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Solar Micrografts for Rural Electrification in Zimbabwe

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Abstract

Access to reliable and sustainable electricity remains a major challenge in many rural areas of Zimbabwe. Solar microgrids offer a promising solution by harnessing abundant solar resources to provide off-grid power. This project investigates the design, implementation, and performance of a solar microgrid system aimed at rural electrification, focusing on the Laboratory LSELM as a practical case study.

Chapter 1 introduces photovoltaic technologies and their applications. Chapter 2 analyzes the solar resource availability in Zimbabwe, providing critical data for system sizing and optimization. Chapter 3 details the design of an off-grid solar microgrid, including the configuration of the solar PV array, battery storage systems, inverters, charge controllers, and low-voltage AC distribution network. Chapter 4 presents the implementation of a 1.4 kW solar microgrid serving Laboratory LSELM, including practical performance results such as system uptime and challenges encountered during roof installation.

The findings demonstrate the feasibility and benefits of deploying solar microgrids for rural electrification, highlighting important considerations for design, implementation, and operation in similar contexts.

Dedication

This project is dedicated with deep gratitude to my beloved parents, whose endless love, encouragement, and sacrifices have been my greatest source of strength throughout this journey. Their unwavering support has inspired me to keep going even in difficult times.

I also dedicate this work to my family, friends, and all those who offered words of advice, motivation, and support that helped me complete this research.

Finally, I extend my appreciation to the staff of the Electrical Engineering Department and my fellow classmates, whose guidance and companionship have enriched my academic experience.

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List of Abbreviations

PV: Photovoltaic

MPPT: Maximum Power Point Tracking

GHG: greenhouse gases

Electron-volts: electron-volts

DC: direct current

AC: alternating current

Isc: Short circuit current

V_{oc}: Open circuit voltage

Pm: Maximum power point

I_m: Current at maximum power point

V_m: Voltage at maximum power point

FF: Fill factor

η: Efficiency

DNI: Direct Normal Irradiance

DHI: Diffuse Horizontal Irradiance

GHI: Global Horizontal Irradiance

E_t: total daily energy load

PSI: Peak Solar Intensity at the earth surface

K_{losses}: determination factor

H_{tilt}: average solar irradiance falling on the specific tilt angle.

t_{manuf}: manufacturer's tolerance in %

F_{dirt}: de-rating due to dirt which is in %

γ: power temperature coefficient in %/ ^{0}C

T_{STC}: standard temperature of the collector

V_{module}: nominal voltage of the module

V_{system}: system array voltage

N_{ms}: number of modules in series

N_{mp}: number of parallel strings of modules

P_{pv}: Power Output of Solar PV Array

N_{mt}: Total number of modules in an array

C_b: Battery Bank Capacity

Nc: number of the autonomy days

DOD_{max}: maximum depth of discharging

$N_{bseries}$: number of batteries in series

$Nb_{paralell}$: number of parallel strings of batteries

N_{btotal}: Total number of batteries in battery bank

PWM: Pulse Width Modulation

General introduction

Access to electricity is a major challenge in many rural areas of Zimbabwe. A large part of the population still relies on traditional energy sources like firewood, candles, and kerosene lamps for lighting and cooking. These sources are not only inefficient but also pose health and environmental risks. Extending the national grid to remote villages is expensive and requires significant investment in infrastructure, which is often not feasible due to economic constraints. As a result, many communities continue to live without access to reliable and affordable electricity.

A promising solution to this problem is the use of solar microgrids. These are small, self-sufficient power systems that generate and distribute electricity locally, without needing a connection to the national grid. Zimbabwe has high solar energy potential making solar power a practical and sustainable option for rural electrification. By harnessing this abundant energy source, solar microgrids can provide a clean, reliable, and cost-effective electricity supply to rural communities, improving their quality of life.

This project focuses on the design, feasibility, and performance analysis of solar microgrids for rural electrification in Zimbabwe. Using MATLAB simulations, different system configurations will be tested to determine the most efficient and cost-effective setup. Key factors such as solar panel efficiency, battery storage capacity, load demand, and weather conditions will be analyzed to ensure optimal performance.

In addition to the technical aspects, this study will also explore the economic feasibility of solar microgrids. The initial installation cost, maintenance expenses, and potential sources of funding will be examined. With growing interest in renewable energy investments, solar microgrids could attract funding from governments, NGOs, and private investors, making them a scalable and financially viable solution for rural electrification.

