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# Youth growth powered by solar energy - Design of a photovoltaic system for a non-profit guesthouse

TESI DI LAUREA MAGISTRALE IN
ENERGY ENGINEERING – ENERGY FOR DEVELOPMENT
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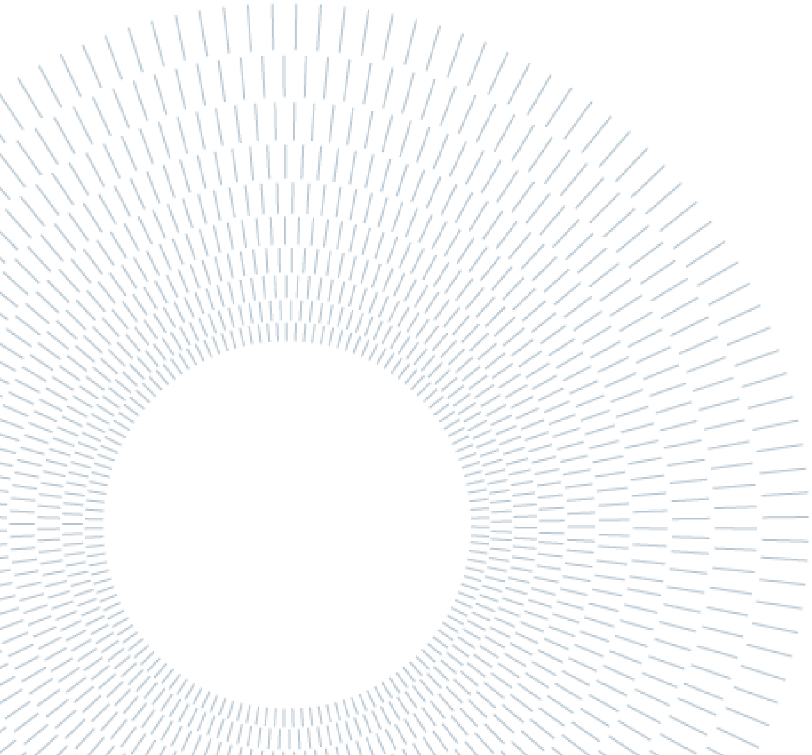


# Abstract

The Zambian national grid does not guarantee reliable and constant access to electricity supply. Therefore, commercial establishments and residential homes are forced to provide themselves with backup systems. The choice of photovoltaic systems for this purpose has been growing in recent years.

This thesis presents a backup PV system, consisting of PV panels, inverter, MPPTs and batteries, designed for a nonprofit hotel facility located in Livingstone. The system is equipped with a control and monitoring system that optimizes its operation under ordinary conditions and during power outages.

The study is framed within the context of an international cooperation intervention, since it is part of the answer to a private donors' call and the beneficiary hotel facility is a nonprofit organization, which aims to professionally train young people in need.

A detailed description of the main components, which make up a photovoltaic system, and general criteria for the design is found in the paper. The study consists of a section devoted to simulations for sizing the PV array and batteries, followed by an exposition of the calculations necessary for sizing and coupling the electrical components.

In addition, an economic analysis of the entire project is presented, focusing on the final benefits to the guesthouse.

**Key-words:** photovoltaic system, backup system, design, Zambia

# Abstract in italiano

La rete nazionale zambiana non garantisce un accesso affidabile e costante alla fornitura elettrica. Perciò esercizi commerciali e abitazioni residenziali sono costretti a fornirsi di sistemi di backup. La scelta di sistemi fotovoltaici per questo scopo sta crescendo negli ultimi anni.

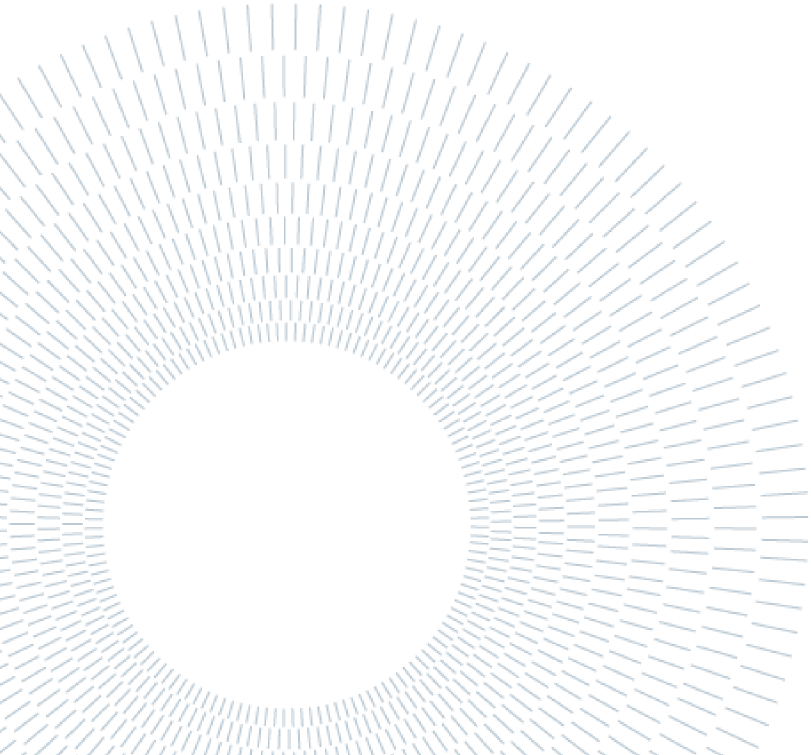
In questa tesi si presenta un sistema fotovoltaico di backup, costituito da pannelli fotovoltaici, inverter, MPPT e batterie, pensato per una struttura alberghiera no-profit situata a Livingstone. L'impianto è dotato di un sistema di controllo e monitoraggio che ne ottimizza il funzionamento in condizioni ordinarie e in caso di blackout.

Lo studio si inserisce nel contesto di un intervento di cooperazione internazionale, facendo parte della risposta a una call di donatori privati ed essendo la struttura alberghiera beneficiaria un'organizzazione no-profit, che ha l'obiettivo di formare professionalmente i giovani in difficoltà.

Nell'elaborato trova spazio una descrizione dettagliata dei principali componenti, che costituiscono un impianto fotovoltaico, e dei criteri generali per la progettazione. Lo studio si compone di una sezione dedicata alle simulazioni per il dimensionamento del campo fotovoltaico e delle batterie, seguita dall'esposizione dei calcoli necessari al dimensionamento e accoppiamento dei componenti elettrici.

Inoltre, viene esposta un'analisi economica dell'intero progetto, focalizzata sui benefici finali per la struttura alberghiera.

**Parole chiave:** impianto fotovoltaico, sistema di backup, progettazione, Zambia



# Contents

# Introduction

The basis of this study is the sizing of a photovoltaic system for Olga's - The Italian Corner, a nonprofit restaurant and guesthouse located in Livingstone, Zambia. Specifically, the objective of the sizing is to handle frequent power outages, ensuring that at least priority loads are covered.

My motivations for choosing this project as my dissertation subject are my interests in international development and cooperation programs and in photovoltaic technology, which were influenced and certainly stimulated by some experiences I had during my undergraduate internship.

The objective of this study is the design of a three-phase photovoltaic plant with a backup system. The paper aims to propose an effective solution to manage blackouts and, at the same time, reduce the hotel's energy expenses.

The sizing was conducted through several simulations to optimize the size of batteries and PV array. Then, the components were selected and the calculations for the electrical sizing of the system and the layout design of panels and structures could be carried out.

The thesis is divided into five chapters: in the first chapter, an introduction to photovoltaic technology is provided through the presentation of the state of the art of the main components. The second chapter presents the criteria for the proper design of a photovoltaic system. The third chapter sets out the case study analyzed and the boundary conditions for system design. In the fourth chapter, sizing results are presented. Finally, the fifth chapter comments on the results obtained.

# 1 Photovoltaic power plant

A solar photovoltaic power plant is an ordinary power plant that converts solar energy into electricity through the photovoltaic effect. It consists of photovoltaic modules, one or more inverters, control and protection electric devices, and possibly an energy storage system. This chapter provides useful information on the state of the art of photovoltaic systems. The main components are presented, and their characteristics discussed in depth.

## 1.1. Photovoltaic cells theoretical description

The solar radiation can be converted into electric power exploiting the **photovoltaic effect**. It is possible through PV cells technology, which is based on the properties of semiconductors. Indeed, PV cells are typically made of Silicon.

The operation curve of an ideal photovoltaic cell is plotted in Figure 1 - VI curve and VP curve for an ideal solar cell.

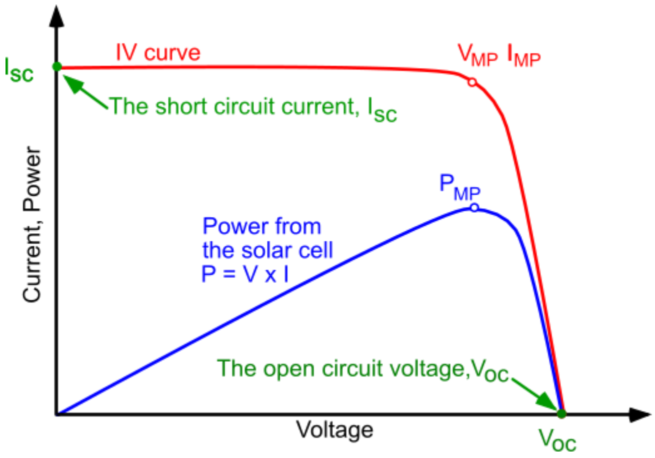


Figure 1 - VI curve and VP curve for an ideal solar cell

Three important conditions, visible in the IV curve, are the Open Circuit, Short Current, and Maximum Power Point. The Open Circuit is the condition of zero output current.

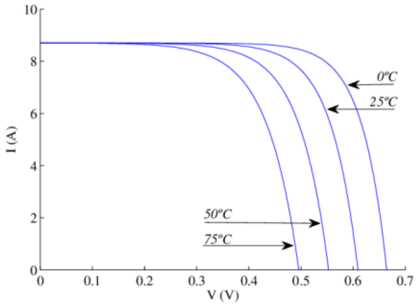


Figure 2 - VI curve changes with temperature variations [4]

The $V_{OC}$ depends mainly on the energy gap of the material. It is strongly affected by the cell's temperature and slightly affected by the irradiation. The Short Current is a condition of zero voltage applied to the cell.

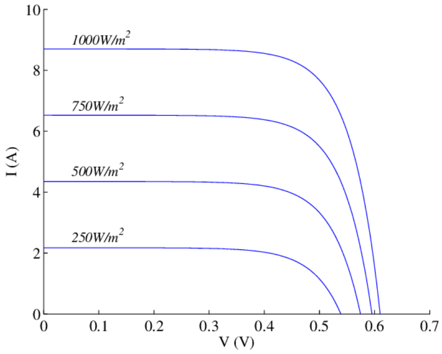


Figure 3 - VI curve changes with irradiation variations [4]

The $I_{sc}$ is the maximum current possible. It is affected by the irradiation and the cell temperature, as it's shown in the Figure 3 - VI curve changes with irradiation variations, and in the Figure 2 - VI curve changes with temperature variations.

The Maximum Power Point is the condition of maximum power output of the cell. This is the working point at which the system should work to have the maximum electricity production possible. Clearly, it's different for different operation curves.

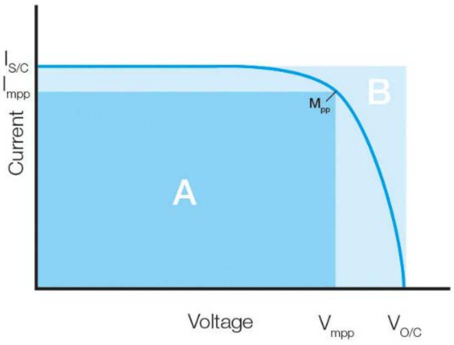


Figure 4 - Fill Factor visual representation

The ratio between $I_{MPP} * V_{MPP}$ and $I_{sc} * V_{OC}$ is called Fill Factor, and it's an indicator of the cell performances. It accounts for the ohmic and recombination losses [5].

To shift from the ideal cell model to the real cell model, it is necessary to take into account all the losses. The resulted PV efficiency equation is the following:

$$\eta = \frac{P_{max}}{P_{in}} = \eta_{ideal}\eta_{photon}FF\eta_V\eta_C^{int} \tag{1}$$

Equation 1 - Solar cell's efficiency equation

$P_{max}$ is the electric power produced by the cell ad $P_{in}$ is the incident solar radiation on the cell surface. $\eta_{ideal}$ accounts for the maximum energy theoretically extractable from an absorbed photon. $\eta_{photon}$ accounts for all the optical losses (reflection, absorption, and grid shadowing losses). The Fill Factor accounts for the ohmic and recombination losses, as already explained. $\eta_V$ is the band gap utilization efficiency, which show the fraction of the band gap that can be used as open-circuit voltage. $\eta_C^{int}$ is the internal collection efficiency, which is calculated as a function of depletion width, minority-carrier diffusion length, solar spectrum, and absorption coefficient [2].

The actual state of art for solar modules' efficiency is 22.8 % [6].

## 1.2. PV modules technical description

A typical silicon cell structure is made of:

- Tempered, anti-glare glass;
- Modules encapsulate (ethylene vinyl acetate);
- Antireflective coating;
- N-type silicon layer;
- P-type silicon layer;
- Traces (metallic conductor);
- Back sheet (polyvinyl fluoride film).

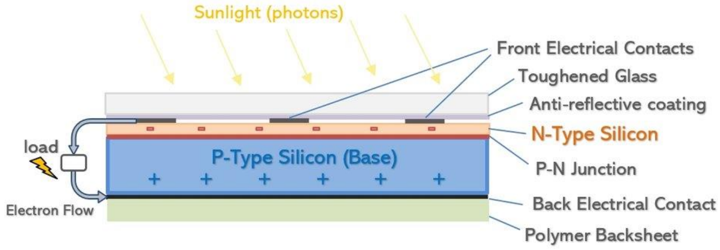


Figure 5 - Solar cell structure [7]

PV technologies can be divided into four main groups:

1. **Conventional technologies**: mono-crystalline silicon and multi-crystalline silicon;
2. **Thin-film technologies**: amorphous silicon, cadmium telluride, gallium arsenide, copper indium selenide;
3. **Third generation technologies**: dye sensitized, quantum dots, organic cells;
4. **Combination of technologies**: multi-junction solar cells.

The main share of the market is the mono-crystalline silicon one, which is forecasted to grow even more in the future years. This technology achieved the leader position mainly because it can offer the best conversion efficiencies [8].

A photovoltaic module consists of 60, 72 or 96 cells connected in series. The cells are connected back and front, with the back layers linked to the top layer of the next cell.

Since the cell are connected in series, following the Ohm laws, it is possible to obtain the IV function of the whole module:

$$\begin{cases} I_{module} = I_{cell,i} & (2.1) \\ V_{module} = \sum_{i}^{ncell} V_{cell,i} & (2.2) \end{cases}$$

Equation 2 – I-V functions for a PV module

The main advantage of the series configuration is limiting the current density and, consequently, reducing the ohmic losses. While there are two main disadvantages:

1. The current must flow through all the cells and each cell, as a current generator, can limit the current flowing. This means that the current is limited by the cell with the worst operating conditions.
2. The solar cell is a diode, so the electrons can flow just in one direction in ordinary conditions. But, if an external voltage with the opposite direction is applied, the current will flow through the cell in the opposite direction, with respect to the built-in voltage of the deflection region, breaking the solar cell.

The behavior of a cell with a negative applied voltage is visible in the VI curve. The solar cell acts as a current generator for positive voltages, and acts as a load, if reversed biased with negative voltages.

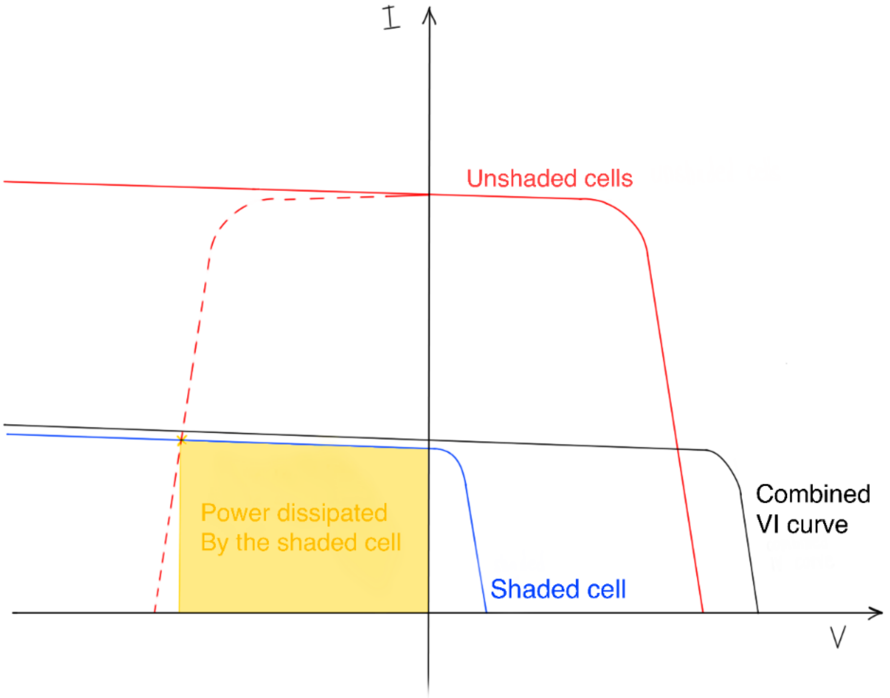


Figure 6 - VI curve in partial shading condition

The condition, pictured in the graph, occurs when the cells, connected in series, have different short-circuit currents due to different irradiation, shadowing, and degradation. The series configuration forces the current to flow in every cell. If the flowing current is higher than the short-circuit current of the cell, it will operate as a load, absorbing electricity instead of producing it. The power absorbed is dissipated as heat, increasing the cell's temperature, therefore this phenomenon is called **hotspot**. If the negative voltage exceeds the **breakdown voltage**, the cell will break.

To prevent hot spots, PV modules have bypass diodes connected in parallel to the cells. Usually, every module has three by-pass diodes, each connected to 20 cells. Under ordinary operation, the solar cells are forward biased and, consequently, the bypass diode will be reversed biased, acting like an open circuit with zero current. If the $I_{sc}$ mismatch among cells' sections would lead to the reverse bias with a negative voltage around 0.5 V, the bypass diode will be forward bias, allowing the flow of the current through the external circuit. Therefore, the current won't be limited by the worse cells' section and no hotspot will occur.

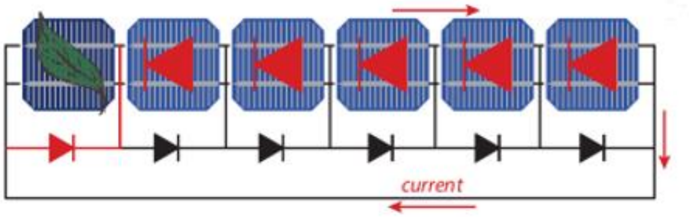


Figure 7 - Bypass diodes for cells series

This configuration allows the module to work at a higher maximum power point, since the current is less affected by the worst operating cell.

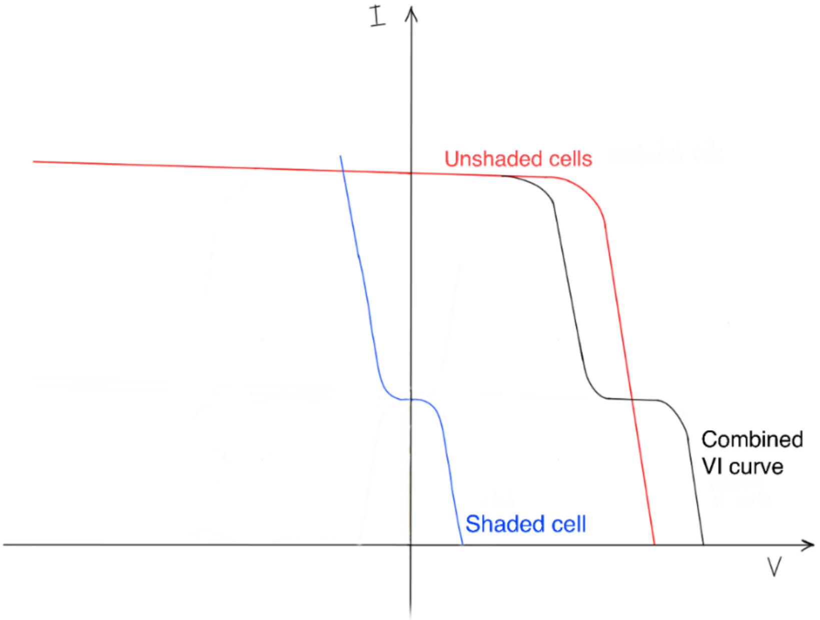


Figure 8 - VI curve of partial shading with bypass diode [3]

The $I_{sc}$ mismatch problem can arise also among different modules when they are connected in series (string). Therefore, bypass diodes are connected in parallel also to PV modules. The functioning is similar to the one of cell's bypass diodes.

In addition, a blocking diode is connected to each string to prevent the current flow from battery to the PV array in nighttime. Usually, the PV array is made of different strings, connected in parallel. Each string must have its blocking diode, also to prevent the current flow from a higher-current string into a lower-current string [9].

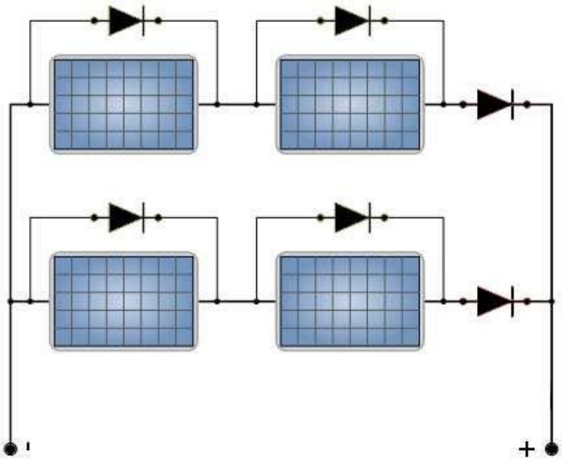


Figure 9 - Bypass and blocking diodes at string level

Finally, it's worth mentioning that most modules on the market are made of advanced PV cells. The most common technologies are the following:

- **PERC/PERL cells**: the top surface of the solar cell is textures using inverted pyramid structures, which are covered by a double layer of antireflection coating, and at the rear surface point contacts are used in combination with thermal oxide passivation layer. This cell structure was adopted because it allows for improved efficiency [10];
- **Back contact cells**: both contacts are placed at the back of the cell; in fact, by using a thin solar cell made of high-quality material, electron-hole pairs generated at the surface can be collected at the back. The advantages are the absence of shading losses on the surface and the absence of the necessary space between the cells, which can be placed closer together [11];
- **Half-cut cells**: modules are composed of six internal cell strings with twenty half-cut cells each. Respectively one string of cells of the upper and lower half are connected to a bypass diode. This configuration leads to a greater tolerance of shading and a decrease in resistive losses [12].

### 1.2.1. Advanced PV modules technologies

Recent years have seen an exponential improvement in solar technology, with next-generation panels featuring a number of innovations in photovoltaic cell design that help to increase efficiency, reduce degradation, and improve reliability. While some of the recent advances, such as PERC, back contact, and half-cut technologies, have been quickly adopted by many manufacturers, other innovations will enter the PV market in the coming years. The main advanced PV modules technologies are listed below [12]:

- **HJT** - Heterojunction cells: HJT solar cells use a crystalline silicon base with additional ultra-thin layers of amorphous silicon on both sides, forming the heterojunction, from which they get their name. The additional layers of amorphous silicon reduce recombination losses in the N-P junction, increasing the cell's efficiency;
- **TOPCon** - Tunnel Oxide Passivated Contact: TOPCon technology is based on a more advanced N-type silicon cell architecture that helps reduce recombination losses in the cell, thereby increasing its efficiency. In fact, having an ultra-thin N-type silicon layer helps reduce these losses with a minimal increase in manufacturing process costs;
- **Gapless Cells -** High-density cell construction: To further increase panel efficiency, many manufacturers have begun to introduce techniques to eliminate the vertical space between cells. By eliminating the standard 2-3 mm vertical gaps between cells, more of the total panel surface area is able to absorb sunlight and thus generate power, thus increasing the total panel efficiency. Several techniques have been developed to minimize or eliminate the space between cells, for example, the switch to the use of much smaller multi-bus bars has made it possible to reduce the space significantly;
- **Multi Busbar -** Multi ribbon and micro-wire busbars: as photovoltaic cells became more efficient, they generated more current, and in recent years most manufacturers have moved from the standard 4 or 5 bars to 9 or more multiple bars (MBBs). An additional benefit of more busbars is that if a micro-crack in the cell occurs due to shocks, heavy loads, or people walking on the panels, more busbars help reduce the possibility of the crack(s) becoming a hot spot, as they provide alternate pathways for current flow;
- **Shingled Cells** - Multiple overlapping cells: shingled cells are an emerging technology that uses overlapping thin strips that can be assembled horizontally or vertically on the panel. The slight overlap of each cell strip conceals a single distribution bar that connects the cell strips. This design covers a larger panel area, as it does not require front side connections that partially shade the cell, thus increasing panel efficiency;
- **Bifacial PV Cells -** Productivity on both sides: bifacial modules can produce energy from both sides of the module, increasing total energy production. They are often more durable because both sides are UV-resistant, and potentially induced degradation problems are reduced when the bifacial module is frameless. They are usually installed on highly reflective surfaces [13].

## 1.3. Solar Inverters

PV modules produce direct current, but most electrical appliances run on alternating current. Therefore, solar inverters are a key part of the system, as they are responsible for **DC-AC conversion**. In addition, inverters provide monitoring services so that installers and owners can observe system performance. But the role of inverters is expanding, adding more and more decision-making and control functions to the system. It is important to note that photovoltaic production requires a control system that defines the operating point of the modules - V and consequently I. These systems are called maximum power point trackers (**MPPT**) and are control algorithms that PV converters use to search for the maximum power point of a PV generator and operate it at its maximum power [13].

Some common MPPT algorithms are based on hill-climbing techniques, such as Perturbation and Observation-based methods and Incremental Conduction. These algorithms assume that the Power-Voltage curve has a single global maximum. As explained earlier, this is not true in the case of partial shading and, consequently, bypass diodes tripping. To address this condition, more complex MTTP methods, such as Particle Swarm Optimization or Genetic Algorithms, have been implemented.

These control systems are often integrated into the solar inverters. In addition, with the rapid growth of electrochemical storage systems, many solar inverters are absorbing the charger/discharger functionality, becoming responsible for battery management as well.

Solar inverters can be classified in many ways. The following categories can be considered [1]:

- **Stand-alone inverters**: they are not connected to the grid. It’s a typical solution for isolated applications, usually coupled with batteries;
- **Grid connected**: the PV plant exports all or part of the produced power to an external grid. Power variations are balanced by the grid itself;
- **Bimodal inverters**: they are on average more expensive and less common. They are the typical solution for backup systems, providing uninterrupted AC power to keep critical equipment running during a power outage. Equipped with an automatic transfer switch, the inverter/charger switches to battery power during a power outage. When AC power is restored, the battery is automatically recharged.

Another classification is possible, based on the configuration topology:

- **String inverters**: with powers ranging from a few hundred watts to a few kilowatts, these inverters are connected directly to one or more strings, depending on their number of inputs and their MPPT. String inverters are usually chosen for installations without shading problems and with panels oriented in the same direction. In fact, these inverters cannot provide module-level MPPT and monitoring. They are commonly used for residential and commercial applications;
- **Central inverters**: with powers from a few kilowatts to a hundred megawatts, these inverters are connected to the entire PV array. This configuration is feasible for large PV arrays with uniform orientation, tilt, and shading conditions. The disadvantages are the lack of shading tolerance, size and noise, DC wiring costs, and very low fault resistance since the failure of a single device results in the failure of the entire system. The main advantages are low capital price per watt, ease of design, and accessibility for maintenance and troubleshooting;
- **Microinverters**: they are typically rated around 50 to 500 W. Each module has one dedicated inverter, with its MPP tracker, connected on the back. This configuration leads to high resilience to partial shading effects, high flexibility for future expansion, minimum DC wiring costs, and module-level monitoring. On the other hand, they imply higher per watt costs and difficulty in maintenance and installation. Some brands have offered modules with integrated microinverters to provide a product that is easier to install [14];
- **Hybrid inverters**: they combine solar inverter, charger, and battery inverter together, using a software to determine the most efficient management of available energy. Usually, the hybrid inverter solution is much lower expensive than the configuration with separated solar inverter and battery charger. But they present some limitations, such as limited surge power output, with low or no backup power capability [15].

A popular alternative to microinverters are **power optimizers**. These systems, using an input control loop, perform MPPT on a per-module basis and allow performance monitoring of each module. In a process-independent manner, power optimizers enable the inverter to automatically maintain a fixed string voltage, at the best point for optimal DC-AC conversion by the inverter, regardless of string length and individual module performance [16]. They are typically less expensive than microinverters but can’t guarantee the same flexibility for future expansion.

## 1.4. Electrochemical energy storage system (ESS)

Solar systems often include **solar batteries**, which are electrochemical energy storage systems that can store overproduction from the PV plant. These components are critical for stand-alone systems to ensure electricity supply when sunlight is not available. But they can also be useful for grid-connected applications to improve self-consumption. In this case, the main constraint to the use of batteries in these types of systems is cost, as they are expensive components, so an economic assessment must be made to find the best configuration.

Solar batteries can be classified on the basis of their chemistry. The main categories are the following [17]:

- **Lead-acid batteries**: they are the oldest type of batteries. They use lead compounds on the electrodes and an acid as the electrolyte, are not very energy dense (meaning their size is usually larger) and are not intended to discharge completely;
- **Flow batteries**: instead of passing ions from one metal compound to another metal compound through an electrolyte, as in other batteries, they pass ions from one liquid reservoir to another, and then back again. These types of batteries are not particularly energy dense, but they can store large amounts of energy compared to a traditional battery. They are not particularly popular now but may become very common in the future;
- **Lithium-ion batteries**: they are the most common type of batteries and use a lithium compound for the electrodes. There are many subcategories, such as lithium-iron-phosphate, which can offer different power densities and different expected lifetimes. Lithium batteries cannot be charged or discharged under certain conditions (high/low voltages, high/low temperatures). To manage charging and discharging according to these requirements, batteries need a control system called **Battery Monitoring System** (**BMS**). Thus, another sub-categorization among these batteries can be made by considering batteries with built-in BMS and batteries with external BMS.

Another classification of solar batteries is based on their position in the system configuration. Solar panels produce DC electricity, and batteries store DC electricity. However, most electrical appliances operate on alternating current, so a DC/AC conversion is always required, and each system has a DC side and an AC side.

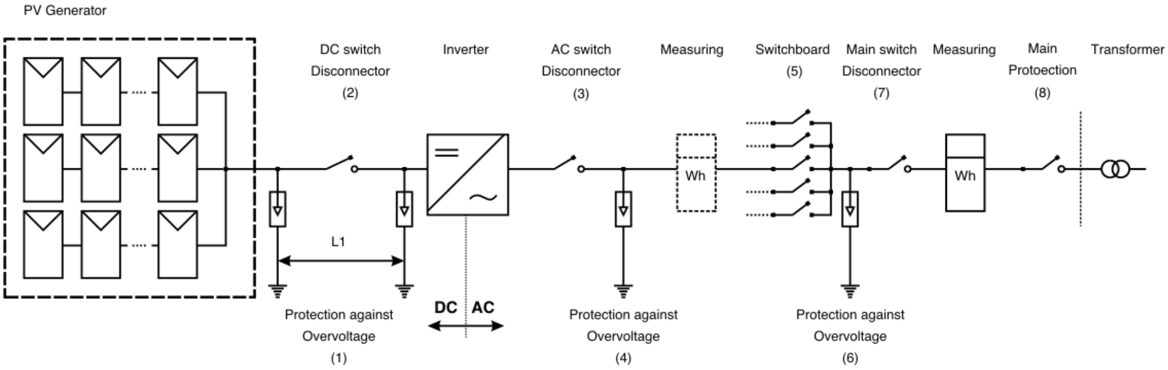


Figure 10 - Example of on-grid PV plant electric diagram

Based on the side to which the battery is connected, two categories can be identified [17]:

- **AC coupled batteries**: they are connected to the AC side of the system, so they have a built-in inverter that allows them to convert AC electricity to DC electricity, store it, and then reverse it back to AC electricity to power loads. These multiple conversions inevitably lead to power loss. However, this solution is commonly used because it allows retrofitting of existing PV systems, as batteries can be added without changing the DC side of the system;
- **DC coupled batteries**: they avoid the need for multiple conversions. These batteries are charged directly from solar panels and use a hybrid inverter that can function as both a solar inverter and a storage inverter. The only drawback is that hybrid inverters can be slightly less efficient than standard inverters in DC/AC conversion.

