appendix A.

4.1. Solar Panels

The solar panels are currently located on the roof of the house, which faces south-east. This location was chosen as it receives sunlight throughout most of the day, and is difficult to access, out of reach of thieves and animals.

Figure 4.1 Solar Panel installation, on the roof of the house.

The installation consists of 10 crystalline silicon PV modules, both mono and polycrystalline, with a total rated power of 1,72 kW (Table 4.1).

Table 4.1 Properties of the current solar panel installation

Solar Panel Model	Surface Area [m^2]	Rated Power [W]	Efficiency	Number	Total Power [W]
Sharp ND-120T1	0,99	120	0,12	2	240
Adanco Solar	1,00	120	0,12	4	480
Yingli YL250P-29b	1,63	250	0,15	4	1000
					1720

Six of the solar panels are mounted within a custom-built frame at an angle of 22º with respect to the horizontal, while the remaining two are mounted directly on the roof at an angle of 16º. Considering the solar irradiation for this angle (as explained in section 1.3.2), along with the surface area and efficiency of each type of PV module, the overall production of the solar panels can be calculated (Eq 4.1).

$$Daily\ Production\ [kWh] = Daily\ Irradiance\ \left[{}^{kWh}/_{m^2}\right] \cdot Surface\ [m^2] \cdot Efficiency \qquad \text{Eq 4.1}$$

Table 4.2 Daily, weekly and monthly production per month

Month	**Production [kWh]**		
	Daily	**Weekly**	**Monthly**
January	4,82	33,71	149,30
February	6,28	43,95	175,78
March	7,79	54,54	241,54
April	8,15	57,07	244,58
May	8,63	60,44	267,67
June	9,37	65,62	281,22
July	10,04	70,31	311,39
August	9,41	65,86	291,66
September	8,27	57,91	248,20
October	6,28	43,95	194,62
November	5,06	35,40	151,70
December	4,39	30,70	135,97
Year Total			**2693,62**

4.2. Batteries

The batteries in the current installation are the 530 Ah TVS5 model manufactured by PowerSafe. They are flooded lead-acid batteries built for deep-cycle applications, such as off-grid solar installations.

Table 4.3 Powersafe TVS5 properties					
Capacity [Ah][2]	**Nominal Voltage [V]**	**Rated DoD**	**Capacity [Wh]**	**Usable Capacity [Wh]**	**Lifetime DoD=50% [cycles]**
390	2	50%	1060	530	2500

The battery bank consists of twelve batteries connected in series, giving the bank a nominal voltage of 24 V a total capacity of 9,36 kWh. However the bank is rated for a maximum DoD of 50%, giving a usable capacity of 4,68 kWh (Table 4.4).

Table 4.4 Battery Bank			
Capacity [kWh]	**Nominal Voltage [V]**	**Maximum DoD**	**Usable Capacity [kWh]**
9,36	24	50%	4,68

4.3. Power Management

4.3.1. Inverter

The inverter is a Victron Energy Multiplus 24/3000/70, aimed at nautical and solar off-grid installations. Its main characteristics are summarised in Figure 4.5.

Table 4.5 Victron Energy Multiplus 24/3000/70 properties					
Inverter				**Charger**	
Input DC Voltage [V]	**Output AC Voltage [V]**	**Output Power [kW]**	**Efficiency**	**Charge Current [A]**	**Float Voltage [V]**
19-33	230 @ 50 Hz	2,5 Nominal 6 Peak	94%	70	28,8

The Multiplus 24/3000/70 is an inverter, battery charger and automatic switch packed within an enclosure. As an inverter it delivers alternating current in the form of a pure sinewave, a requirement for loads that contain electronic circuits, drawing power from a 24 V battery bank. As a battery charger it delivers a maximum of 70 A of direct current

[2] If discharged over a period of 12 hours.

at 24 V when connected to an external AC source, in this case the backup generator. The charging curve can be changed depending on the type of battery being used.

It also functions as an automatic switch, detecting when an external AC source is connected, and connecting all loads to it, switching quickly enough to provide an uninterrupted power supply to all loads (UPS functionality). When the load demands more power than the external AC power source can provide it compensates by providing additional power from the batteries.

Other features include a multi-functional relay, which can be programmed to act as a starter relay for a generator, providing an automatic starting functionality. The device also can be connected to a computer (via an RJ45 connector) and can be remotely operated. These features however are not being exploited in the current installation.

4.3.2. Battery Charger

The battery charger currently being used is the MorningStar Tristar-60. It forms part of the DC part of the installation and regulates the current flowing from the solar panels to the batteries.

Table 4.6 MorningStar Tristar-60 properties

Inverter				Charger	
System Voltage [V]	**Charging Current [A]**	**Maximum Solar Voltage [V]**	**Efficiency**	**Charge Current [A]**	**Float Voltage [V]**
24	60	125	94%	70	28,8

It uses pulse-width modulation technology, and includes short-circuit and over-voltage protection, to avoid damage to the solar panels and batteries. It also includes network connectivity via an RJ45 port.

4.4. Backup Generator

The backup generator currently being used is a PRAMAC EM2800 portable generator (Table 4.7). It is placed by the tool shed 20 metres away from the residence, in an outside environment to avoid the accumulation of toxic fumes.

Table 4.7 PRAMAC EM2800 properties					
Output Voltage [V]	**Rated Power [W]**	**Maximum Power [W]**	**Maximum Current [A]**	**Fuel**	**Fuel Tank Capacity [L]**
230 @50 Hz	2500	2800	12,17	Petrol	3,6

4.5. AC Panel

The electrical installation is divided into two main circuits, each with its own RCD: indoors and outdoors. The indoor circuit is divided into four sub-circuits, each with its own circuit-breaker: the kitchen, living areas, bedrooms and bathrooms, and the outdoor circuit does not have any sub-circuits.

Figure 4.2 AC panel of the installation, with two RCDs at each end and six circuit-breakers (one of which is unused).

Table 4.8 AC Panel properties				
Indoor				**Outdoor**
RCD I=25 A, IΔn=30mA, 230 VAC				**RCD** I=25 A, IΔn=30mA, 230 VAC
Kitchen	**Living Areas**	**Bedrooms**	**Bathroom**	**Outdoor**
CB 16 A	CB 16 A	**CB** 10 A	**CB** 10 A	**CB** 16 A
Lighting Dishwasher Washing machine Oven Deep-Fryer Blender Coffee machine Internet Alarm	Lighting Computer Screen Weather station Sound system Printer Piano Laptops Vacuum cleaner	Lighting Mobile phones Sound system	Lighting Extractor fan Hair dryer Toothbrush	Lighting Well pump Pool filter Pool chlorinator House pump Pressure washer

4.6. Current Electrical Consumption

To be able to size the new installation correctly first the current power consumption must be determined.

4.6.1. Methodology

In order to accurately determine the power requirements of the residence two different periods are defined:

- **Winter Months:** October-March, period with the least hours of light.
- **Summer Months:** April-September, period with the most hours of light.

Also two different functioning modes are defined:

- **Weekend Usage Mode:** The residents are only at the house at the weekends, during the midweek period consumption is lower than at the weekend.
- **Holiday Mode:** Period when the residents are at the house for at least a whole week, may occur throughout the year.

In weekend usage mode, when the residents are only at the house at the weekends, the consumption is lower on weekdays than at the weekend. For this reason the consumption is analysed on a weekly level. However during in holiday mode the consumption is the same for every day of the week, and the analysis is carried out on a daily level.

All the devices in the residence that consume electrical power are analysed by examining their specifications sheet. The following factors have been considered:

- **Average Power:** Power used on average while the device is functioning, measured in W.
- **Peak Power:** Maximum power used by the device at any point during its functioning cycle, measured in W.
- **Runtime:** Time period during which the device is consuming power, measured in hours.
- **Cycles per day:** Number of times the device runs a day.
- **Functioning days:** Days of the week during which the device works.

From these five parameters the energy consumption of each device are calculated and grouped according to which sub-circuit the device belongs.

Table 4.9 Power and consumption of the different subcircuits

Circuit	**Sub-circuit**	**Peak Power [W]**	**Weekend Usage**		**Holidays**	
			Winter Week [Wh]	**Summer Week [Wh]**	**Winter Week [Wh]**	**Summer Week [Wh]**
Indoor	**Kitchen**	10.075	26.730	26.410	54.880	53.760
	Living Areas	1.642	6.673	5.873	16.321	13.521
	Bedrooms	355	2.070	1.170	7.245	4.095
	Bathroom	2.261	929	929	5.088	5.088
Outdoor	**Outdoor**	3.595	3.170	15.800	12.845	26.075
	Total	17.928	39.572	50.182	96.379	102.538

The kitchen is the most important part of the installation in terms of peak power and weekly usage throughout the year, as it concentrates big appliances such as the oven and the dishwasher along with the internet router and modem, which run without interruption.

The outdoor circuit consumption is much higher during the summer months due to the pool filter and chlorinator only run during this period.

4.7. Analysis

4.7.1. Weekend Usage

During the weeks that the residents are only at the house at the weekend two parts of the week can be distinguished in terms of consumption: weekdays and weekend days.

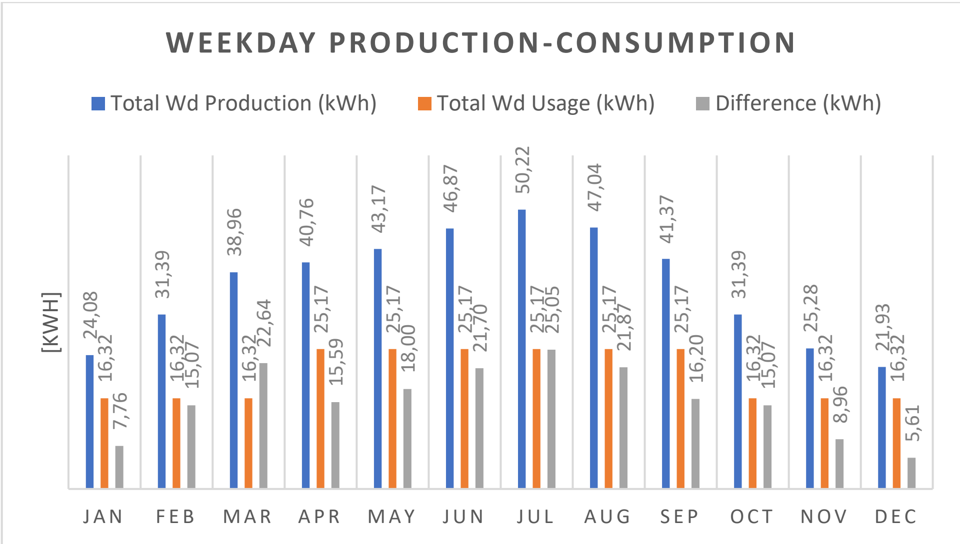


Figure 4.3 Midweek production, consumption and difference between the two values throughout the year.

Figure 4.3 plots the solar panels' production compared to the consumption requirements for the midweek period, that is Monday to Friday. During weekdays the consumption is much lower than the production throughout the entire year. This is because there are few devices consuming power during the week, and devices with high consumption, such as the dishwasher, only run at the weekend.

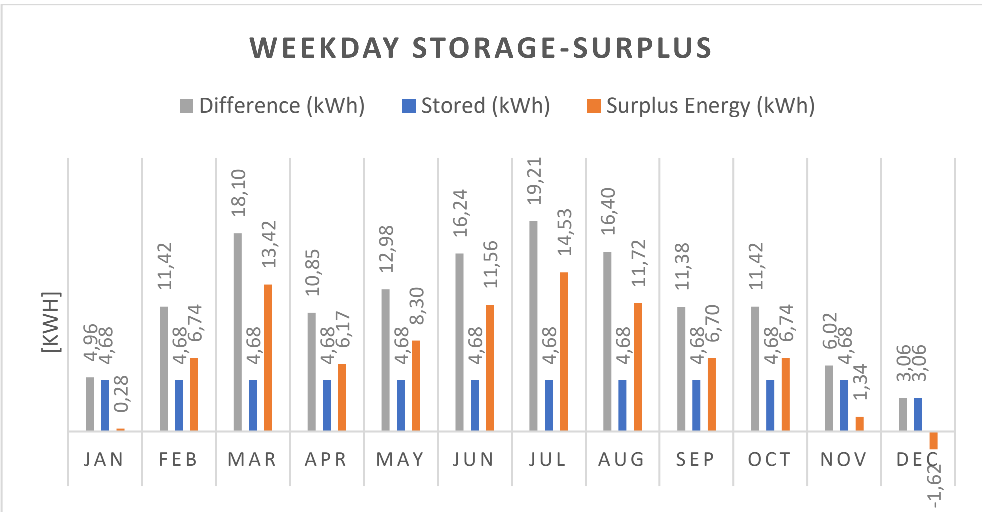


Figure 4.4 Production-Consumption difference during the midweek period.