By the end of this research, the aim is to develop a practical model that can be implemented in Zimbabwe and adapted for other regions facing similar energy challenges. Providing reliable electricity to rural communities will not only improve living standards but also support education, healthcare, and economic development, contributing to overall national progress.

1.0 Chapter 1: Photovoltaic Technologies

1.1 Introduction

The growing demand for electrical energy across the world has led to a heavy dependence on power generators to meet consumer needs. Unfortunately, generating electricity by burning fossil fuels has serious environmental consequences, particularly the emission of greenhouse gases (GHG). This has created an urgent need to reduce such emissions and shift towards cleaner energy sources. As a result, renewable energy solutions like solar and wind power have gained significant attention. Among these, solar photovoltaic (PV) technology stands out as one of the most widely adopted options, offering a clean, stable, scalable, and cost-effective way to produce electricity for the long term. Because of these benefits, many governments around the world have invested in developing and expanding solar PV infrastructure. [1]

To promote the growth of solar PV, governments have introduced various policies. These include production-focused measures such as subsidies for manufacturers, technology transfers, public investments in research and development (R&D), as well as collaborations between industries and research institutions. On the consumer side, policies like subsidies for users, tax incentives, renewable energy mandates, and favorable financing options have been implemented to encourage adoption. [1]

Today, a wide variety of PV materials are available globally, with hundreds of manufacturers producing solar modules that vary in efficiency and design limitations. The overall cost of setting up a solar PV system often depends on the type of module used and the specifics of the project. This chapter focuses on reviewing both well-established and recent information about solar PV technologies, looking at the materials used, module efficiency, and the current state of solar PV applications worldwide. [1]

1.2 Principle of Photovoltaic System

The photovoltaic effect is the fundamental process that allows a solar cell to turn sunlight into electricity. Sunlight is made up of tiny energy particles known as photons, and each photon carries a certain amount of energy depending on its wavelength within the solar spectrum. When these photons strike the surface of a solar cell, they can either bounce off (reflected) or be absorbed by the material. Only the absorbed photons contribute to generating electricity. [2]

Once a photon is absorbed, its energy is passed on to an electron inside the material, usually silicon. This extra energy allows the electron to break free from its usual position around the atom. The freed electron is now able to move, and this movement of electrons forms an electric current that can flow through an external circuit to provide power. [2]

To create an electric field inside the solar cell that pushes electrons in a specific direction, two types of semiconductor material called P-type and N-type are combined to form a p-n junction. These special materials are made by adding small amounts of other elements to pure silicon in a process called doping. By doping, manufacturers can control the number of electrons in the material:

- To make N-type silicon, phosphorus is added, which brings extra electrons since phosphorus atoms have five valence electrons.
- To create P-type silicon, boron is added, which has three valence electrons, creating "holes" where electrons can go. [2]

Silicon is the most widely used material for making solar cells because of its ideal properties for conducting electricity when exposed to sunlight. Each silicon atom contains 14 electrons, with four valence electrons that participate in forming strong bonds, known as covalent bonds, with neighboring silicon atoms. These bonds help form the crystal structure of the material. [2]

To adjust and improve the electrical behavior of the silicon, the doping process introduces atoms with either three or five valence electrons, modifying how electricity flows through the cell. [2]

In some types of solar cells, such as polycrystalline thin-film cells, different semiconductor materials are used for the top and bottom layers to improve performance and efficiency.[2]