In the design of a photovoltaic system with ESS, other important characteristics that must be considered are the following [18]:

- **Capacity of the battery**: it is the amount of energy the battery is capable of storing and can be measured as energy [kWh] or charge [Ah]. Actual capacity can differ significantly from nominal capacity depending on the age of the battery, its charging history, charging/discharging regimes, etc.

- **Depth of discharge** (**DoD**): it is an important parameter that measures the battery's ability to discharge and, consequently, deliver energy. In fact, the maximum DOD determines the fraction of energy that can be drawn from the battery without causing serious damage to the battery itself.
- **Roundtrip efficiency**: it is a system-level metric that measures the ability of the energy storage system to convert and store electricity. It indicates the amount of energy that can be drawn from a battery for each unit of energy input.
- **Battery lifetime**: it is measured with three different indicators: expected years of operation, expected throughput and expected cycles. Throughput measures the amount of electricity, which is possible to move through the battery over its lifetime. Cycles measure how many times you can charge and discharge a battery.
- **Maximum charging current**: the bulk current is the maximum charging current of the battery, which must not be exceeded because it would cause the battery to fail. As a rule, the maximum current for lead-acid batteries cannot exceed 20% of the battery capacity and for lithium batteries 50% of the battery capacity. For instance, for a 100 Ah lead-acid battery the maximum charge current will be 20 A. So, maximum charge current is another crucial parameter in the battery system design. Manufacturers report the allowable voltages and currents, in the datasheet, manual and on the battery itself.

# 2 Design criteria for a PV system

This chapter contains the main directions for designing a photovoltaic system. The first necessary assessments are the study of loads, which will shape the size and configuration of the system, and the evaluation of resources, which will obviously focus on solar irradiance, as it will determine the annual energy production of the photovoltaic system. Once the feasibility of the design has been assessed, the selection of major components can be carried out. There are several suggestions for making a smart, efficient, and cost-effective choice of PV panels, inverters and ESSs. In addition, it is essential to check compatibility and mutual matching between components. Next, the design and sizing of the electrical system should be carried out. Standards for electrical protection and control devices and cable sizing vary from country to country. In this chapter, the UK standards, which are those applied in Zambia, are discussed in more detail. In addition, the mounting system must be selected after an executive inspection to assess the site and installation conditions. Finally, the design phase concludes with an economic analysis to check the economic feasibility of the project and the financial outlook.

## 2.1. Loads analysis

For off-grid and backup systems, the initial step of loads analysis is critical for proper system sizing. This assessment is less important or unnecessary for on-grid systems, since loads, not covered by the system's output, will always be met by grid electricity.

Loads analysis is based on a large amount of data on consumers' electricity use, in terms of energy consumption, power demand, consumption habits and timing. When all these data are not available for design, assumptions are made by considering realistic scenarios or similar cases. Then, all the information is compiled into a table listing the appliances and their power ratings, hours of operation, and functioning windows. Appliances can also be divided into different user classes to account for different usage habits.

The main objective of loads analysis is to estimate the energy consumed and plot the Load Curve. There are several methods to do so. A simple model for calculating the energy consumed uses the following formula [21]:

$$E_c = \sum_{j}^{User\ Class} N_j \left( \sum_{i}^{Appliance} n_{ij} P_{ij} h_{ij} \right) \tag{3}$$

Equation 3 - Estimation of energy consumed

The index $i$ accounts for the type of electric appliance, while $j$ accounts for the type of user class. $N_j$ is the number of users within class $j$ and $n_{ij}$ is the number of appliances $i$ within class $j$. $P_{ij}$ is the power rate of appliance $i$ within class $j$. Finally, $h_{ij}$ is the functioning duration of appliance $i$ within class $j$. The daily energy consumption $E_c$ is typically needed in intuitive sizing techniques for off-grid systems and is useful for cross-checking results for other advanced methods.

To design, the **Load Curve** is typically more important. It is the electric power required as a function of time. It is possible to plot daily, monthly, or annual Load Curves. Usually, the daily one is the most important for plant's components sizing.

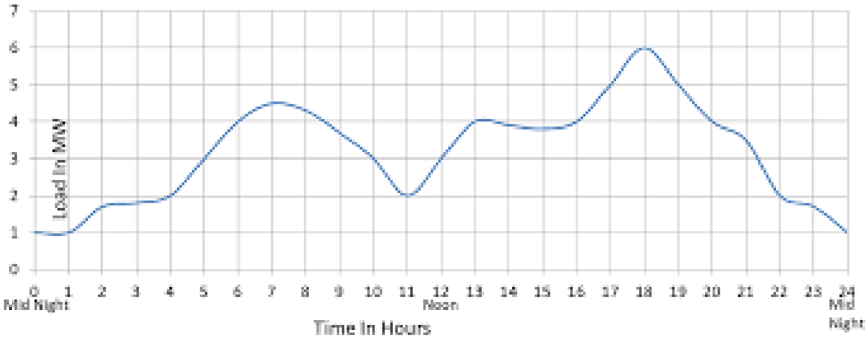


Figure 11 - Example of daily Load Curve [22]

Different approaches can be adopted to estimate it. The most common is the functioning windows approach, which is based on the definition of multiple functioning timeslots for each appliance type. The sum of all the functioning windows of an appliance type throughout the day gives the functioning duration of that appliance $h_{ij}$.

Then, the load curve is calculated as:

$$P(t) = \sum_{j}^{User\ Class} N_j \left( \sum_{i}^{Appliance} n_{ij} P_{ij}(t) \right) \tag{4}$$

where:

$$\begin{cases} t \in Fw_{ij} \rightarrow P_{ij}(t) = P_{ij} & \text{(4.1.a)} \\ t \notin Fw_{ij} \rightarrow P_{ij}(t) = 0 & \text{(4.1.b)} \end{cases}$$

Equation 4 - Functioning Windows Approach for Load Curve estimation

This approach required information about functioning moments of appliances. Moreover, if the week-weekend and seasonal variations are considered, the amount of data required becomes huge. It is important to notice that the assumption here is that all the appliances of a certain category ($n_{ij}$) are on at the same time. This is often not true. Therefore, this load curve overrates the Power Peak. This could be an acceptable issue since it allows a conservative design but can also lead to oversizing of plant's components. To deal with it, it is possible to consider a Coincidence Factor, or use more advanced and complex methods, such as stochastic methods and appliances behavior modeling.

## 2.2. Resources assessment and forecasted energy production

Another crucial step is the assessment of resources and location. Indeed, if the availability of energy resources at the chosen location is insufficient, the project could not be feasible. For off-grid power systems, this stage often includes the evaluation of different types of resources, such as wind speed, rivers presence, biomass production, and fossil fuels supply. Clearly, for photovoltaic systems, the focus of the assessment is **solar irradiation**, which is defined as the radiative energy received by a surface per a unit area during a 60 min period, measured in [Wh/m2].

Data collection on irradiation is possible through:

- International GIS (Geographic Information System) databases, such as PVGIS and IRENA global atlas;
- National GIS databases;
- Data from local meteorological or airport stations;
- Direct data collection on the field.

Through the yearly irradiation data is possible to estimate the PV system annual production and, therefore, establish the feasibility of the project.

A first calculation can be performed through the following formula:

$$E_p = AVG_{Irradiance}\,\eta_{PV}\,Area_{TOT}\,\eta_{INVERTER}\,\eta_{BOS} \tag{5}$$

Equation 5 - Annual energy produced

The $AVG_{Irradiance}$ is the average yearly irradiation on the selected location and is measured in [kWh/year/m2]. $\eta_{pV}$ accounts for the PV panels efficiency and $\eta_{INVERTER}$ for the inverter efficiency. $\eta_{BOS}$ is the Balance of System efficiency and accounts for the fouling losses, reflection losses, deviations from standard test conditions, mismatching losses, beam linear losses, and DC losses.

For off-grid systems, this value $E_p$ must be greater than the yearly load consumption. For backup system, it should be at least comparable to the priority loads consumption. Whereas for on-grid systems the evaluation is primarily economic. This is a rough assessment. To get a better and accurate view of the situation, it is necessary to compare the load curve and the production curve as a function of time.

In addition to the resource evaluation, a location assessment is also necessary. It is usually done during the preliminary inspection, which should be occur before the starting of the design. The main information needed to perform this analysis are the following:

- **Available area**: photovoltaic panels are often mounted on the roof, and consequently space is a major constraint. This strongly influences the choice of power to be installed and the panel model. If the location limits the physical size of the system, one solution might be to use more efficient but more expensive PV modules. Also, adequate space should be left around the strings to allow for maintenance operations. Finally, if the system will be installed on a roof, it is important to assess the strength of the roof and the feasibility of mounting.
- **Shading**: PV systems are strongly affected by shading, as explained above. Therefore, it is critical to evaluate distant obstacles on the horizon line and nearby shading, such as other buildings, trees, or objects on the roof itself such as chimneys. Changes in shading due to different positions of the sun over the year must also be considered. There are several specific softwares for this assessment.
- **Orientation**: in the northern hemisphere, the ideal orientation of PV systems is south, while in the southern hemisphere, it is north. If this ideal

orientation is not possible, for example because the sides of the roof face in other directions, east and finally west orientations are also fine.

- **Tilt**: the optimal tilt for maximum annual yield can be calculated as the geographic latitude minus 10-15 degrees. This means that the optimal tilt decreases approaching the equator. An increase in tilt favors summer production and penalizes winter production, and vice versa. For sloped roof applications, panels are usually installed at the roof pitch to minimize mounting expenses.

## 2.3. Choice of the main components of the plant

An important step of the design is the selection of the main components of the plant. This is often based on a technical-economic trade-off between efficiency and costs.

### 2.3.1. PV modules selection

The core component of the plant is photovoltaic field and, consequently, the PV modules. So, an accurate selection of the most suitable ones for the given application is crucial. The main factors that must be considered are [23]:

- PV module nominal efficiency;
- Temperature coefficients;
- Warranties;
- Power tolerance;
- Certifications;
- Price;
- Reliability of the manufacturer.

PV module **efficiency** is the key factor for determining the solar system output. It is possible to calculate it with the following formula:

$$\eta_{PV} = \frac{V_{MPP} I_{MPP}}{Area_{module} Irradiance_{STC}} \tag{6}$$

Equation 6 - PV module efficiency

$Irradiance_{STC}$ is the irradiance on the module surface at Standard test conditions, i.e., operating conditions with 1000 [W/m2], 25°C, 1.5 AM. AM stand for Air Mass, which is a measure that quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust [24].

Real operating conditions will differ from STC, but $\eta_{PV}$ is still a good indicator of module performances. Basically, the higher the efficiency, the less space is required to install a given power rating. Thus, this criterion is important for space-constrained applications. Otherwise, other considerations take priority.

**Temperature coefficients** have a strong impact on module performance, as will be explained later. Therefore, they must be considered in technical and economic calculations. A simple way to verify the real output potential of modules, under conditions more similar to real operating conditions than STC, is to check the power rating at NOCT conditions (defined as 800 [W/m2], 20°C, 1 [m/s] wind velocity).

There are two types of warranties. The traditional warranty is the product warranty, which protects customers from manufacturing defects that can cause the system to malfunction. It is usually a 10-year warranty but can be up to 25 years. The power warranty, on the other hand, offers more guarantees, as manufacturers ensure a certain power output of the module for a certain period. This warranty is based on the efficiency decay assured at the 25th year of operation and throughout the lifetime of the module. This type of warranty has two subcategories:

- Straight-line step-down warranty: the manufacturer guarantees 90% of the rated peak power at STC for 10 years and 80% from the 11th year to the 25th year;
- Linear warranty: it is a superior type of warranty. The manufacturer allows for a small drop in production the first year and then a linear fall in production until the 25th year.

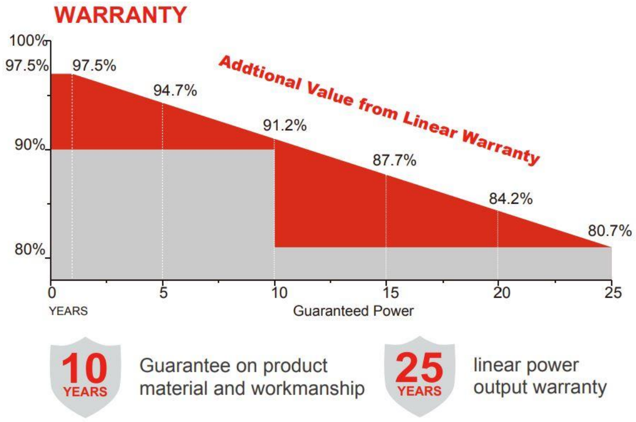


Figure 12 - Linear and step-down power warranties

Another important parameter to consider is the **power tolerance**, which is the amount of deviation from the guaranteed output. Positive power tolerances guarantees that the module will produce power greater or equal to rated. The larger is the range, the better is the quality of the module [25].

It is essential that the module has all the necessary certifications that guarantee its performance and safe operation. Clearly, these differ from country to country.

**Price** is obviously an essential factor in the module selection. It has a direct correlation with quality, so, typically, high performances panels are more expensive. It is necessary to perform a technical-economic optimization analysis to identify the better choice for each application.

Finally, it is important to assess the **reliability of the manufacturer** since PV modules have long-term warranties. This is the most difficult measure to quantify. Combined consideration of the published opinions of investment analysts, the existence of a reserve account for warranty obligations and the capitalization of that account, whether there is a third-party company supporting the warranty, and to what extent are factors to be taken into account [26].

### 2.3.2. Solar inverter selection

After module selection, the second component to be chosen is the solar inverter. The most important parameter is the power rating of the inverter, which should ensure efficient utilization of the PV array. The size of the inverter should be similar to the installed PV power. But other factors, such as geographical and location considerations, may lead to different solutions. Indeed, it must be considered that PV module performance varies significantly with irradiance and temperature. In geographic areas where the climate is temperate and solar irradiance is plentiful, the modules will operate close to rated output, and the size of the inverter should be equal to the installed field power. In areas with higher temperatures, however, the efficiency of the modules decreases, and the power output is lower than the rated power. Therefore, a smaller inverter is sufficient and preferable as it will have a lower cost. Similar considerations can be made for site-specific factors. Inclination, azimuth, shading, and fouling conditions contribute to the overall derating factor of the system, which is used to determine the power output of the solar system in a real operating scenario. Bearing this in consideration, appropriate evaluations can be made on the size of the inverter.

The parameter of the inverter size with respect to the solar field output is the array-to-inverter ratio, which is the DC rating of your solar array divided by the maximum AC output of your inverter. This value ranges typically between 1.15 to

1.25, and it is recommended to not be higher than 1.55, to avoid clipping phenomena. Clipping occurs when the solar array output is too high for the inverter to handle and, consequently, it will limit the amount of energy converted, resulting in overall power losses [27].

Once the size is defined, the factors that guide the choice among the available configurations are price, performances, such as conversion efficiency, and system flexibility, which depends strictly on the designed configuration of the PV modules.

For applications with significant shading issues, a range of different panel orientation, and generally different conditions for many sections of the plant, solutions with a high number of MPPT are required. Microinverters can be considered, as they provide a DC-AC conversion at module-level. The size of a microinverter corresponds to the energy output of the single solar panel. Another option is constituted by power optimizers, which can guarantee a MPP tracking for each module or couple of modules but would be less costly than microinverters.

Moreover, the inverter selection must carefully consider the converter's operating boundaries, that must match with the PV array features and grid requirement. The most important constraints are the following [28]:

- **DC side**:
    - Maximum DC power input: it is the maximum input power that the inverter can handle. As explained, inverters can be oversized with respect to the rated power of the module array, but this limit must be considered. Usually, for a standard inverter, this value is about 1.5 times the installed power of the field.
    - DC operating voltage range: this range represents the allowable voltages at the DC input terminals of the PV converter. The maximum value determines the limit to the number of modules connected in series, as it will be explained later. The conversion of direct current to alternating current also needs a certain minimum voltage to start. For this reason, there is also a minimum voltage value that establishes the minimum number of modules in series.
    - MPPT voltage range: this range represents the voltages at which the PV converter can operate the maximum power point tracking. It's narrower than the DC operating voltage range. It imposes a limit on the maximum allowable voltage and, therefore, on the maximum number of modules in series.

    - Maximum DC input: it is the maximum input current that the inverter can handle. Inverters with multiple inputs have an overall maximum input current and a maximum current for each input in the data sheet. This constraint dictates the maximum number of strings that can be paralleled per input and globally.
- **AC side**:
    - Maximum AC output: it is the maximum output current of the PV inverter, which is used to determine the short-circuit current contribution of the PV plant.
    - Rated and maximum AC power output: they are the nominal and maximum power converted from DC to AC by the PV converter.
    - Output voltage and frequency values: for systems connected to the public distribution grid, are imposed by the grid itself with defined tolerances. It is therefore essential to choose inverters that operate according to the grid's requirements.

### 2.3.3. Matching of PV modules' array and inverter

The PV module configuration must match the PV inverter constraints mentioned above. The voltage constraints impose limits on the number of modules in series and the current constraint imposes a limit on the number of strings in parallel. The match must be verified by considering not only the rated conditions, but also the most extreme conditions of irradiance and temperature at the selected location.

To identify these conditions, it is necessary to use some empirical equations, based on the temperature coefficients of the module. To make them clearer, the definition of STC and NOCT must be taken in mind, so they are below reported [29]:

- **Standard Test Conditions (STC)**: It is an industry standard that indicates a cell temperature of 25°C and an irradiance of 1000 W/m$^2$ with an air mass spectrum 1.5 (AM1.5);
- **Normal Operating Cell Temperature (NOCT)**: it is defined as the temperature reached by open circuited cells in a module assuming 800 W/m$^2$ irradiance, 20°C ambient temperature and wind speed of 1m/ s with the PV module at a tilt angle of 45°.

The temperature coefficients are defined as the rate of change of a parameter with respect to the change in temperature, usually measured as a percentage per degree change [%/°C]. There is current, voltage, and power temperature coefficients. The current temperature coefficient ($\alpha$) is positive, which means that a module produces the greatest amount of current at the highest temperature and irradiance. In contrast voltage and power coefficients (β and $\gamma$) are negative, meaning that the maximum voltage and power of a PV panel are experienced at the lowest temperature. This is consistent with the characteristic curves of solar cells, seen above.

The performances of a module in real operating conditions (instantaneous irradiance G and cell temperature Tc) can be found using the following formulas [15]:

$$I_{sc}(G,T_c) = I_{sc,STC} * \frac{G}{G_{STC}} * (1 + \alpha * \left(T_c - T_{c,STC}\right)) \tag{7}$$

Equation 7 - Short Circuit Current in real conditions

$$V_{OC}(T_C) = V_{OC,STC} * (1 + \beta * \left(T_c - T_{c,STC}\right)) \tag{8}$$

Equation 8 - Open Circuit Voltage in real conditions

$$P_{MPP}(G,T_c) = \frac{G}{G_{STC}} * P_{MPP,STC} * (1 + \gamma * \left(T_c - T_{c,STC}\right)) \tag{9}$$

Equation 9 - Maximum Power in real conditions

The cells temperature must be calculated as a function of the irradiance and the ambient temperature through the following formula:

$$T_c(G,T_{amb}) = T_{amb} + \frac{NOCT - T_{NOCT}}{G_{NOCT}} * G \tag{10}$$

Equation 10 - Cell temperature in real conditions

Knowing the extreme conditions of the PV array, matching with the inverter should be done by observing the conditions below, where n is the total number of panels, s the number of panels in series, and p the number of strings in series.

$$\frac{V_{inv,DC,min}}{V_{OC}\left(T_{c,max}\right)} < s < \frac{V_{inv,DC,max}}{V_{OC}\left(T_{c,min}\right)} \tag{11}$$

Equation 11 - Inverter DC operating voltage range

$$\frac{V_{inv,MPPT,min}}{V_{MPP}(T_{c,max})} < s < \frac{V_{inv,MPPT,max}}{V_{MPP}(T_{c,min})} \tag{12}$$

Equation 12 - Inverter MPPT voltage range

$$p < \frac{I_{inv,DC,max}}{I_{SC}(T_{c,max}, G_{max})} \tag{13}$$

Equation 13 - Inverter maximum DC current constraint

$$n < \frac{P_{inv,DC,max}}{P_{MPP}(T_{c,min}, G_{max})} \tag{14}$$

Equation 14 - Inverter maximum DC power constraint

This procedure should be used for each MPPT input and is suitable for inverters with integrated or external MPPT. But it is not valid for a system with power optimizers. In fact, in that case the electrical characteristics of the modules must fit the input limits of the power optimizers, and the power optimizers parallel and series connections must meet the requirements of the inverter.

Power optimizers (PO) are connected to one module for residential applications or two modules for industrial applications. In this case, the operating limits are as follows:

$$P_{MPP}(G_{STC}, T_{c,STC}) < P_{PO,nom} \tag{15}$$

Equation 15 - Power Optimizer input power limit

$$V_{OC}(T_{c,min}) < V_{PO,max} \tag{16}$$

Equation 16 - Power Optimizer maximum input voltage limit

$$I_{SC}(G_{max}, T_{c,max}) < I_{PO,max} \tag{17}$$

Equation 17 - Power Optimizer maximum input current limit

For matching power optimizers with inverters, the manufacturer usually provides in the data sheet the maximum and minimum number of series and parallel connections acceptable from the inverter.

### 2.3.4. Selection and sizing of the ESS

The energy storage system selection and sizing are strongly linked to the consumption habits. So, as much information as possible must be collected on needed energy and consumption patterns e.g., through electricity bills.

The main logic behind battery sizing for on-grid system is to have a battery capacity equal to the minimum between PV overproduction and cumulative load demand not instantaneously met by the PV plant. The main rationale of battery sizing for on-grid systems (and backup system) is to have a battery capacity equal to the minimum between the PV overproduction and the cumulative load demand not met instantaneously by the PV system in a given time slot (typically one day).

$$Battery\ Size\ [kWh] = \min\left( E_{overproduction}; E_{unmet\ load}\right)_{daily} \tag{18}$$

Equation 18 - Battery Size Calculation for on-grid systems

Clearly, for off-grid the reasoning is different. A rough formula to compute the battery capacity need is the following [30]:

$$Battery\ Capacity\ [Ah] = \frac{Consumption_{appliances}\left[\frac{Wh}{day}\right] * Days\ of\ Autonomy}{DOD * \left(1-\eta_{battery}\right) * V_{nom,battery}} \tag{19}$$

Equation 19 - Battery Capacity calculation for backup systems

This capacity can guarantee the meeting of the loads for the given period of autonomy.

A more precise calculation should be performed through weekly, monthly, or yearly simulations, in order to have a better optimization of the battery capacity.

In cases where the building is not yet inhabited, consumption data are not available. So, a solution could be to use consumption profiles from similar applications or try to build the future consumption curve by making a list of electronic appliances and their forecasted consumption times with the customer.

However, the capacity of batteries is not the only parameter that must be taken into account in the choice of the storage system. Other important factors are the Depth of Discharge (DOD), the roundtrip efficiency, and the battery lifetime [31].

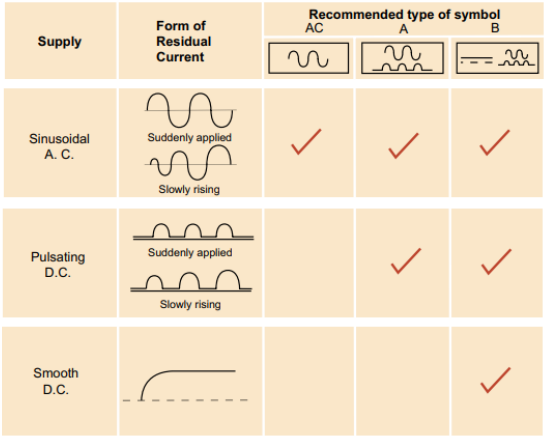
## 2.4. Design and sizing of the electrical system

The PV system also consists of a number of protection and monitoring devices, which ensure safe operating conditions and measure the energy flows.

Different countries refer to different electrical system standards for connection to the main grid. The standard for Zambia is the British standard (Engineering Recommendation G83-G59). The connection is governed by **Engineering Recommendation G59/2-1** if the generator generates more than 16A per phase (3.68 kW per phase). For system less than 16A per phase, **Engineering Recommendation G83/2** applies. It is easier to connect systems of less than 16A power to the national grid because less paperwork is required and the acceptance procedure by the Distribution Network Operator (DNO) is simpler. Moreover, an additional protection device is mandatory for the bigger plants, as it will explained later.

The standards mandate the following protection and switch devices, and cable requirements [32]. For AC side:

- **Residual-current circuit breaker (RCCB)**: where an electrical system includes a PV power system that is unable to prevent DC fault currents from entering the AC side of the system, and where an RCD (Residual-current device) is required to meet the general requirements of the electrical system in accordance with BS 7671, the RCD selected should be a Type B RCCB. If there is any doubt about the ability of the inverter to prevent DC fault currents from entering the AC side of the system, the manufacturer should be consulted. RCDs are classified according to their response to signals as picture in Figure 13 - RCD categorization.



| Supply | Form of Residual Current | Recommended type of symbol<br>AC | <br>A | <br>B |
|---|---|---|---|---|
| Sinusoidal A. C. | Suddenly applied<br>Slowly rising | ✓ | ✓ | ✓ |
| Pulsating D.C. | Suddenly applied<br>Slowly rising | | ✓ | ✓ |
| Smooth D.C. | | | | ✓ |

Figure 13 - RCD categorization

- **Main AC Insulator:** the PV system must be connected to an insulation switch that isolates line and neutral conductors, is securable in off position, and is in an accessible location. This switch shall be located adjacent to the inverter, to disconnect the inverter form the source of supply. For a single-phase inverter, an unswitched fuse connection unit mounted next to the inverter can be used. However, it is suggested that, for routine maintenance purposes, a connection unit with switched fuses offers a better degree of control and therefore should be preferred.
- **Inverter Production Meter**: it is necessary to install a meter at the output of the inverter to display/record the energy delivered by the PV system (kWh). In addition, it is highly recommended to display the instantaneous power delivered (kW). An approved kWh meter, connected to measure generation, will be necessary to facilitate the payment of any financial incentives (e.g., Feed in Tariff payments). The meter must be placed in a location where the consumer can observe it.
- **Building Export Meter**: if necessary to allow payment for exported electricity, an approved meter, for export kWh reading, may be required. It is necessary to contact the energy supplier to find out the requirements and arrange for its installation.
- **G59 Mains Protection Relay**: this protection device sits between the embedded generator and the grid. It monitors the quality and stability of the power grid. If the grid supply fluctuates outside any of the preset operating parameters, the relay causes a protective device such as an MCCB or other type of locally installed switch to open and disconnect the PV system from the grid. The G59/2-1 standard establishes the settings to which the relay must be programmed, but each DNO may have additional requirements covering voltage, frequency, rate of change, and phase angles. This system serves to prevent "isolation," in which the solar system (built-in generator) continues to generate and supply power to the local power grid. This situation can be dangerous for technicians working nearby and can prevent reconnection of local devices when the power grid stabilizes or is restored. However, "intentional isolation" in which the embedded generator continues to operate as a backup power system may be allowed in some circumstances. It needs a specific agreement with the DNO and an inverter suitable for the backup function [33].
- **Cables**: the AC cable connecting the inverter to the consumer unit should be sized to minimize voltage drop, which should possibly not exceed 1%

drop. However, in larger installations this may not be feasible or economical due to the very large size of the resulting cable. In this case, the designer should minimize the voltage drop as much as possible and stay within the voltage drop limits of BS 7671.

For the DC side, all components' ratings must be derived from the maximum voltage and current of the relative part of the PV array adjusted in accordance with certain safety factors. For mono- and multi-crystalline silicon modules, it must be considered as a minimum:

- Voltage: $V_{OC\_STC} * 1.5$ ;
- Current: $I_{SC\ STC} * 1.25$ .

For all the other module types it must be considered:

- Specific calculations of the worst case $V_{OC}$ and $I_{SC}$, calculated from manufacturer's data for a temperature range of -15°C to 80°C and irradiance up to 1250 $\frac{W}{m^2}$;
- A calculation of any increase I n $V_{OC}$ and $I_{SC}$ over the initial period of operation. This increase is to be applied in addition to that calculated above.

The recommended devices for DC side are the following ones:

- **Overcurrent Protection**: in systems with multiple strings some fault scenarios can result in the current from several adjacent strings flowing through a single string, so that overcurrent protective devices are required. Hence, the selection of overcurrent protective measures depends upon the system design and the number of strings. The use of MCBs (Miniature Circuit Breakers) is allowed if they meet the criteria of string fuses, are intended for use in an inductive circuit, and operate for currents flowing in both directions through the device. A system equipped with removable string fuses also meets string isolation requirements;
- **Isolation Switches**: it is mandatory a readily accessible load break switch disconnector on DC side of the inverter. Moreover, it is mandatory a readily accessible means of strings and sub-array isolation. Switching for string and sub-array are optional;
- **Overvoltage Protection**: Surge Protective Devices (SPDs) are usually installed to provide lightning protection.

It is always desirable to keep voltages low to minimize the associated risks. However, in many systems, the DC voltage will be very high. In this case, the method of protection against shock is usually **double insulation**. Moreover, the use of properly sized cables, connectors and enclosures and controlled installation techniques becomes essential in providing the adequate protection. In addition, double insulation of the DC circuit minimizes the risk of creating accidental shock current paths and the risk of fire.

Cables should be sized so that the overall voltage drop, at the array's maximum operating power (STC), between the array and the inverter is < 3%. The strong attention to cable voltage drop is justified because it has many disadvantages and risks for the system.

This is a list of the negative effects of a high voltage drop [31]:

- Energy is lost and, therefore, the system is less efficient. Batteries will be discharged quicker;
- The system current will increase. High system currents can lead to premature inverter overloads;
- Voltage drop during charging will cause batteries to be undercharged;
- The inverter receives a lower battery voltage. This can potentially trigger low voltage alarms;
- The battery cables heat up. This can cause melting wiring insulation or cause damage to cable conduits or contented equipment. In extreme cases cable heating can cause fire;
- All devices connected to the system have a shorter lifetime because of DC ripple.

Main design precautions to prevent voltage drops are:

- Keep cables as short as possible (Maximum battery cable lengths are typically specified in the installer's manual);
- Use cables with sufficient cable thickness;
- Make tight connections (following recommendations in the manual);
- Check that all contacts are clean and not corroded;
- Use quality cable lugs and crimp these with the appropriate tool;
- Use quality battery isolator switches;
- Reduce the amount of connections within a cable run;
- Use DC distribution point or busbars;
- Follow wiring legislation.

All these information must be kept in mind during the cables sizing. It is based on two fundamental principles:

1. Cable capacity $I_z$ must be higher than the operating current $I_b$of the system;
2. The voltage drop across the cable terminals must respect the imposed limits.

In addition, the cables must have a rated voltage suitable for the system. In DC, the system voltage must not exceed 50% of the nominal voltage of the cables which refers to their use in AC [28].

The actual cable sizing is done accordingly to the Appendix 4 of BS 7671. The considered parameters for the sizing are [34]:

- $I_z$, which is the current-carrying capacity of a cable for continuous service;
- $I_t$, which is the value of current tabulated in the appendix for the type of cable and installation method concerned, for a single circuit in the ambient temperature stated in the current-carrying capacity tables;
- $I_b$, which is the design current of the circuit, i.e. the current intended to be carried by the circuit in normal service;
- $I_n$, which is the rated current or current setting of the protective device;
- $I_2$, which is the operating current (i.e. the fusing current or tripping current for the conventional operating time) of the device protecting the circuit against overload.

The appendix provides some the following rating factors:

- $C_a$, factor for ambient temperature;
- $C_g$, factor for grouping;
- $C_i$, factor for thermal insulation;
- $C_t$, factor for operating temperature of conductor;
- $C_c$, factor for the type of protective device or installation condition.

The rated current or current setting of the protective device ($I_n$) must not be less than the design current ($I_b$) of the circuit, and the rated current or current setting of the protective device (In) must not exceed the lowest of the current carrying capacity ($I_z$,) of any of the conductors in the circuit. When the overcurrent device is intended to provide overload protection, $I_2$ must not exceed $1.45 * I_z$ and $I_n$ must not be greater than $I_z$. When the overcurrent device is intended to provide fault current protection $I_n$ may be greater than $I_z$ and $I_2$ may be greater than $1.45 * I_z$.