The energy produced by the solar panels which is not consumed is used to charge the battery bank and is therefore stored. We can observe in figure 4.4 that for every month of the year except December the PV modules produce enough energy to fully charge the batteries to their useful capacity of 4,68 kWh. The surplus energy that cannot be stored is considered wasted, as it is not used in any way.

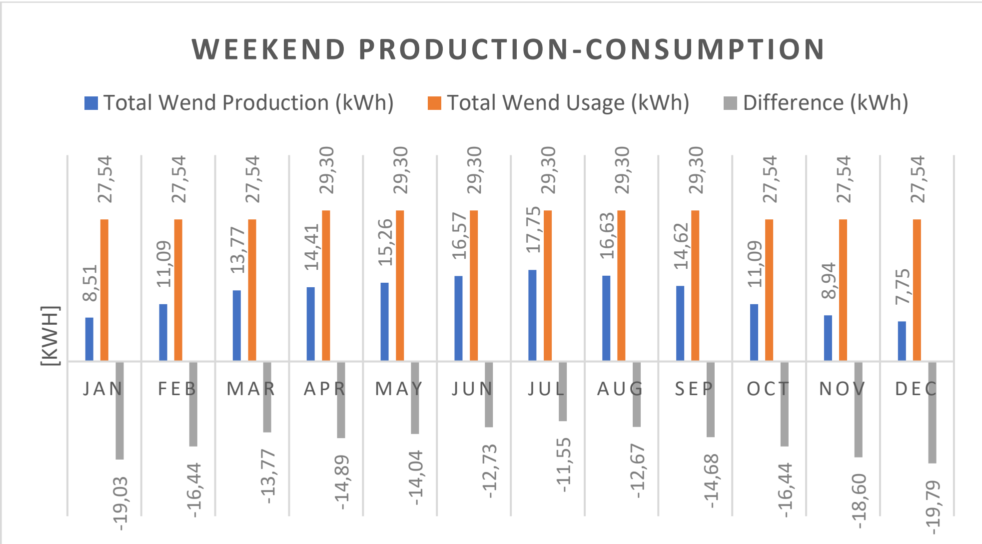


Figure 4.5 Weekend production, consumption and difference between the two values throughout the year.

During the weekend the daily consumption increases as it when the residents are at the house, and more electrical appliances are used. The consumption demands are higher than the solar power production for all the months in the year (Figure 4.5), which translates into a production deficit. This is the opposite of what happens during the midweek period, when the PV modules produce more energy than is required by the residence, and the excess can be put into storage.

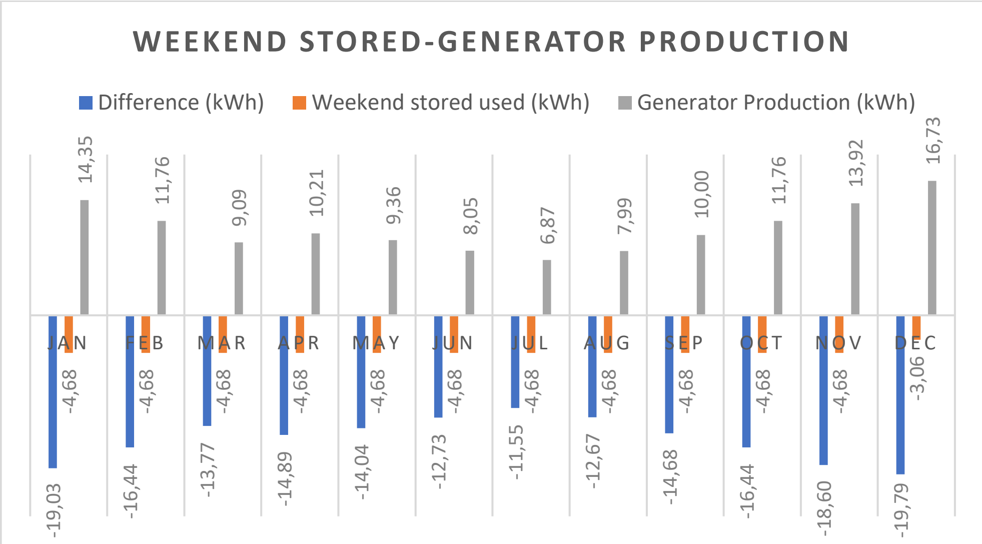


Figure 4.6 Production-Consumption difference, stored and generator-produced energy during the weekend period, throughout the year.

The energy required by the residential loads that the solar panels are not able to produce comes from two sources (Figure 4.6): the energy stored in the battery bank and the backup generator. First the batteries provide the required power until they reach 50% DoD, at which point the backup generator takes over.

The demand on the backup generator is highest during the winter months, when the solar panel production is at its lowest (Figure 4.7). In December the generator runs for 6,7 hours each weekend, which translates into 3,35 hours a day, while in July it only runs for a total of 2,75 hours each weekend, 1,37 hours a day.

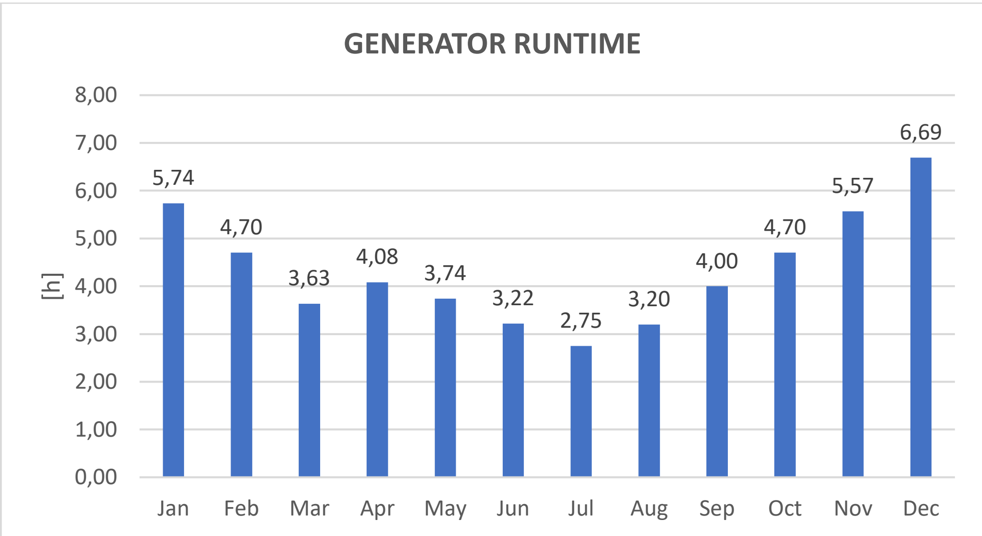


Figure 4.7 Generator runtime throughout the year.

If we analyse the weekly production and usage as a whole (Figure 4.8) for four months the solar panel production exceeds the consumption requirements, and excess energy is produced. This means that the generator is not needed during these months, and the system is completely self-sufficient.

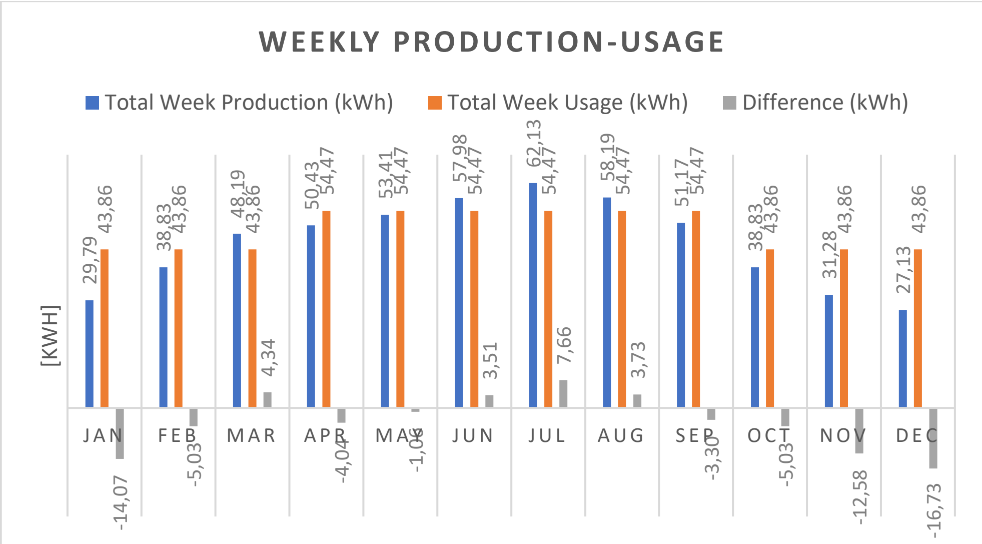


Figure 4.8 Overall weekly production, consumption and difference between the two values throughout the year.

However, this analysis considers the capacity of the batteries sufficiently large to not have wasted energy, meaning that all the energy produced which is not used immediately can be stored. This is evidently not the case in the current installation, as the battery capacity of 4,68 kWh is insufficient to store all the excess energy produced during the midweek period and make it usable during the weekend.

Therefore the first analysis that differentiates the midweek period from the weekend is much more accurate and will be the basis for sizing the new installation.

4.7.2. Holidays

During the holiday period of the year the residents are at the house throughout the whole week, and the power consumption is considered equal for each day of the week. This allows for the analysis to be carried out daily.

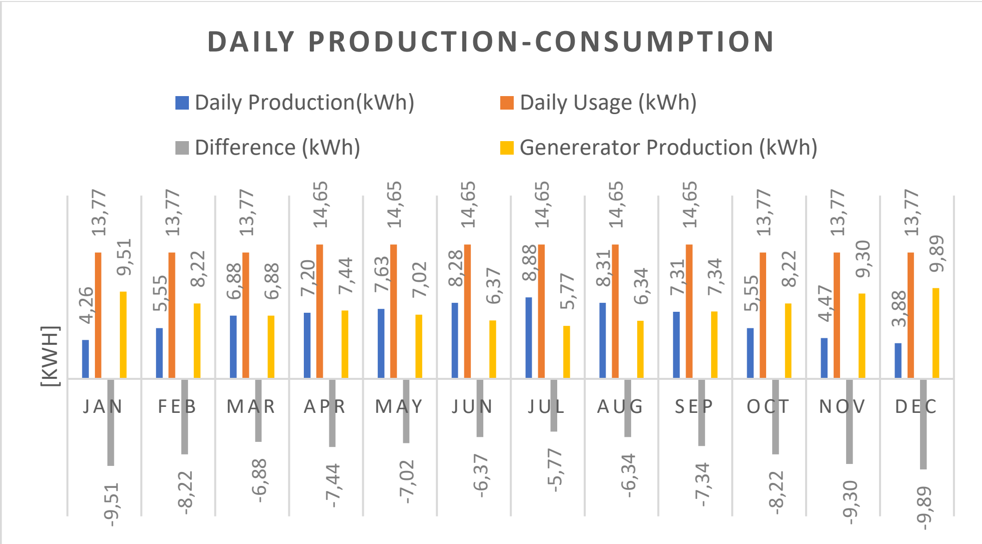


Figure 4.9 Overall weekly production, consumption and difference between the two values throughout the year.

The energy demand of the house exceeds the production throughout the entire year, meaning there is an energy production deficit, which is highest during the winter months. The energy required by the house that cannot be produced by the solar panels comes only from the generator, as there is no excess energy produced from the solar panels in the battery bank.