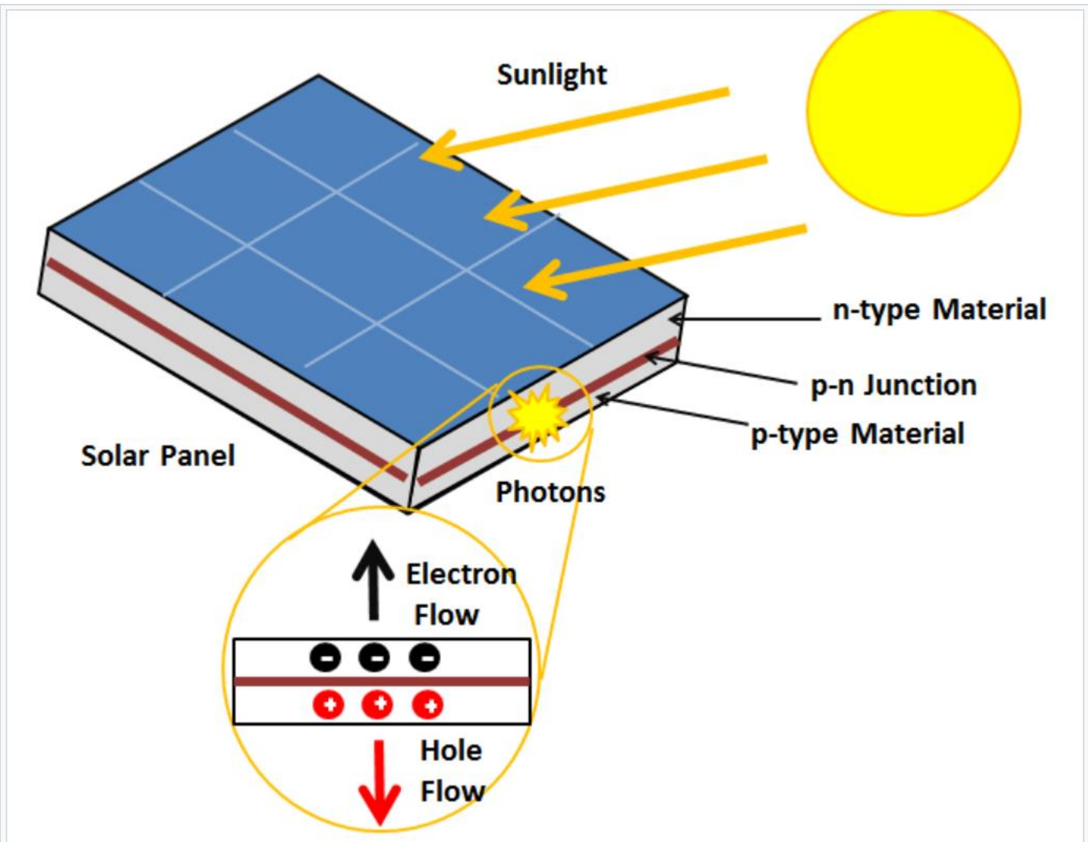

Figure 1.2 Photovoltaic effect

1.3 Working principle of a solar cell

The sunlight that reaches the Earth is made up of bundles of photons, which are tiny packets of energy. Each photon carries a specific amount of energy, and within the solar spectrum, there are photons of various energy levels. For a solar cell to generate electricity, these photons must be absorbed by the material of the solar cell. However, whether a photon is absorbed or not depends on its energy and the band-gap energy of the semiconductor material used in the solar cell. Both the energy of photons and the band-gap energy are usually measured in electron-volts (eV), which is a unit used to express very small amounts of energy. [3]

The operation of a solar cell can be explained in simple steps:

1. When sunlight hits the front surface of the solar cell, the semiconducting material inside the cell absorbs the photons. [3]
2. As a result, electron-hole pairs are created. Here, electrons carry a negative charge, while holes are like empty spaces that act as positive charges. When the solar cell is connected to an external electrical load, these electrons and holes are separated at the junction inside the cell. Electrons move towards the negative terminal (cathode), and holes move towards the positive terminal (anode). This separation builds up an electric potential difference (voltage) between the two terminals. [3]
3. This voltage drives a current through the external circuit. Since electrons move in a single direction, the current produced is direct current (DC). [3]

Thus, when sunlight falls on a solar cell, it can directly power DC devices. However, it's important to note that the amount of electricity produced depends on how much sunlight hits the cell. This means that electricity generation varies throughout the day, as sunlight intensity changes. Also, other factors like temperature, shading, and the quality of the solar cell can affect how much current is generated. [3]