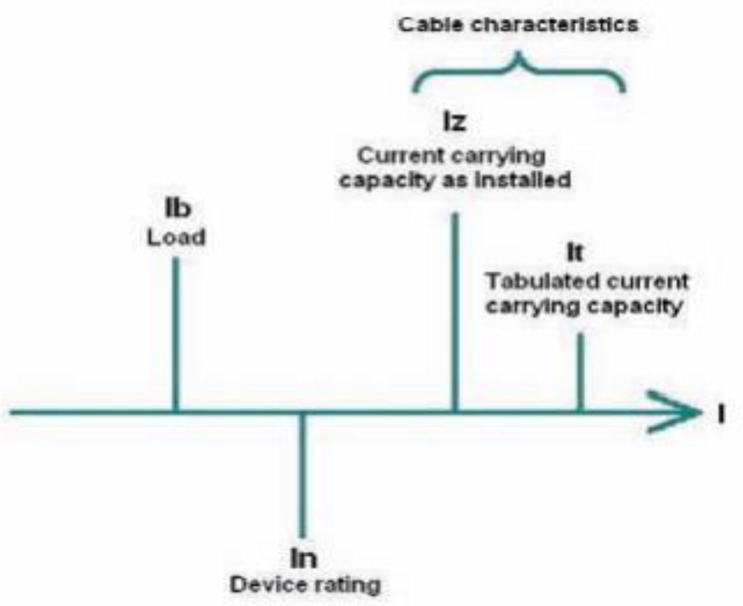


Figure 14 - Coordination of load, device, and cable characteristics

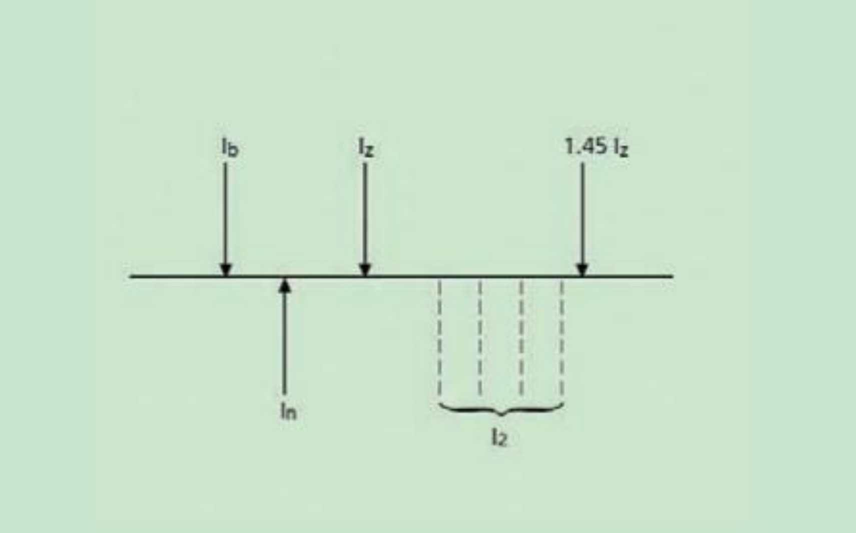


Figure 15 - Coordination for overload protection

To find the cable cross-section, it is necessary to calculate the $I_t$ since $I_z = I_t C_a C_g C_i C_c$ and $I_z \geq I_n$, by combining them, the formula is:

$$I_t \geq \frac{I_n}{C_a C_g C_i C_c} \tag{20}$$

Equation 20 - Calculation of the tabulated current

The cable cross-section is tabulated according to the values of $I_t$ and the type of cable. For example, for an insulated, PVC-coated flat cable with shielding, installed in an insulated wall, a 6 mm2 cable is adequate as it has a tabulated value rating of 32 A for installation method A. Then, the cable sizing must include the computation of the voltage drop, through the following equation:

- For the DC side:

$$\Delta V_{\%} = R_{cable} * \frac{I}{V} \tag{21}$$

Equation 21 - Voltage drop for DC cables

The cables resistance can be calculated considering the cross-section $A$, the line length $l$, and the copper resistivity $\rho_{Cu}$:

$$R_{cable} = \rho_{Cu}(T_{cable}) * \frac{2l}{A} \tag{22}$$

Equation 22 - Resistance of an electric cable

- For the AC side:

$$\Delta V_{\%} =* I * l * \frac{r_l * cos\varphi +* sin\varphi}{V} \tag{23}$$

Equation 23 - Voltage drop on an AC cable

$k$ is a parameter which is equal to 2 for monophasic system and 1.73 for triphasic system, $r_l$ and $x_l$ are the specific resistance and reactance of the line and $cos\varphi$ is the power factor. Values of resistance and reactance ($\Omega/km$) are tabulated as function of the cable section.

Finally, the following figures show examples of mono- and three-phase systems layouts [32].

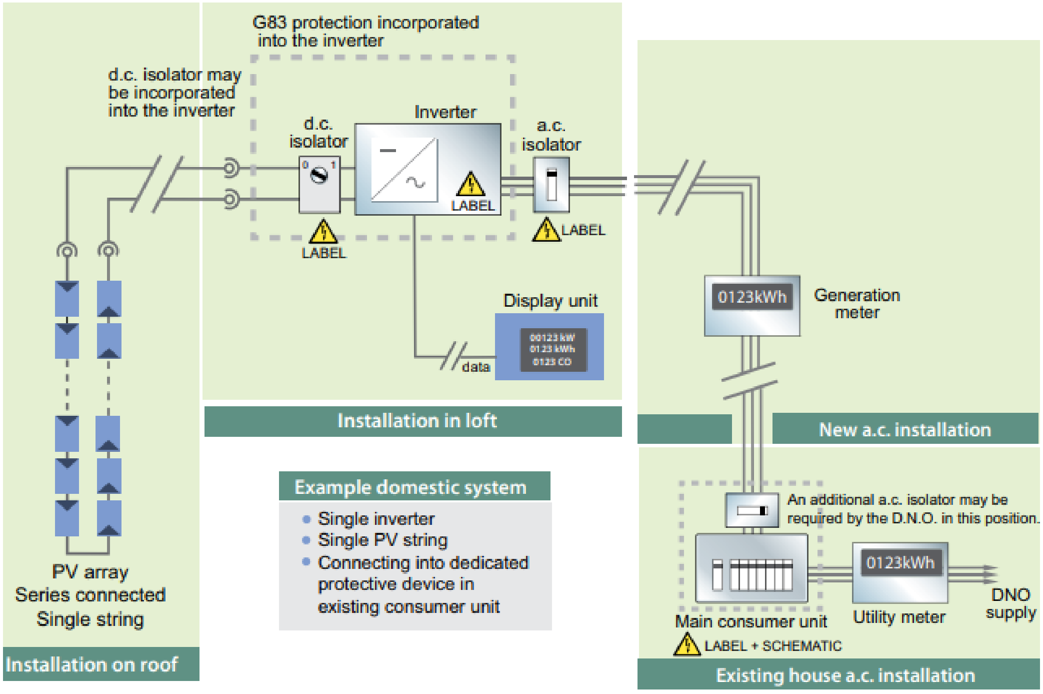


Figure 16 - Example of monophase system layout

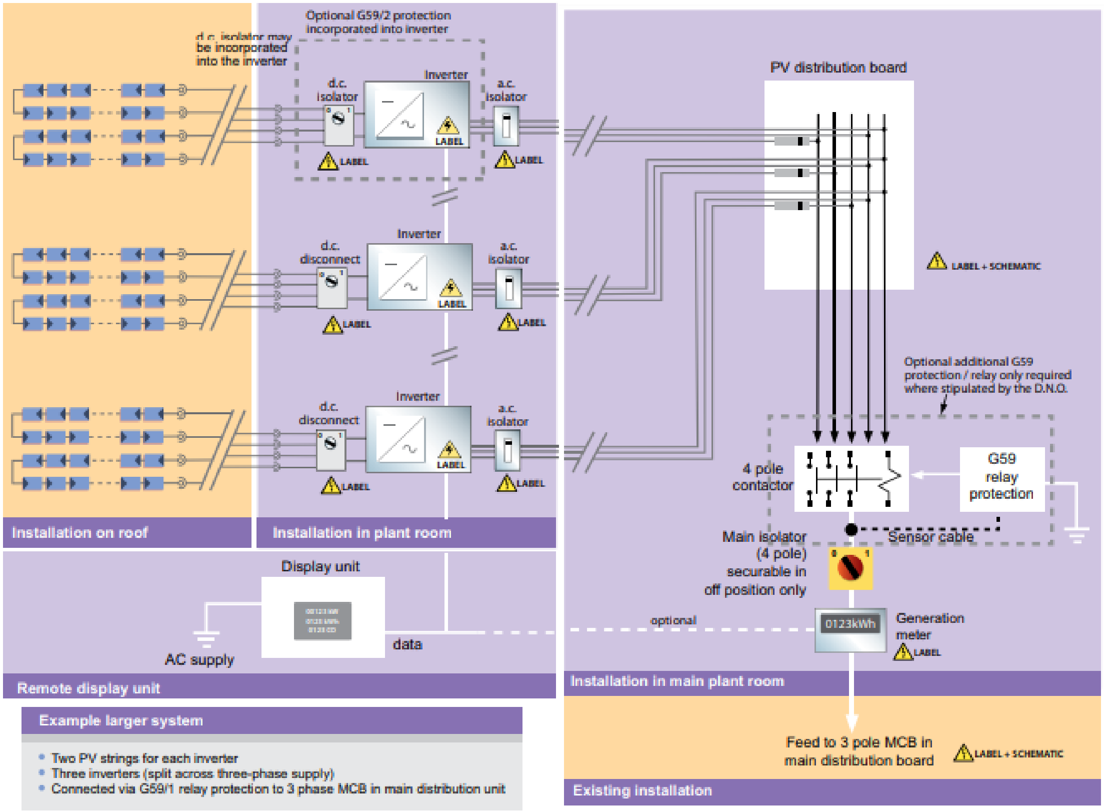


Figure 17 - Example of three phase system layouts

## 2.5. Selection of the mounting system

The roof structure must be checked to ensure that it can withstand the imposed loads. This includes an on-site inspection by a suitably competent person. If the roof shows abnormalities, such as signs of structural distress or signs of post-construction modifications, a qualified structural engineer should be consulted.

Then, the choice of the mounting system depends on many variables. The main ones are the geographical location, which will determine the likelihood of wind and snow presence, the configuration of the PV array, the material and shape of the roof, the height of the installation, which will proportionally determine the average wind speed, and the presence of other obstacles, that can act as a wind shield. Therefore, the most suitable mounting system must be identified specifically for each application. Moreover, it is important that the manufacturer will provide a certificate of resistance to wind and, eventually, snow loads for the selected structure.

For roof-mounted PV systems, the most common mounting structures are of two types [35]:

- **Roof Mount without roof penetration**: the most common rack solution for PV systems installed on flat roofs is the ballasted roof mounting. It uses the weight of concrete or sand to ensure that the system resists all kinds of external forces, such as wind tensile forces. The main advantages are the low material costs, the better arrangement of the panels in the available space, and the fact that no roof penetration is needed. The possible need for a structural engineer and the reinforcement of the roof because of the additional weight are the main disadvantages.
- **Roof Mount with roof penetration**: photovoltaic panels can be attached to pitched roofs through special metal frames that allow partial or full integration to the roof itself. These supports offer a high degree of safety against snow and wind loads and high resistance to weather corrosion. The main advantages are low material costs, utilization of unused space, and safe access only for authorized persons. The main concerns for this solution are the need for a professional installer, poor ventilation of the modules, fixed tilt and orientation, and the possible presence of pull-out forces. In addition, it is critical to carefully consider the age of the roof and all precautions to avoid fire problems.

## 2.6. Economic analysis

An essential part of system design is economic analysis, which ensures the **economic feasibility** of the project.

The base of the economic analysis is the computation of the PV plant annual electricity production, which can be assessed through a simulation on hourly base or, as a rough calculation, by the following formula:

$$AEP\left[\frac{MWh}{y}\right] = G_{mod}\left[\frac{kWh}{m^2}\right] * A_{modules}[m^2] * \eta_{PV}\eta_{INV}\eta_{BOS} \tag{24}$$

Equation 24 - Annual Energy Production Equation

Known the Annual Energy Production of the plant, to perform the economic analysis it is necessary to assess [36]:

- **Capital Expenditure (CAPEX)**: it refers to funds that are used by an investor for the purchase, improvement, or maintenance of long-term assets, which are usually physical, fixed and non-consumable assets such as property, equipment, or infrastructure. For PV plant a rough calculation of CAPEX can be done through the following formula:

$$CAPEX = \frac{P_{nom,PV} * (c_{mod} + c_{inv}) + C_{batt}}{1 - c_{supp,wir} - c_{inst} - c_{eng,ind} - c_{conn}} \tag{25}$$

Equation 25 - CAPEX calculation

$c_{mod}$ is module cost (\$/Wp), $c_{inv}$ is the inverters cost (\$/Wp), and $C_{batt}$ is the investment cost of batteries. While $c_{supp,wir}$ is the support system and wiring cost, $c_{inst}$ is the installation cost, $c_{eng,ind}$ is the engineering and indirect cost, and $c_{conn}$ is the grid connection cost (% of CAPEX).

- **Operating Expenditure (OPEX)**: an operating expense is an expense a business incurs through its normal business operations. For a PV plant it can calculated as:

$$OPEX\left[\frac{\$}{year}\right] = CAPEX * (c_{O\&M} + c_{ins}) \tag{26}$$

Equation 26 - OPEX calculation

$c_{O\&M}$ is the operation and maintenance annual cost and $c_{ins}$ is the insurance annual cost as percentage of CAPEX.

- **Savings**: for a residential or industrial PV system, excess production is sold, but the main objective of non-utility scale systems is to maximize self-consumption. Therefore, savings are regarded as positive income. They are computed as follows:

$$S_i \left[\frac{\$}{year}\right] = AEP_0 * \delta_{PV} * i * SC_{\%,i} * C_{ee,i} + AEP_0 * \delta_{PV} * i * \left(1 - SC_{\%,i}\right) * P_{ee,i} + C_{inc} \tag{27}$$

Equation 27 - Yearly savings for a PV plant

The indicator $i$ shows the considered year from the plant installation. $\delta_{PV}$ is the linear yearly decay factor of PV panels, $SC_{\%,i}$ is the self-consumption percentage of the overall production, $C_{ee,i}$ is the cost of electricity for the selected consumer, $P_{ee,i}$ is the selling price of electricity of the selected plant, and $C_{inc}$ is the annual income from any incentives.

If the hourly consumption profile of the building is available, the information from the production forecast can be used to simulate the operation of the entire system, achieving much more accurate results.

Then, the economic parameters that ca be calculated are [36]:

- **Total Specific Plant Cost**:

$$TSPC \left[\frac{\$}{kWp}\right] = \frac{CAPEX}{P_{nom,imp}} \tag{28}$$

Equation 28 - TSPC equation

- **Net Present Value (NPV):**

$$NPV \left[\frac{\$}{year}\right] = \sum_{i=1}^{N}(S_i - CAPEX_i - OPEX_i) * \frac{(1+j)^i}{(1+d)^i} \tag{29}$$

Equation 29 - NPV equation

$j$ is the inflation rate and $d$ is the discount rate (%).

- **Pay Back Time (PBT)**: it is the number of year N after which the NPV is greater than zero.
- **Internal Rate of Return (IRR)**: it is the discount rate that makes null the NPV.
- **Levelized Cost of Electricity (LCOE)**:

$$LCOE\left[\frac{\$}{kWh}\right]=\frac{CAPEX+OPEX_0}{AEP_0}+\sum_{i=1}^{N}\frac{OPEX_i*\frac{(1+j)^i}{(1+d)^i}}{AEP_0*(1-\delta_{PV})^i*\frac{(1+j)^i}{(1+d)^i}} \quad (30)$$

Equation 30 - LCOE equation

# 3 Case study

This chapter will present the selected case study to which most of the design criteria were applied. The framework of the project is a proposal in response to a request from donors, by the EQUA company, the technical partner, and Professor Diappi, the project leader, for the installation of a photovoltaic system on a nonprofit guesthouse.

## 3.1. Project description

*Olga's —The Italian Corner* is a restaurant with a guesthouse, located in Livingstone.

It is a social enterprise; indeed, it is the final stage of an educational project for vulnerable youth of Livingstone's poorest neighborhoods. All Olga's profits from the restaurant and the guesthouse go to finance the activities of the Youth Community Training Centre (YCTC), a certified vocational training center, offering free training to youth orphans of HIV/AIDS.

The business, like all others in Zambia, is heavily impacted by frequent power outages, which are a significant and widespread problem with the country's national grid. The unreliability of the electricity supply led to the purchase of a diesel generator, set to cope with the outages. This type of electricity generation is highly inefficient and, therefore, quite expensive. As a result, the cost of power outages for Olga's is quite high. In addition, it is likely that ZESCO, the Zambian TSO, will increase electricity rates in the coming years, as the national power generation and grid systems need large investments and will require more maintenance work.

So, the aim of the project is to increase the Olga's degree of independence from the national grid, to:

- be less affected by power outages;
- lower electricity costs.

The proposed solution to meet these requirements consists of a photovoltaic system, coupled with a battery pack. The system would consist of a rooftop PV array, MPPTs, solar inverters, and an electronic system to intelligently manage the charging and discharging of the batteries. All the components can be purchased locally in Livingstone or in Lusaka.

The peak power of the PV panel array will be at least 23 kWp—this is considering 335 W PV panels, which are quite common in Zambia. The suggested battery pack size is 28 kWh to maximize self-consumption in ordinary operation and ensure coverage of priority loads in case of power outages.
With this configuration, *daily load coverage* is expected to be approximately *80% during the peak season* —April through October — and approximately *65% during the off-peak season* — November through March. It will also ensure that *priority loads are met for 13 hours during power outages*, which is a key feature of the system.
This configuration will save Olga's approximately $7.200 each year. The remaining energy purchased from ZESCO will represent an annual cost of approximately $1.600.
Several components can be used to create the configuration. EQUA company has provided a basic proposal for the PV system and two different battery options, based on quotes from local suppliers. The selected options are the following.

| OPTION A | OPTION B |
|---|---|
| Victron inverter and 28 kWh batteries<br>2-years warranty | Victron inverter and 28.8 kWh Pylontech batteries<br>10-years warranty |

Table 1 – Batteries Options

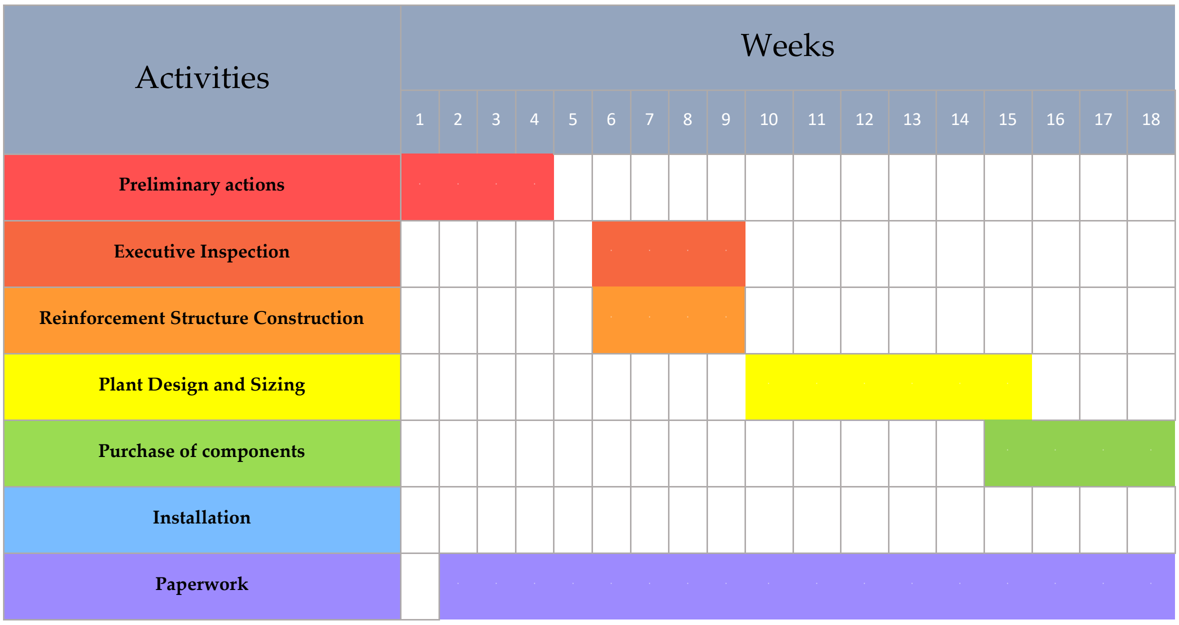
Cost perspectives are provided below.

| | OPTION A | OPTION B |
|---|---|---|
| **PV system and installation** | $ 37.850 | $ 37.850 |
| **Batteries and installation** | $ 26.500 | $ 15.900 |

| | | |
|---|---|---|
| **Structure strengthening** | $ 60.000 | $ 60.000 |
| **Travels expenditures** | $ 26.100 | $ 26.100 |
| **TOT** | $ 150.450 | $ 139.850 |

Table 2 – Costs summarized

The whole project will take approximately 35 weeks from the contract signing. The timeline is summarized below.



| Activities | Weeks | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| **Preliminary actions** | 🟥 | 🟥 | 🟥 | 🟥 | | | | | | | | | | | | | | |
| **Executive Inspection** | | | | | | 🟧 | 🟧 | 🟧 | 🟧 | | | | | | | | | |
| **Reinforcement Structure Construction** | | | | | | 🟧 | 🟧 | 🟧 | 🟧 | | | | | | | | | |
| **Plant Design and Sizing** | | | | | | | | | | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | |
| **Purchase of components** | | | | | | | | | | | | | | | 🟩 | 🟩 | 🟩 | 🟩 |
| **Installation** | | | | | | | | | | | | | | | | | | |
| **Paperwork** | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 |

Table 3 – Calendar of activities summary part 1

| Activities | Weeks | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
| **Preliminary actions** | | | | | | | | | | | | | | | | | |
| **Executive Inspection** | | | | | | | | | | | | | | | | | |
| **Reinforcement Structure Construction** | | | | | | | | | | | | | | | | | |
| **Plant Design and Sizing** | | | | | | | | | | | | | | | | | |
| **Purchase of components** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | |
| **Installation** | | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | |
| **Paperwork** | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 |

Table 4 - Calendar of activities summary part 2

## 3.2. Loads analysis

The demand load profile represents realistic and logical disaggregated energy consumption patterns for the Olga's hotel and restaurant.

*Appliance power parameters* are required for load simulation. These parameters include device configuration definitions (number and time of use) and device power specifications. Olga's provided us with a list of the electric devices and their power consumption.

| **LOADS** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Devices** | Place | Num. | Power (W) | TOT Power | Volt. (V) | Curr. (A) | Consump time (hrs) | Ah | Energy (kWh/day) |
| **UPRIGHT FRIDGE** | KITCHEN | 3 | 375 | 1125 | 240 | 4,69 | 8 | 37,5 | 9,0 |
| **MNI FIDGES** | ROOMS | 5 | 67 | 335 | 240 | 0,50 | 8 | 4,0 | 2,7 |
| **GYSERS (boilers)** | ROOMS | 9 | 1500 | 13500 | 240 | 12,50 | 6 | 75,0 | 81,0 |
| **KITCHEN BOILER** | KITCHEN | 1 | 2000 | 2000 | 240 | 12,50 | 6 | 75,0 | 12,0 |
| **STOVE** | KITCHEN | 1 | 9,6 | 9,6 | 240 | 40,00 | 18 | 720 | 0,2 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **DEEP FREEZER** | LOUNGE | 3 | 350 | 1050 | 240 | 4,38 | 8 | 35,0 | 8,4 |
| **TELEVISION 1** | LOUNGE | 1 | 37 | 37 | 240 | 0,15 | 12 | 1,85 | 0,4 |
| **TELEVISION 2** | DINING | 1 | 40 | 40 | 240 | 0,17 | 12 | 2,0 | 0,5 |
| **TELEVISION 3** | DINING | 1 | 29 | 29 | 240 | 0,12 | 12 | 1,45 | 0,3 |
| **TELEVISIONS** | ROOMS | 5 | 40 | 200 | 240 | 0,83 | 12 | 10,0 | 2,4 |
| **LIGHTS** | TOILET | 3 | 8 | 24 | 12 | 2,00 | 6 | 12,0 | 0,1 |
| **LIGHTS** | KITCHEN | 2 | 8 | 16 | 12 | 1,33 | 6 | 8,0 | 0,1 |
| **LIGHTS** | PASSAGE | 2 | 8 | 16 | 12 | 1,33 | 6 | 8,0 | 0,1 |
| **LIGHTS** | LOUNGE | 3 | 8 | 24 | 12 | 2,00 | 6 | 12,0 | 0,1 |
| **LIGHTS** | OFFICE | 2 | 8 | 16 | 12 | 1,33 | 6 | 8,0 | 0,1 |
| **LIGHTS** | SECURITY | 8 | 10 | 80 | 14 | 5,71 | 14 | 80,0 | 1,1 |
| **COMPUTER** | OFFICE | 1 | 80 | 80 | 240 | 0,33 | 10 | 3,33 | 0,8 |
| **LAPTOP** | OFFICE | 2 | 40 | 80 | 240 | 0,33 | 10 | 3,33 | 0,8 |
| **DECODER** | LOUNGE | 1 | 72 | 72 | 240 | 0,30 | 24 | 7,20 | 1,7 |
| **WIFI** | OFFICE | 1 | 55 | 55 | 240 | 0,23 | 24 | 5,50 | 1,3 |
| **PHONE CHARGING** | LOUNGE | 1 | 10 | 10 | 240 | 0,04 | 6 | 0,25 | 0,1 |
| **CONTINGENCY** | UNKNOWN | 1 | 100 | 100 | 240 | 0,42 | 10 | 4,17 | 1,0 |

Table 5 – Building Loads

Among these devices, we identified the priority loads which must be necessarily covered in case of blackout.

The following table of appliances has been considered as priority loads reference for the rest of the study:

| **PRIORITY LOADS** | | | | | |
|---|---|---|---|---|---|
| **Devices** | Location | N | Power (W) | TOT Power (W) | Energy [kWh/day] |
| **UPRIGHT FRIDGE** | KITCHEN | 3 | 375 | 1125 | 9,0 |
| **MINI FRIDGES** | ROOMS | 5 | 67 | 335 | 2,7 |
| **STOVE** | KITCHEN | 1 | 9,6 | 9,6 | 0,1 |
| **DEEP FREEZER** | LOUNGE | 3 | 350 | 1050 | 8,4 |
| **LIGHTS** | TOILET | 1 | 37 | 37 | 0,4 |
| **LIGHTS** | KITCHEN | 1 | 40 | 40 | 0,5 |
| **LIGHTS** | PASSAGE | 1 | 29 | 29 | 0,3 |
| **LIGHTS** | LOUNGE | 5 | 40 | 200 | 2,4 |
| **LIGHTS** | OFFICE | 3 | 8 | 24 | 0,1 |
| **LIGHTS** | SECURITY | 2 | 8 | 16 | 0,1 |
| **CONTINGENCY** | UNKNOWN | 2 | 8 | 16 | 0,1 |

Table 6- Priority Loads Table

Another input parameter for the load simulation model is the **appliance use behavior pattern**. This parameter defines when and how much energy each appliance draws from the grid as a digitized time-series.

The hotel has 9 rooms, and its guests are usually tourists and businessmen. To get appliance use behavior pattern, reasonable assumptions was made about the electrical devices' utilization times, considering the two user types. Moreover, we considered two different patterns for peak season (April-October) and off-peak season (November-March). The **occupancy rate** for the off-peak season has been considered at 55% and for the peak season at 100%, in order to be conservative. These considerations led to the following typical days for the two seasons:

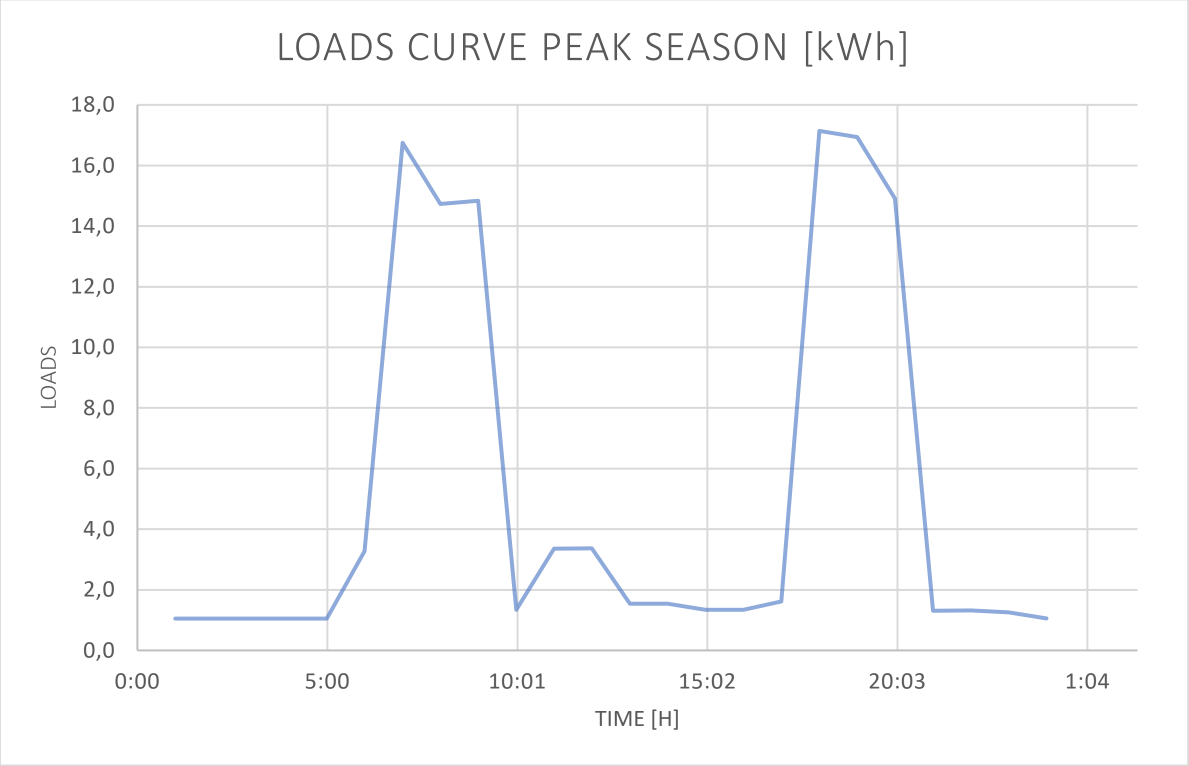


Figure 18 – Peak Season Load Profile

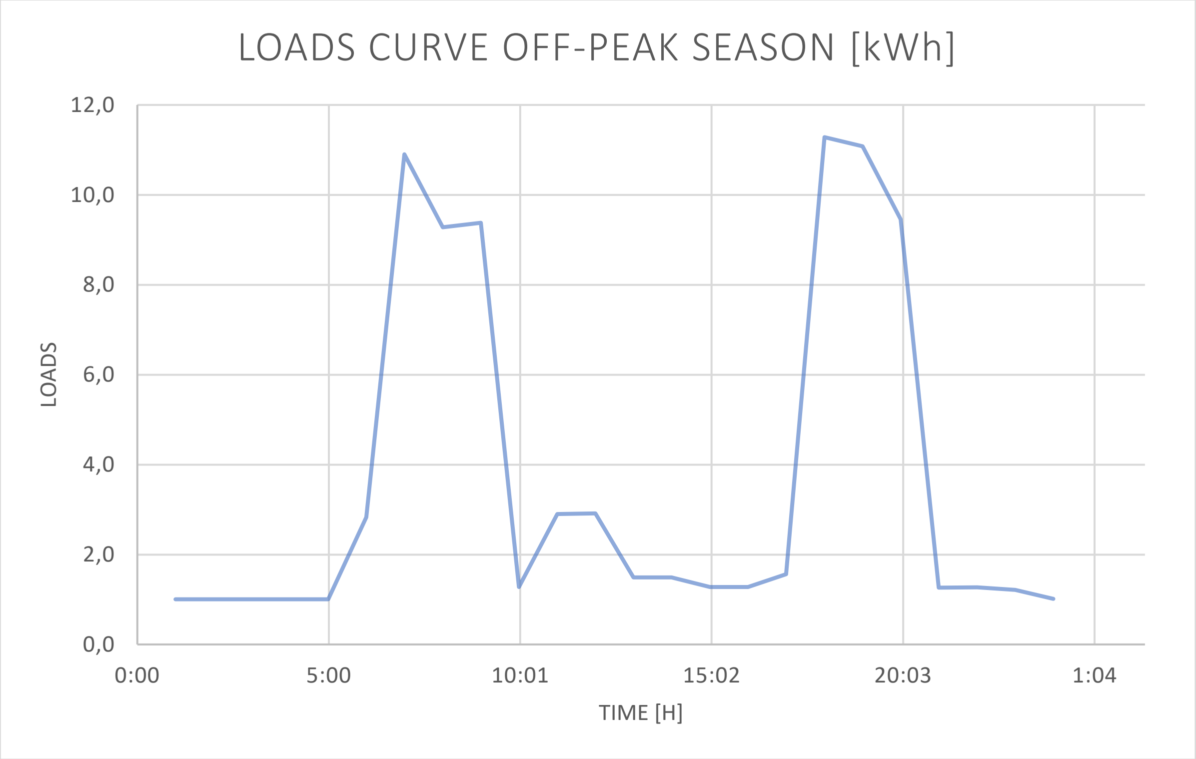


Figure 19 – Off-Peak Season Loads Profile

Following the same assumptions, also the priority loads profile has been plotted:

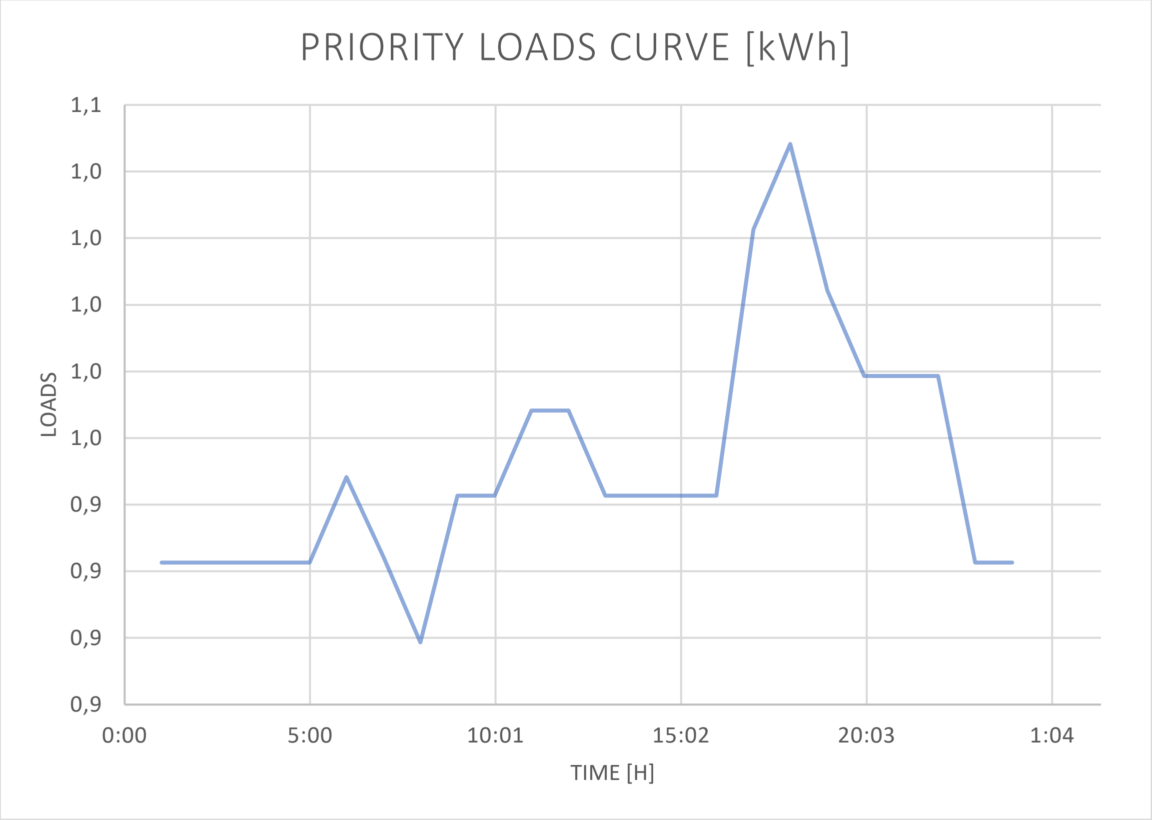


Figure 20 – Priority Loads Profile

These profiles have been utilized to run the simulations of the different PV system configurations.