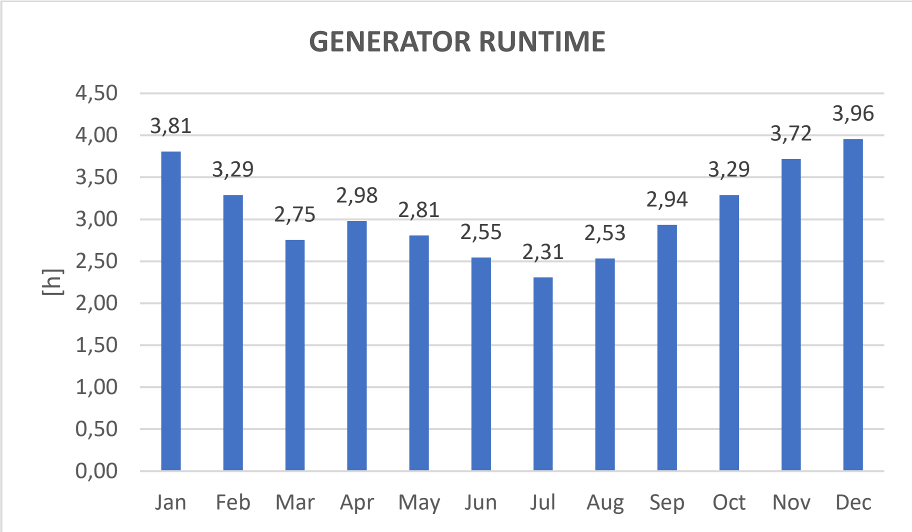


Figure 4.10 Overall weekly production, consumption and difference between the two values throughout the year.

To meet the power demands of the residence the generator must run every day during a holiday period, from a minimum of 2,31 hours in July to a maximum of 3,96 hours in December (Figure 4.10).

If we take into account that in all months except April, July and August the system works in weekend mode, and that in April land July one week is in holiday mode and in August there are two weeks in holiday mode the monthly consumption and production can be calculated (Figure 4.11).

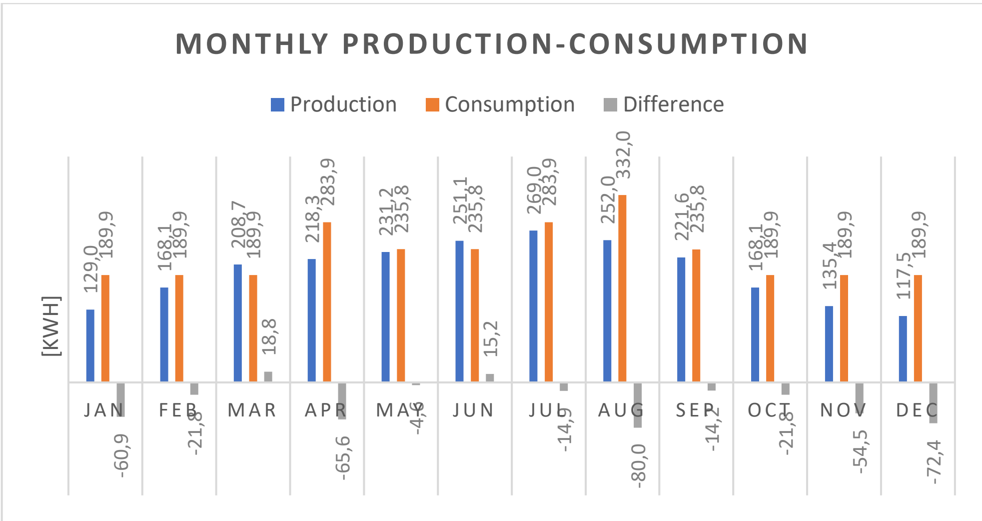


Figure 4.11 Monthly production and consumption values as well as the difference between them.

For most months of the year the consumption requirements are higher than the production, except for March and June. This means the energy required by the residence that cannot be produced by the panels must come from the backup generator.

Finally by adding up all the monthly values the yearly numbers can be calculated. As can be expected the system produces less energy than the consumption requirements of the residence, specifically 376,6 kWh less (Figure 4.12).

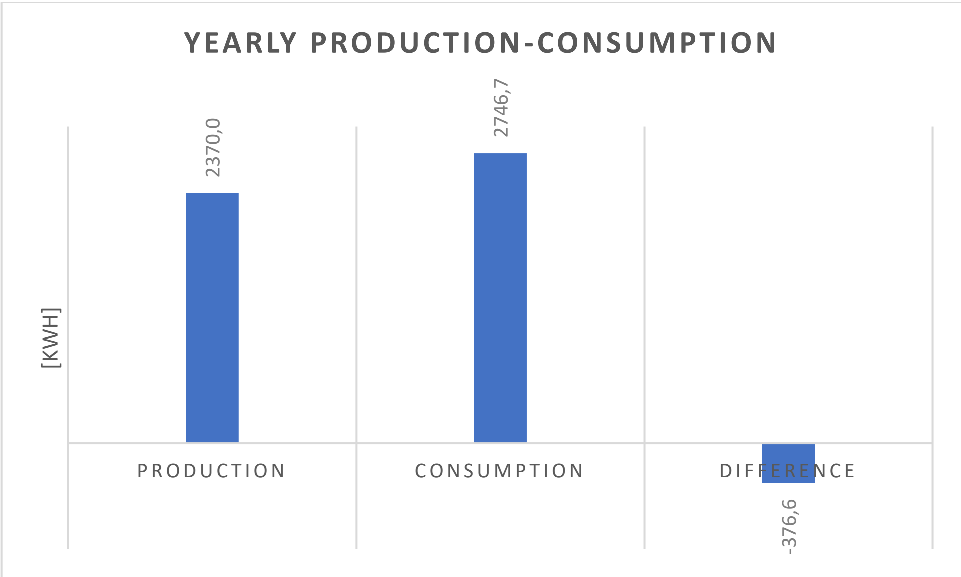


Figure 4.12 Yearly production and consumption values as well as the difference between them.

4.7.3. Conclusions

After analysing the current installation the weak points of the installation have been identified and are where the new installation must improve to meet the objective of reducing the generator production to zero.

In first place we will look at when the system runs in the weekend usage mode. During the midweek period the solar panels produce more energy than is consumed by the residence, however the batteries are not able to store all of it, meaning that a big part of the energy is lost, up to 14,53 kWh a week in July, 29,3% of the total production. If all the excess energy produced by the panels were stored the generator production would be reduced, and for four months of the year it would not be required at all. For the months of the year where the current weekly production is insufficient increasing the production would reduce the deficit to zero.

For the holiday period it is evident that a production increase is required, as it is the only way to reduce the difference between the consumption and the production.

By only relying on PV modules for energy production the installation is heavily reliant on the weather, specifically the cloud cover. The previous analysis considers mean values for solar radiation throughout the year, however it is easy to see that if there is little or no solar production for a day or more the generator production must increase to compensate. If bad weather conditions occur during the midweek period the generator cannot operate, and the installation may be forced to shut down out when the batteries drain below 80% DoD.

Finally, regarding the backup generator, the portable generator used in the current installation outputs a bad sinewave at irregular frequencies, causing lights to flicker and also certain electronic devices cannot run when the generator is connected.

5. Design of the New Installation

After analysing the current installation and the electrical consumption needs of the residence a new electrical installation can be designed. The new installation aims to minimise the use of the backup generator to zero and solve the problems that the previous one presented.

5.1. Design Process

In first place the technical requirements of the new system are examined, including consumption and operating conditions. From these requirements different solutions are developed and are examined on a technical and economical level.

5.2. Requirements

The owners have put forward the following specifications that the new installation must fulfil:

1. The installation must cover the daily energy consumption of a holiday day with good weather without using battery power.
2. The system must be able to operate during a weekend or holidays with one day of bad weather without requiring the backup generator.
3. The installation must function under any weather circumstances during the midweek period.
4. All devices must be able to run when the backup generator is working, maintaining the power of the current generator.
5. The system must be able to supply electricity overnight during the whole year without using the backup generator.
6. Allow for a 10 % growth in consumption.

5.3. Restrictions

There are several restrictions imposed by the location of the different components of the installation.

In first place the size of the roof limits the space the solar panels can occupy. The house has a sloping roof at an angle of 16º, with one half facing South-South-East and the other North-North-West. To maximise production the panels must be placed on the southern side of the roof.

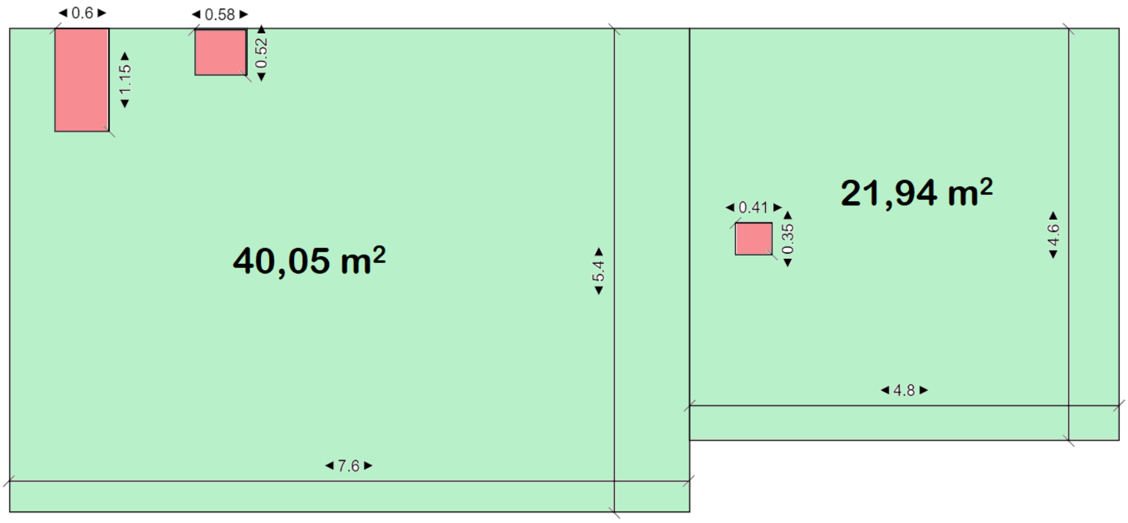


Figure 5.1 Southern half of the roof, with its dimensions and usable (green) and non-usable (red) surface.

The southern half of the roof is divided in two, with one area corresponding to the old house and the other to the new extension. The two rooves are at different heights, so solar panels must either be placed on one or the other. Also each roof has areas which are unusable (figure 5.1) due to the existence of a skylight and a chimney on the old roof and a chimney on the new roof. The old roof has a surface area of 40,05 m^2 and the new roof an area of 21,94 m^2, with a total surface area of 62 m^2.

The other restriction affects the size of the battery bank. The area where the batteries are to be placed is an underground room, with a constant temperature of about 15ºC and humidity of 90% throughout the year and has a ventilation system to evacuate dangerous gases produced by the battery charging process. The maximum dimensions of the battery bank are 1x2 metres.

5.4. Consumption

As explained in the previous section there are two modes the system can function in according to consumption requirements: weekend usage and holidays. The detailed calculations can be found in Appendix A.

5.4.1. Daily Consumption

Power demand is not evenly spread out throughout the day, as most devices only function for a limited period of time. In order to analyse the consumption profile more accurately the day is divided in two periods: daytime, when the sun is out and the solar panels are producing, and night-time, when there is no solar radiation and the solar panel production is zero.

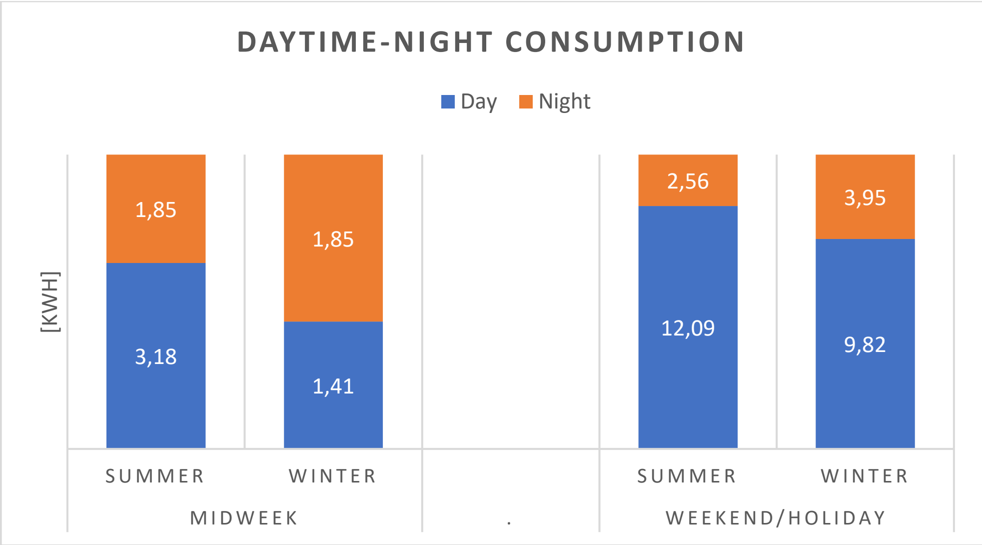


Figure 5.2 Daytime and nigh-time consumption values according to time of year and functioning mode.