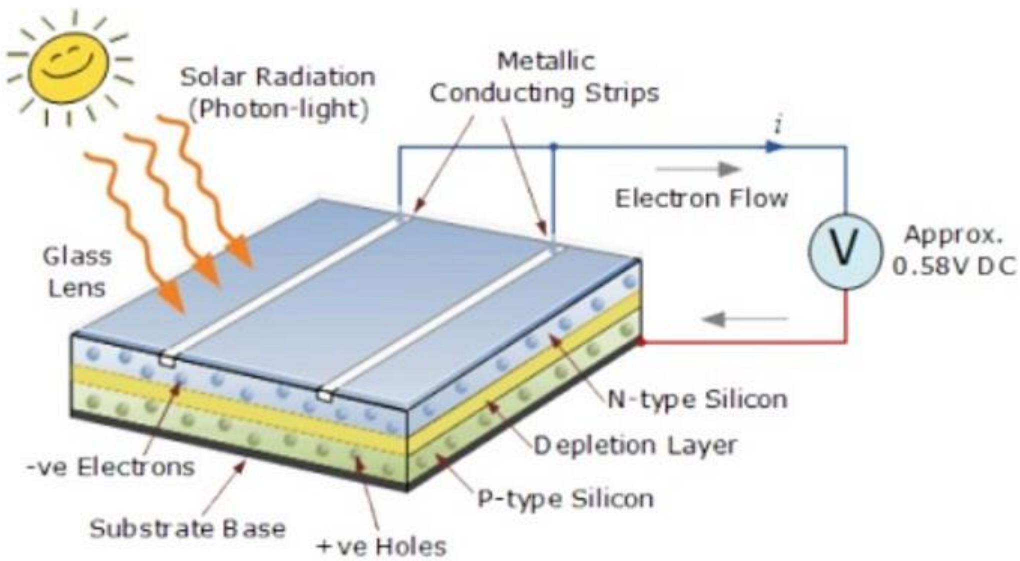

Figure 1.3 Photovoltaic Cell

1.4 Solar photovoltaic technologies

A solar cell is a device designed to convert light energy directly into electricity using the photovoltaic effect . Its electrical properties, such as current, voltage, and resistance, change depending on the amount of light it receives, whether from natural sunlight or artificial sources. [1]

Solar cells are the core components of photovoltaic (PV) modules, which are widely used in the solar energy industry. Beyond generating electricity, solar cells have various other applications. They serve as photo detectors in systems that automatically turn streetlights on and off, as well as in other light-sensitive devices, such as infrared detectors. Additionally, they are used as light sensors in scientific experiments and research.[1]

1.4.1 Monocrystalline Solar Cell

Monocrystalline solar modules are built from solar cells which are made out of silicon ingots, cylindrical in shape. These types of panels are known for having the highest efficiency levels because they are manufactured using high-purity silicon. Monocrystalline silicon solar panels are known for being space-efficient, making them ideal where space is limited. Additionally, these panels are quite costly, which makes them less practical for large-scale solar power projects. [4]

Figure 2.4.1 Monocrystalline Solar module

1.4.2 Polycrystalline Solar Cells

Polycrystalline silicon solar cells are produced by melting raw silicon and pouring it into square molds. Once cooled, the silicon is cut into square-shaped wafers (Maehlum, 2015). This manufacturing process creates less silicon waste compared to the production of monocrystalline panels. Since the method used to produce polycrystalline cells is simpler and less costly, these panels are generally more affordable, making them a practical option for large-scale solar PV projects and rural electrification initiatives. Below is an example of a typical polycrystalline solar module. [4]

Figure 1.4.2 Polycrystalline solar module

1.4.3 Thin film Solar Cells

Thin-film solar cells are created by coating a substrate with one or more layers of photovoltaic material. Depending on the substrate used, thin-film modules can be made from materials like amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or organic photovoltaic cells (OPC). These types of panels generally have the lowest efficiency, typically ranging between 7% and 13%, mainly because the silicon used in their production is less pure. [4]

One advantage of thin-film solar cells is that high temperatures have a smaller effect on their performance, and they are less expensive compared to monocrystalline (mono-Si) and polycrystalline (p-Si) panels. However, a key drawback is that thin-film modules tend to degrade faster over time than the other two technologies. [4]

Figure 1.4.3 Thin film Solar

1.5 Comparison of different types of PV modules

Feature	Monocrystalline	Polycrystalline	Thin-film
Material	Single-crystal silicon [1]	Multi-crystal silicon [1]	Amorphous silicon [1]
Efficiency	14-24% [2]	11-14% [2]	6 – 9% [3]
Cost	High [5]	Moderate [5]	Low [5]
Space required	Least [5]	Medium [5]	Most [5]
Temperature Sensitivity	Moderate (better than Polycrystalline but loses some efficiency in heat; improves in cold) [5]	High (more affected by heat than Monocrystalline; improves in cold) [5]	Low (least affected by temperature changes, stable in heat, small gain in cold) [5]
Flexibility	Rigid [5]	Rigid [5]	Flexible [5]
Lifespan	Longest [5]	Medium [5]	Shortest [5]