The above explained formula for estimating energy consumed was considered:

$$E_c = \sum_{j}^{User\ Class} N_j \,( \sum_{i}^{Appliance} n_{ij} P_{ij} h_{ij}) \tag{31}$$

Equation 31 - Estimation of energy consumed

The results are a daily energy consumption of **124 kWh** in the high season and **88 kWh** in the low season. This leads to an estimated annual energy consumption of about 38300 kWh. Considering power outages, the amount of energy purchased from the main grid should range from 28700 to 38300 kWh. Through the ZESCO website, it was possible to verify the actual energy purchased by Olga's in 2021, which was about 32000 kWh, confirming the validity of the calculations.

## 3.3. Resources assessment

Livingstone is the capital of the Southern Region of Zambia. The region has a hot semi-arid climate with heavy rainfalls in the rain seasons and very hot dry seasons. Moreover, large temperature differences are recorded between daytime and night.

The region has no significant wind speeds [37], [38], therefore the option of a micro wind turbine was discarded.

The typical irradiation day for each month has been calculated from the data of European Photovoltaic Geographical Information System (PVGIS) [39], considering the GPS coordinates of the hotel. For each month, the radiation pattern of a day in the past two years, which has a daily irradiation equal to the average daily irradiation for that month, was considered. The calculations led to the following irradiation distribution:

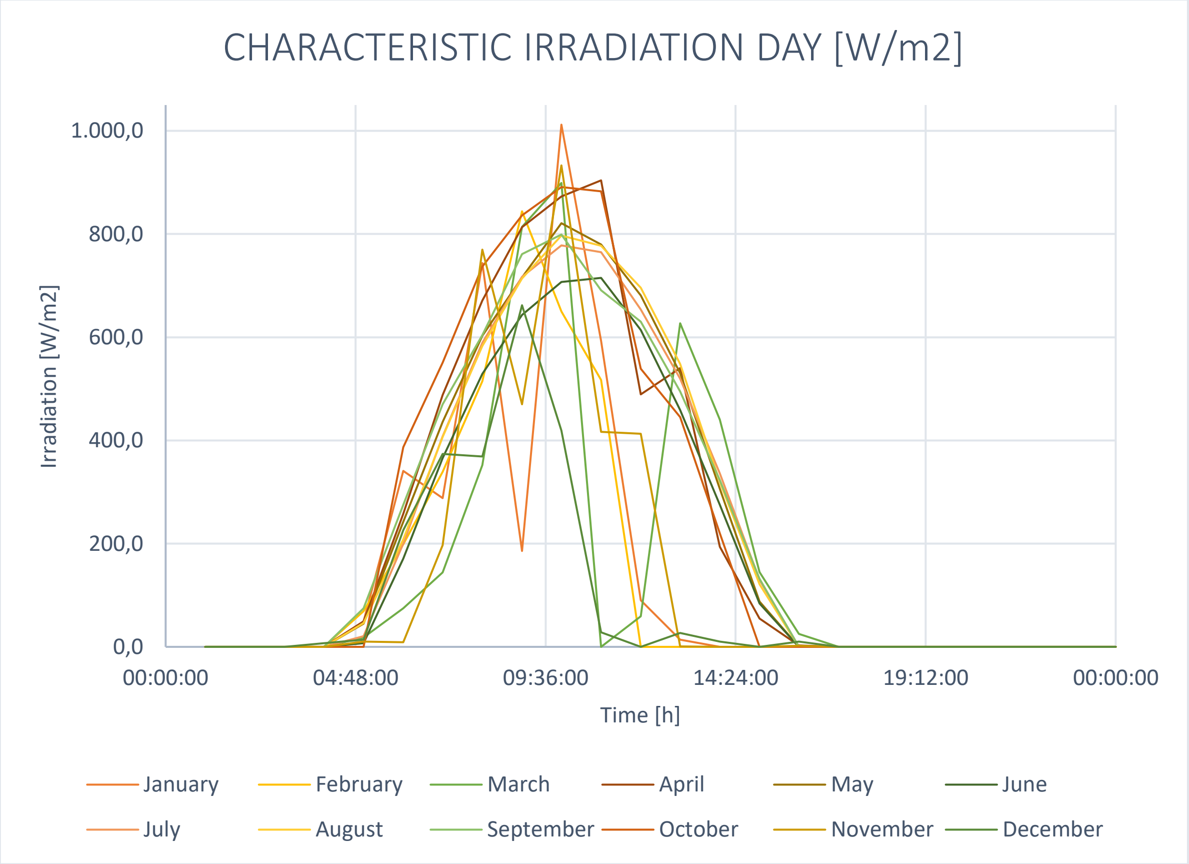


Figure 21 – Typical Irradiation Day for Each Month

For subsequent calculations, the characteristic day of July was considered representative of the peak season trend and the characteristic day of February of the non-peak season. Some test simulations were carried out to verify that the choice of different representative months does not result in large differences.

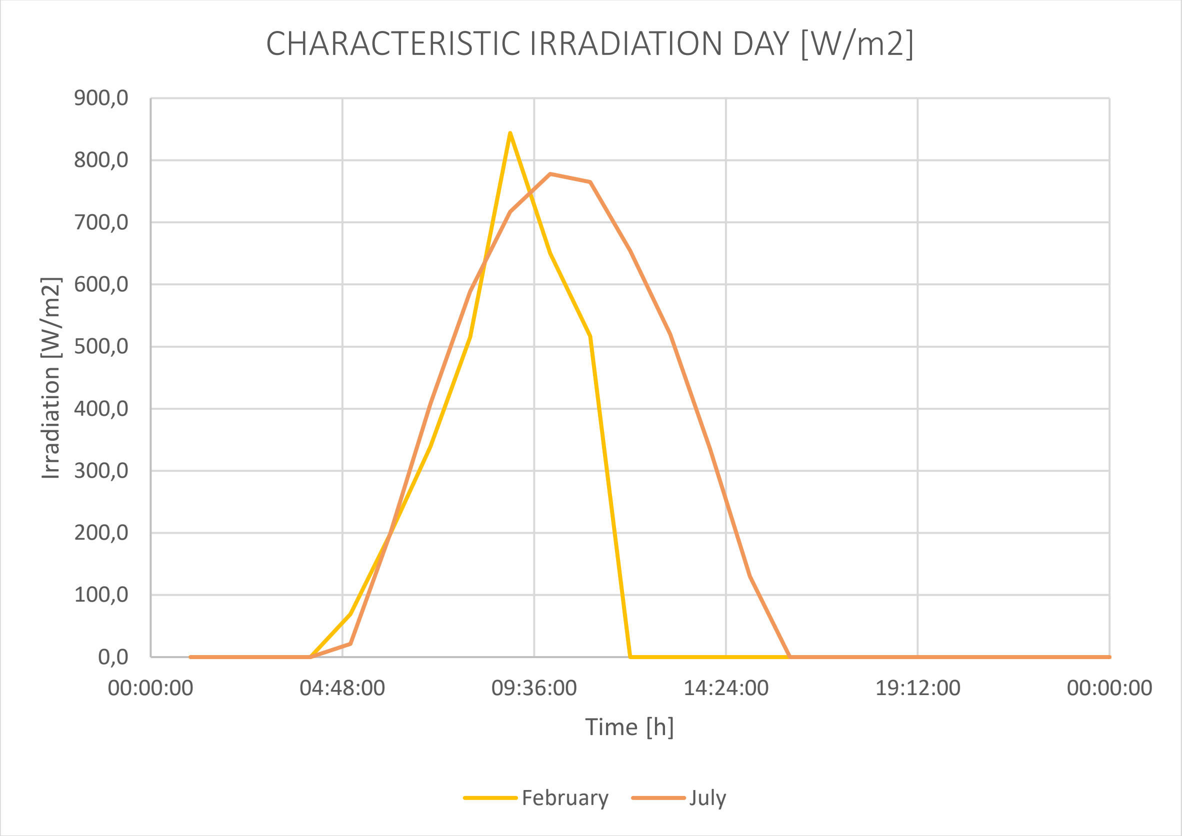


Figure 22 - Typical irradiation day for peak and off-peak seasons

The irradiation potential of the whole country is impressive. The exploitation of this resource through photovoltaic system will have a key role in the development of the Zambian energy system.

# 4 Results

The following chapter summarizes all the design results and explains the design process in depth. Since there was no opportunity for an executive site survey, as the project is still at an early stage, the executive design was based on several assumptions and it is likely that during design some will be corrected, leading to future variations in the final design.

## 4.1. Preliminary design

A first assessment to identify the best PV system configuration has been performed considering an average PV panel of 335 W peak, which is a panel size quite common in Africa.

Common geometrical dimensions of the PV panels are also considered. So, the height considered is 1.960 m and the length is 0.992 m, resulting in a panel area of 1.944 m2. The rooftop geometrical dimensions have been provided by the Olga's staff. Then, a first layout configuration has been drawn, as shown in Figure 23 - Preliminary PV panels layout.

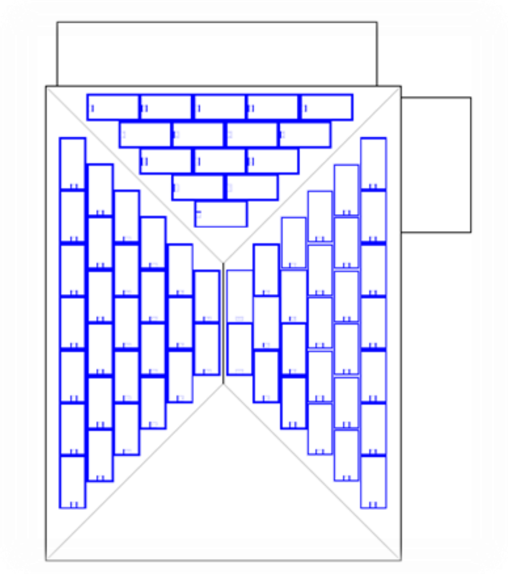


Figure 23 - Preliminary PV panels layout

The north pitch of the roof has room for 15 PV panels, while the east and west pitches can each accommodate 27 PV panels. The global installation comprehends 69 PV panels.

This is the configuration with the maximum PV panel installation. The south-facing roof pitch was not considered because Livingstone is below the equator line and therefore the south-facing panels would receive low irradiance.

Two different configurations are considered:

1. 15 PV panels on the north pitch, leading to 5.025 kWp installed;
2. The maximum PV panel installation, which consists of 23.115 kWp installed.

To estimate the expected energy production of the plant in the two configurations, the average monthly irradiance on each roof pitch has been calculated from PVGIS data [39]. The above explained formula for a rough calculation of the energy production has been used for each month:

$$E_p = AVG_{Irradiance}\,\eta_{PV}\,Area_{TOT}\,\eta_{INVERTER}\,\eta_{BOS} \tag{32}$$

Equation 32 - Energy production equation

Average value has been considered for the efficiencies:

- $\eta_{PV}$ equal to 17%;
- $\eta_{INVERTER}$ equal to 95%;
- $\eta_{BOS}$ equal to 80%.

The resulting annual production for the first configuration is **8951 kWh/year**. This production is rather low compared to the building loads. In fact, just the priority loads alone require 8334 kWh/year. Therefore, this option was dropped in favor of the second one.

The maximum PV panel installation configuration offers a calculated annual output of **38221 kWh/year**. The calculated load demand of the entire building is around 38260 kWh/year, so an installation with this configuration can provide good load coverage throughout the year.

In addition, the daily productions of the two configurations were plotted, using the irradiance data of the characteristic days of the peak and off-peak seasons.

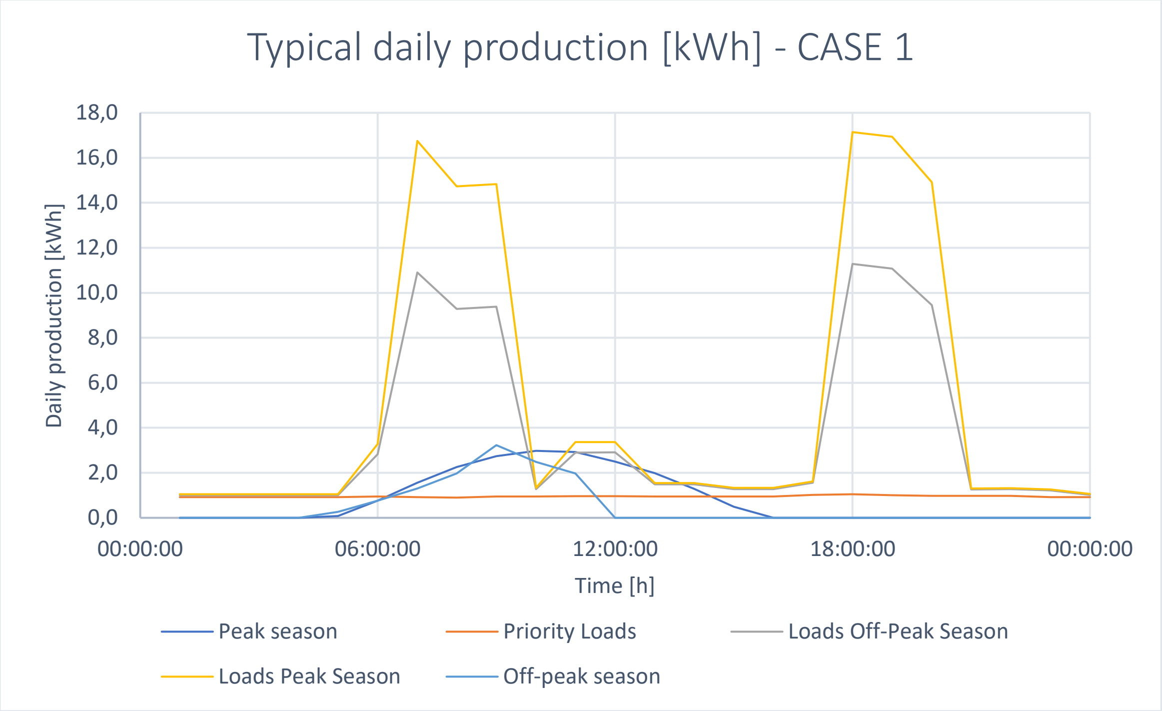


Figure 24 - Typical daily production for the configuration 1

As pointed out, this configuration would make a very small contribution to the building's energy requirements. It also does not guarantee coverage of priority loads.

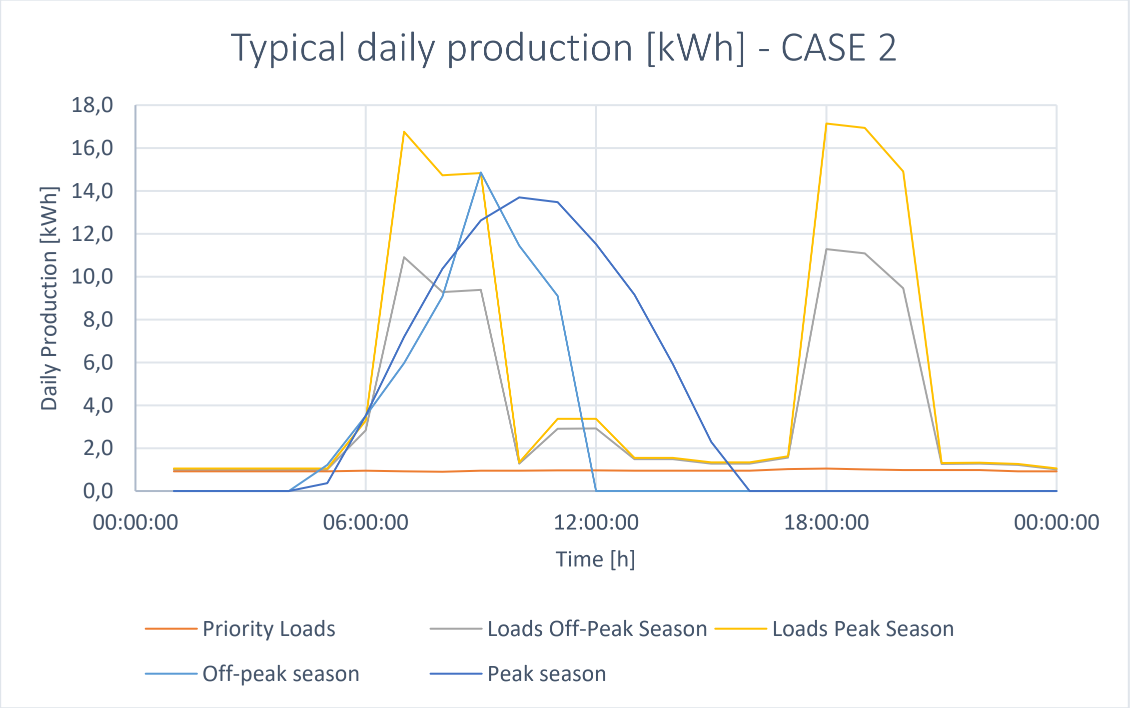


Figure 25 - Typical daily production for configuration 2

For the second configuration, production is high, especially in the peak season. But as the graph shows, electricity consumption and PV production are not well overlaid. Peak loads in the evening are completely outside the solar production bell. To maximize self-consumption and, therefore, minimize electricity cost, the use of battery power is suggested. This enables us to store the energy produced in the middle of the day and use it in the evening when demand is much higher.

In order to choose the batteries size, some simulations have been performed, considering four possible options:

1. Batteries capacity equal to the energy required by priority loads in a day;
2. Batteries capacity equal to the plant overproduction in peak season;
3. Batteries capacity equal to the average plant overproduction between peak season and off-peak season;
4. Batteries capacity equal to the plant overproduction in off-peak season.

The overproduction is calculated as the **average overproduction** for the peak and off-peak seasons and corresponds to 60 kWh and 28 kWh, respectively. The simulations were carried out with the irradiance data of the characteristic days of the two seasons.

1. The first simulation was performed with peak season loads since they are the most critical. A high season week, consisting of a sequence of characteristic days, has been considered. The curve of loads and production are the same for each day of the week just because we used the data calculated previously on the typical day of consumption and the characteristic day of production. In fact, the focus of the graph is on battery trends.

The battery capacity is equal to the energy required by the priority loads during the 18 hours from 17:00 to 10:00. This is the time interval when sunlight may not be available and, therefore, the loads must be powered by the batteries. In a typical day this required energy is equal to **17 kWh**. The rationale behind the simulation is to have the batteries discharged every hour, providing the energy needed to meet the priority loads, while keeping enough energy stored to meet the demand of the priority loads for the remaining hours before dawn, in the event of a power outage.

The idea is to have enough energy stored at all times to deal with a power outage until the photovoltaic panels start producing electricity again. The results are the following:

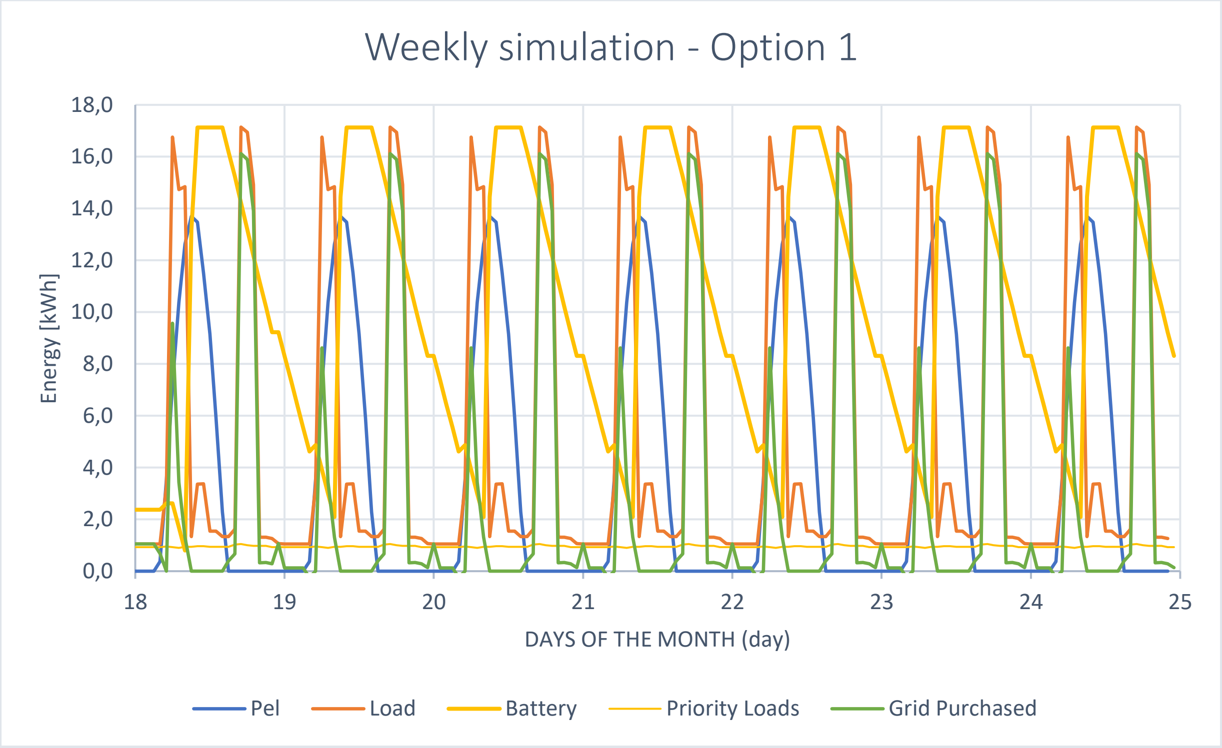


Figure 26 - Battery simulation, Option 1

Another simulation was performed by simulating a power outage from 17:00 to 05:00, which was considered the most critical time for blackouts. The simulation confirmed that this battery capacity can meet **priority loads for the simulated 13 hours**.

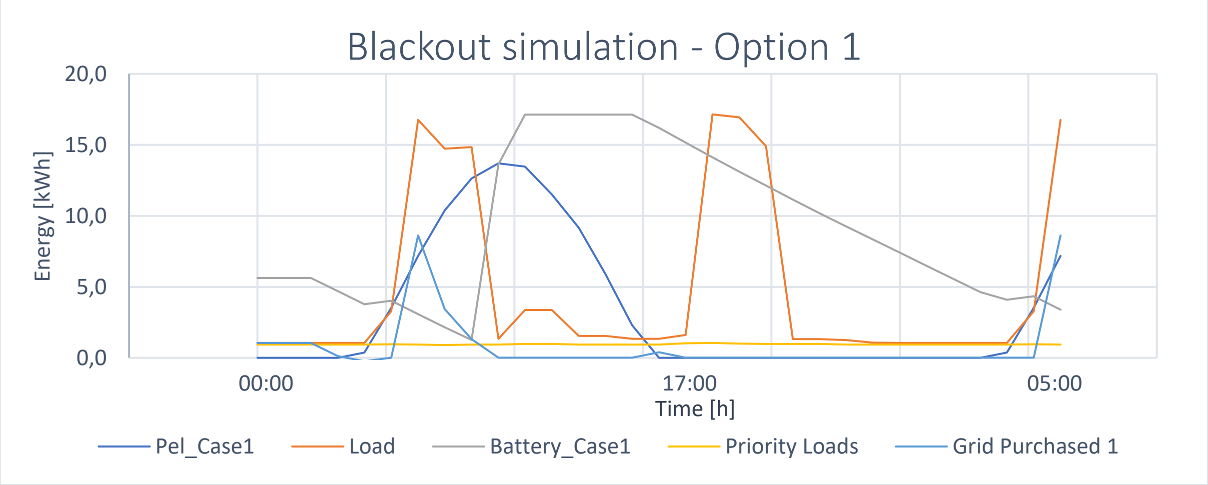


Figure 27 - Blackout simulation, Option 1

2. The second simulation was performed considering a battery capacity equal to the average overproduction of the plant in a week in high season, which is about **60 kWh**.

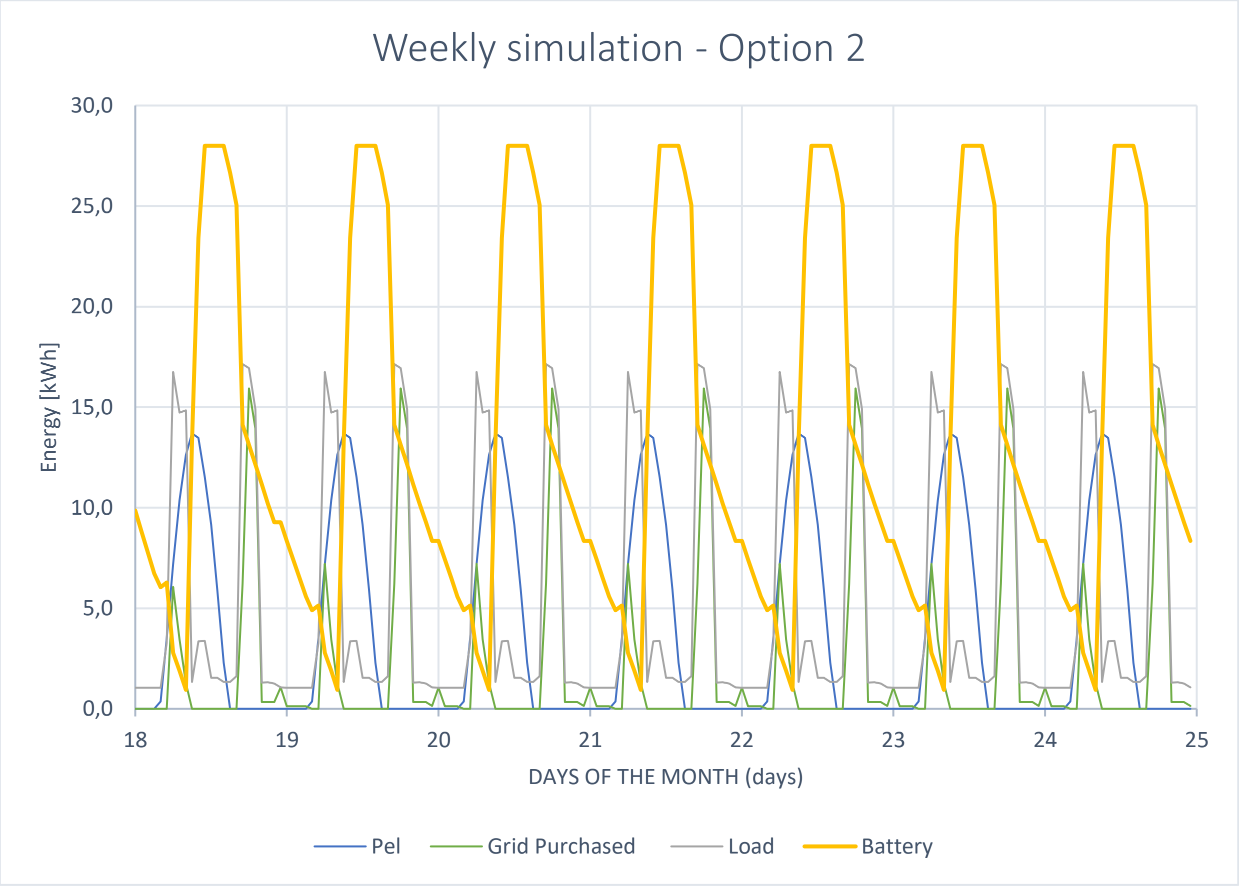


Figure 28 - Battery Simulation, Option 1

The size of this battery is enormous; in fact, it can be seen that it is never fully charged. Moreover, it would involve unreasonable investment costs, so this option has been abandoned.

3. The third simulation was performed considering a battery capacity equal to the average plant overproduction between peak season and off-peak season, which is about **44 kWh**.