While in holiday mode or weekend usage mode at the weekend, the daytime consumption is much greater than the night-time value. However during the midweek period the night-time consumption is more important than in the previous case and is greater than the daytime consumption during the winter.

Requirement 4 states that the system must always be able to run overnight without the backup generator and considering requirement 5 along with the critical value of overnight consumption, the first condition for the new installation is deduced.

5.4.2. Weekend Usage

In the weekend usage mode the consumption depends on the time of week and the time of year. During the midweek period consumption is relatively low both in the winter and in the summer, with the summer value being higher due to the swimming pool filtering operations.

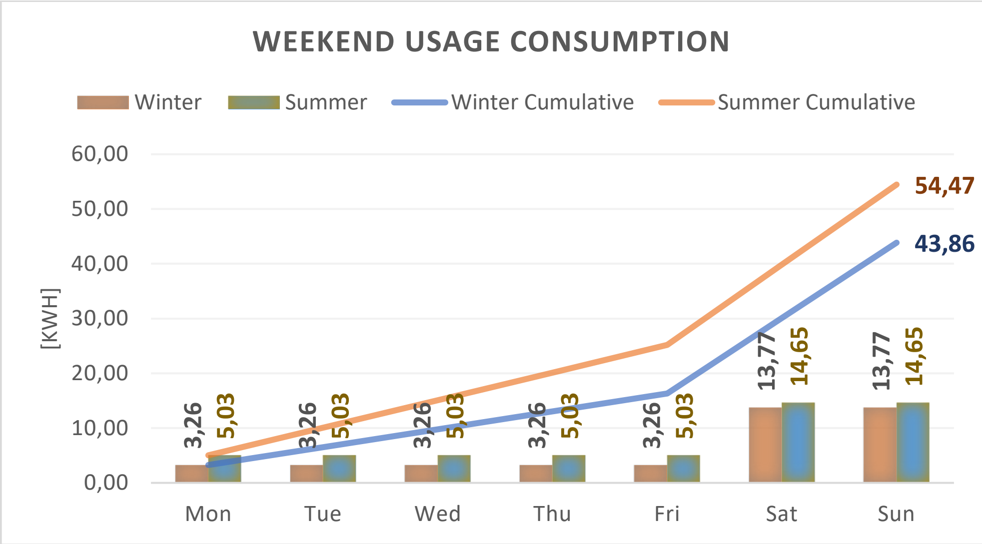


Figure 5.3 Daily and cumulative consumption throughout the week in weekend usage mode.

The line that represents cumulative consumption (Figure 5.3) rises at a constant rate from Monday to Friday and grows much faster at the weekend.

5.4.3. Holidays

In the holiday mode the consumption is the same for every day of the week, it only depends on the time of year.

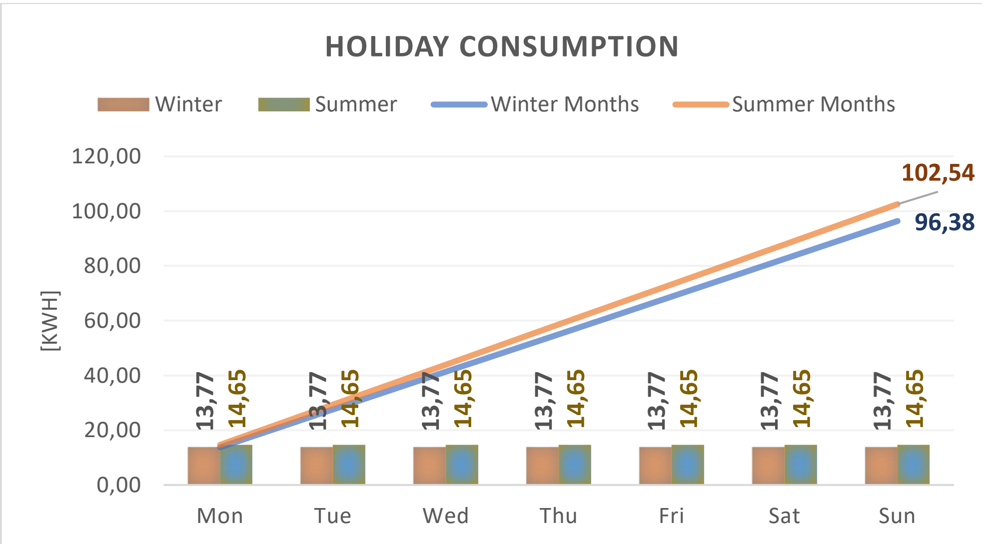


Figure 5.4 Daily and cumulative consumption throughout the week in holiday mode.

As the daily consumption value is constant the cumulative consumption climbs at a steady rate throughout the week.

5.5. Technical Specifications

Once the consumption has been analysed the requirements can be translated into technical specifications for the new system. The first five requirements will be analysed taking into account the sixth, to allow for a 10 % growth in consumption.

1) **The installation must cover the daily energy consumption of a holiday day with good weather without using battery power.**

While functioning in holiday mode the consumption is the same for every day of the week, unlike the weekend usage mode, with lower consumption during the midweek period, when the batteries can be recharged. Therefore the daily energy demands must be covered by the production of the solar panels, as the wind turbine acts as a backup device, due to its irregular production.

As both the energy production and energy consumption vary throughout the year two periods with different consumption must be considered.

Table 5.1 First Condition: Minimum daily production

Time of year	Holiday daily consumption [kWh/day]	Potential consumption growth	Minimum Daily Solar Production [kWh]
Winter	13,77	10%	15,15
Summer	14,65		16,11

2) **The system must be able to operate during a weekend or holidays with one day of bad weather without requiring the backup generator.**

Bad weather conditions occur when the weather conditions are at their worst for solar and wind power generation, and are considered to be the following:

- Windspeed is zero or insignificant, not sufficient for the turbine to produce power.
- The solar panels production is negligible and is considered zero.

The critical value for daily consumption is given at the weekends and in holiday mode during the summer and is 14,65 kWh. The new system must be capable of providing for 10 % more than the current critical value from the stored energy in the battery bank.

As the capacity of the battery bank is fixed only the critical daily consumption value is considered, in this case a summer weekend or holiday day.

Table 5.2 Second Condition: Minimum battery capacity for bad weather day

Current critical daily consumption [kWh/day]	Potential consumption growth	Minimum Usable Battery Capacity [kWh]
14,65	10%	16,11

3) **The installation must function under any weather circumstances during the midweek period.**

The critical weather circumstances considered will be two days of bad weather, with absolutely no production. More than two days of bad weather is considered extremely unlikely and is not taken into account in the calculations.

As in the previous requirement, the battery capacity is fixed so only the critical midweek consumption is used in the calculations.

Table 5.3 Third Condition: Minimum battery capacity for midweek functioning

Critical midweek daily consumption [kWh/day]	Potential consumption growth	Days of autonomy	Minimum Usable Battery Capacity [kWh]
5,03	10 %	2	11,07

4) **All devices must be able to run when the backup generator is working, maintaining the power of the current generator.**

The backup generator used in the current system is a portable generator with a nominal output power of 2,5 kW. Portable generators must run at a constant rotational speed to produce a high-quality sinewave at constant frequency, however their rotation speed is directly affected by the loads connected to it.

In the new system the output of the backup generator must not affect the functioning of the different appliances.

5) **The system must be able to supply electricity overnight during the whole year without using the backup generator.**

During the nocturnal hours there is no solar production, while the wind turbine may function, depending on the weather conditions. Under bad weather conditions the wind turbine production is zero and all the energy required must come from the battery bank.

As in the previous requirements, the battery capacity is fixed so only the critical overnight consumption is used in the calculations.

Table 5.4 Fifth Condition: Minimum battery capacity for overnight consumption

Critical Overnight Consumption [kWh]	Potential Consumption Growth	Minimum Usable Battery Capacity [kWh]
3,95	10 %	4,35

6. New Installation

Once the technical specifications have been defined we can proceed to the design of the new installation. This consists of sizing the different components to meet the specifications and also how they are interconnected. The detailed calculations can be found in Appendix A.

6.1. Solar Panels

6.1.1. Angle

The angle at which the solar panels are installed greatly affects amount of solar radiation they receive and in turn their production. The optimum angle (taking the horizontal angle as reference) to receive the maximum solar radiation varies throughout the year, reaching a maximum during the winter and a minimum during the summer. Five possible configurations have been selected and analysed according to the radiation received during the year (Table 6.1).

Table 6.1 Solar radiation received depending on the angle configuration

Configuration	Angle	Total year radiation [kWh]
Year-Round Adjusted	28º-58º	1652,7
Optimal Year Round	43º	1568,81
Summer Adjusted	28º	1566,06
Winter Adjusted	58º	1492,74
Flat Surface	0º	1402,25

The best configuration for maximum radiation is the year round adjusted setup, which consists in changing the angle of the solar panels each month to adapt to the changing angle of the sun. This is not practical however as it requires the solar panels to be mounted in a frame with an adjustable height, and someone must manually change the height of the frames each month.

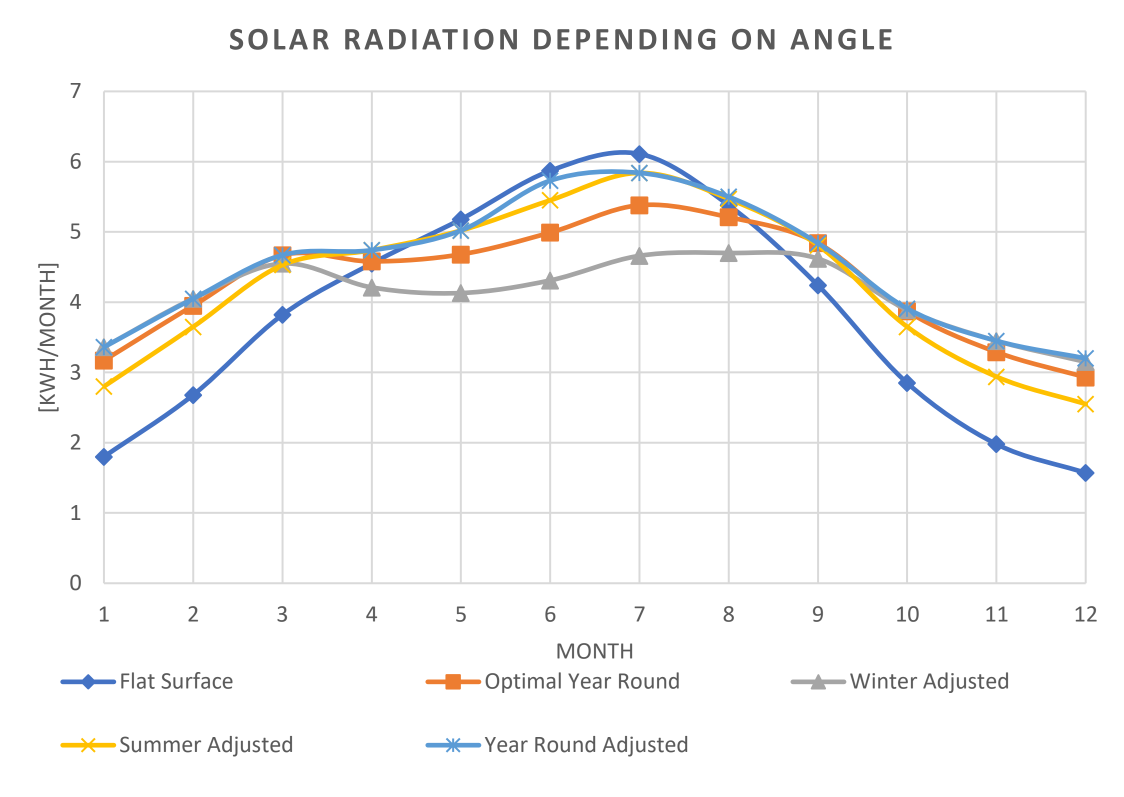


Figure 6.1 Solar radiation received according to the angle of the solar panels.