Table 1.5 Comparison of different types of PV modules

1.6 Parameters of Solar Cells

A solar cell is a device that transforms sunlight directly into electricity. The efficiency and performance of this conversion depend on specific parameters of the solar cell. These parameters help to measure how effectively the solar cell turns sunlight into electrical energy. Below is a list of the key parameters that define a solar cell's performance: [3]

- Short circuit current (I_{sc})
- Open circuit voltage (V_{oc})
- Maximum power point
- Current at maximum power point (I_m)
- Voltage at maximum power point (V_m)
- Fill factor (FF)
- Efficiency (η), [3]

These parameters are best explained using the Current-Voltage (I-V) curve of a solar cell. The I-V curve is illustrated in Figure . In this graph, the Y-axis typically represents the current, while the X-axis represents the voltage. [3]

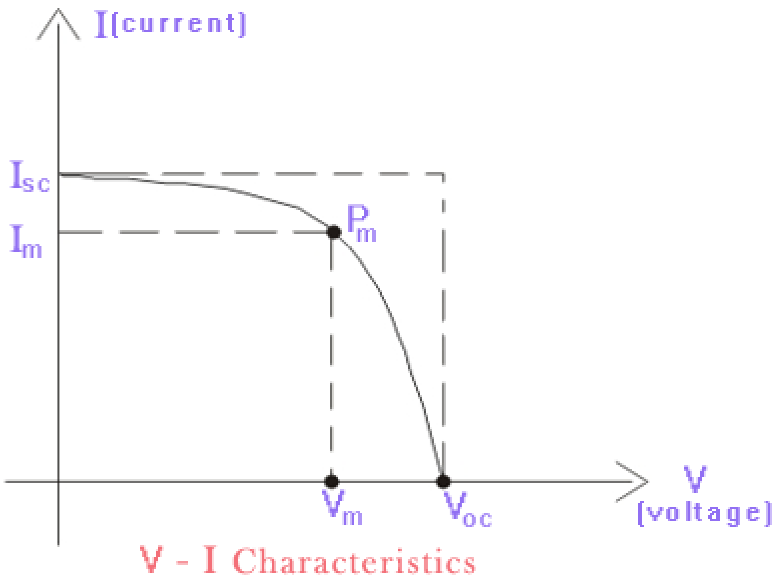

Figure 1.6 (I-V) curve of a solar cell 2

Based on Figure , the main solar cell parameters are defined. Usually, the values of these parameters are provided by manufacturers or researchers under Standard Test Conditions (STC), which refer to a solar irradiance of 1000 W/m² and a cell temperature of 25°C during testing. [3]

1.6.1 Short circuit current (I_{sc})

This is the maximum current that a solar cell can generate, known as the short-circuit current (I_{sc}). Generally, the higher the I_{sc}, the better the cell's performance. It is usually measured in Amperes (A) or milliamperes (mA). The value of this maximum current depends on several factors, such as the type of cell technology, surface area of the cell, intensity of sunlight received, and the tilt angle of the cell. [3]

Often, instead of giving the total current, manufacturers or researchers provide the current density, which is simply the short-circuit current (I_{sc}) divided by the area (A) of the solar cell. This current density is represented by the symbol 'J', and specifically, the short-circuit current density (Jsc) is expressed as: Jsc = Isc / A. [3]

$$J_{sc} = \frac{Isc}{A} \quad \text{------------------------(1.1)}$$

[3]

1.6.2 Open circuit voltage (V_{oc})

This refers to the maximum voltage that a solar cell can generate, known as the open-circuit voltage (V_{oc}). In general, the higher the V_{oc}, the better the quality of the cell. It is usually measured in volts (V) or sometimes in millivolts (mV). The value of V_{oc} mainly depends on the type of cell technology used and the operating temperature of the cell. [3]

1.6.3 Maximum power point (P_m or P_{max})

This is the maximum power output that a solar cell can generate under Standard Test Conditions (STC), and it is known as P_m. The higher the P_m, the better the performance of the cell. This value is measured in watts (W). Since it represents the peak output, it is sometimes called peak power (W_{peak} or W_p). [3]

Although a solar cell can operate at various combinations of current and voltage, it will only deliver maximum power when working at a specific current and voltage. This point is called the Maximum Power Point (P_m) and is indicated on Figure . Typically, this maximum power point appears at the 'knee' or 'bend' of the I-V curve. [3]

Mathematically, P_m is expressed as:

$$P_m \text{ or } P_{max} = I_m \times V_m \quad \text{------------------------(1.2)}$$