The simulation results are similar to the previous configuration:

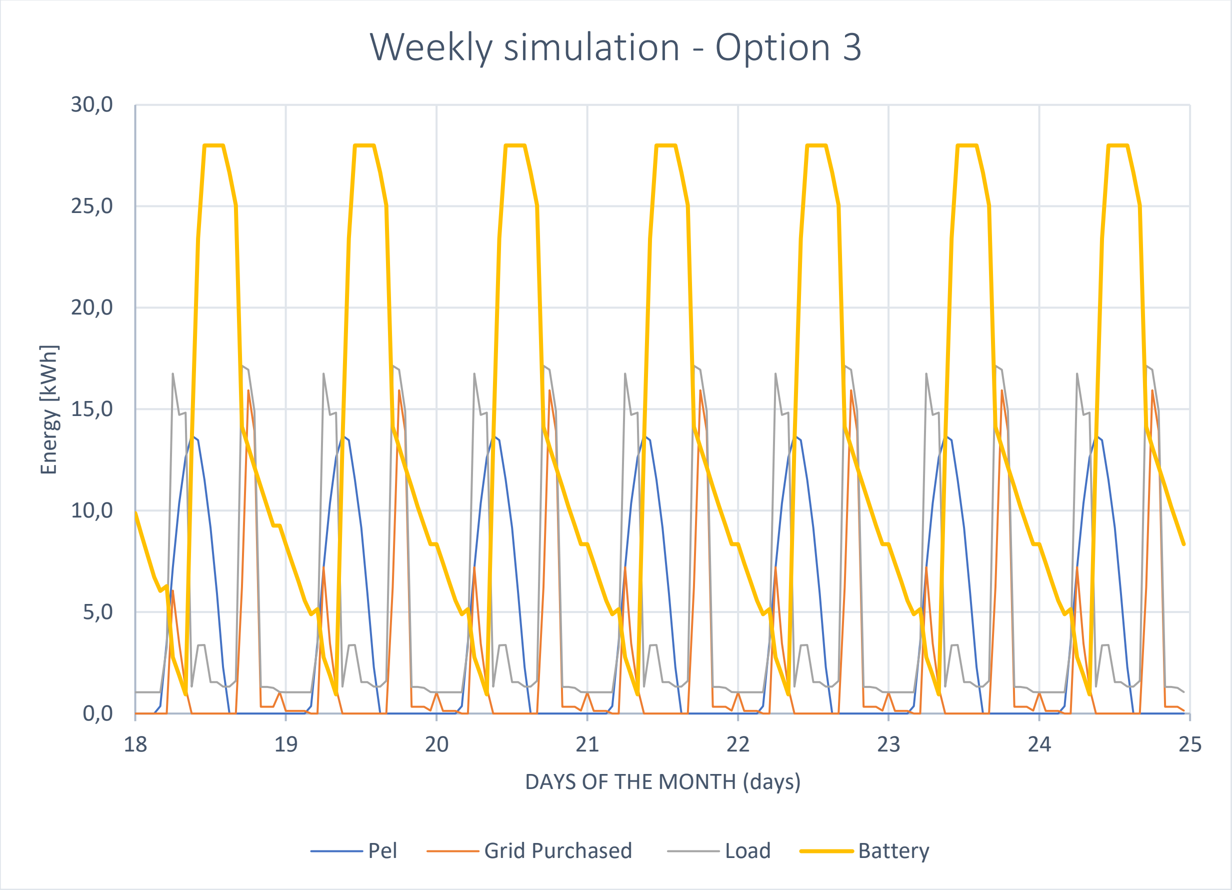


Figure 29 - Battery Simulation, Option 3

As it is possible to see, the batteries size is uselessly big. It not reasonable to use oversized batteries due to the high investment costs of this component. Therefore, also this option was abandoned.

4. The fourth simulation has a batteries capacity equal to the plant average daily overproduction in off-peak season, which is about **28 kWh**.

The batteries behavior was programmed to have them discharging every hour to satisfy **all the loads**, *but* ***only*** *if the energy stored was enough to cover the loads of that specific hour and all the following priority loads until the sunrise*. If the energy stored at a specific time does not satisfy this constraint, the batteries discharge only for the energy portion available, keeping the constraint energy, and they meet part of the total loads or just the priority loads for that hour. In this way, the system can maximize self-consumption, but at the same time service as an efficient backup in case of power outage.

In a characteristic peak season week, the trend of the batteries is pictured in the following graph, where it is visible also the energy purchased by the grid:

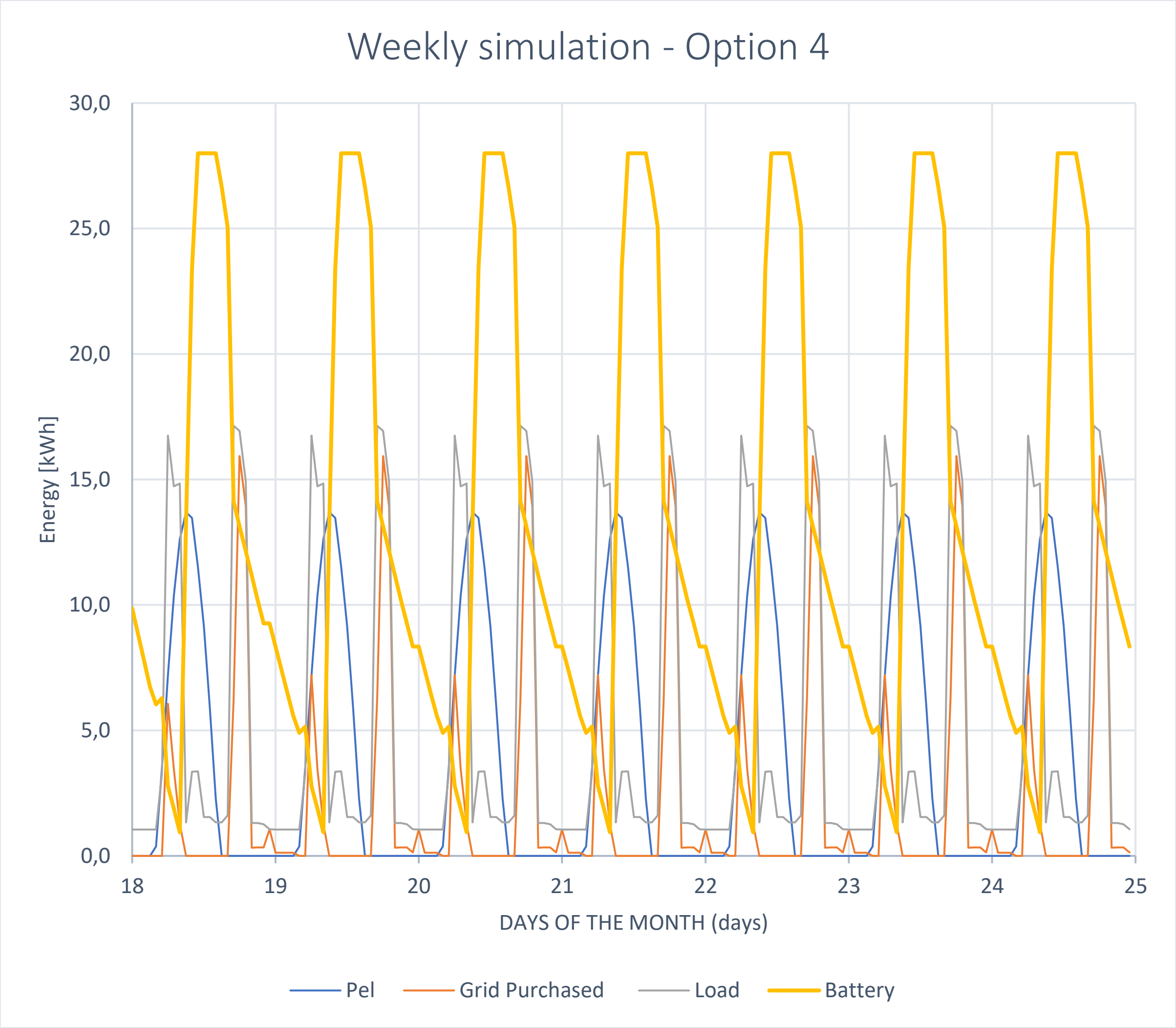


Figure 30 – Battery simulation, Option 4

Another simulation was performed to evaluate the configuration resilience to outages. We considered to deal with 3 blackout each of 13 hours, from 17:00 to 05:00, in three different days of the week.

The system successfully guarantees the meeting of *priority loads and part of the other loads* for the whole duration of the outages. It covers all the loads from 21:00 to 05:00, and only part of the loads from 17:00 to 21:00. The simulation is plotted in the following graph:

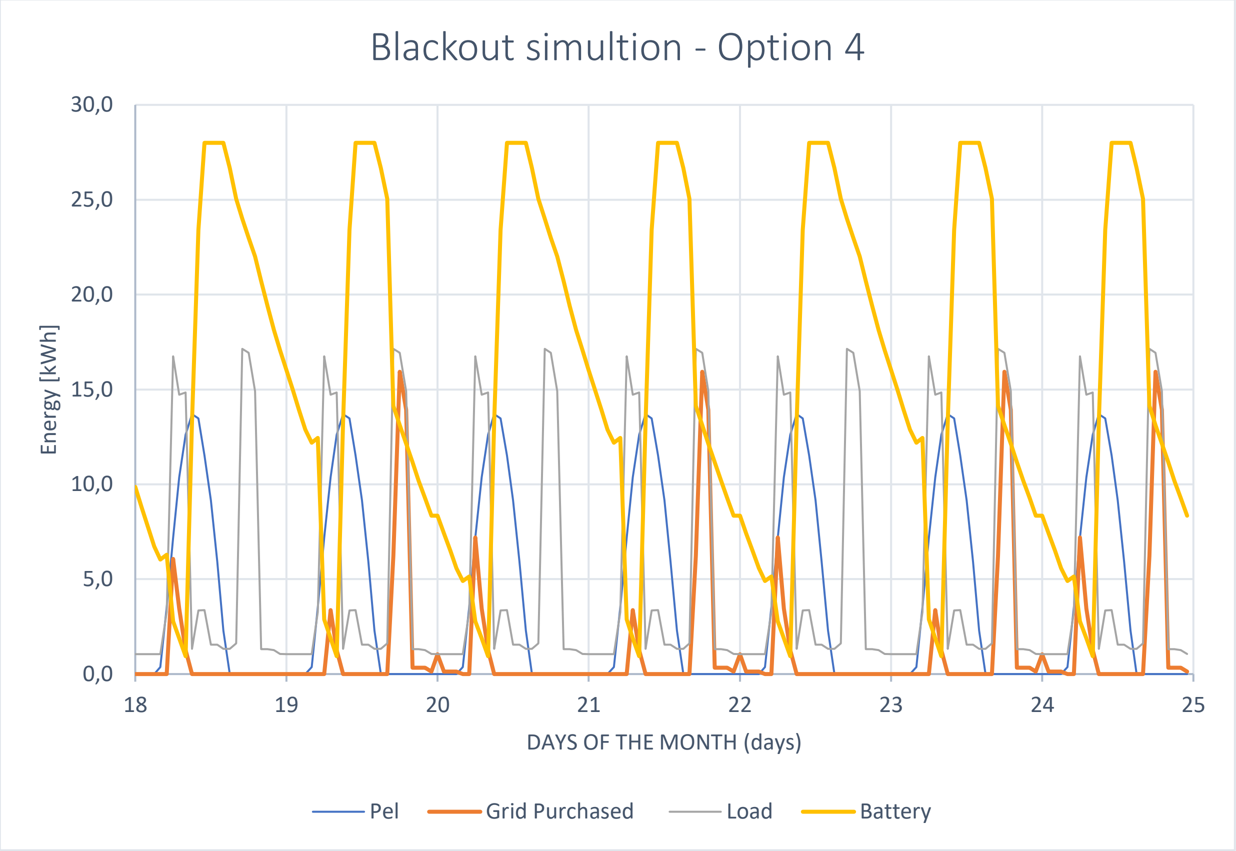


Figure 31 – Battery simulation with Outages, Option 4

To summarize, the cases simulated are reported in Table 7 – Performed simulations.

| **Battery capacity** | **Simulations** |
|---|---|
| 17 kWh | Weekly simulations with and without outages |
| 60 kWh | Weekly simulations without outages |
| 44 kWh | Weekly simulations without outages |
| 28 kWh | Weekly simulations with and without outages |

Table 7 – Performed simulations

Since the objective of the plant is to deal with blackouts, but also to lower the electricity cost and increase the degree of independence from the national grid, the third configuration is the best one among the above presented.

Batteries with a capacity of **28 kWh** allows to have high self-consumption on daily basis and to successfully deal with power outages. Therefore, this configuration has been considered as reference for the components research and the further calculations.

With this configuration, daily load coverage is expected to be approximately 80% during the peak season —April through October — and approximately 65% during the off-peak season — November through March.

An important consideration for this project is the environmental impact of the PV system. Zambia's energy mix has a CO2 intensity of 13.1 t CO2/TJ [40]. This means that each kWh of energy produced in Zambia emits 47 g of CO2, which is quite low and is the result of the large share of hydropower in the energy mix. The CO2 emission generated by a diesel generator is estimated to be 0.8-0.93 kg CO2/kWh [41]. The average value of 86.5 g CO2/kWh was considered. Also considering the percentage of energy produced by the diesel generator, Olga's average emissions for its energy is **58 g CO2/kWh**. Whereas, once the PV system is installed, Olga's will benefit from zero-emission energy for about 72% of its total consumption. The remaining 28% will be purchased from the grid, leading to a CO2 intensity for the guesthouse of about **13 g CO2/kWh.**

## 4.2. Budget

A **preliminary quotation** was prepared, based on bids from local suppliers and advice from manufacturers' representatives. The list of components is also based on advice from local suppliers on the availability of materials.

The following components allow to set up a three-phase configuration with a battery management system.

System Components Budget

| Product / Services | Units | Tot Cost | Brief description |
|---|---|---|---|
| **FV panels** - 335W | 69 | $11.040 | This type of panel is very common in SSA. An average price was considered. |

| | | | |
|---|---|---|---|
| Inverter brand: **Victron**<br>Model: **Quattro 48/8000/110-100/100** | 3 | $9.075 | This model of inverter is configured for backup operation and can manage two clusters of loads (in this case: primary loads and ordinary loads). |
| MPPT brand: **Victron**<br>Model: **Victron Bluesolar MPPT 250/100** | 6 | $5.040 | ZICTA (Zambia Information and Communication Technologies Authority) requires a license for any smart product to be imported into the country. This MPPT has the required license. |
| **Support structures** for fixing panels to sheet metal roofs | 69 | $2.300 | To estimate this cost, the average cost [€/panel] of the structures has been considered. |
| **Electrical system components**: cables, connectors, switchboards, cable trays and cable protection tubes | - | $4.400 | To estimate this cost, the average cost has been considered. |
| Protection system for AC + DC sides and housing | - | $115 | To estimate this cost, the average cost has been considered. |
| Management system**: Interface MK3-USB (VE.Bus to USB**) and **Cerbo GX** | 1 | $360 | This Victron management system controls battery charging and discharging and provides a user interface. |
| **Mechanical installation** of supports and modules, **electrical installation**, and **certification** of the electrical system | - | $850 | To estimate this cost, a hourly cost of labor of 1 $/h has been considered. |

| | | | |
|---|---|---|---|
| Material **transportation** | - | $620 | To estimate this cost, an average transport cost has been considered. |
| **EQUA's contribution**: documentation, design, and support of the whole system | - | $3.050378 | This cost is inclusive of all work performed by EQUA, except travels expenditures. |
| Other costs | - | $1.000 | It is important to consider other costs that will be well defined in the executive part (e.g., scaffolding rental). |
| **TOT Costs, VAT included** | - | **$37.850** | The specific cost, corresponding to this quote, is: **1646 $/kWp** |

Table 8 – System Components Budget

In addition to the cost of the system components, the budget also includes expenses for *two trips* by EQUA engineers and Prof. Diappi, project responsible: for the executive inspection (one week) and for the final installation (ten days). EQUA planned to send two engineers to the site for the executive inspection and three engineers – two senior engineers and one junior – for the installation phase.

The summary table is the following.

| Trips Budget | | | |
|---|---|---|---|
| | **Units** | **Cost** | **Brief description** |
| Flights from Milan to Livingstone | 14 | $18.820 | The calculated cost considers the round-trip travel of all mission members and the average price of flights for this route. |

| | | | |
|---|---|---|---|
| Accommodations | 54 | $4.240 | The calculated cost considers accommodation for one week for four people with the average cost of hotels in Livingstone. |
| Foods, transportation, and others | - | $2.800 | An average expenditure of about $200/day was considered. |
| Trip to Lusaka | 1 | $200 | The transportation cost of traveling to Lusaka, to meet with suppliers, was considered separately. |
| **TOT Costs** | - | **$26.060** | This total cost has considered all the above costs, considering that there will be two trips. |

Table 9 – Travels Budget

Finally, since the roof's resistance to the weight of the panels is unclear, the construction of a pergola structure, above the roof, on which the modules can be installed was considered. This structure will also lower the temperature of the rooms under the sheet metal roof, providing shade and some thermal insulation through the layer of air between the roof and the structure.

The cost of work to build the structure was estimated at about **$60.000** and the time needed at two weeks.

Also, for batteries, costs were estimated through quotes from local and international suppliers. To account for any extra costs, which are not foreseeable at this time, a **10% safety margin** was considered on the final total cost of each battery option.

**Option A: Victron LiFePO4 Battery 25,6V/200Ah**

This option was suggested by the Victron representative. All components are made by the same brand and makes it easier to find a single source supplier.

Please note that these batteries come with a **2-year warranty.**

| Option A: Victron Battery | | | |
|---|---|---|---|
| **Product / Services** | **Units** | **Tot Cost** | **Brief description** |
| Battery: **Victron LiFePO4 Battery** 25,6V/200Ah – Smart-a da 5,12 kWh | 7 | $21.080 | This battery is made by the same producer of the inverters. |
| Meter and platform/loader | 1 | $360 | To estimate this cost, the average cost has been considered. |
| Brand: Victron<br>Product: **VE.Bus BMS + SmartShunt** 500A/50mV | 1 | $200 | These components are important for battery management and battery communication with all other components. |
| Current Clamps | 1 | $380 | To estimate this cost, the average cost of the structures has been considered. |
| Cables, connectors, switchboards, cable trays and cable protection tubes | - | $1.500 | To estimate this cost, the average cost has been considered. |
| Mechanical installation of supports and batteries, electrical installation, and certification of the electrical system | - | $120 | To estimate this cost, a hourly cost of labor of 1 $/h has been considered. |

| | | | |
|---|---|---|---|
| Material **transportation** | - | $115 | To estimate this cost, an average transport cost has been considered. |
| **EQUA's contribution**: documentation, design, and support of the whole system | - | $350 | This cost is inclusive of all work performed by EQUA, except travels expenditures. |
| **TOT Costs, VAT included** | - | **$26.500** | Please note that this cost includes the 10% safety margin. |

Table 10 – Batteries option A Budget

This solution for ESS is rather expensive and offers the financial outlook pictured in the Figure 32 - Option A Infographic, considering a change of batteries and inverter after 10 years.

| OPTION A |
|---|

| | Cost [USD] |
|---|---|
| PV system and installation | $ 37.850 |
| Batteries and installation | $26.500 |
| Structure strengthening | $60.000 |
| Executive inspection | $26.060 |
| TOT | $150.450 |

Victron inverter and batteries

Panels installed on the roof pitches

**NB** we are assuming that donors cover the entire initial investment

Figure 32 - Option A Infographic

By saving on energy purchase and self-generation, Olga's will be able to purchase batteries and inverters, which we estimate need to be replaced every ten years. In addition, considering this battery option, the guesthouse will have a cumulative savings of **$108.300**, at the end of the plant's life cycle.

**Option B: Pylontech US2000C**

These batteries are widely used in Europe. They have a good price and can work with a Victron inverter. Note that these batteries come with a **10-year warranty**.

They are slightly smaller in size than other battery options.

| Option B: Pylontech Battery | | | |
|---|---|---|---|
| **Product / Services** | **Units** | **Tot Cost** | **Brief description** |
| Battery: **Pylontech US2000C** 48V 2.4kWh LiFePO4 | 12 | $11.290 | These batteries are compatible with the selected inverter. |
| Meter and platform/loader | 1 | $360 | To estimate this cost, the average cost has been considered. |
| Accessories for connection and communication with the inverter | 1 | $600 | These components are important for battery management and battery communication. |

| | | | |
|---|---|---|---|
| Current Clamps | 1 | $380 | To estimate this cost, the average cost of the structures has been considered. |
| Cables, connectors, switchboards, cable trays and cable protection tubes | - | $1.500 | To estimate this cost, the average cost has been considered. |
| Mechanical installation of supports and batteries, electrical installation, and certification of the electrical system | - | $120 | To estimate this cost, the average cost has been considered. To estimate this cost, a hourly cost of labor of 1 $/h has been considered. |
| Material **transportation** | - | $115 | To estimate this cost, an average transport cost has been considered. |
| **EQUA's contribution**: documentation, design, and support of the whole system | - | $350 | This cost is inclusive of all work performed by EQUA, except travels expenditures. |
| **TOT Costs, VAT included** | - | **$15.900** | Please note that this cost includes the 10% safety margin. |

Table 11 – Batteries option B Budget

This solution offers the financial perspective picture in the Figure 33 - Option B Infographic, considering a change of batteries and inverter after 10 years.

OPTION B

| | Cost [USD] |
|---|---|
| PV system and installation | $37.850 |
| Batteries and installation | $15.900 |
| Structure strengthening | $60.000 |
| Executive inspection | $26.060 |
| TOT | $139.850 |

Victron inverter and Pylontech batteries

Panels installed on the roof pitches

NB we are assuming that donors cover the entire initial investment

Figure 33 - Option B Infographic

By saving on energy purchase and self-generation, Olga's will be able to purchase batteries and inverters, which we estimate need to be replaced every ten years. In addition, considering this second battery option, the guesthouse will have a cumulative savings of **$111.500**, at the end of the plant's life cycle.

## 4.3. Economic analysis

Electricity consumption for the hotel and restaurant was estimated based on the data provided, as explained above. We *estimated* the electric bill for the entire facility at approximately **$3790 USD/year**, not including outages' costs. With the diesel costs, the total electricity cost was estimated to be approximately **$8700/year** [42]–[44].

The price of electricity used for the calculation is 0.132 $/kWh, taken from ZESCO's website [45]. While the cost of diesel fuel is calculated as an average of the cost of diesel fuel in Zambia from 1991 to 2022, which is about $1.1/L [43], [46]. To move from the cost of diesel fuel to the cost of electric kWh, the average efficiency of a diesel generator set was taken to be 0.44 L/kWh [44]. The percentage of electricity produced by the diesel generator set compared to the total load demand is 28%, which represents the self-production due to power outages, taken from the literature [47]. Therefore, 72% of the electric kWh consumed by the building is purchased at the cost of electricity, while the remaining 28% is purchased at $0.44/kwh.

With the selected configuration, Olga's will save approximately **$7260** each year since the remaining energy purchased from ZESCO will account for about $1440. In fact, from the simulations with a battery capacity of 28 kWh, the electricity purchased annually from the grid is 15180 kWh, which, when outages are taken into account, drops to 10920 kWh actual. This corresponds to an electricity expenditure of $1440 and, therefore, an annual savings of $7620.

The savings are proportional to electricity price and cost of diesel genset generated electricity. In particular, the relationship with the last is linear:

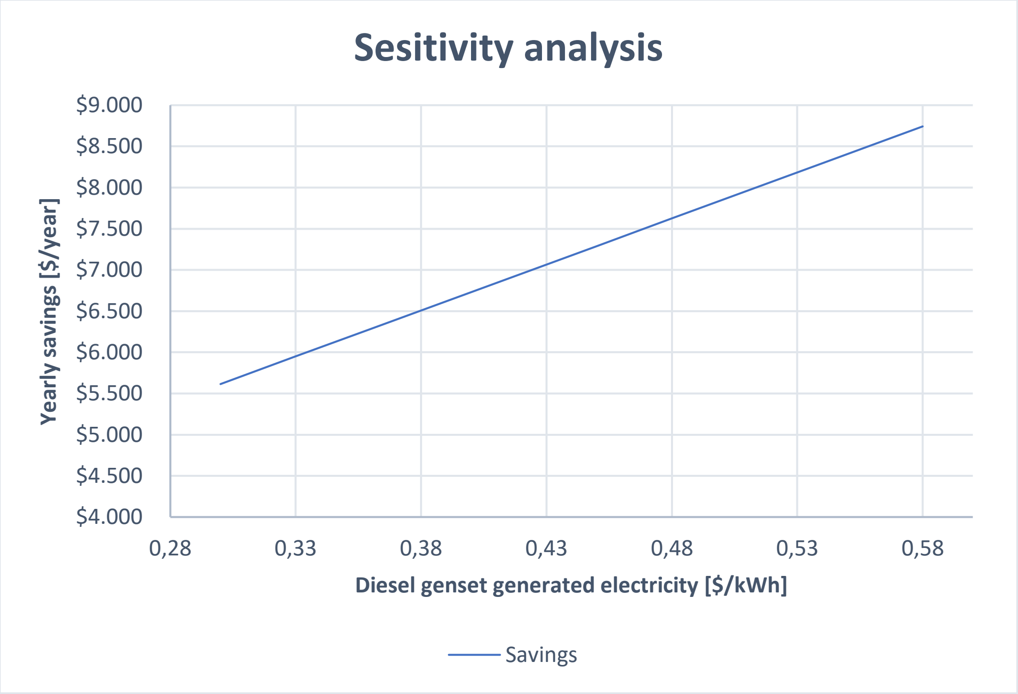


Figure 34 - Saving sensitivity analysis on diesel genset generated electricity

Considering the battery option B, this project has PBT of 24 years, due to the high expenses for the creation of the pergola structure and the cost of inspections.

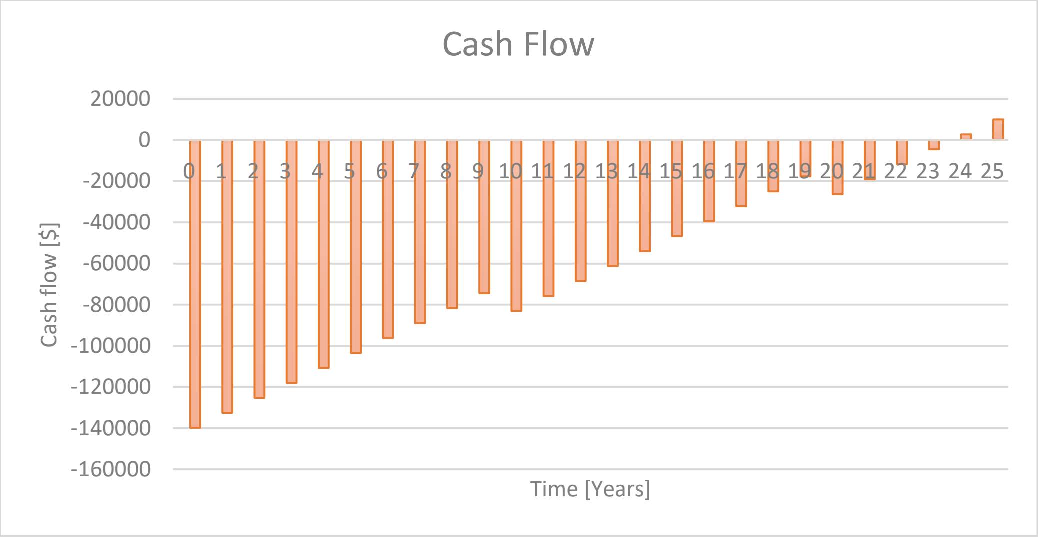


Figure 35 - Project Cash Flow

But since the initial investment is covered by donors, economic considerations must focus on variable costs. As shown in the tables above, Olga's would have substantial savings that can cover the costs of components that need to be replaced over the life of the plant.

An important factor to check for a PV power plant is the Levelized Cost of Energy (LCOE). It has been calculated as follows:

$$LCOE\left[\frac{\$}{kWh}\right]=\frac{CAPEX+OPEX_0}{AEP_0}+\sum_{i=1}^{N}\frac{OPEX_i*\frac{(1+j)^i}{(1+d)^i}}{AEP_0*(1-\delta_{PV})^i*\frac{(1+j)^i}{(1+d)^i}} \tag{33}$$
$$=0.21\ [\frac{\$}{kWh}]$$

Equation 33 - LCOE equation

An average annual value of 1% was considered for the PV system derating factor. While for the inflation and discount rates the most recent values available have been utilized, respectively 10% [48] and 12% [49].

The LCOE of the main grid is $0.13/kWh, while the LCOE of the diesel genset is about $0.44/kWh, as mentioned above. Consequently, the current equivalent LCOE for Olga’s, considering a self-generated energy percentage of 28%, is $0.22/kWh, slightly lower than that of the PV system.

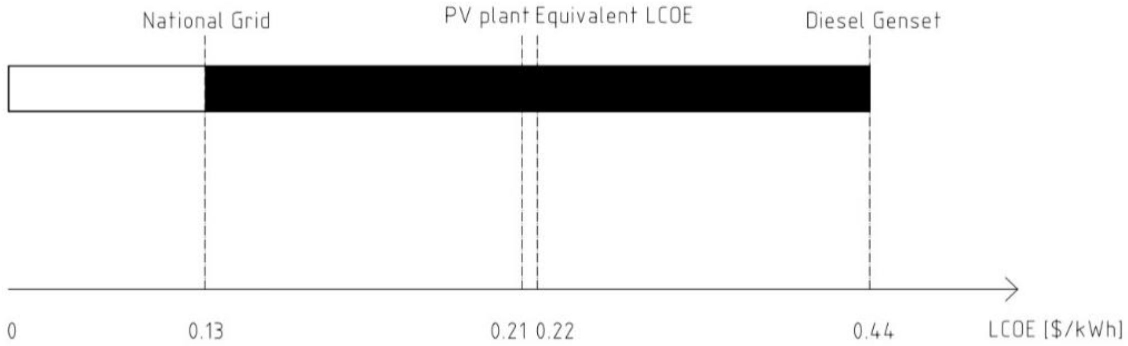


Figure 36 - LCOE comparison

To better understand the weight of self-generated energy on the LCOE, a sensitivity analysis was performed, considering a range of self-generated energy percentages from 10% to 50%.

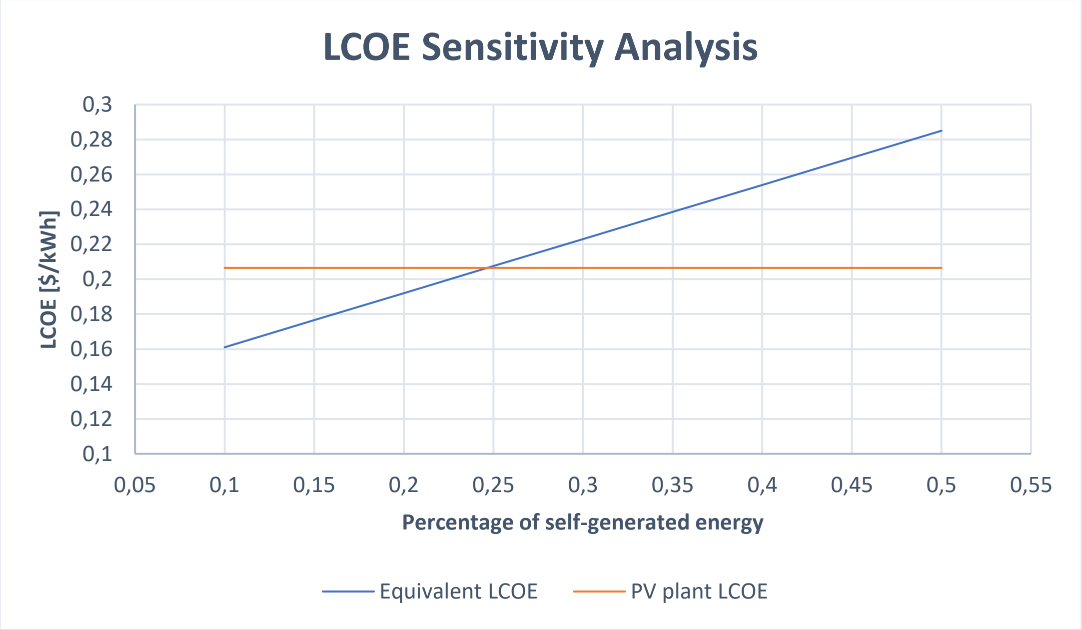


Figure 37 - LCOE sensitivity analysis

As it is possible to see Figure 37 - LCOE sensitivity analysis, there is a threshold above which the PV system is more cost-effective than the combination of electricity purchased from the grid and diesel genset generation. This limit corresponds to a percentage of self-generated electricity equivalent to the 24.6% of total energy consumed. This means that for percentages above this the PV system will be worthwhile in 25 years.

## 4.4. Executive design

In order to carry out the executive design, an inspection is essential. Since this will take place at a later stage of the project, a more detailed design will be shown in this chapter, but it may be modified after the actual executive inspection. The design criteria explained above will be applied in the following calculations and decisions.

Olga's guesthouse and restaurant consists of a main building flanked by an elegant wood and thatch structure under which tables are arranged. The main building has a four-pitch roof supported by wooden beams and made of trapezoidal sheet metal. t is planned to install PV panels on three pitches of this trapezoidal sheet metal roof. Since the strength of the roof structure is unclear, some structural strength assessments will be carried out to see if the installation can be done safely.