The next best configuration is the optimal year-round angle of 43º, which is adjusted half way between the summer and winter configurations. It is not the best configuration for any given month of the year (Figure 6.1), however the yearly total is the highest among the fixed angle configurations.

The angle of 43º degrees is therefore selected for the installation. This must be taken into account when choosing the dimensions of the solar panels, so they do not cast shade on one another. All calculations using the current solar panels consider the angle to be 43º, not the angle of the old installation.

6.1.2. Technological Solution

In this project two possible technological solutions have been considered: crystalline silicon panels and thin film panels. Thin film panels are discarded due to the choice of installation angle. The non-rigid nature of these panels is makes them only installable on solid surfaces, however the angle of the roof is 16º, too low for optimal radiation reception. By using crystalline silicon panels the current PV modules can be used in the new installation as the technology is compatible.

Therefore crystalline silicon panels are chosen. In the silicon panel family there are two main types: monocrystalline and polycrystalline. Polycrystalline panels are chosen due to their lower cost, higher availability and lower temperature dependence. Also the aesthetic appearance of the panels is not important, which is one of the advantages of monocrystalline panels.

6.1.2.1. First Solution

The model of polycrystalline panel chosen is the Perlight Solar RS270, due to its high nominal output of 270 W and good efficiency of 17% (Table 6.2).

Table 6.2 Properties of the Perlight Solar RS270 solar panel

Panel Length [m]	Panel Width [m]	Surface Area [m^2]	Open Circuit Voltage [V]	Rated Power [W]	Efficiency
1,64	0,992	1,63	38,23	270	0,17

To comply with the first technical requirement of 13 units of the Perlight Solar RS270 solar panel are required (Table 6.3).

Table 6.3 Number of RS270 solar panels required depending on the month

Month	Required daily production [kWh]	Current panels [kWh]	Additional Required [kWh]	Unitary Production RS270 [kWh]	Number required
January	15,15	5,45	9,69	0,86	11
February	15,15	6,79	8,35	1,07	8
March	15,15	8,03	7,11	1,26	6
April	16,11	7,88	8,24	1,24	7
May	16,11	8,05	8,06	1,26	6
June	16,11	8,58	7,53	1,35	6
July	16,11	9,25	6,86	1,45	5
August	16,11	8,96	7,15	1,41	5
September	16,11	8,32	7,79	1,31	6
October	15,15	6,66	8,49	1,04	8
November	15,15	5,66	9,49	0,89	11
December	15,15	5,04	10,11	0,79	13

Due to the varying solar radiation throughout the year the number of RS270 solar panels required depends on the month, reaching a maximum value of 13 in December, when solar radiation is at a minimum. Therefore 13 solar panels must be installed to comply with the first technical specification, giving the solar panel configuration shown in Table 6.4.

Table 6.4 Proposed solar panel installation

Solar Panel Model	Surface Area [m²]	Rated Power [W]	Efficiency	Number	Total Power [W]
Sharp ND-120T1	0,99	120	0,12	2	240
Adanco Solar	1,00	120	0,12	4	480
Yingli YL250P-29b	1,63	250	0,15	4	1000
Perlight Solar RS270	1,63	270	0,17	13	3510
Total	33,65			23	5230

This configuration however does not comply with the restrictions, as it requires a surface are greater than that available on the roof. If we consider the area of the solar panels of 33,65 m^2 it is lower than the roof surface area of 62 m^2. This does not consider the shade cast by the solar panels, as they are mounted at a greater angle than that of the roof (Figure 6.2).

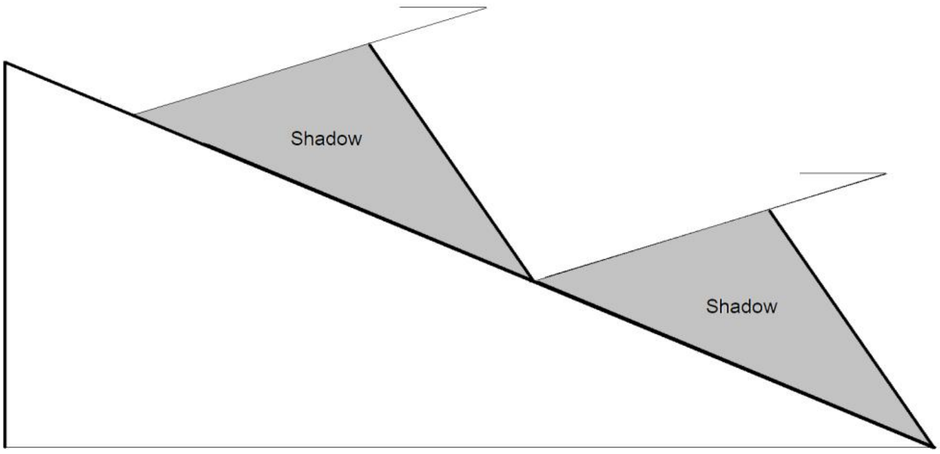


Figure 6.2 Setup of the solar panels taking into account the shade they cast.

For the shade cast by the first row of panels not to affect the next row of panels the minimum angle of the sun must be used, as it causes the maximum shade. The lowest angle of the sun occurs in winter and is 32º to the horizontal and the distance between each row must be a minimum of 2,2 metres. On the old roof this allows for a total of 14 panels to be installed in two rows.

Table 6.5 Highest density panel configuration on the old roof

Panel length [m]	Panel width [m]	Row separation [m]	Minimum roof length [m]	Roof width [m]	Installable rows	Number of panels
1,64	0,992	2,2	4,25	7,6	2	14

On the new roof the placement of the chimney allows for the installation of one row of 4 panels and another of 3 panels, giving a total of seven panels (Table 6.6).

Table 6.6 Highest density panel configuration on the new roof

Panel length [m]	Panel width [m]	Row separation [m]	Minimum roof length [m]	Roof width [m]	Installable rows	Number of panels
1,64	0,992	2,2	2,04	4,8	1 row of 4 1 row of 3	7

The maximum number of installable panels is therefore 21, lower than the 25 required to comply with the first technical specification. Therefore a second solution that complies with the space restrictions is required.

6.1.2.2. Second Solution

After presenting these findings to the owners of the residence they have proposed a modification to the requirements of the system. They said that they only ever spend a whole week or more at the house during Easter, July and August. The rest of the year they only visit the residence at the weekends. Therefore the first requirement and technical specification is modified to the following:

1) **The installation must cover the daily energy consumption of a holiday day with good weather without using battery power during the months of March, April, July and August. During the rest of the year the system must function during the weekend without requiring the backup generator.**

Table 6.7 Modified First Condition: Minimum daily production

Month	Holiday daily consumption [kWh/day]	Potential consumption growth	Minimum Daily Solar Production [kWh]
March	13,77	10 %	15,15
April	14,65		16,11
July	14,65		16,11
August	14,65		16,11

In Table 6.7 the minimum daily production for March, April, July and August is specified. During the rest of the year the system must function in weekend usage mode without requiring the backup generator.

Table 6.8 Number of RS270 panels required according to the modified condition

Month	Required daily production [kWh]	Current panels [kWh]	Additional Required [kWh]	Unitary Production RS270 [kWh]	Number required
March	15,15	8,03	7,11	1,26	6
April	16,11	7,88	8,24	1,24	7
July	16,11	9,25	6,86	1,45	5
August	16,11	8,96	7,15	1,41	5

Redoing the previous calculations to find how many RS270 modules are required for the four months of the modified condition (Table 6.8) we find that only 7 panels are required. This gives a total of 17 solar panels (Table 6.9), lower than the maximum of 21, and a maximum total power of 3,61 kW.

Table 6.9 Proposed solar panel installation (modified condition)

Solar Panel Model	Surface Area [m^2]	Rated Power [W]	Efficiency	Number	Total Power [W]
Sharp ND-120T1	0,99	120	0,12	2	240
Adanco Solar	1,00	120	0,12	4	480
Yingli YL250P-29b	1,63	250	0,15	4	1000
Perlight Solar RS270	1,63	270	0,17	7	2160
Total	25,51			17	3610

Now the functioning of the proposed installation in weekend mode for the rest of the year must be checked. The second condition states that the system must be able to run during a weekend with one day of bad weather, meaning with one day's worth of production.

Table 6.10 Required battery capacity for bad weather conditions

Month	Total Wend Production (kWh)	Total Wend Usage (kWh)	Weekend stored used (kWh)
January	12,30	30,29	17,99
February	15,33	30,29	14,96
March	18,12	30,29	12,17
April	17,77	32,23	14,46
May	18,16	32,23	14,07
June	19,36	32,23	12,87
July	20,87	32,23	11,35
August	20,21	32,23	12,01
September	18,78	32,23	13,45
October	15,02	30,29	15,27
November	12,77	30,29	17,53
December	11,37	30,29	18,92

The proposed solar panel configuration requires a minimum battery capacity of 18,92 kWh (Table 6.10) in order for the installation to function throughout the year in weekend mode.

6.2. Battery Bank

Conditions 1 (modified), 2, 3 and 5 affect the capacity of the battery bank, with condition 1 (modified) imposing the highest minimum capacity of 23,05 kW.

Given the size of the installation required and the restrictions imposed by the location of the battery bank lithium ion batteries are discarded. Their main advantages are their reduced size, zero maintenance and quick charge cycle, all at a much higher cost than the lead-acid alternative. In the proposed installation the size of the battery bank is not of high importance, and maintenance is very straightforward as the batteries are easily accessible. Also, the owners have more experience with lead-acid batteries, as they are a more tried and tested technology.

Commercial lead acid battery banks function at either 12 V, 24 V or 48 V, achieved by stringing 6, 12 or 24 batteries in series, as the nominal voltage of a lead acid cell is 2 V. Both the battery chargers and inverter are designed to work at the mentioned voltages and must be taken into account when searching for a charger or an inverter. The voltage at which the bank should function depends on the charge and discharge currents. With a higher battery bank voltage, the batteries must supply less current to provide the same power than in a lower voltage bank. For example, if the solar panels produce 2,4 kW of power, with a 12 V battery bank the battery charger would output 200 A, while in a 48 V system it would only output 50 A. This allows the cables to be thinner in higher voltage banks.

In order to minimise the cable section a voltage of 48 V is chosen for the battery bank, and therefore the bank will be composed of 24 individual batteries. The chosen battery model is the Turbo Energy 6 SOPzS 965, a deep-discharge lead-acid battery (Table 6.11).

Table 6.11 Properties of the Turbo Energy 6 SOPzS 965 battery bank

Cell voltage [V]	Cell capacity [Ah]	Cell capacity [kWh]	Bank voltage [V]	Bank capacity [kWh]	Maximum DoD	Maximum usable capacity [kWh]
2	846	1,692	48	40,608	80%	32,486

The maximum usable capacity of the battery bank is 32,486 kWh, higher than the required battery capacity or functioning in critical conditions of 23,05 kWh. However the battery bank will not always work under critical conditions and to estimate the lifetime of the battery bank the average DoD must be calculated. To calculate the average DoD one weekend of bad weather has been considered for each month, as well as two midweek days of bad weather (Table 6.12).

Table 6.12 Battery DoD and estimated lifetime

Minimum discharge [kWh]	Minimum DoD	Maximum discharge [kWh]	Maximum DoD	Average DoD	Estimated Lifetime
1,85	4,56 %	23,05	56,76 %	12,72 %	7.500 cycles ≈20 years

6.3. Wind Turbine

The wind turbine will act as a renewable energy backup for the solar panels, as it can function at night and in low-light conditions. A HAWT will be evaluated for use in the installation, as it is better adapted to onsite the wind conditions. Specifically, VAWTs are ruled out due to their bad performance in gusty conditions and specially their low market availability. Also the owners have experience with HAWTs, as the residence used to have one.

Table 6.13 FSH 2000W 48V Wind Turbine Properties

Nominal speed [m/s]	Power output [kW]	Air Density [kg/m^3]	Area [m^2]	Coefficient	Betz
12,5	1 Nominal 2 Maximum	1,225	2,48	0,337	0,593

The model of HAWT chosen is the FSH 2000W 48V (Table 6.13). In order to establish its production the coefficient C_p of the turbine must be determined (Eq. 6.2), using its nominal functioning values.

$$P = C_p * P_{wind} = \frac{1}{2} C_p \rho v^3 A$$ Eq 6.1

$$C_p = \frac{P_{out}}{P_{in}} = \frac{P_{nom}}{\frac{1}{2} \rho {v_{nom}}^3 A}$$ Eq 6.2

By using equation 6.1 with the average wind speed values the average power can be determined, and also the monthly and yearly production values (Table 6.14).

Table 6.14 Wind turbine production

Month	Days	Avg wind speed (m/s)	Avg Power (W)	Production (kWh)
January	31	3,17	16,31	12,13
February	28	3,73	26,52	17,82
March	31	3,86	29,56	21,99
April	30	4,18	37,40	26,92
May	31	3,66	25,12	18,69
June	30	3,41	20,30	14,62
July	31	3,62	24,35	18,12
August	31	3,44	20,75	15,44
September	30	3,16	16,11	11,60
October	31	2,75	10,64	7,91
November	30	3,39	19,98	14,39
December	31	2,40	7,08	5,27
TOTAL		3,41		184,90

The yearly output of the wind turbine is 184,9 kWh, 33 times less than the output of the solar panels. This is due to the low average wind speed at the location of the residence, which is also very unsteady and variable in direction. Furthermore the yearly production of an additional RS270 solar panel doubles the yearly production of the wind turbine, while reducing installation and maintenance costs (Table 6.15).

Table 6.15 Yearly wind turbine vs. solar panels production comparison

Solar Panels Production [kWh]	Wind Turbine Production [kWh]	Total Production [kWh]	Production Increase with Wind Turbine	RS270 Solar Panel Production [kWh]
6086,98	184,9	6271,88	3,04 %	423,58

Therefore the installation of a wind turbine is ruled out, and the solar array will be the only renewable energy production source.

6.4. Backup Generator

Requirement number 4 states that all appliances should be able to function with the backup generator running. Two possible alternatives will be analysed: a portable generator with a battery charger and an inverter generator.

6.4.1. Portable Generator and a Battery Charger

The problem in the current installation comes from the generator being connected directly to the residential loads, providing bad quality AC. The design of the Inverter/Charger currently installed connects the residential loads to the backup generator when it is functioning and uses any remaining power to charge the battery bank.

By connecting the generator to a battery charger, the AC current generated is rectified into DC current. The output of the battery charger is then connected to the terminals of the battery bank, and the current is either used to charge the batteries or is fed into the inverter, which produces high quality AC current.

6.4.2. Inverter Generator

By using an inverter generator, the problem is solved without requiring any further modifications. The construction of the inverter generator means that it outputs a high-quality sinewave, and all electronic devices can be used safely when it is running.

In this case the inverter generator option is chosen, as it is the simplest solution. It can be used as a backup source of power in case of a failure of the inverter, and also it is much quieter and more efficient than the portable generator.

6.5. Power Management System

The new installation will be a DC-Coupled system, for the following reasons:

- Only one inverter is required, therefore the cost of the installation is reduced compared to an AC-Coupled system.
- The distance from the solar panels to the battery bank and PMS is under 10 metres, with the losses due to the Joule effect being negligible. Also by using an MPPT

charger the PV modules may operate at a higher voltage than the battery bank, allowing the cable section to be reduced without requiring AC conversion.

- There is only one solar panel site, on the roof of the house, and all the panels will face in the same direction at the same angle, making microinverter technology unnecessary.
- The solar batteryless inverter (or microinverters) would be place outdoors, making it susceptible to weather damage and theft, as it is an expensive piece of equipment.

Three components make up the PMS in DC-Coupled systems: the solar battery charger, the inverter and the AC panel.

The proposed solution is the Voltronic Axpert MKS RS 5000W, a device that combines an inverter, solar battery charger, grid battery charger and automatic switch.

Table 6.16 Voltronic Axpert MKS RS 5000W properties

Inverter		**Solar Battery Charger**		**Grid Battery Charger**	
Voltage (V)	230 ± 5%	**PV Array Voltage (V)**	min. 60 max. 145 VOC	**Input Voltage (V)**	170-280
Nominal Output Power (W)	5000 (pf=1)	**Max. Array Power (W)**	4000	**Max. Charge Power (W)**	2880
Surge Power (VA)	8000	**Max. Charge Current (A)**	80	**Max. Charge Current (A)**	60
Efficiency	93 %	98 %			

6.5.1. Solar and Grid Battery Charger

The Voltronic Axpert MKS RS 5000W incorporates an MPPT solar battery charger, with a maximum array power of 4000 W. MPPT technology allows the charger to be extremely efficient, with 98 % of the power produced by the PV modules being fed into the system.

The input voltage from the solar array must be a minimum of 60 V and a maximum open circuit voltage of 145 V. This must be taken into account when designing the layout and configuration of the solar array.

The grid battery charger accepts input voltages from 170 V to 280 V, and has a maximum charge current of 60 A. Since the battery bank is at 48 V this gives a maximum charge power of 2880 W, giving a combined 6880 W of charge power when combined with the solar charger.

6.5.2. Inverter

The inverter included in the device has a nominal output of 5000 W at a power factor of 1, with a maximum peak power of 8000 VA. This amount of power allows for all the lighting along with the coffee machine, dishwasher, washing machine and the oven, as well as the 24-hour loads.

The device outputs a pure sinewave at 230 V ± 5% and at 50 to 60 Hz depending on the installation, which in this case is 50 Hz, the grid frequency in Spain.

6.5.3. Transfer Switch

The transfer switch in the Voltronic Axpert MKS RS 5000W allows the load to be connected directly to the AC input, in what is called *bypass* mode. The transfer time can be set at 10 ms for installations with personal computers, which is the case in this installation, or at 20 ms for installations with only home appliances such as lights and kitchen appliances.

6.5.4. PMS Efficiency

Finally the solar array and battery bank sizing calculations must be redone taking into account the efficiency of both the solar charger and the inverter. The output of the solar charger is calculated multiplying the solar array production by the efficiency of the charger (Eq 6.3) and the inverter input is the result of dividing the residential consumption by the efficiency of the inverter (Eq 6.4).

$$Solar\ Charger\ Output = \eta_{charger} \cdot Solar\ Array\ Production \qquad \text{Eq 6.3}$$

$$Inverter\ Input = \frac{Residential\ Consumption}{\eta_{inverter}} \qquad \text{Eq 6.4}$$

Table 6.17 Number of RS270 panels required considering the PMS efficiency					
Month	**Required daily production [kWh]**	**Current panels [kWh]**	**Additional Required [kWh]**	**Unitary Production RS270 [kWh]**	**Number required**
March	16,29	7,87	8,41	1,24	7
April	17,33	7,72	9,61	1,21	8
July	17,33	9,07	8,26	1,42	6
August	17,33	8,78	8,54	1,38	6

Due to the losses in the inverter and the solar battery charger the number of additional panels is increased in 2 units to a total of 10, making the total number of solar panels 18 (Table 6.17). This number is lower than the maximum of 21 the roof space allows for.

Table 6.18 Required battery capacity considering PMS efficiency			
Month	**Bad weather weekend production [kWh]**	**Total Weekend Usage [kWh]**	**Battery capacity required [kWh]**
January	12,77	37,01	21,58
February	15,91	37,01	18,88
March	18,81	37,01	16,39
April	18,45	39,38	18,78
May	18,85	39,38	18,43
June	20,10	39,38	17,36
July	21,67	39,38	16,01
August	20,99	39,38	16,60
September	19,50	39,38	17,88
October	15,59	37,01	19,16
November	13,25	37,01	21,17
December	11,80	37,01	22,42

The maximum required discharge has increased to 22,42 kWh in December (Table 6.18) and is still within the capacity of the battery bank (Table 6.19). In consequence the battery bank need not be modified.

Table 6.19 Battery DoD and estimated lifetime considering PMS efficiency					
Minimum discharge [kWh]	**Minimum DoD**	**Maximum discharge [kWh]**	**Maximum DoD**	**Average DoD**	**Estimated Lifetime**
1,75	4,3 %	22,42	55,21 %	13,86 %	7.400 cycles ≈20 years

6.5.5. AC Panel

The current AC panel is sized correctly for the installation, with all the safety features required for a residential installation. It only lacks a circuit breaker at the entrance of the panel, to section off the AC distribution from the inverter. To protect the inverter the breaker must trip before the inverter's maximum current is reached, which is 34,78 A. The closest commercially available breaker is sized 32 A, which will be used in the panel.

6.6. Wiring

After completing the design process and sizing all the components of the system the connectivity between the different components must be defined.

The solar array consists of 18 solar panels, 10 RS270 panels and the ones inherited from the old installation.

Table 6.20 Proposed solar panel installation						
Solar Panel Model	**Nominal Voltage [V]**	**Open Circuit Voltage [V]**	**Short Circuit Current [A]**	**Rated Power [W]**	**Number**	**Total Power [W]**
Sharp ND-120T1	12	21,3	7,81	120	2	240
Adanco Solar	12	21,6	7,5	120	4	480
Yingli YL250P-29b	24	38,4	8,79	250	4	1000
Perlight Solar RS270	24	38,23	9,13	270	8	2160
Total					18	3880

Two of the models of solar panels work at a nominal voltage of 12 V while the other two work at 24 V. By connecting two 12 V panels in series an equivalent 24 V panel is obtained, as voltage is additive in series connections.

The solar array must be arranged in strings, the industry name for a number of panels connected in series with each other. To determine the length of the strings the solar charger input limits must be considered. Specifically, the maximum voltage of the array, given when in open circuit must not exceed the maximum input voltage of the charger (Eq. 6.5). Also under nominal conditions the array voltage must be higher than the minimum input voltage of the charger (Eq. 6.6).

$$n_{max} = \frac{Max. Charger\ Input\ (V)}{V_{OC}} \quad \text{Eq 6.5}$$

$$n_{min} = \frac{Min. Charger\ Input\ (V)}{V_{nom}} \quad \text{Eq 6.6}$$

<table>
<tr><th colspan="7">Table 6.21 Solar panels string sizing</th></tr>
<tr><th rowspan="2">Solar Panel Model</th><th colspan="2">Panel Voltage (V)</th><th colspan="2">Solar Charger Input (V)</th><th colspan="2">String Length</th></tr>
<tr><th>Nominal</th><th>OC</th><th>Minimum</th><th>Maximum</th><th>Minimum</th><th>Maximum</th></tr>
<tr><td>Sharp ND-120T1[3]</td><td rowspan="4">24</td><td>42,6</td><td rowspan="4">60</td><td rowspan="4">145</td><td>3</td><td>3</td></tr>
<tr><td>Adanco Solar[4]</td><td>43,2</td><td>3</td><td>3</td></tr>
<tr><td>Yingli YL250P-29b</td><td>38,4</td><td>3</td><td>3</td></tr>
<tr><td>Perlight Solar RS270</td><td>38,23</td><td>3</td><td>3</td></tr>
</table>

[3] Equivalent 24 V panel.
[4] Equivalent 24 V panel.

By taking into account the open circuit voltage of each panel and the maximum input voltage of the solar charger the maximum string length is found to be 3 (Table 6.21), the same as the minimum string length.

<table>
<tr><th colspan="8">Table 6.22 Solar array string layout</th></tr>
<tr><th>String Number</th><th>Panel 1</th><th>Panel 2</th><th>Panel 3</th><th>Nominal String Voltage [V]</th><th>Nominal Power [W]</th><th>Nominal Current [A]</th><th>Cable section [mm^2]</th></tr>
<tr><td>1</td><td>Sharp</td><td>Adanco</td><td>Adanco</td><td rowspan="4">72</td><td>720</td><td>10</td><td>1</td></tr>
<tr><td>2</td><td>Yingli</td><td>Yingli</td><td>Yingli</td><td>750</td><td>10,42</td><td>1</td></tr>
<tr><td>3</td><td>Yingli</td><td>Perlight</td><td>Perlight</td><td>790</td><td>10,97</td><td>1</td></tr>
<tr><td>4, 5</td><td>Perlight</td><td>Perlight</td><td>Perligh</td><td>810</td><td>11,25</td><td>1</td></tr>
</table>

In total the solar array is comprised of five strings of four different configurations (Table 6.22). In reality the first string is comprised of six 12 V panels, while the rest are made up of 24 V panels. A more detailed schematic of the string connections can be found in Appendix B. In order to size the cables used to connect the different panels within each string the IEC-60227-3 rule is used. For each current rating a minimum cable section is given, and the results can be seen in table 6.23.