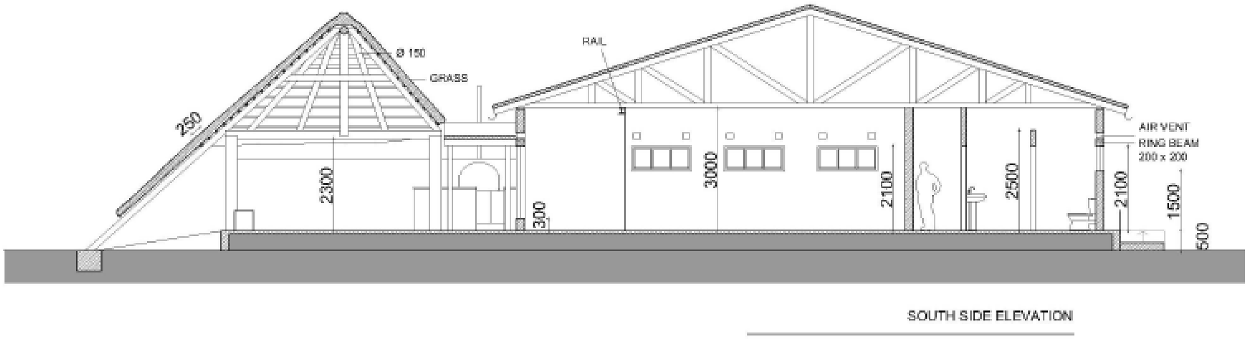


Figure 38 - Olga's building Elevation and Section

In case of structural problems, the solutions are reinforcing the existing structure or building a pergola structure, above the roof. In the latter case, the panels would have to be mounted on a horizontal plane, not sloping, and consequently the mounting structures described below would not be suitable. A second selection of flat roof structures would be needed. In fact, the option considered in this chapter is to install the panels directly on the sheet metal roof, possibly after reinforcement work.

### 4.4.1. Selection of the PV panels and mounting system

The choice of PV panels has as its main constraint the availability of supply in Zambia. Therefore, the choice fell on a brand that is very present and widespread in Africa: **Canadian Solar** [50]. The brand is born in 2001 with the mission of fostering sustainable development and energy transition by bringing electricity powered by the sun to millions of people worldwide. Nowadays it one of the world's largest solar photovoltaic products and energy solutions providers [51]. The company has an office in South Africa, Cape Town, and can guarantee assistance to Olga's if the need arises in the future.

The selected model is the **HiKu CS3L** with a peak power of **335 Wp** [52]. The company guarantees a 12-year warranty on materials and workmanship and a 25-year warranty on linear power performance, which ensures less than 2% power degradation in the first year and no more than 0.55% annual power degradation thereafter. PV panels' dimensions are 1765 X 1048 X 35 mm. Thus, each one has an area of 1.85 $m^2$.

The roof has an overall area of about 273 $m^2$, so, it can accommodate a large number of panels. To evaluate the possible arrangement of the panels, the layout was drawn.

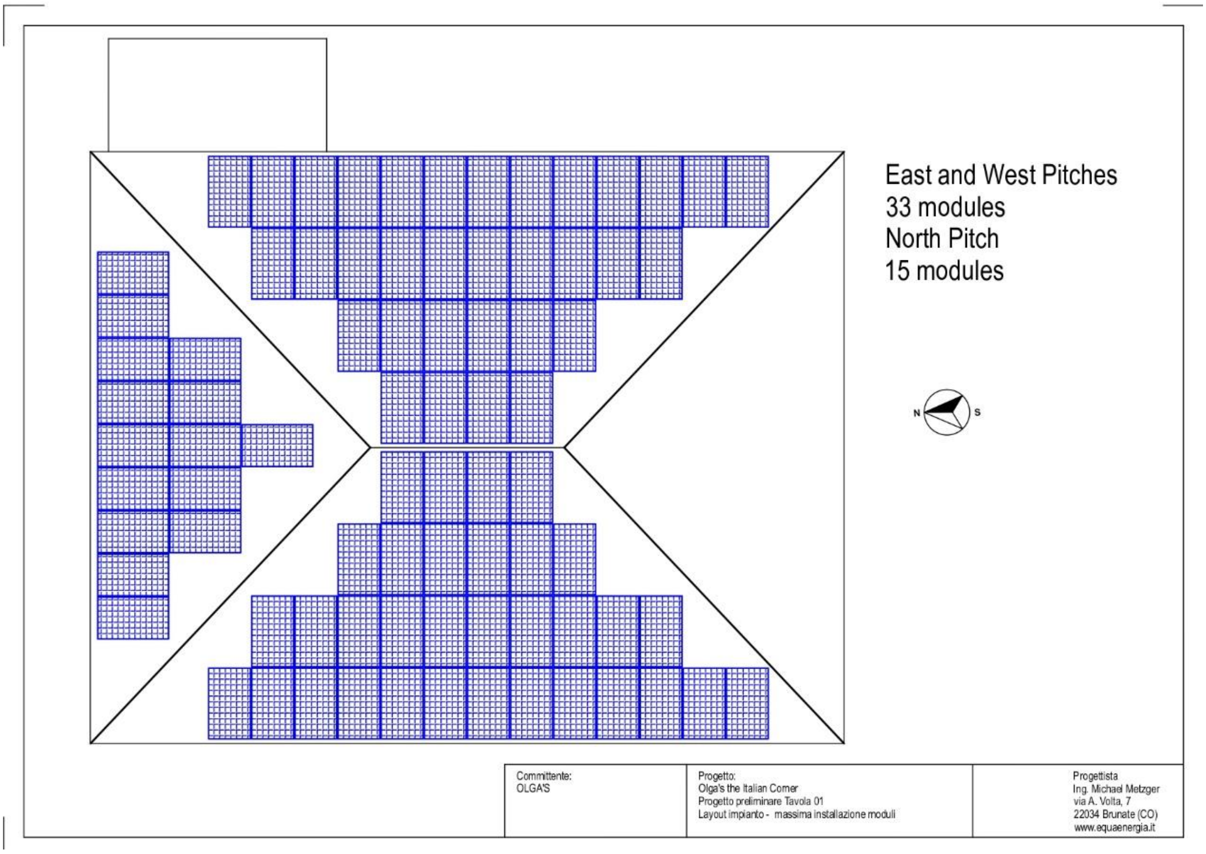
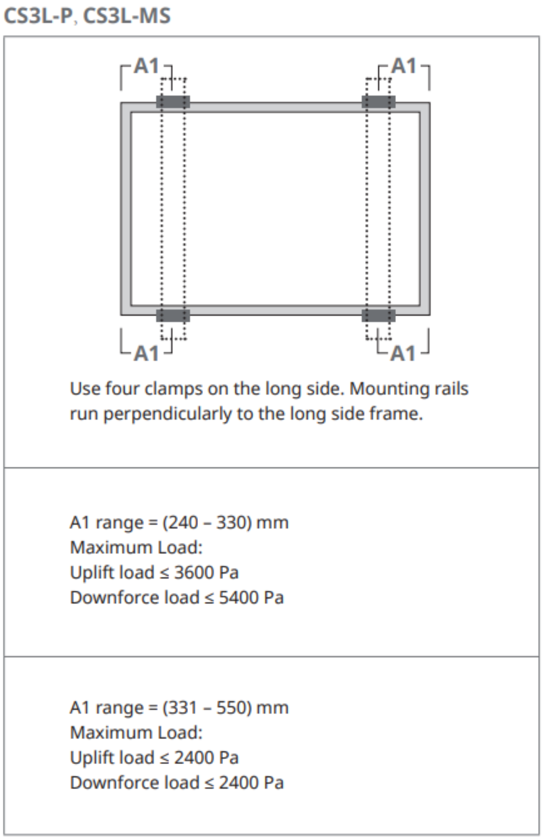


Figure 39 - PV panels layouts

Actually, there is room for three more modules, but this is the best configuration because of electrical constraints, which will be explained later. So, **81 panels** will be installed leading to an installed peak power of **27.135 kWp**.

The PV panel manual also provides guidance on the installation of the mounting system. For this model, it is necessary to fix the clamps by leaving 240 to 330 mm from the edges. This is to ensure resistance to uplift loads up to 3600 Pa and downward loads up to 5400 Pa.

Since it does not snow at the location under investigation, the most significant danger to roof-mounted PV panels is wind. Livingstone is not particularly windy; on average the wind speed is around 4-6 m/s. Therefore, no special precautions need to be taken except to carefully follow the normal instructions provided by manufacturers.



**CS3L-P, CS3L-MS**

Use four clamps on the long side. Mounting rails run perpendicularly to the long side frame.

A1 range = (240 – 330) mm
Maximum Load:
Uplift load ≤ 3600 Pa
Downforce load ≤ 5400 Pa

A1 range = (331 – 550) mm
Maximum Load:
Uplift load ≤ 2400 Pa
Downforce load ≤ 2400 Pa

Figure 40 - Directions for panel assembly from the manual [53]

The selected mounting system is the **MiniRail** mounting system by K2 company. It was developed specifically for trapezoidal sheet metal and allows easy changing of the module orientation thanks to the universal module clamps which are rotatable by 90°, is extremely lightweight and comes stacked completely on pallets [54].

The MiniRail set is composed of the short rail for mounting solar modules on trapezoidal sheet metal roofs, including 4 thread-forming tapping screw with sealing washer. The surface of the rail base and the washer are covered with a layer of EPDM for insulation from water. Universal end and mid clamp set for fastening solar modules completes the system. The materials used are EN AW-6063 T66 aluminum, EPDM and A2 stainless steel.

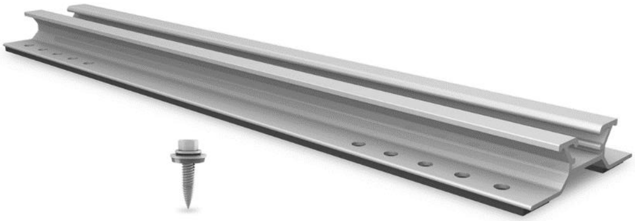


Figure 41 - MiniRail main components

The main advantages are the statically optimized short rail system, the mounting ease, and the universal module clamps. Moreover, these models are optimized for storage and transport. Finally, by adding **MiniFive** additional adapter to the system, panel tilt can be increased by 5°, resulting in significantly higher yields due to improved rear ventilation, optimized irradiation angles and improved module power. For the application studied, the improved ventilation would be an important driver for panel productivity and improved building thermal insulation, which is a major concern due to the high temperatures of the location.

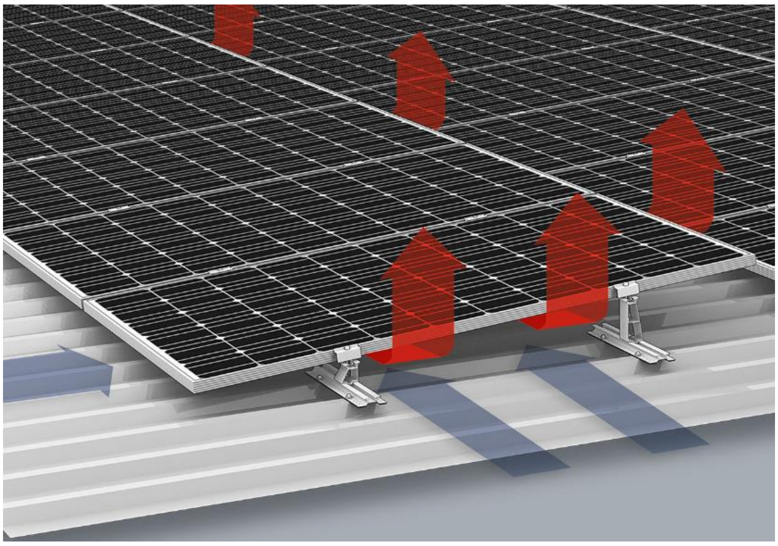


Figure 42 - MiniFive example of functioning

This mounting structure is suitable for roofs with a pitch between 5° and 75°, made of trapezoidal sheet metal. Therefore, it can be used for Olga's roof, which is pitched 19°. Other requirements are listed below and should be verified during the executive inspection:

- Sheet metal thicknesses: ≥ 0.5 mm steel or aluminum;

- Sandwich trapezoidal sheet metal: manufacturer's approval required;
- Traverse width: 22 mm minimum;
- Tread spacing: 101 - 350 mm depending on the width of the trapezoid;
- Minimum fretwork width around the hole: Ø ≥ 20 mm;
- Module frame height: 30 - 50 mm.

The last requirement is met because the frame height of the selected module is 35 mm. All others must be checked on site.

Also considering the constraints of the modules, a second layout with the mounting structure was drawn.

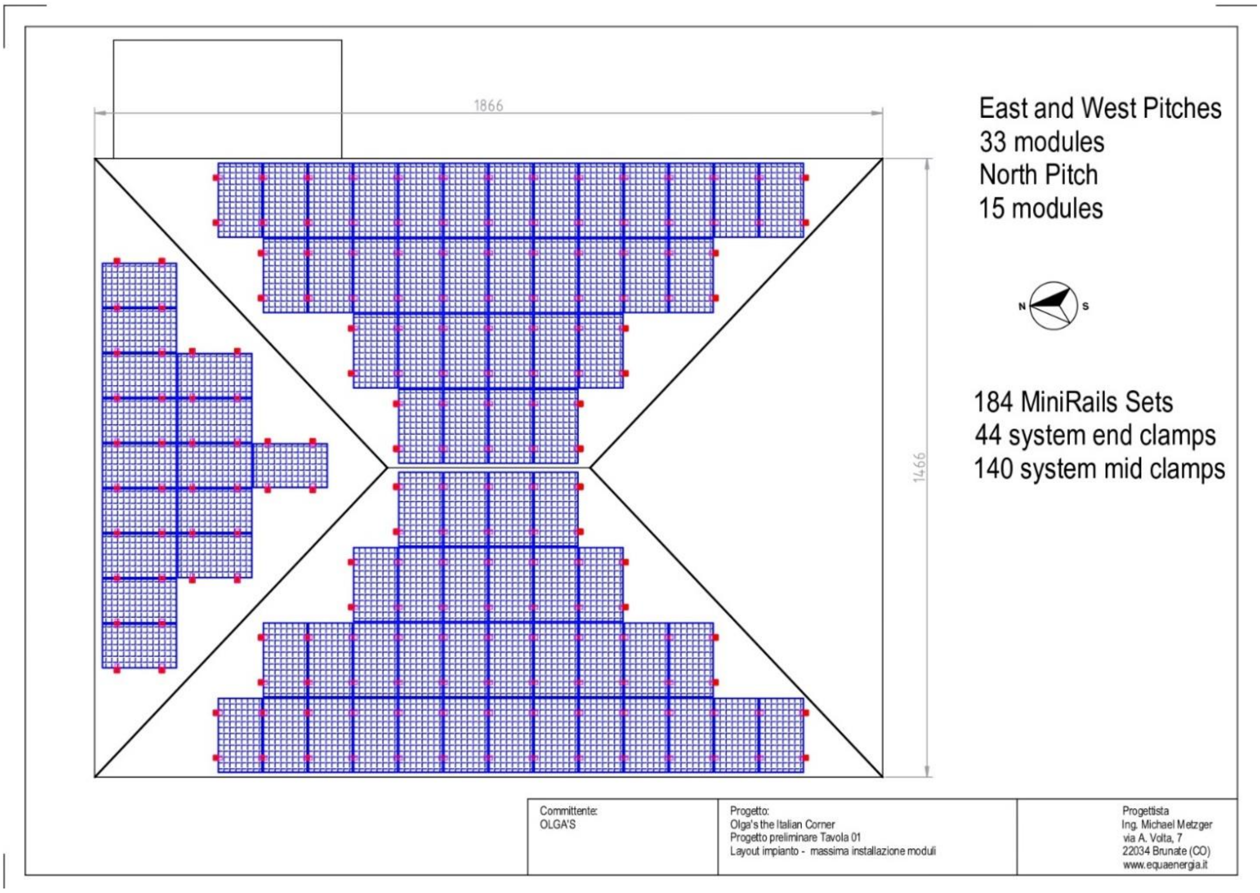


Figure 43 - PV panels and mounting structures layout

As shown in Figure 43 - PV panels and mounting structures layout, the needed MiniRail sets are 184, with 44 universal end clamps and 140 universal mid clamps.

### 4.4.2. Selection of the inverter and batteries brands

Once the dimensions of the PV array and batteries have been chosen, the brand selection of all components can be made. The considerations, usually applied to component selection and outlined above, are difficult to apply in this application due to the limited availability of materials.

The choice of **Victron Energy** [55] as the main brand is motivated by the worldwide network of certified dealers, suppliers, and installers that the company can offer. This can guarantee not only the availability of materials now, but also local support available throughout the life of the plant. In addition, Victron offers an efficient monitoring system, with remote access through an online platform, which would be very useful for monitoring and troubleshooting in the future.

The main components are the three **Quattro 48/8000/110-100/100**, which are powerful sine inverter, battery charger and automatic switch in a compact casing [56]. It also includes two AC inputs to connect two independent voltage sources, such as the national power grid and a diesel generator. The Quattro automatically selects the source where the voltage is present or, if present in both, the one in the first AC-in-1 input. It also has two AC outputs, which are extremely useful for defining two different modes of operation for ordinary loads and priority loads.

Homes or buildings equipped with solar panels or other sustainable energy sources have a potential self-contained energy supply that can be used to power essential items in the event of a power outage. One problem in this regard, however, is that grid-coupled solar panel systems shut down as soon as grid power fails. With a Quattro and batteries, this problem can be solved since the Quattro can replace the grid power supply during a power outage. When sustainable power sources produce more energy than needed, the Quattro will use the surplus to charge the batteries; in the event of a shortage, the Quattro will provide additional power from its battery energy resources. In the event of a power failure, the Quattro switches to backup inverter operation and takes over the power supply of connected devices. This is done so quickly that it does not disturb the operation of computers and other electronic devices [57]. This makes Quattro very suitable as a **backup system** and is the main reason for its choice for this project.

The Quattro can supply a huge charging current. This implies heavy loading of the shore connection and expensive wiring. Then, for both the AC inputs a maximum current can be set. Moreover, the Quattro is equipped with 3 programmable relays. The relays can be programmed for all kinds of other applications. It is equipped also with 2 analog/digital input/output ports, usable for several purposes. One application is communication with the BMS of a lithium-ion battery.

The manual provides valuable information for installing the inverter. For instance, it prescribes that the Quattro must be surrounded by a free space of at least 10 cm for cooling purposes and it must be posed close to the batteries to reduce voltage loss across the battery leads to a minimum. The Quattro has no internal fuses, so they must be installed externally at the DC side.

The inverter does incorporate a mains frequency isolating transformer. This precludes the possibility of DC current at any AC port. Therefore, type A RCD's can be used.

The AC inputs must be protected by a fuse or magnetic circuit breaker rated at 100A or less, and cable cross section must be sized accordingly. If the input AC supply is rated at a lower value, the fuse or magnetic circuit breaker should be downsized accordingly.

For the AC output 1, an earth leakage circuit breaker and a fuse or circuit breaker rated to support the expected load must be included in series with the output, and cable cross-section must be sized accordingly. The maximum rating of the fuse or circuit breaker is 135A for 8kVA models.

The AC output 2 support loads of up to 50A. An earth leakage circuit breaker and fuse rated at max. 50A must be connected in series with it.

The Quattro does not include MPPTs. Thus, they will be coupled with nine **BlueSolar 150/70 MPPTs**, which have the dual function of maximum power point trackers and solar chargers [58]. This is the most advanced model of MPPT, compatible with Quattro, that is available for purchase in Zambia. This is because **ZICTA** (Zambia Information and Communication Technologies Authority) does not allow smart products to be imported into the country without a license from them, and all later models of MPPTs, which have smart features, such as bluetooth, do not have a valid license.

The BlueSolar charger is protected against over-temperature. The output is fully rated up to an ambient temperature of 40°C. Should the temperature further increase, the output current will be derated.
As stated in the manual, the battery supply must be protected by a fuse, with a fuse rating between 80A and 100A for BlueSolar MPPT 150/70.
For the PV array side, it is necessary to provide a way to disconnect all current-carrying conductors of a photo-voltaic power source from all other conductors in a building or other structure. Therefore, a disconnect switch per string will be installed. The manual prescribes the use of flexible multi-stranded copper cable for the battery and PV connections. The typically utilized cable is the FG21M for

photovoltaic applications. It has a red sheath for the positive pole and black for the negative pole.

This solar charger has a maximum charge current of 70A and a maximum PV voltage of 150V. This product has a 5-year limited warranty. This limited warranty covers defects in materials and workmanship in this product and lasts for five years from the date of original purchase of this product.

Finally, **Pylontech US2000** modules were selected. Each module has a capacity of 2.4 kWh, so twelve modules will be placed in parallel to achieve an overall rated capacity of 28.8 kWh.

These batteries are non-toxic and non-polluting. Cathode material is made from LiFePO4 with safety performance and long cycle life. Battery management system (BMS) has protection functions including over-discharge, over-charge, over-current and high/low temperature. The system can automatically manage charge and discharge state and balance current and voltage of each cell. Flexible configuration, multiple battery modules can be in parallel for expanding capacity and power.

The working temperature range is from -10° to 50°. Moreover, the small size and light weight, standard of 48cm embedded designed module, is comfortable for installation and maintenance.

The modules must be connected in parallel. The provided power cables for modules connection can support a maximum current of 120A. If the battery string’s current over this limit, it must configure 2 pare external power cables to reach 240A, as shown in Figure 44 - Pylontech US2000 wiring for high currents [59].

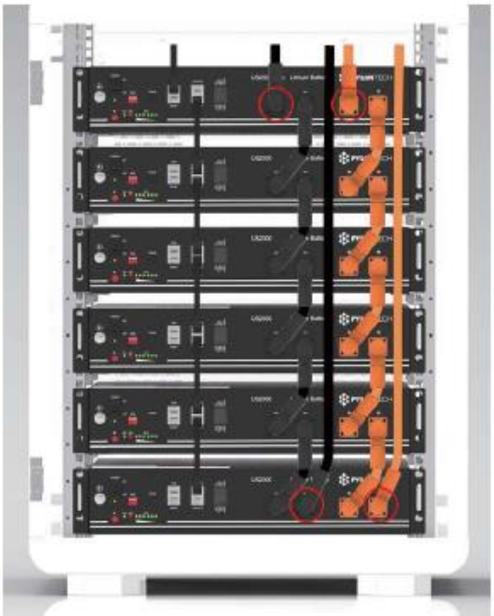


Figure 44 - Pylontech US2000 wiring for high currents

Data sheets for the main components - photovoltaic panels, inverters, MPPTs, and batteries - are given in the Appendix B.

### 4.4.3. Electrical sizing and electrical diagram

The MPPTs introduce some electrical constraints, which must be respected by the PV module configuration. The electrical constraints imposed by the BlueSolar MPPT are listed below:

| Model | BlueSolar MPPT 150/70 | |
|---|---|---|
| PV rated power | 4000 | W |
| PV maximum open circuit voltage | 145 | Vdc |
| PV maximum short circuit current | 50 | A |
| Rated charging current for batteries | 70 | A |

Table 12 - BlueSolar MPPT electrical constraints

To know the maximum number of modules connectable to each MPPT, it is necessary to divide the maximum input DC power by the nominal power of the module.

$$Max\ Modules\ Number = \frac{4 * 10^3}{335}\left[\frac{W}{W}\right] = 11\ [-] \tag{34}$$

Equation 34 - Max Modules Number per MPPT

The maximum number of strings in parallel can be found by dividing the maximum DC input current of the MPPT by the maximum current of a module at the worst conditions. Since the current grows with increasing temperature, the worst conditions occur with the highest ambient temperature. It's also been considered a maximum irradiance of 1000 $\frac{W}{m^2}$. The maximum average temperature in Livingstone is 32.6 °C. Then, it's necessary to calculate the corresponding cell temperature and the relative DC current through the following formulas:

$$T_{cell} = T_{amb} + \frac{NOCT - T_{ref,NOCT}}{G_{NOCT}} * G_{ref}\ [°C] = 58.8\ [°C] \tag{35}$$

Equation 35 - Max Cell Temperature in Livingstone

Anyway, to be conservative a maximum temperature of 80 °C has been considered.

$$I_{cell,worst\_cond} = I_{SC,ref} * \frac{G}{G_{ref}}\left(1 + \alpha * \left(T_{cell} - T_{cell,ref}\right)\right) = 12.15[A] \tag{36}$$

Equation 36 – Max Cell Current Calculation

The following data from the PV module datasheet and a meteorological database are being utilized for the calculations:

| **NOCT Electrical Data** | | |
|---|---|---|
| **NOCT** | 41 | °C |
| **Tnoct_ref** | 20 | °C |
| **Gnoct** | 800 | W/m2 |
| **References** | | |
| **Gref** | 1000 | W/m2 |
| **Tc_ref** | 25 | °C |
| **Geographical site info** | | |
| **Tamb_max** | 32.6 | °C |
| **Tamb_min** | 6.3 | °C |
| **PV module:**<br>**HiKu CS3L** | | |

| Electrical data | | |
|---|---|---|
| **$\alpha$(Isc)** | 0.05 | %/°C |
| **β(Voc)** | -0.28 | %/°C |
| **γ(Pmpp)** | -0.36 | %/°C |

Table 13 - Data for electrical constraint calculations

The maximum number of strings results equal to:

$$Max\ Strings\ Number = \frac{I_{DC,input\ MPPT}}{I_{cell,worst\_cond}}\ [-] = 4 \tag{37}$$

Equation 37 – Max Number of Strings Calculation

To calculate the maximum and the minimum number of modules per string, it's necessary to calculate the voltage of the strings in the worst conditions; with the lowest ambient temperature, which determines the higher string voltage. The formulas utilized are the following ones:

$$T_{cell\_min} = T_{amb} + \frac{NOCT - T_{ref,NOCT}}{G_{NOCT}} * G_{ref}\ [°C] = 32.55\ [°C] \tag{38}$$

Equation 38 - Minimum cell temperature in Livingstone

$$V_{cell,worst\_cond} = V_{OC,ref} * \left(1 + \beta * \left(T_{cell} - T_{cell,ref}\right)\right) [V] = 42.16\ [V] \tag{39}$$

Equation 39 - Cell voltage in real conditiond

Again, to be conservative a minimum temperature cell of 0 °C and a maximum temperature cell of 80 °C were considered. Then, these results are obtained:

$$Max\ Modules\ per\ String = \frac{V_{DC,\max\ \_input\ MPPT}}{V_{max,worst\_cond}}\ [-] = 3 \tag{40}$$

Equation 40 - Maximum Number of modules in series

It is important to remember that the string in parallel must have the same number of modules in series, since they must work at the same voltage. Finally, the combination of strings in parallel and modules in series, which matches with the

MPPTs, has been defined. There will be three strings in parallel of three modules in series each.

| BlueSolar MPPT 150/70 | | | |
|---|---|---|---|
| | Limit value | Calculated Value | |
| Voltage ok | 145 | 126,47 | V |
| Current ok | 50,00 | 34,58 | A |
| Power ok | 4000 | 3015,00 | W |

Table 14 - Limits verification

Thus, the total number of PV panels must be a multiple of 3. The PV modules will then be 81, meeting the geometric constraint. The MPPTs will be 9, divided into three balanced groups. Each could provide to the Quattro a maximum power of about 9 kW, so the inverter is slightly undersized (88,9% of the PV array power).

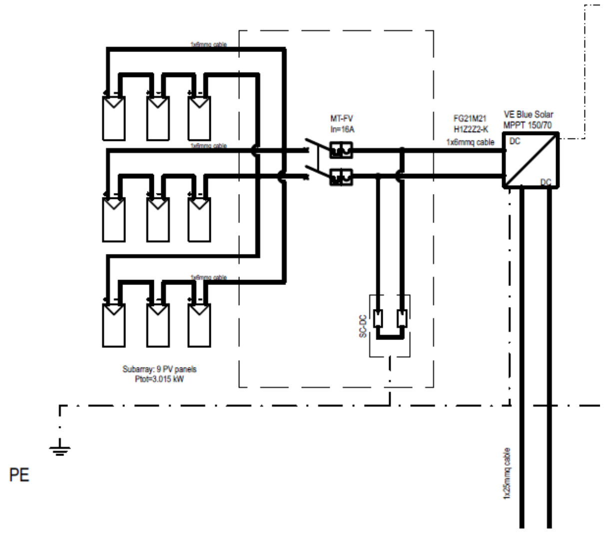


Figure 45 - Zoom on the PV modules configuration for one MPPT

Seven MPPTs will have all PV panels connected from the same roof pitch, so they will be perfectly efficient. While the remaining two MPPTs will have, respectively, six panels from the north pitch and three panels from the west pitch, and six panels from the east pitch and three panels from the west pitch, so they will be less efficient. Unfortunately, this is a choice forced by the electrical and geometrical limitations of the installation. All the MPPTs will be connected in parallel with the Quattro inverters and the batteries, through a busbar. The electrical configuration will create three balanced groups, composed of three MPPTs, one Quattro, and a stack of four battery modules in parallel. This expedient allows to significantly decrease the current on the DC side from the PV arrays to the other components and enables an easier and cheaper cables sizing. The reason is that this will reduce the current flowing through the cables and the bus bars. Current entering the bus bar from an MPPT may travel through a short path to the inverter or battery. This current does not have to travel through the entire busbar. This keeps the local current value low [31].

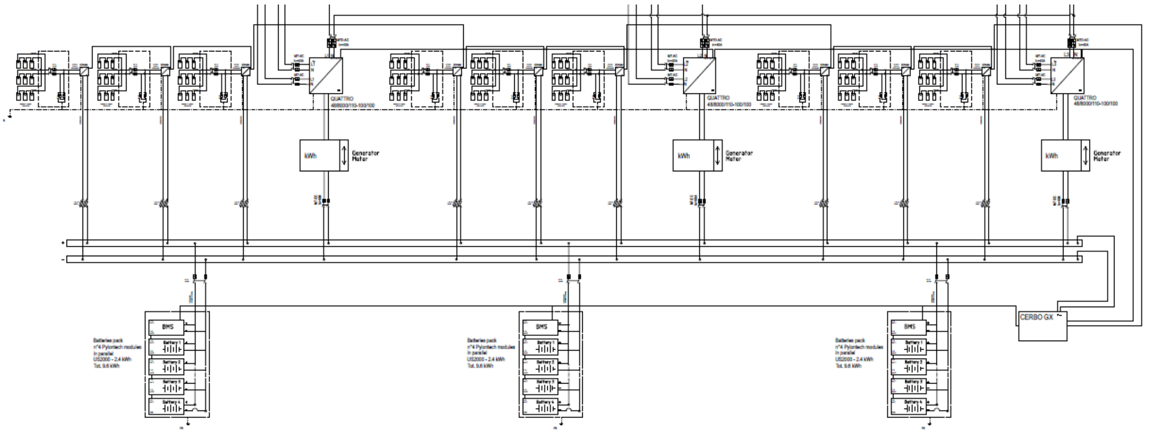


Figure 46 - DC side electrical diagram

Then, to proceed with the sizing of the circuit breakers and protections for the DC side, a calculation of all currents is required. Due to the configuration alternating MPPTs and inverters, the maximum PV array current is limited to the maximum current of three MPPTs instead of nine.

| DC Max Charge current | | |
|---|---|---|
| From MPPTs to Quattro and battery | | |
| I charge max | 70 | Adc |
| I charge max TOT | 210 | Adc |

Table 15 - Max Current from the PV array

So, the maximum charging current from the MPPTs, flowing through each section of the busbar, is 210 A. While the maximum charging current from the Quattro to the battery modules results from the datasheet as pictured in Table 16 - Maximum Charging Current from Quattro.

| DC Max Charge current | | |
|---|---|---|
| From Quattro to batteries | | |
| Imax | 200 | Adc |
| Imax TOT | 600 | Adc |

Table 16 - Maximum Charging Current from Quattro

This current is significantly high, but it is not a real constraint since it can be set to any value through the Quattro control system. Therefore, it will be set equal to the maximum current resulting from the other constraints.

The last current to consider is the discharge current, which depends on the batteries and the possible maximum discharge current of the Quattro.

| DC Max Discharge current | | |
|---|---|---|
| From batteries to Quattro | | |
| I max disch battery | 50 | Adc |
| I max disch battery TOT | **600** | Adc |
| I rated disch battery | 25 | Adc |
| I rated disch TOT | 300 | Adc |
| I abs Quattro TOT | **500** | Adc |

Table 17 - Maximum Discharge Currents

The maximum current that can be drawn by the inverters was calculated as:

$$I_{abs\ Quattro\ TOT} = \frac{8000[W] * 3\ [inverters]}{48\ [V]} = 500\ [A] \tag{41}$$

Equation 41 - Maximum discharging current by Quattros calculation

This should be the maximum current flowing through the bus bar and DC cables. But it is very high and would result in a huge cable cross section. To reduce the complexity and cost of wiring, it was decided to reduce the power that can be absorbed by the inverters Quattro from the battery pack. This is possible through the Victron control app, through which the power of the Quattro can be limited. Therefore, at times when the batteries provide power to the system (at night and when it is raining or cloudy), the power of the inverters must be limited manually through the app. To avoid damage to the cables in case Olga's staff forgets, there will be a switch on the side of the battery that will let through only the maximum current safety allowed by the system. It was decided to limit the power of each Quattro to 3000 W, therefore the new maximum current that can be drawn by the inverters is equal to 187.5 A.

Therefore, the busbar must support a maximum current of 210 A, determined by the maximum charging current of the MPPT groups. The section of the busbar must be equal to the largest cross section calculated for DC cables.

Once the flowing currents are calculated, it is possible to apply the BS 7671 and calculate the protections' nominal currents and cables cross sections. For each section of the wiring, the $I_b$, which is the design current of the circuit, has been identified. Then, it is necessary to choose the $I_n$, which is the rated current or current setting of the protective device. It must be equal to or higher than $I_b$ and depends on the available protection devices sizes on the market. Finally, the following formula must be applied:

$$I_t \geq \frac{I_n}{C_a C_g C_i C_c} \tag{42}$$

Equation 42 - Calculation of the tabulated current

In this case, the only rating factor to consider is $C_a$, factor for ambient temperature. The maximum system temperature has been considered 35 °C. The type of cable chosen is the single-core 70°C thermoplastic insulated cables, non-armoured, with or without sheath, which correspond to the tables 4B1 of the BS 7671 Appendix 4 [60]. So, the $C_a$ factor results equal to 0.94. Knowing $I_t$, it possible to obtain the cables cross section and maximum current supported by the cables through the table 4D1A of the BS 7671 Appendix 4 [61]. The results of the calculations are summarized in the table below.

| **From PV to MPPT ∀ MPPT** | | | **From MPPT to busbar ∀ MPPT** | | | **From batteries to busbar ∀ battery** | | | **From inverters to busbar ∀ inverter** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ib** | 35 | A | **Ib** | 70 | A | **Ib** | 210 | A | **Ib** | 63 | A |
| Magnetothermic switch | | | DC fuse | | | Magnetothermic switch | | | Magnetothermic switch | | |
| **In** | 36 | A | **In** | 80 | A | **In** | 210 | A | **In** | 80 | A |
| | | | | | | | | | | | |
| **It** | 38 | A | **It** | 85 | A | **It** | 223 | A | **It** | 85 | A |
| Cable choice | | **6mmq** | Cable choice | | **25mmq** | Cable choice | | 95mmq | Cable choice | | 25mmq |
| **Iz** | 41 | A | **Iz** | 101 | A | **Iz** | 232 | A | **Iz** | 101 | A |
| | | | | | | or (second option) | | | | | |
| | | | | | | Cable choice | | 2x21,15 mmq | | | |
| | | | | | | **Iz** | 240 | A | | | |

Table 18 - Sizing of protections and cables DC side

Once the cross section of the cable has been determined, it is necessary to check the voltage drop throughout the cables. It is possible through the table 4D1B of the BS 7671 Appendix 4, which provides a voltage drop factor in $\frac{mV}{A*m}$ [62]. Then, the following formula must be applied:

$$\Delta V = mV * I_b * L \tag{43}$$

Equation 43 - Voltage drop

The cable length was 2 m since the components should be as close as possible. Finally, to evaluate the voltage drop percentage, the nominal voltage of 48V was considered.

| **From PV to MPPT ∀ MPPT** | | | **From MPPT to busbar ∀ MPPT** | | | **From batteries to busbar ∀ battery** | | | **From inverters to busbar ∀ inverter** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Delta V** | 7,3 | mV/m*A | **Delta V** | 1,75 | mV/m*A | **Delta V** | 1,75 | mV/m*A | **Delta V** | 1,75 | mV/m*A |
| **Percentage** | 0,5 % | ok | **Percentage** | 0,5 % | ok | **Percentage** | 0,8 % | ok | **Percentage** | 0,5 % | ok |
| | | | | | | | | | | | |
| **Tot voltage drop** | | 2,25 % | | | | | | | | | |

Table 19 - Voltage drops of DC cables

The overall voltage drop is below 3% as prescribed by the standards. Moreover, the generation meters are posed on the DC side of each Quattro inverter to allows the DNO to track the plant production.

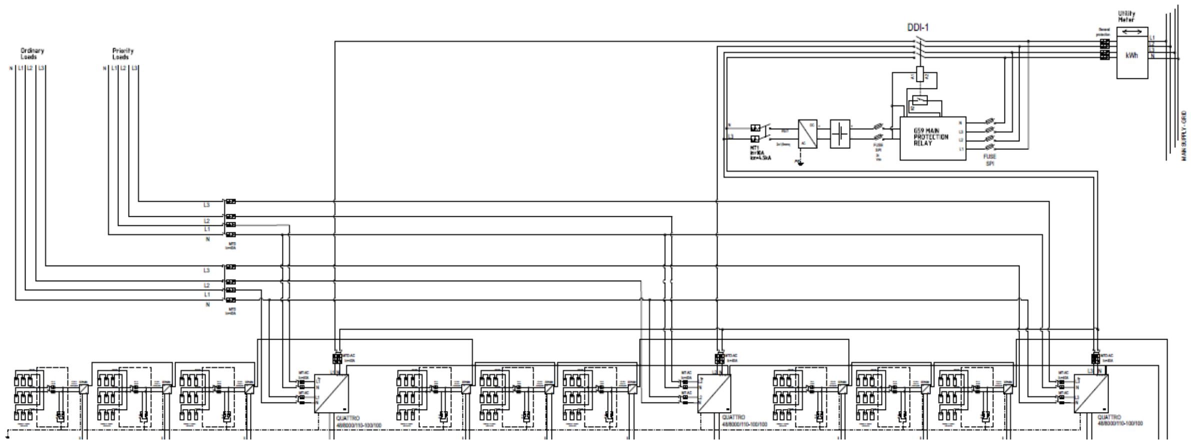


Figure 47 - AC side electric diagram

The same process has been carried out also for the AC side, obtaining the results, summarized in the following table.

| **Ordinary Loads** | **Priority Loads** | **Ordinary Loads** | **Priority Loads** |
|---|---|---|---|
| Each inverter | Each inverter | Parallel 3ph 1 | Parallel 3ph 2 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ib** | 39 | A | **Ib** | 39 | A | **Ib** | 39 | A | **Ib** | 39 | A |
| MT switch | | | MT switch | | | type A RCD | | | type A RCD | | |
| **In** | 40 | A | **In** | 40 | A | **In** | 40 | A | **In** | 40 | A |
| | | | | | | | | | | | |
| **It** | 43 | A | **It** | 43 | A | **It** | 43 | A | **It** | 43 | A |
| Cable choice | | **10mm q** | Cable choice | | **10mm q** | Cable choice | | **10mm** q | Cable choice | | **10mm q** |
| **Iz** | 57 | A | **Iz** | 57 | A | **Iz** | 50 | A | **Iz** | 50 | A |

Table 20 - Sizing of protections and cables AC side, part 1

| | | | | | |
|---|---|---|---|---|---|
| **Input AC** | | | **Input AC** | | |
| Each inverter | | | Each inverter | | |
| **Ib** | 39 | A | **Ib** | 39 | A |
| MT switch | | | MT switch | | |
| **In** | 40 | A | **In** | 40 | A |
| | | | | | |
| **It** | 43 | A | **It** | 43 | A |
| Cable choice | | **10mmq** | Cable choice | | **10 mmq** |
| **Iz** | 46 | A | **Iz** | 46 | A |

Table 21 - Sizing of protections and cables AC side, part 2

| **Ordinary Loads** | | | **Priority Loads** | | | **Ordinary Loads** | | | **Priority Loads** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Each inverter** | | | Each inverter | | | Parallel 3ph 1 | | | Parallel 3ph 2 | | |
| **Delta V** | 4,4 | mV/m*A | Delta V | 4,4 | mV/m*A | Delta V | 3,8 | mV/m*A | Delta V | 3,8 | mV/m*A |
| **Percentage** | 0,4 % | ok | Percentage | 0,4 % | ok | Percentage | 0,2 % | ok | Percentage | 0,2 % | ok |
| | | | | | | | | | | | |

Table 22 - Voltage drops of AC side, part 1

| **Input AC** | | | **Input AC** | | |
|---|---|---|---|---|---|
| **Each inverter** | | | Each inverter | | |
| **Delta V** | 4,4 | mV/m*A | Delta V | 3,8 | mV/m*A |
| **Percentage** | 0,2% | ok | Percentage | 0,2% | ok |
| | | | | | |
| **Tot voltage drop** | | 1,10% | | | |

Table 23 - Voltage drops of AC side, part 2

The overall voltage drop must be about 1% for the AC side.

Finally, **Engineering Recommendation G59/2-1** applies because the generators generates more than 16A per phase. Therefore, the G59 Mains Protection Relay must be installed between the embedded generator and the grid. The precise settings of the relay must be concorded with the DNO.

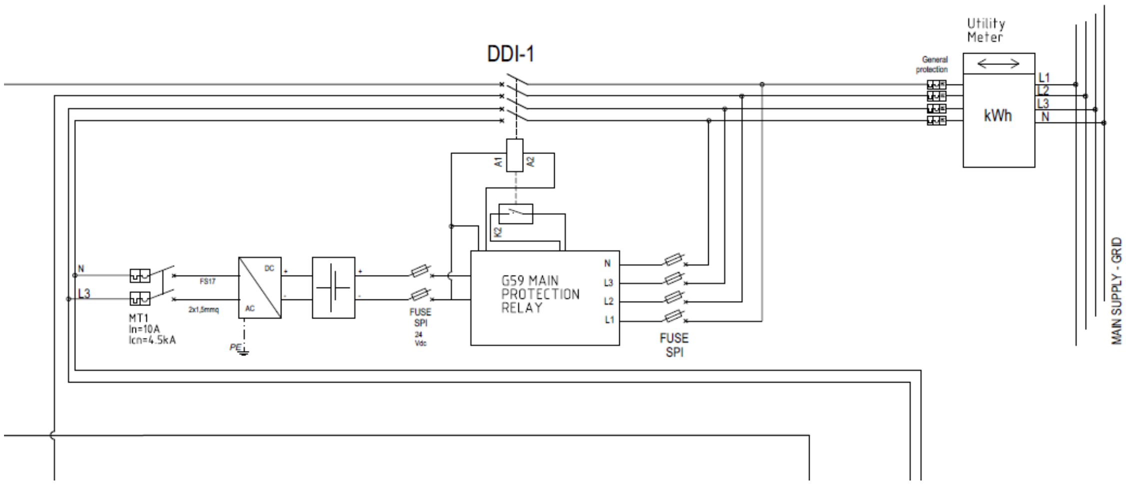


Figure 48 - Focus on G59 main protection relay

The final electrical diagram is the following page.

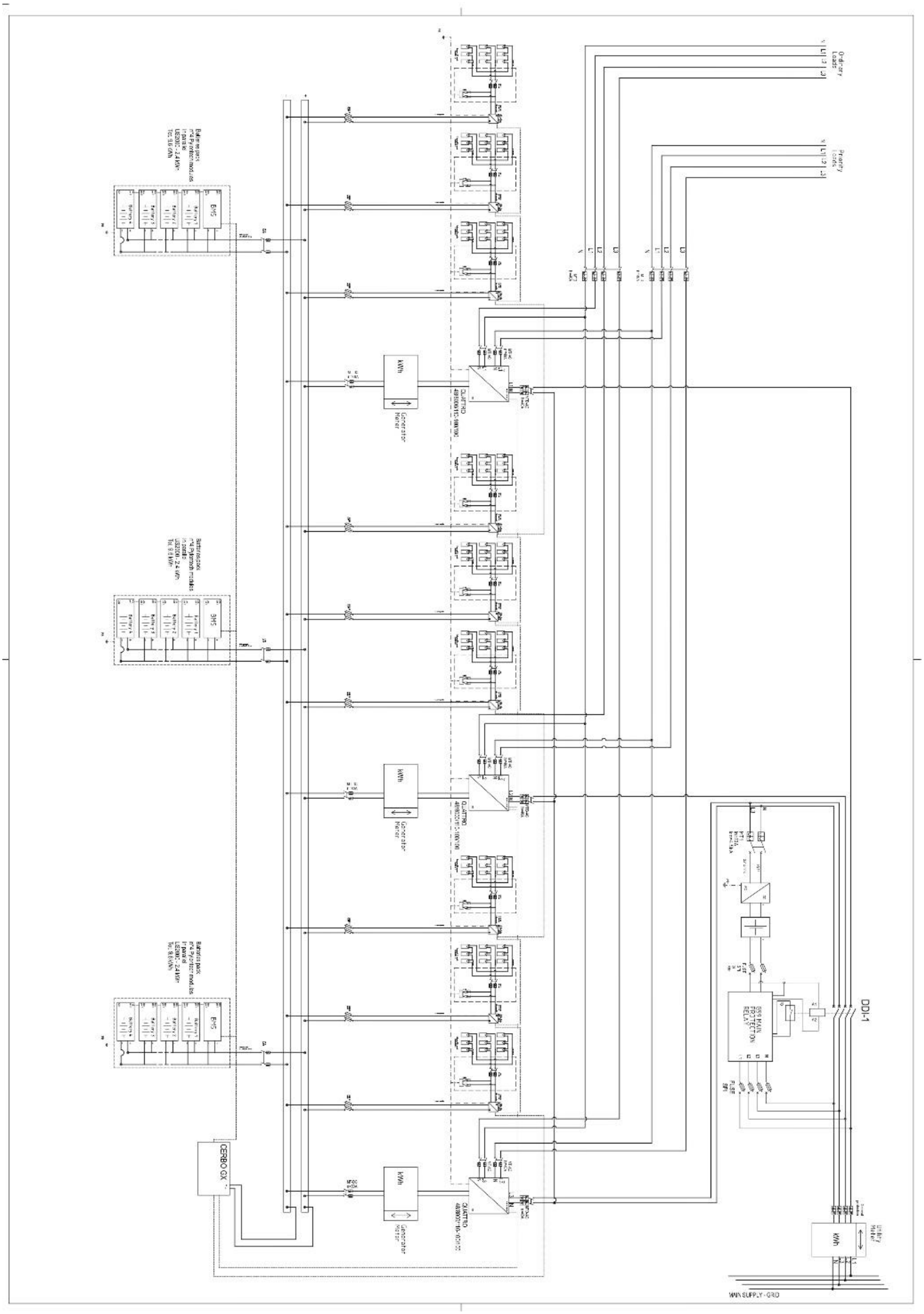


Figure 49 - Electrical Diagram

A final comment needed concerns the control and monitoring system. The **Cerbo GX** system is connected to the Victron Remote Management (VRM) portal and can also be accessed through the application or the GX Touch interface. It is directly connected to battery BMSs, Quattro inverters and MPPTs. It provides immediate monitoring of battery charge status, power consumption, PV generator and power harvesting, and verification of tank levels and temperature measurement. It allows easy control of the input current limit from the AC side of the inverter, start/stop (automatic) of the Quattro, and customization of various system optimization options. In addition, it is a valuable tool for remote troubleshooting.

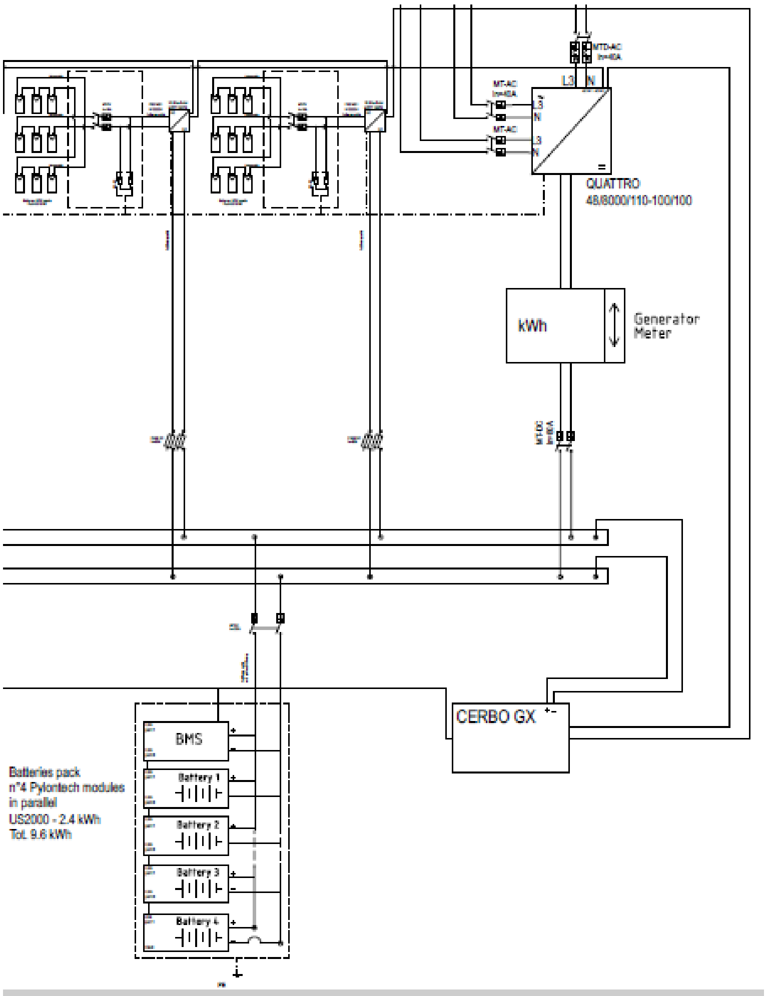


Figure 50 - Focus on Cerbo GX connections

# 5 Final remarks

This thesis work focused on the design of a three-phase photovoltaic system that could serve as a backup system during power outages. The general design criteria have been applied to the case study of a Zambian nonprofit guesthouse; a project placed within the framework of an international cooperation operation.

The study produced interesting results, especially from a technical perspective. It was shown that a photovoltaic system of at least 23 kWp, installed on the roof of the building, and a battery pack with at least 28 kWh of capacity can guarantee coverage of priority loads and part of other loads for 13 hours in the event of a blackout. The system can also ensure a very good percentage of self-consumption, which helps reduce electricity costs considerably. The executive sizing has led to the identification of components on the local market with which the system itself can be realized. This part of the sizing was severely limited by the inability to conduct a site inspection and, consequently, will have to be revised and corrected following the actual executive inspection.

From an economic point of view, high investment costs have been found, mainly due to the possible support structure and travel for the preliminary and executive inspections. This highlights how it is always more cost-effective to cooperate with companies stationed in the proximity of the facilities and, for development projects, how the transmission of necessary know-how to local professionals should be the focus of cooperation. From the perspective of Olga's staff, who would receive the facility as a donation, the economic savings would be substantial, as the calculations have shown. The savings would allow for necessary component replacements over the years and, at the end of the plant's life, would cumulatively amount to approximately $111,500.

A final consideration regarding the monitoring system is important. The brand chosen for the core of the plant offers a customizable monitoring system that connects all plant components. It is critically important not only for optimized management of the entire system in ordinary and backup operations, but also to ensure that the installation company can verify the proper functioning of components and troubleshoot problems remotely as well.

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# A Appendix A

This appendix will give more information about the cooperation framework in which the presented case study is posed.

The landscape of international cooperation has evolved over the decades, going through different visions, from the financial push paradigm to the governance paradigm, to the present day. The goal of today's cooperation is economically, socially, and environmentally sustainable development, and underpinning the implementation projects are increasingly the concepts of multifactorality, cooperation among different stakeholders, and the uniqueness of each ecosystem in which action is taken. The tools used in planning interventions have also changed over time. Today the main tools used for energy planning in the development sector are project cycle management (**PCM**) and comprehensive energy solution planning (**CESP**).

PCM consists of six phases:

1. **Programming**: the priorities of the intervention, the geographical area targeted, and the social groups involved are typically chosen by the donors or international organizations coordinating the project;
2. **Identification**: the initial elaboration of the operation in terms of stakeholder identification and analysis of the problems, objectives and strategies to be used takes shape at this stage;
3. **Formulation**: once the relevance and feasibility of the project has been confirmed, a detailed project design including activities, management and coordination arrangements, and a timeline study is carried out;
4. **Financing**: it is essential to prepare a budget and financial plan based on the activities;
5. **Implementation**: the project is actually implemented at this stage and the results achieved;
6. **Evaluation**: this phase conceptually closes the PCM circle, but temporally accompanies the project throughout its implementation through monitoring, review, and reporting activities.

For the project presented in this thesis, the identification and formulation phases were addressed by the team, and the resulting output is set out in the following paragraphs.

The project's CESP has already been reported in chapter Results. Also CESP consists of several phases:

1. **Needs identification**: the application of this phase is varied since the definition of energy access is broad and needs may be different. In the case illustrated, the main needs of the beneficiaries were to cope with frequent blackouts and to reduce their electricity bills;
2. **Base load demand and forecast resource assessment**;
3. **Solution identification and strategy selection**;
4. **Technical design and optimization**;
5. **Comprehensive design and business model identification**;
6. **Impact evaluation**: this aspect of CESP has not been covered in this thesis as the project is still in an embryonic stage and its evaluation will be done much later in time.

## A.1. PCM identification phase

### A.1.1. Stakeholders' analysis

The beneficiary of the project will be Olga's - The Italian Corner and, consequently, the Youth Community Training Center. The applicant organization is still Olga's, which belongs to the Catholic Diocese of Livingstone. The official supervisors of the project are Lucia Wegner, an economist, donor and longtime Olga's collaborator, and Lidia Diappi, a professor at the Milan Polytechnic and supervisor of past construction activities since Olga's inception. Finally, the implementing agency will be EQUA SRL, as the project's technical partner.

### A.1.2. Problems analysis

Zambia electrical energy system is based on hydropower, which accounts for 84% of the total electrical power production [63]. Hydropower is a *renewable* energy source, but it may not be a *reliable* energy source. In fact, in **2014-2015**, the country experienced an **electricity crisis** due to low seasonal rainfall. The event clearly showed the national problem of infrastructures and equitable energy distribution. In Zambia, 43% of the total population is connected to the national grid. This percentage rises to nearly 80% in urban areas and drops to about 14% in rural areas [64].

But being connected to the grid doesn't necessarily mean having reliable access to power. Load shedding is, in fact, a very common practice. Therefore, households and businesses experience many blackouts per month. Between 2015 and 2016, most households experienced up to 16 hours of blackouts per day. In general, Zambia is aligned with power outage trends in sub-Saharan Africa. In the region, 76.2% of businesses have experienced power outages, which on average occur **8.3 times in a typical month** [65], **with each outage lasting an average of 5.8 hours**. Outages cost an average of 8.5% of annual sales [47].

The Zambian government is looking to improve infrastructure, also through public-private partnerships and funding from foreign donors. There is a focus on solar technologies that could provide access to electricity even in rural areas. The main electricity supplier is the Zambian Electricity Supply Corporation Limited (ZESCO), which is a state-owned company, established in 1970. Requests for privatization are increasing due to complaints about poor grid management. To address the energy crisis, ZESCO scheduled load shedding in advance, announcing times and zones. Planned outages have been up to 12 hours per zone. The company claims that the grid is becoming more reliable, and load shedding will no longer be necessary. Currently, many outages still occur due to maintenance work and other causes [45].

Olga's is located in the Southern Region, which is slightly less affected by the power outages problem than other regions of Zambia, but still had to purchase a diesel generator to deal with it. Producing electricity through a diesel generator set is expensive and inefficient, so power outages are a significant cost to the hotel.

In addition, Zambia's electricity **costs are likely to increase** in the following years. In 2014, Zambia had the lowest electricity tariffs in SSA because ZESCO had a minimal variable cost of power generation, as almost all of the power came from renewable hydropower, which has no marginal costs associated with generation. After the 2014-2015 energy crisis, ZESCO raised rates several times and this trend appears to continue in the coming years [65].

### A.1.3. Objectives analysis

The technical objectives of the project are the following:

1) Provide an **efficient and cost-effective backup system** to address power outages. This must ensure that it covers at least priority loads in the event of a power outage and must offer lower costs than the current diesel generator backup system;
2) Lower the fossil fuel dependence of the hotel, moving to a **greener source of energy,** to decrease its environmental impact;

3) Increase Olga's **degree of independence from the national grid** to lower the current electric cost and prevent the likely increase in energy costs.

### A.1.4. Strategy analysis

The technical proposal of the EQUA company consists of a **photovoltaic system** composed of photovoltaic panels, hybrid inverters and battery pack. This solution allows Olga's to exploit the potential of solar energy, which is remarkably high throughout the country, and to benefit from government incentives on renewable energy, such as zero VAT on photovoltaic panels and solar batteries [66].

The solar field can be installed on the roof of the hotel. It provides Olga's with energy during sunny hours, covering all or part of the loads and thus lowering electricity cost. By coupling the system with a battery pack, the energy produced can be stored and used to cover peak loads that are not directly covered by solar production. It allows the hotel to lower its cost even more and be more independent from the national grid throughout day and night. In addition, batteries are critical for dealing with power outages and ensuring that at least priority loads are met.

## A.2. PCM formulation phase

### A.2.1. Logical framework

| | **OBJECTIVES** | **INDICATORS** | **MEANS OF VERIFICATION** | **ASSUMPTIONS** |
|---|---|---|---|---|
| **Overall objectives** | **1.** Install an efficient and cost-effective backup system<br>**2.** Lower the electricity cost<br>**3.** Increase the degree of | **1.1** Costs of blackouts for the hotel – In 6 months<br>**2.1** Cost of energy for the hotel – In a year<br>**3.1** Amount of energy | **1.1** Diesel and batteries operating costs comparison – At the end of the project<br>**2.1** Cost comparison – Before and at the end of the project<br>**3.1** Cost comparison – | |

| | | | | |
|---|---|---|---|---|
| | independence from the national grid | purchased from the grid – In a year | Before and at the end of the project | |
| **Specific objectives** | **1.** Renewable and reliable energy self-production to address power outages | **1.1** Decrease dependence on fossil fuels: amount of diesel fuels bought every semester – In a year<br>**1.2** Number of hotel activities' interruption due to outages – In 6 months | **1.1** Diesel tickets – Every semester<br>**1.2** Survey to Olga's staff – In a year | ● The photovoltaic system works properly<br>● No significant change in climate and weather conditions in the next years |
| **Expected results** | **1.** Installation of a photovoltaic system with batteries pack<br>**2.** Long term financial sustainability | **1.1** Connection of the system to the national grid<br>**2.1** Yearly saving for Olga's with respect to the current situation | **1.1** Connection official document – After system installation<br>**2.1** Electricity cost comparison and maintenance tickets – In one year after the system installation | ● People use correctly and take care of the new technologies introduced<br>● No changes in politics and legislation |
| **Activities**<br>*Preliminary and side actions* | **0.1** Contract signing<br>**0.2** Online meeting with professor Diappi<br>**0.3** First payment tranche | | | ● Availability of workers to build the photovoltaic system<br>● Technologies suppliers are reliable |

| | | | | |
|---|---|---|---|---|
| | **0.4** Ask preliminary authorizations<br>**0.5** Online meeting with Olga’s staff | | | - Local availability of materials<br>- Absence of natural disasters or vandalism and corruption<br>- Availability of local workers for the maintenance and managing of the system |
| *Executive Inspection* | **1.1** EQUA and professor Diappi trip organization<br>**1.2** On-site research of a technician for the roof strength assessment<br>**1.3** Technical measures of the building<br>**1.4** Electrical measurement and assessment<br>**1.5** Meeting with local suppliers and technicians in Livingstone<br>**1.6** Meeting with suppliers and technicians in Lusaka | | | |
| *Reinforcement structure construction* | **2.1** Structure analysis<br>**2.2** Reinforcement design<br>**2.3** Components purchase<br>**2.4** Reinforcing components and fitting up | | | |
| *Plant Design and Sizing* | **3.1** Components choice<br>**3.2** PV panels layout<br>**3.3** Electrical system sizing<br>**3.4** Wiring diagram<br>**3.5** Writing the technical report | | | |

| | | | | |
|---|---|---|---|---|
| *Purchase of components* | **4.1** Final online meetings with suppliers<br>**4.2** Purchase of the components<br>**4.3** Transport logistic organization<br>**4.4** Supply and transport time | | | |
| *Installation* | **5.1** EQUA and professor Diappi trip organization<br>**5.2** Construction of the structure for supporting the roof/installation of the panels<br>**5.3** Meetings with local technicians<br>**5.4** PV modules installation on the roof<br>**5.5** Installation of inverters, batteries pack, and all the other electrical components<br>**5.6** System final check<br>**5.7** Start-up of the system | | | |
| *Paperwork* | **6.1** Checking installation normative for power production systems in Zambia<br>**6.2** Asking authorization to the Energy | | | |

| | | | | |
|---|---|---|---|---|
| | Regulation Board<br>**6.3** Payment of taxes<br>**6.4** Grid connection authorization<br>**6.5** Asking for other needed authorizations<br>**6.6** Final documentation<br>**6.7** Last payment tranche | | | |

Table 24 – Logical Framework Matrix

### A.2.2. Description of activities

**Preliminary and side actions**

The aim of all preliminary and side actions is to lay the foundations for further development of the project.

**0.1** EQUA and Olga's will sign the official contract.
**0.2** Online meeting with professor Diappi, Olga's and EQUA to define and confirm the following steps of the project.
**0.3** First payment tranche to EQUA.
**0.4** EQUA will ask all the preliminary authorization needed for the start of the project, including for instance the visas for the coming trips.
**0.5** Online meeting with the Olga's staff to gather more information and define the following steps.

**Executive Inspection**

A photovoltaic system will be installed, following the energy politics of the national government. The system will consist of PV panels, inverters, and batteries back.

**1.1** EQUA and professor Diappi will coordinate to organize the executive inspection trip.
**1.2** EQUA and professor Diappi will leave and stay in Zambia for a week. EQUA engineers present in Livingstone will look for a local technician which is able to perform a solidity assessment of the hotel's roof in order to precede with a secure PV module installation.
**1.3** EQUA engineers present in Livingstone will do the necessary technical measurement of the building, such as the roof dimensions.
**1.4** EQUA engineers present in Livingstone and, eventually, local electrician will do the necessary electrical measurement of the hotel electrical system.

**1.5** EQUA engineers and professor Diappi will meet the local suppliers in Livingstone to define components supply.
**1.6** EQUA engineers and professor Diappi will meet the local suppliers in Lusaka to define components supply.

### Construction of the reinforcement structure

The structural soundness of the roof structure is unclear, so the possible construction of a reinforcement or arbor structure over the existing roof must be included in the project design.

**2.1** Local experts will conduct an analysis of the structure, verifying the strength and durability of the roof
**2.2** The design phase of the reinforcement structure will be carried out
**2.3** The Livingstone diocese will purchase the necessary components
**2.4** Assembly of the components will be carried out by a local construction company.

### Plant Design and Sizing

After the executive inspection, all the needed information would be gathered, so it will be possible to start the plant design. EQUA will design the whole system in detail.

**3.1** EQUA engineers will choice the components among the ones proposed by the Livingstone and Lusaka suppliers.
**3.2** EQUA engineers will create the PV panels layout with the measurements taken on the site.
**3.3** EQUA will precede with the system sizing and final design.
**3.4** EQUA will provide the wiring diagram.
**3.5** EQUA will also provide a complete technical report with all the information for installation.

### Purchase of components

EQUA will purchase the selected components and will manage their shipping.

**4.1** Final meeting with the selected supplier to precisely define the purchase details.
**4.2** Equipment purchases with the contracts signing.
**4.3** EQUA will manage the shipping and stocks logistic, in collaboration with a local actor (all the equipment must be available at Olga’s for the installation phase).
**4.4** It will be necessary to wait for the supply and transportation time, which could be quite long.

**Installation**

After the design of the system and the purchase of the components, the actual construction of the photovoltaic system has to be done. It will take approximately 10 days. This phase of the project will include local technicians from previously contacted local companies.

EQUA and professor Diappi will coordinate to organize the trip.

**5.1** Consideration was given to building a structure above the roof to ensure its stability and ease of installation.
**5.2** Meeting with technicians from local companies to coordinate and define work schedules and methods.
**5.3** Local technicians will install the solar modules on the hotel's roof, with the supervision and the collaboration of the EQUA engineers.
**5.4** Local electricians will install the solar inverters, batteries and all the other electrical components, with the supervision and the collaboration of the EQUA engineers.
**5.5** After the installation phase, EQUA's engineers will check the entire system in detail, according to international standards.
**5.6** Start-up of the system

**Paperwork**

An important aspect of the project is also the regulatory research and submission of the necessary documents. EQUA will ensure that all necessary approvals are obtained, with the collaboration of Olga's staff and local stakeholders.

**6.1** EQUA will study the regulatory framework for power production system in Zambia. EQUA will partner with local stakeholders to gather more information.
**6.2** If necessary, EQUA will ask the Energy Regulation Board for the necessary authorizations.
**6.3** EQUA will ensure that all fees charged will be paid, over the course of the project.
**6.4** EQUA will provide the necessary documentation to connect the hotel's photovoltaic system to the national grid.
**6.5** EQUA will provide all the other necessary documentations and certifications.
**6.6** EQUA will also provide final documentation after final inspection and system start-up.
**6.7** Last payment tranche from donors to EQUA.