Table 6.23 Solar array cable section

Nominal Array Voltage [V]	**Number of Strings**	**Panels per String**	**Output Current [A]**	**Cable section [mm^2]**
72	5	3	53,89	16

In order to calculate the diameter of cable required to connect the solar array to the charger the maximum voltage drop is used. A maximum loss of voltage of 1% is recommended by *IDAE*, the Spanish Institute for Energy Diversification. By using equation 6.7 the cable section is calculated. The distance from the panels to the charger L is 5 metres, the current under nominal conditions I is 53,89 A, the conductivity of copper γ is 56 m/(mm^2·W) and the voltage drop is 0,72 V. By inputting these values into equation 6.7 the required section is found to be 13,36 mm^2.

$$S = \frac{2 \cdot L \cdot I}{\gamma \cdot \Delta V} \quad \text{Eq 6.7}$$

The closest commercially available section is 16 mm^2, which will be used to join the solar array with the charger. According to IEC-60227-3 the maximum current allowed for this sectional area is 68 A to avoid overheating, higher than the planned maximum current. Therefore 16 mm^2 cable can safely be used.

Table 6.24 Battery bank cable section

Battery Bank Voltage [V]	Solar Charger		AC Charger		Maximum Current [A]	Cable Section [mm^2]
	Input Power [W]	Current [A]	Input Power [W]	Current [A]		
48	4000	80	2880	60	140	70

As for the connection to the battery bank the critical condition is given when the inverter/charger is charging the batteries with both the solar charger and the AC charger at full power, giving a maximum current of 140 A. Since the distance between the two components is under one metre the voltage drop is considered negligible and the cable can be sized according to IEC-60227-3 (Table 6.24). In this case the minimum diameter required is 70 mm^2.

Table 6.25 AC Panel cable section

AC Panel Voltage [V]	Inverter		Cable Section [mm^2]
	Input Power [W]	Current [A]	
230	5000	21,74	4

Finally the connection between the inverter and the AC Panel must be sized. As with the connection to the battery bank the distance between the inverter and the AC Panel is under one metre. Using the same sizing procedure the required section is found to be 4 mm^2 (Table 6.25).

The wiring connecting the backup generator to the PMS is already installed in the current installation and can be reused.

6.7. Operation Simulation

With the new installation designed and all the components sized a simulation of the system operation under the conditions at the residence can be carried out.

In first place the yearly production and consumption are calculated. To calculate the yearly consumption 4 weeks of holiday mode functioning have been considered, specifically one week in April (Easter), one week in July and two weeks in August. For the rest of the weeks weekend usage mode is considered. The yearly production is just over 6 MWh, nearly doubling the consumption at 3,25 MWh (Figure 6.3). Specifically, the excess production amounts to 2,84 MWh, 46,6% of the total production. From this analysis it may seem that the system is oversized, but first a monthly and weekly analysis must be carried out.

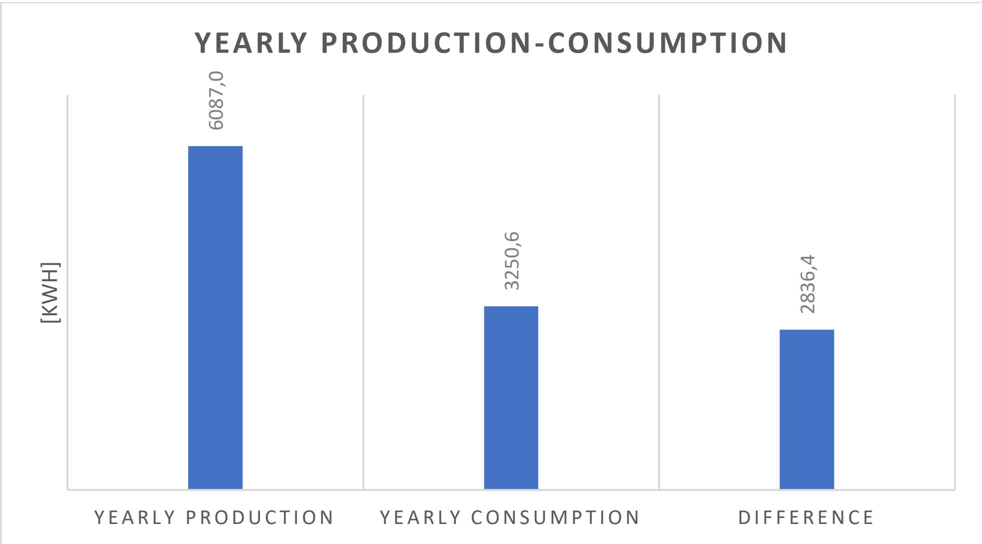


Figure 6.3 Yearly production and consumption, as well as the difference between the two values.

When each month is analysed separately weekend usage mode is considered except for the 4 weeks of holiday mode mentioned above, in the months of April, July and August. For every month of the year the production is higher than the consumption, reaching a maximum difference of 336,9 kWh in March and a minimum of 127,6 kWh in December (Figure 6.4).

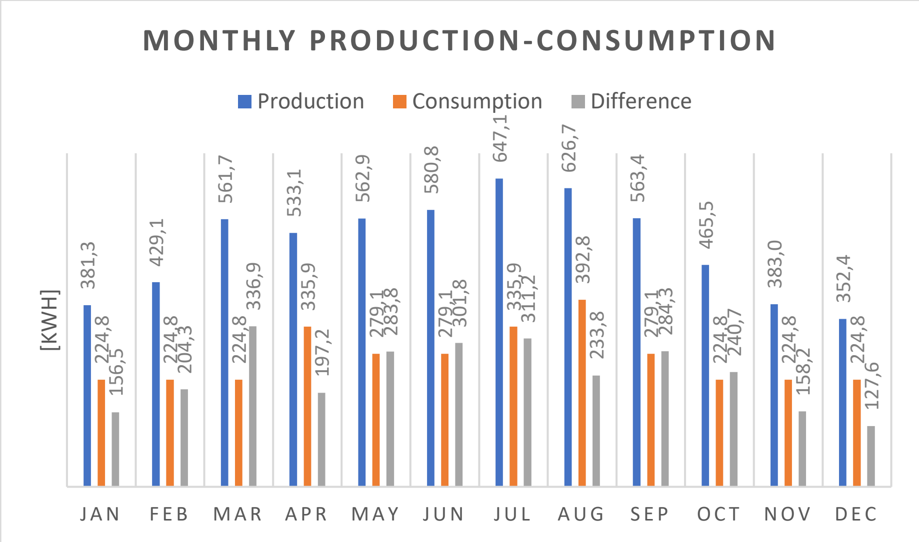


Figure 6.4 Monthly production and consumption, as well as the difference between the two values.

The system has a higher production than the consumption requirements both on a yearly and a monthly level. Therefore, the system is able to supply the energy requirements of the residents, although a big part of the energy produced is not being exploited.

6.7.1. Weekend Usage

In weekend mode the week is divided in two periods according to consumption: the midweek and the weekend. During the midweek period consumption is low and the difference between production and consumption is positive, of up to 70,49 kWh in July and a minimum of 35,29 kWh in December (Figure 6.5).

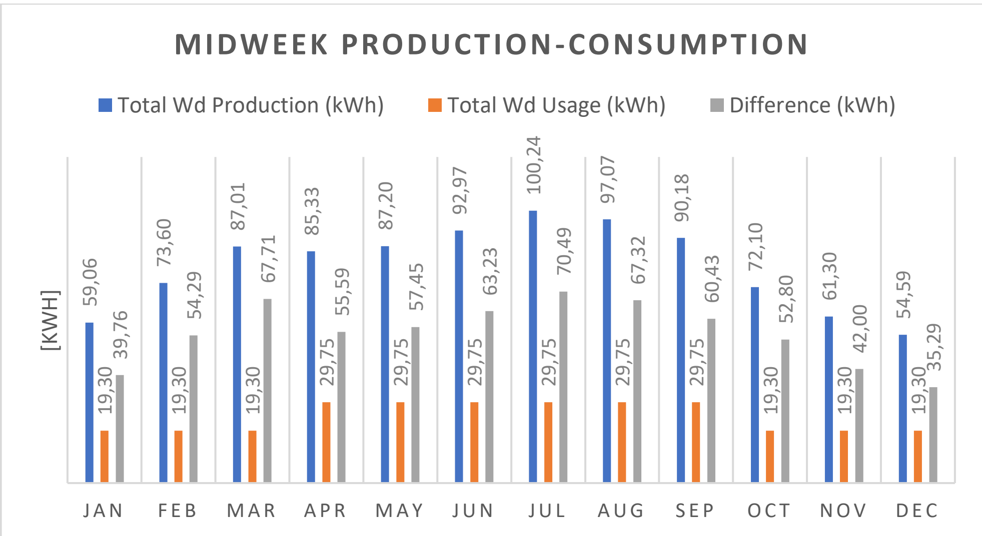


Figure 6.5 Midweek production and consumption in weekend usage mode.

Of the energy produced that is not consumed by the residence only a small part is stored (Figure 6.6). This is due to the fact that during the previous weekend the batteries, in good weather conditions, do not fully discharge, and only the energy consumed during the weekend can be replaced.

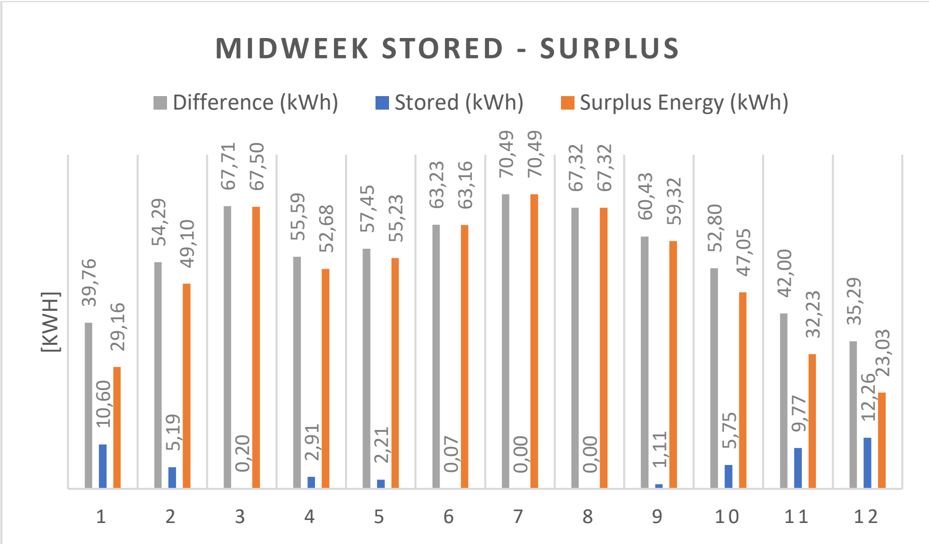


Figure 6.6 Midweek stored and surplus energy in weekend usage mode.

During the weekend period the consumption exceeds the production in all the months except July and August, as can be seen in Figure 6.7. The maximum difference between the consumption and the production is 12,26 kWh in December, an amount of energy that can be supplied by the battery bank.