## A.2.3. Activity scheduling

### GANTT diagram

The project schedule is summarized in the following GANTT diagram. The time frame of the diagram begins with the signing of the contract between Olga's and EQUA.

| Activities | | Weeks | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| **Preliminary actions** | | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | |
| 0.1 | Contract signing | ■ | | | | | | | | | | | | | | | | | |
| 0.2 | Online meeting with professor Diappi and donors | | ■ | | | | | | | | | | | | | | | | |
| 0.3 | First payment tranche | | ■ | | | | | | | | | | | | | | | | |
| 0.4 | Ask preliminary authorizations | | ■ | ■ | | | | | | | | | | | | | | | |
| 0.5 | Online meeting with Olga's staff | | | | ■ | | | | | | | | | | | | | | |
| **Executive Inspection** | | | | | | | ■ | ■ | ■ | ■ | | | | | | | | | |
| 1.1 | EQUA and professor Diappi trip organization | | | | | | ■ | ■ | | | | | | | | | | | |
| 1.2 | Research of a technician for the roof strength assessment | | | | | | | | | ■ | | | | | | | | | |
| 1.3 | Technical measures of the building | | | | | | | | | ■ | | | | | | | | | |
| 1.4 | Electrical measurement and assessment | | | | | | | | | ■ | | | | | | | | | |
| 1.5 | Roof strength assessment | | | | | | | | | ■ | | | | | | | | | |
| 1.6 | Meeting with local suppliers and technicians in Livingstone | | | | | | | | | ■ | | | | | | | | | |
| 1.7 | Meeting with suppliers and technicians in Lusaka | | | | | | | | | ■ | | | | | | | | | |
| **Reinforcement Structure Construction** | | | | | | | ■ | ■ | ■ | ■ | | | | | | | | | |
| 2.1 | Structure analysis | | | | | | ■ | | | | | | | | | | | | |
| 2.2 | Reinforcement design | | | | | | ■ | ■ | | | | | | | | | | | |
| 2.3 | Components purchase | | | | | | | ■ | ■ | | | | | | | | | | |
| 2.4 | Reinforcement components and fitting up | | | | | | | | ■ | ■ | | | | | | | | | |
| **Plant Design and Sizing** | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 3,1 | Components choice | | | | | | | | | | ■ | ■ | ■ | | | | | | |
| 3,2 | PV panels layout | | | | | | | | | | | | ■ | | | | | | |
| 3,3 | Electrical system sizing | | | | | | | | | | | | ■ | ■ | | | | | |
| 3,4 | Wiring diagram | | | | | | | | | | | | | ■ | ■ | | | | |
| 3,5 | Writing the technical report | | | | | | | | | | | | | | ■ | ■ | | | |
| **Purchase of components** | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ |
| 4,1 | Final online meetings with suppliers | | | | | | | | | | | | | | | ■ | ■ | | |
| 4,2 | Purchase of the components | | | | | | | | | | | | | | | | | ■ | |
| 4,3 | Transport logistic organization | | | | | | | | | | | | | | | | | ■ | ■ |
| 4,4 | Supply and transport time | | | | | | | | | | | | | | | | | | ■ |
| **Installation** | | | | | | | | | | | | | | | | | | | |
| 5,1 | EQUA and professor Diappi trip organization | | | | | | | | | | | | | | | | | | |
| 5,2 | Building of the structure for the module installation | | | | | | | | | | | | | | | | | | |
| 5,3 | Meetings with local technicians | | | | | | | | | | | | | | | | | | |
| 5,4 | PV modules installation on the roof | | | | | | | | | | | | | | | | | | |
| 5,5 | Installation of inverters, batteries pack, and all the other | | | | | | | | | | | | | | | | | | |
| 5,6 | System final check | | | | | | | | | | | | | | | | | | |
| 5,7 | Start-up of the system | | | | | | | | | | | | | | | | | | |
| **Paperwork** | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 6,1 | Checking installation normative for power production systems | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | |
| 6,2 | Asking authorization to the Energy Regulation Board | | | | | | | | | | | | | | | ■ | ■ | ■ | |
| 6,3 | Payment of taxes | | | | | | | | | | | | | | | | | ■ | |
| 6,4 | Grid connection authorization | | | | | | | | | | | | | | | | ■ | ■ | ■ |
| 6,5 | Asking for other needed authorizations | | | | | | | | | | | | | | | | ■ | ■ | ■ |
| 6,6 | Final documentation | | | | | | | | | | | | | | | | | | |
| 6,7 | Last payment tranche | | | | | | | | | | | | | | | | | | |

Table 25 – First half of the project GANTT diagram

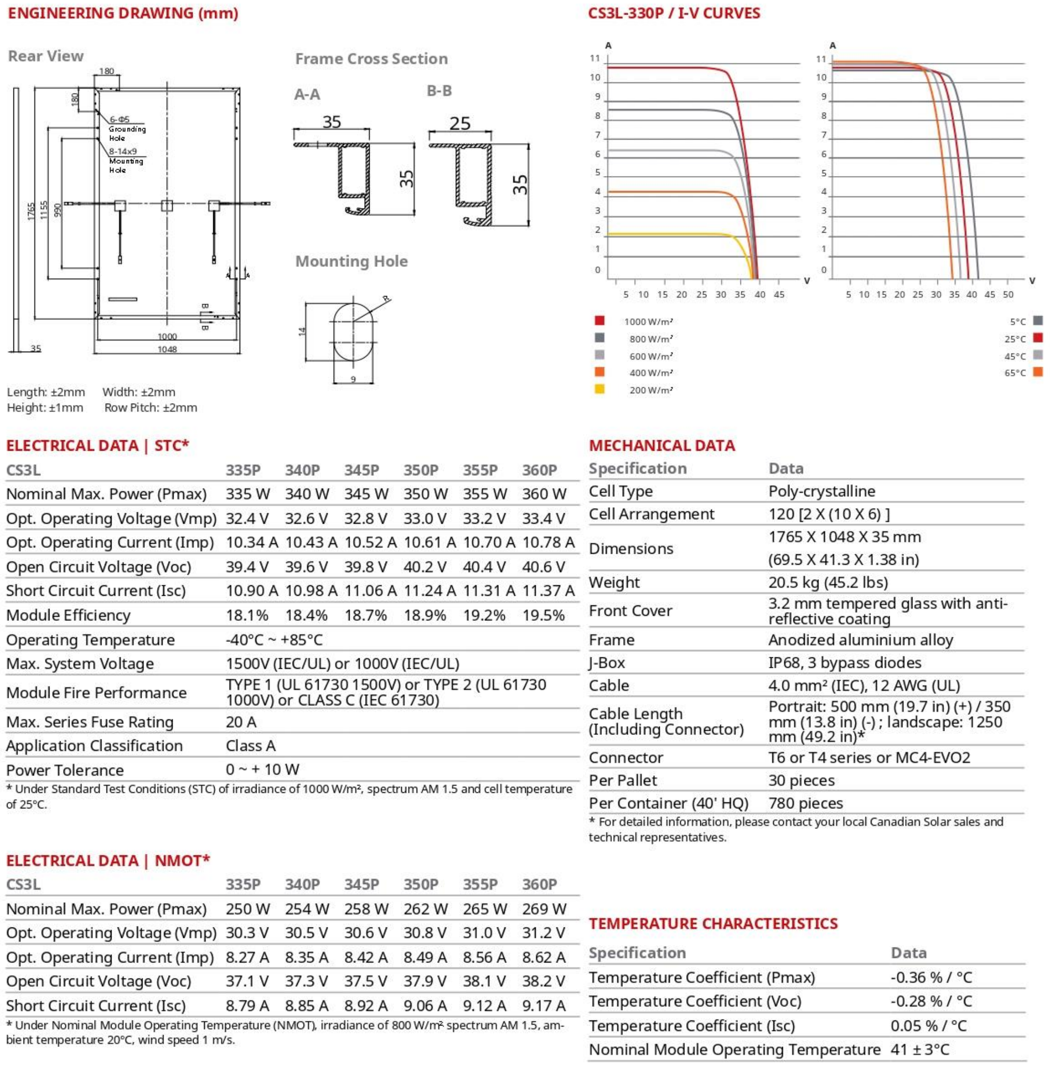
| Activities | | Weeks | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
| **Preliminary actions** | | | | | | | | | | | | | | | | | | |
| 0.1 | Contract signing | | | | | | | | | | | | | | | | | |
| 0.2 | Online meeting with professor Diappi and donors | | | | | | | | | | | | | | | | | |
| 0.3 | First payment tranche | | | | | | | | | | | | | | | | | |
| 0.4 | Ask preliminary authorizations | | | | | | | | | | | | | | | | | |
| 0.5 | Online meeting with Olga's staff | | | | | | | | | | | | | | | | | |
| **Executive Inspection** | | | | | | | | | | | | | | | | | | |
| 1.1 | EQUA and professor Diappi trip organization | | | | | | | | | | | | | | | | | |
| 1.2 | Research of a technician for the roof strength | | | | | | | | | | | | | | | | | |
| 1.3 | Technical measures of the building | | | | | | | | | | | | | | | | | |
| 1.4 | Electrical measurement and assessment | | | | | | | | | | | | | | | | | |
| 1.5 | Roof strength assessment | | | | | | | | | | | | | | | | | |
| 1.6 | Meeting with local suppliers and technicians in | | | | | | | | | | | | | | | | | |
| 1.7 | Meeting with suppliers and technicians in Lusaka | | | | | | | | | | | | | | | | | |
| **Reinforcement Structure Construction** | | | | | | | | | | | | | | | | | | |
| 2.1 | Structure analysis | | | | | | | | | | | | | | | | | |
| 2.2 | Reinforcement design | | | | | | | | | | | | | | | | | |
| 2.3 | Components purchase | | | | | | | | | | | | | | | | | |
| 2.4 | Reinforcement components and fitting up | | | | | | | | | | | | | | | | | |
| **Plant Design and Sizing** | | | | | | | | | | | | | | | | | | |
| 3,1 | Components choice | | | | | | | | | | | | | | | | | |
| 3,2 | PV panels layout | | | | | | | | | | | | | | | | | |
| 3,3 | Electrical system sizing | | | | | | | | | | | | | | | | | |
| 3,4 | Wiring diagram | | | | | | | | | | | | | | | | | |
| 3,5 | Writing the technical report | | | | | | | | | | | | | | | | | |
| **Purchase of components** | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | |
| 4,1 | Final online meetings with suppliers | | | | | | | | | | | | | | | | | |
| 4,2 | Purchase of the components | | | | | | | | | | | | | | | | | |
| 4,3 | Transport logistic organization | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | |
| 4,4 | Supply and transport time | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | |
| **Installation** | | | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | |
| 5,1 | EQUA and professor Diappi trip organization | | | | | | | | 🟦 | 🟦 | | | | | | | | |
| 5,2 | Building of the structure for the module installation | | | | | | | | 🟦 | 🟦 | | | | | | | | |
| 5,3 | Meetings with local technicians | | | | | | | | | | | | 🟦 | 🟦 | 🟦 | | | |
| 5,4 | PV modules installation on the roof | | | | | | | | | | | | | 🟦 | | | | |
| 5,5 | Installation of inverters, batteries pack, and all the | | | | | | | | | | | | | | 🟦 | | | |
| 5,6 | System final check | | | | | | | | | | | | | | 🟦 | | | |
| 5,7 | Start-up of the system | | | | | | | | | | | | | | 🟦 | | | |
| **Paperwork** | | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 |
| 6,1 | Checking installation normative for power production | | | | | | | | | | | | | | | | | |
| 6,2 | Asking authorization to the Energy Regulation Board | | | | | | | | | | | | | | | | | |
| 6,3 | Payment of taxes | | | | | | | 🟪 | | | | | | | 🟪 | | | |
| 6,4 | Grid connection authorization | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | |
| 6,5 | Asking for other needed authorizations | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | 🟪 | | | | | | | | | | |
| 6,6 | Final documentation | | | | | | | | | | | | | | | 🟪 | 🟪 | |
| 6,7 | Last payment tranche | | | | | | | | | | | | | | | | | 🟪 |

Table 26 – Second half of the project GANTT diagram

# B Appendix B

Excerpts from the data sheets of selected components are provided in this appendix for completeness.

## B.1. PV panels datasheet



**ENGINEERING DRAWING (mm)**

Length: ±2mm Width: ±2mm
Height: ±1mm Row Pitch: ±2mm

**CS3L-330P / I-V CURVES**

**ELECTRICAL DATA | STC***

| CS3L | 335P | 340P | 345P | 350P | 355P | 360P |
|---|---|---|---|---|---|---|
| Nominal Max. Power (Pmax) | 335 W | 340 W | 345 W | 350 W | 355 W | 360 W |
| Opt. Operating Voltage (Vmp) | 32.4 V | 32.6 V | 32.8 V | 33.0 V | 33.2 V | 33.4 V |
| Opt. Operating Current (Imp) | 10.34 A | 10.43 A | 10.52 A | 10.61 A | 10.70 A | 10.78 A |
| Open Circuit Voltage (Voc) | 39.4 V | 39.6 V | 39.8 V | 40.2 V | 40.4 V | 40.6 V |
| Short Circuit Current (Isc) | 10.90 A | 10.98 A | 11.06 A | 11.24 A | 11.31 A | 11.37 A |
| Module Efficiency | 18.1% | 18.4% | 18.7% | 18.9% | 19.2% | 19.5% |
| Operating Temperature | -40°C ~ +85°C | | | | | |
| Max. System Voltage | 1500V (IEC/UL) or 1000V (IEC/UL) | | | | | |
| Module Fire Performance | TYPE 1 (UL 61730 1500V) or TYPE 2 (UL 61730 1000V) or CLASS C (IEC 61730) | | | | | |
| Max. Series Fuse Rating | 20 A | | | | | |
| Application Classification | Class A | | | | | |
| Power Tolerance | 0 ~ + 10 W | | | | | |

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

**ELECTRICAL DATA | NMOT***

| CS3L | 335P | 340P | 345P | 350P | 355P | 360P |
|---|---|---|---|---|---|---|
| Nominal Max. Power (Pmax) | 250 W | 254 W | 258 W | 262 W | 265 W | 269 W |
| Opt. Operating Voltage (Vmp) | 30.3 V | 30.5 V | 30.6 V | 30.8 V | 31.0 V | 31.2 V |
| Opt. Operating Current (Imp) | 8.27 A | 8.35 A | 8.42 A | 8.49 A | 8.56 A | 8.62 A |
| Open Circuit Voltage (Voc) | 37.1 V | 37.3 V | 37.5 V | 37.9 V | 38.1 V | 38.2 V |
| Short Circuit Current (Isc) | 8.79 A | 8.85 A | 8.92 A | 9.06 A | 9.12 A | 9.17 A |

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m² spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

**MECHANICAL DATA**

| Specification | Data |
|---|---|
| Cell Type | Poly-crystalline |
| Cell Arrangement | 120 [2 X (10 X 6) ] |
| Dimensions | 1765 X 1048 X 35 mm<br>(69.5 X 41.3 X 1.38 in) |
| Weight | 20.5 kg (45.2 lbs) |
| Front Cover | 3.2 mm tempered glass with anti-reflective coating |
| Frame | Anodized aluminium alloy |
| J-Box | IP68, 3 bypass diodes |
| Cable | 4.0 mm² (IEC), 12 AWG (UL) |
| Cable Length (Including Connector) | Portrait: 500 mm (19.7 in) (+) / 350 mm (13.8 in) (-) ; landscape: 1250 mm (49.2 in)* |
| Connector | T6 or T4 series or MC4-EVO2 |
| Per Pallet | 30 pieces |
| Per Container (40' HQ) | 780 pieces |

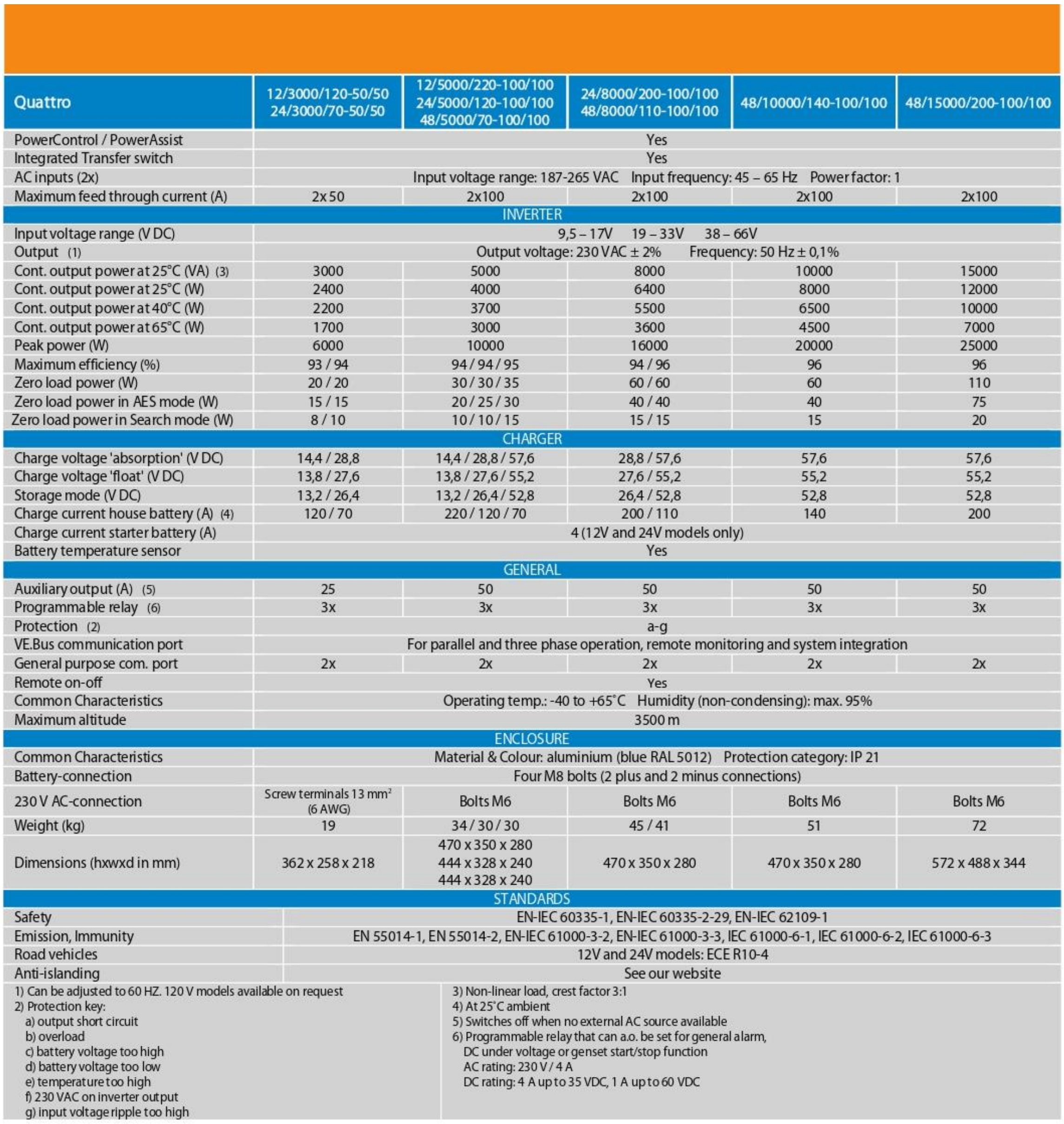
* For detailed information, please contact your local Canadian Solar sales and technical representatives.

**TEMPERATURE CHARACTERISTICS**

| Specification | Data |
|---|---|
| Temperature Coefficient (Pmax) | -0.36 % / °C |
| Temperature Coefficient (Voc) | -0.28 % / °C |
| Temperature Coefficient (Isc) | 0.05 % / °C |
| Nominal Module Operating Temperature | 41 ± 3°C |

Figure 51 - Canadian Solar HiKu CS3L Datasheet

## B.2. Inverter and MPPT datasheets

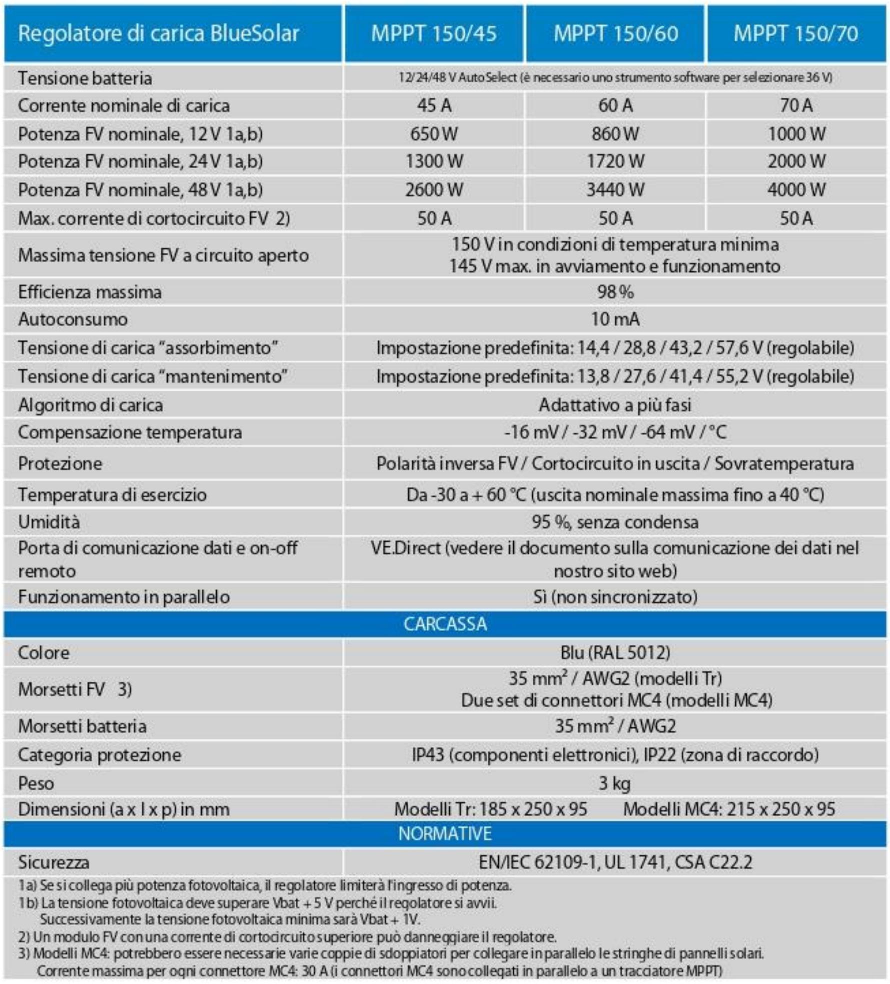


| Quattro | 12/3000/120-50/50<br>24/3000/70-50/50 | 12/5000/220-100/100<br>24/5000/120-100/100<br>48/5000/70-100/100 | 24/8000/200-100/100<br>48/8000/110-100/100 | 48/10000/140-100/100 | 48/15000/200-100/100 |
|---|---|---|---|---|---|
| PowerControl / PowerAssist | Yes | | | | |
| Integrated Transfer switch | Yes | | | | |
| AC inputs (2x) | Input voltage range: 187-265 VAC Input frequency: 45 – 65 Hz Power factor: 1 | | | | |
| Maximum feed through current (A) | 2x 50 | 2x100 | 2x100 | 2x100 | 2x100 |
| INVERTER | | | | | |
| Input voltage range (V DC) | 9,5 – 17V 19 – 33V 38 – 66V | | | | |
| Output (1) | Output voltage: 230 VAC ± 2% Frequency: 50 Hz ± 0,1% | | | | |
| Cont. output power at 25°C (VA) (3) | 3000 | 5000 | 8000 | 10000 | 15000 |
| Cont. output power at 25°C (W) | 2400 | 4000 | 6400 | 8000 | 12000 |
| Cont. output power at 40°C (W) | 2200 | 3700 | 5500 | 6500 | 10000 |
| Cont. output power at 65°C (W) | 1700 | 3000 | 3600 | 4500 | 7000 |
| Peak power (W) | 6000 | 10000 | 16000 | 20000 | 25000 |
| Maximum efficiency (%) | 93 / 94 | 94 / 94 / 95 | 94 / 96 | 96 | 96 |
| Zero load power (W) | 20 / 20 | 30 / 30 / 35 | 60 / 60 | 60 | 110 |
| Zero load power in AES mode (W) | 15 / 15 | 20 / 25 / 30 | 40 / 40 | 40 | 75 |
| Zero load power in Search mode (W) | 8 / 10 | 10 / 10 / 15 | 15 / 15 | 15 | 20 |
| CHARGER | | | | | |
| Charge voltage 'absorption' (V DC) | 14,4 / 28,8 | 14,4 / 28,8 / 57,6 | 28,8 / 57,6 | 57,6 | 57,6 |
| Charge voltage 'float' (V DC) | 13,8 / 27,6 | 13,8 / 27,6 / 55,2 | 27,6 / 55,2 | 55,2 | 55,2 |
| Storage mode (V DC) | 13,2 / 26,4 | 13,2 / 26,4 / 52,8 | 26,4 / 52,8 | 52,8 | 52,8 |
| Charge current house battery (A) (4) | 120 / 70 | 220 / 120 / 70 | 200 / 110 | 140 | 200 |
| Charge current starter battery (A) | 4 (12V and 24V models only) | | | | |
| Battery temperature sensor | Yes | | | | |
| GENERAL | | | | | |
| Auxiliary output (A) (5) | 25 | 50 | 50 | 50 | 50 |
| Programmable relay (6) | 3x | 3x | 3x | 3x | 3x |
| Protection (2) | a-g | | | | |
| VE.Bus communication port | For parallel and three phase operation, remote monitoring and system integration | | | | |
| General purpose com. port | 2x | 2x | 2x | 2x | 2x |
| Remote on-off | Yes | | | | |
| Common Characteristics | Operating temp.: -40 to +65°C Humidity (non-condensing): max. 95% | | | | |
| Maximum altitude | 3500 m | | | | |
| ENCLOSURE | | | | | |
| Common Characteristics | Material & Colour: aluminium (blue RAL 5012) Protection category: IP 21 | | | | |
| Battery-connection | Four M8 bolts (2 plus and 2 minus connections) | | | | |
| 230 V AC-connection | Screw terminals 13 mm² (6 AWG) | Bolts M6 | Bolts M6 | Bolts M6 | Bolts M6 |
| Weight (kg) | 19 | 34 / 30 / 30 | 45 / 41 | 51 | 72 |
| Dimensions (hxwxd in mm) | 362 x 258 x 218 | 470 x 350 x 280<br>444 x 328 x 240<br>444 x 328 x 240 | 470 x 350 x 280 | 470 x 350 x 280 | 572 x 488 x 344 |
| STANDARDS | | | | | |
| Safety | EN-IEC 60335-1, EN-IEC 60335-2-29, EN-IEC 62109-1 | | | | |
| Emission, Immunity | EN 55014-1, EN 55014-2, EN-IEC 61000-3-2, EN-IEC 61000-3-3, IEC 61000-6-1, IEC 61000-6-2, IEC 61000-6-3 | | | | |
| Road vehicles | 12V and 24V models: ECE R10-4 | | | | |
| Anti-islanding | See our website | | | | |

1) Can be adjusted to 60 HZ. 120 V models available on request
2) Protection key:
  a) output short circuit
  b) overload
  c) battery voltage too high
  d) battery voltage too low
  e) temperature too high
  f) 230 VAC on inverter output
  g) input voltage ripple too high

3) Non-linear load, crest factor 3:1
4) At 25°C ambient
5) Switches off when no external AC source available
6) Programmable relay that can a.o. be set for general alarm,
  DC under voltage or genset start/stop function
  AC rating: 230 V / 4 A
  DC rating: 4 A up to 35 VDC, 1 A up to 60 VDC

Figure 52 – Victron QUATTRO Datasheet



| Regolatore di carica BlueSolar | MPPT 150/45 | MPPT 150/60 | MPPT 150/70 |
|---|---|---|---|
| Tensione batteria | 12/24/48 V Auto Select (è necessario uno strumento software per selezionare 36 V) | | |
| Corrente nominale di carica | 45 A | 60 A | 70 A |
| Potenza FV nominale, 12 V 1a,b) | 650 W | 860 W | 1000 W |
| Potenza FV nominale, 24 V 1a,b) | 1300 W | 1720 W | 2000 W |
| Potenza FV nominale, 48 V 1a,b) | 2600 W | 3440 W | 4000 W |
| Max. corrente di cortocircuito FV 2) | 50 A | 50 A | 50 A |
| Massima tensione FV a circuito aperto | 150 V in condizioni di temperatura minima<br>145 V max. in avviamento e funzionamento | | |
| Efficienza massima | 98 % | | |
| Autoconsumo | 10 mA | | |
| Tensione di carica "assorbimento" | Impostazione predefinita: 14,4 / 28,8 / 43,2 / 57,6 V (regolabile) | | |
| Tensione di carica "mantenimento" | Impostazione predefinita: 13,8 / 27,6 / 41,4 / 55,2 V (regolabile) | | |
| Algoritmo di carica | Adattativo a più fasi | | |
| Compensazione temperatura | -16 mV / -32 mV / -64 mV / °C | | |
| Protezione | Polarità inversa FV / Cortocircuito in uscita / Sovratemperatura | | |
| Temperatura di esercizio | Da -30 a + 60 °C (uscita nominale massima fino a 40 °C) | | |
| Umidità | 95 %, senza condensa | | |
| Porta di comunicazione dati e on-off remoto | VE.Direct (vedere il documento sulla comunicazione dei dati nel nostro sito web) | | |
| Funzionamento in parallelo | Sì (non sincronizzato) | | |
| CARCASSA | | | |
| Colore | Blu (RAL 5012) | | |
| Morsetti FV 3) | 35 mm² / AWG2 (modelli Tr)<br>Due set di connettori MC4 (modelli MC4) | | |
| Morsetti batteria | 35 mm² / AWG2 | | |
| Categoria protezione | IP43 (componenti elettronici), IP22 (zona di raccordo) | | |
| Peso | 3 kg | | |
| Dimensioni (a x l x p) in mm | Modelli Tr: 185 x 250 x 95 Modelli MC4: 215 x 250 x 95 | | |
| NORMATIVE | | | |
| Sicurezza | EN/IEC 62109-1, UL 1741, CSA C22.2 | | |

1a) Se si collega più potenza fotovoltaica, il regolatore limiterà l'ingresso di potenza.
1b) La tensione fotovoltaica deve superare Vbat + 5 V perché il regolatore si avvii.
Successivamente la tensione fotovoltaica minima sarà Vbat + 1V.
2) Un modulo FV con una corrente di cortocircuito superiore può danneggiare il regolatore.
3) Modelli MC4: potrebbero essere necessarie varie coppie di sdoppiatori per collegare in parallelo le stringhe di pannelli solari.
Corrente massima per ogni connettore MC4: 30 A (i connettori MC4 sono collegati in parallelo a un tracciatore MPPT)

Figure 53 – Victron BlueSolar MPPT Datasheet

# B.3. Batteries datasheet

| Basic Parameters | US2000C | US3000C | Phantom-S |
|---|---|---|---|
| Nominal Voltage（V） | 48 | 48 | 48 |
| Nominal Capacity (Wh) | 2400 | 3552 | 2400 |
| Usable Capacity (Wh) | 2280 | 3374.4 | 2200 |
| Dimension（mm） | 442*410*89 | 442*420*132 | 440*440*88.5 |
| Weight（Kg） | 24 | 32 | 24 |
| Discharge Voltage（V） | 44.5 ~ 53.5 | 44.5 ~ 53.5 | 44.5 ~ 53.5 |
| Charge Voltage（V） | 52.5 ~ 53.5 | 52.5~53.5 | 52.5~53.5 |
| Charge / Discharge Current（A） | 25(Recommend) | 37 (Recommend) | 25(Recommend) |
|  | 50 (Max@60s) | 74 (Max@60s) | 50 (Max@60s) |
|  | 90 (Peak@15s) | 90 (Peak@15s) | 100（Peak@15s） |
| Communication Port | RS485，CAN | RS485，CAN | RS485，CAN |
| Single string quantity(pcs) | 16 | 16 | 8 |
| Working Temperature/℃ | 0~50 | 0~50 | 0~50 |
| Shelf Temperature/℃ | -20~60 | -20~60 | -20~60 |
| Humidity | 5%~95% | 5%~95% | 5%~95% |
| Altitude (m) | <2000 | <2000 | <2000 |
| Design life | 15$^+$ Years（25℃/77℉） | 15$^+$ Years（25℃/77℉） | 15$^+$ Years（25℃/77℉） |
| Cycle Life | >6000, 25℃ | >6000, 25℃ | >6000, 25℃ |
| Authentication Level | IEC62619/CE /UN38.3 | VDE2510-50/IEC62619/UL1973<br>UL9540A/CE/UN38.3 | IEC62619/CE /UN38.3 |
| Feature | Pre-Charge<br>Dual-active protection<br>Flexible current steps<br>Dry contact wake up | Pre-Charge<br>Dual-active protection<br>Flexible current steps<br>Dry contact wake up |  |

Figure 54 - Pylontech US2000 Datasheet

# List of Figures

# List if Tables

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