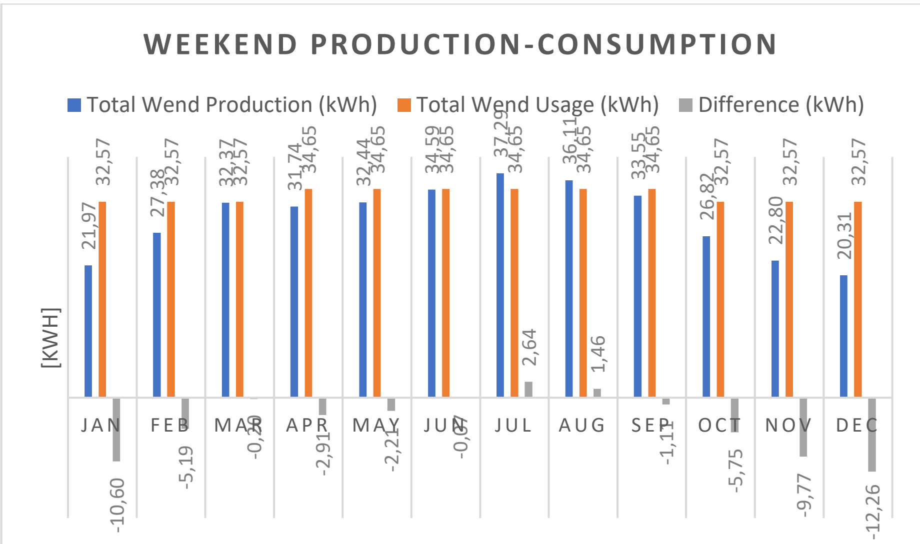


Figure 6.7 Weekend produced and consumed energy, in weekend usage mode.

Finally the weekly production and consumption balance is always in favour of the production, with a difference of up to 73,13 kWh in July and as low as 23,03 kWh in December (Figure 6.8).

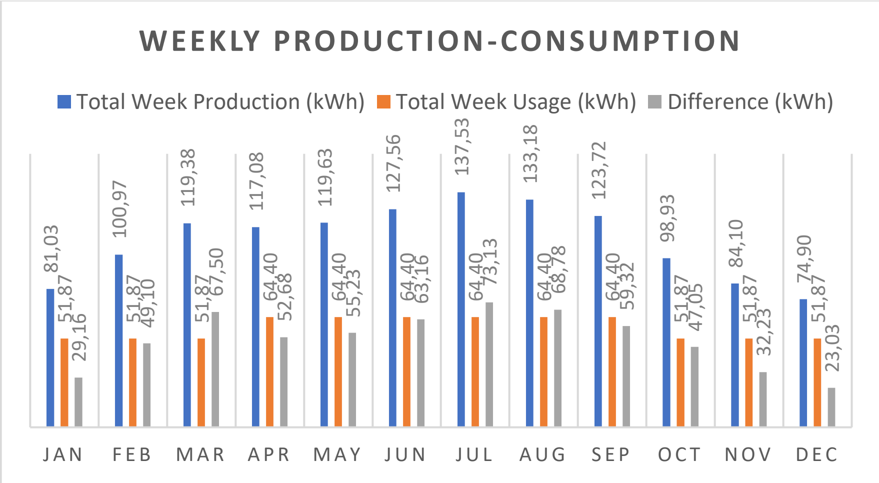


Figure 6.8 Weekend produced and consumed energy, in weekend usage mode.

Therefore, in weekend usage mode the system functions perfectly throughout all the months of the year.

6.7.2. Holidays

The installation has been sized to operate in holiday mode without requiring the backup generator during the months of March, April, July and August, therefore daily consumption must not exceed the production during these months. This condition is met during the aforementioned months and also in May, June and September, so the system can effectively function in holiday mode from March through September (Figure 6.9).

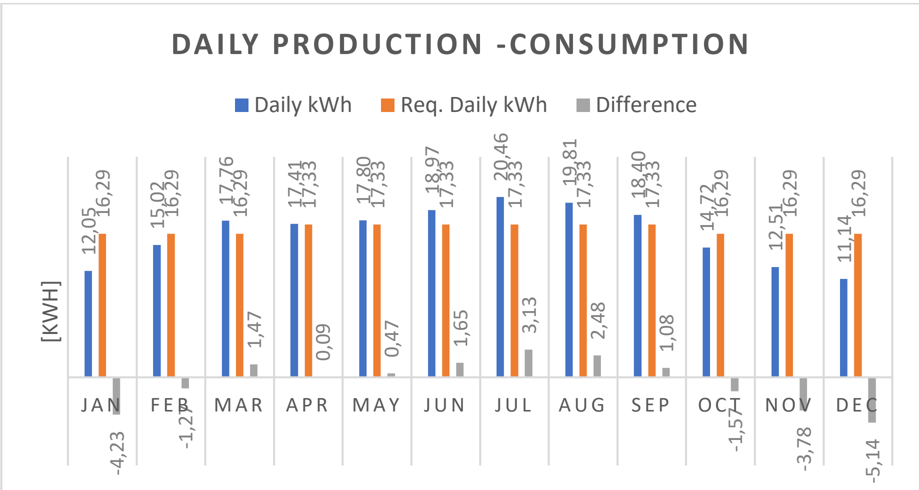


Figure 6.9 Daily production and consumption of the residence in holiday mode.

By analysing the holiday week as a whole the difference between production and consumption is positive between March and September and negative in the other months (Figure 6.10). However, considering the battery bank is fully charged from the previous week the system can function also in February, October and November, with a maximum discharge of 26,43 kWh, equivalent to a DoD of 65,08 %, admissible as it is under 80 % and without reducing the battery life as it would only occur once a year.

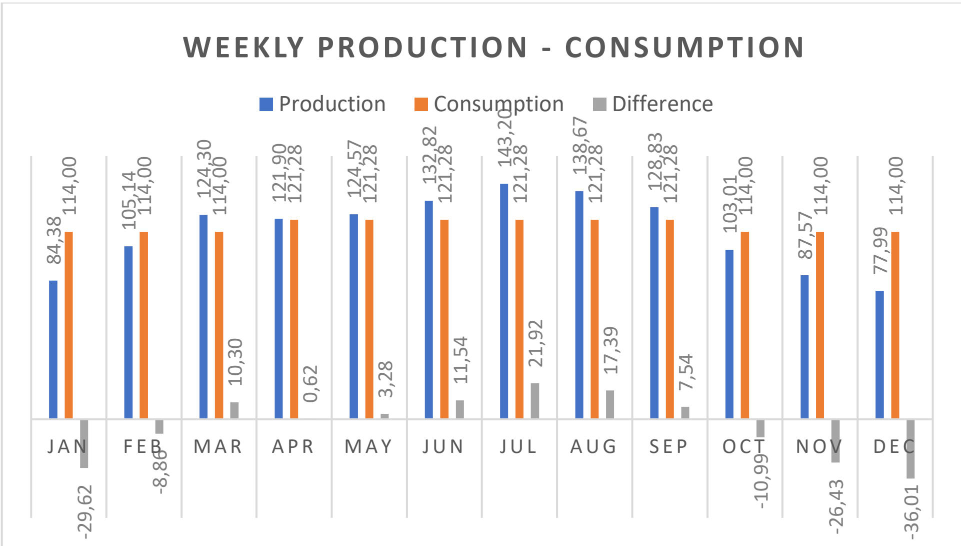


Figure 6.10 Weekly produced and consumed energy, in holiday mode.

6.8. Maintenance

The installation must be regularly maintained to keep it safe and ensure the components last their planned lifetime.

The solar panels must be inspected every six months for damages in both the panels themselves and the structure, and for dirt accumulated on the surface of the panels, which must be cleaned off with water.

The battery bank also requires regular maintenance. Every six months the batteries must be inspected visually and the electrolyte levels checked. The procedure to check the electrolyte can be found in the appendix.

The RCDs on the AC Panel must be tested at least once a year, and all the wiring in the installation must be checked for damages in the insulation.

7. Budget

Once the new installation is designed and all the necessary components accounted for a budget for the project can be calculated.

Table 7.1 Materials cost for the new installation

Item	Description	Quantity	Retail Price [€]	Total Cost [€]
Perlight Solar RS270	Solar Panel	8	149,58	1.196,64
7 frame 30º solar panel frame	Solar Panel Support	2	262,48	524,96
4 frame 30º solar panel frame	Solar Panel Support	1	150,25	150,25
100 mts of single-pole 1,5 mm^2 cable	Solar Panel Wiring	1	30,25	30,25
1 metre single-pole 16 mm^2 cable	Solar Panel Wiring	20	1,53	30,58
75 mts PVC tube	Solar Panel Wiring	1	18,01	18,01
Junction box	Solar Panel Wiring	1	7,51	7,51
Connectors	Solar Panel Wiring	2	5,54	11,08
Turbo Energy 6 SOPzS 965	Batteries	24	175,06	4.201,39
1 metre single-pole 70 mm^2 cable	Battery Wiring	2	7,47	14,94
Voltronic Axpert MKS RS 5000W	PMS	1	696,89	696,89
1 metre single-pole 4 mm^2 cable	PMS	3	0,34	1,32
Mallorca inverter generator	Backup Generator	1	904,96	904,96
32 A C. Breaker	PMS	1	21,89	21,89
Total (No IVA)				7.810,67
Total				9.450,91

The total cost of materials is 9.450,91 €, however the cost of the design of the installation and installation of the different components must also be considered. However in this project these calculations are merely hypothetical, as the design and installation would be carried out by the owners themselves, and therefore have no cost whatsoever.

For the realisation of the engineering project and documents 50 hours of work by a junior engineer have been considered. For the installation two 8 hour days work by a team of two electricians is considered.

Table 7.2 Cost of labour

Item	**Labour Force**	**Number**	**Hours Required [h]**	**Hourly Rate [€/hour]**	**Cost [€]**
Engineering Project	Junior Engineer	1	50	30	1.500
Installation	Electrician	2	16	20	640
Total					2.140

The total cost of the project is 11.560,91 €.

8. Environmental Impact

Can Carbassa is located in an area of natural interest, therefore it is important to evaluate the impact the new installation will have on the environment. The main objective of the project is to reduce the use of the backup generator to zero. By doing so the CO_2 emissions and noise pollution produced when the generator is running would be eliminated.

To calculate the CO_2 emissions in the original installation the litres of fuel consumed by the generator must be calculated. To do so for all of the weeks of the year the installation works in weekend usage mode, except a week in April (Easter), a week in July and two weeks in August when it works in holiday mode. Also a generator efficiency of 20% is considered, along with Eq. 8.1, which relates petrol consumption with CO_2 emissions.

$$C_8H_{18} + 12.5\ O_2 \rightarrow 8\ CO_2 + 9\ H_2O \qquad \text{Eq 8.1}$$

Table 8.1 Generator yearly CO_2 production

Efficiency	Yearly Production [kWh]	Petrol Calorific Value [kWh/l]	Petrol per kWh [kWh/l]	Petrol Consumption [l]	CO2 Output [kg]
0,2	711,78	9,1	0,55	391,09	1631,84

The yearly CO_2 production is approximately 1.6 metric tons (Table 8.1), which will be saved with the new installation. As for the noise pollution the PRAMAC generator, when running, produces 71 dB, while the new *Mallorca* inverter generator produces 59 dB, a notable reduction. Also, the new generator will only run on counted occasions, compared to the old generator which ran on a daily basis.

The solar panels, installed on the roof, will occupy a significantly larger area than in the old installation, however this will not impact the environment significantly as it is unused space.

9. Conclusions

This project was initiated with the aim of redesigning the electrical installation of Can Carbassa, sizing it accordingly and improving its reliability to reduce the runtime of the backup generator to zero. With respect to the initial objectives we can say the following:

- The proposed solution reduces the use of the generator to zero during holidays in the months between March and October, and can also function for a week in February and November, thanks to the battery bank. In weekend usage mode the system can function throughout the year.
- The new installation is a scaled-up version of the current installation, with a number of technological advances such as the MPPT solar charger and an integrated PMS unit. The problem with the old installation was that it was undersized.
- The main problem with the current installation is the lack of battery capacity, due to the undersized bank and also sulfation, as the batteries have been discharged many times.
- The new installation is sized to work in holiday mode, when resources are optimised. In weekend usage mode the solar array produces more energy than can be stored or used during the week and goes to waste.

In light of these findings a number of recommendations are made to the residents:

- To increase consumption during the midweek period. This way the capacity of the installation is better exploited. For example the pool filter could run during the midweek period on a timer, that remotely controls when it starts and stops.
- To start renewing the system by replacing the battery bank. It is the critical failure point of the current system.

A proposed continuation of this project is the automation of the system and incorporating connectivity into the installation, in order to improve its efficiency and ease-of-use.

Lastly the objective of including network connectivity to the system has not been met due to lack of time. The proposed PMS device has connectivity, yet the AC panel does not. A proposal for the continuation of this project is making the new installation controllable from a distance, as it is very interesting for the owners as they spend most of their time away from the residence.

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