[3]

1.6.4 Current at maximum power point (I_m)

This refers to the current output of a solar cell when operating at its Maximum Power Point (P_m), known as I_m. It is always lower than the short-circuit current (I_{sc}). The value of Im is measured in amperes (A) or milliamperes (mA). [3]

1.6.5 Voltage at maximum power point (V_m)

This is the voltage generated by a solar cell when it operates at its Maximum Power Point (P_m), called V_m. It is always less than the open-circuit voltage (V_{oc}). The value of V_m is measured in volts (V) or sometimes millivolts (mV). [3]

1.6.6 Fill factor (FF)

As the name implies, the Fill Factor (FF) is the ratio of the area of the I_m-V_m rectangle to the area of the I_{sc}-V_{oc} rectangle (both shown as dotted lines in Figure 3). The equation for FF is given below. It represents how "square" the I-V curve is. A higher Fill Factor means a better-performing solar cell. FF is usually expressed as a percentage (%), and the closer the I-V curve is to a square shape, the better the quality of the cell. [3]

$$FF = \frac{Im \times Vm}{Isc \times Voc} \quad \text{------------------------------(1.3)}$$

or

$$FF = \frac{Pm}{Isc \times Voc} \quad \text{------------------------------(1.4)}$$

[3]

The formula for maximum power (P_{max} or P_m) can also be expressed using I_{sc}, V_{oc}, and FF as follows:

$$P_m = I_{sc} \times V_{oc} \times FF \text{ ------------------------(1.5)}$$

[3]

1.6.7 Efficiency (η)

The efficiency of a solar cell is defined as the ratio of its maximum output power (P_m or P_{max}) to the input power (P_{in}). This efficiency is usually expressed as a percentage (%), indicating how much of the incoming solar radiation is converted into electrical energy. Under Standard Test Conditions (STC), the input power is typically taken as 1000 W/m². Since this value represents power per unit area (power density), to calculate the actual efficiency, we need to multiply it by the area of the solar cell. Therefore, the efficiency can be written as:

$$\eta = \frac{Pm}{Pin} \text{ ---------------------------------(1.6)}$$

$$\eta = \frac{\text{Isc} \times \text{Voc} \times \text{FF}}{Pin \times A} \text{ ------------------------(1.7)}$$

[3]

1.7 Factors Affecting Electricity Generated by a Solar Cell

There are five main factors that influence the amount of power produced by solar cells. These factors are listed below:

1. The conversion efficiency (η)
   - A more efficient solar cell is able to generate more power from the same surface area.
2. The amount of light (P_{in})
   - The more sunlight that hits the solar cell, the more power it can produce. On the other hand, less sunlight leads to lower power generation.
3. The solar cell area (A)
   - The current density (J_{sc}) of a solar cell is always constant.
   - However, a larger solar cell area will generate higher current, while a smaller area will produce lower current.
4. The angle at which day light falls (θ)
   - When sunlight hits the solar cell directly and perpendicularly, it generates the maximum possible power output.
5. The operating temperature (T)
   - For a solar cell, as the temperature increases, the power output decreases.

[3]

1.8 Conclusion

In conclusion, photovoltaic (PV) technologies represent one of the most promising solutions for sustainable energy generation, especially in regions with abundant solar resources like Zimbabwe. This chapter has provided an overview of how PV systems work, including the basic principles of converting sunlight into electricity using solar cells, as well as an explanation of PV panel datasheets, which provide essential technical specifications for system design.

2.0 Chapter 2 : Solar Resource Analysis in zimbabwe

2.1 Introduction

Zimbabwe, located in Southern Africa, enjoys abundant sunlight for most of the year due to its favorable geographic position and climate. With many rural communities still lacking access to electricity, solar energy has become one of the most promising solutions to address energy poverty and improve living conditions. The country's high levels of solar radiation make it a suitable candidate for solar power systems, especially in areas where extending the national grid is not economically viable.

Despite the availability of sunlight, understanding the patterns and variations of solar radiation across different regions is crucial for designing reliable energy systems. Solar energy production can be affected by several factors such as weather changes, seasonal shifts, and local geographical features. Therefore, gaining insight into the solar resource characteristics helps in determining the appropriate size of solar installations and storage requirements to ensure consistent power supply.

As Zimbabwe seeks to transition toward more sustainable and decentralized energy solutions, solar energy stands out as a key resource that can drive rural development and support economic growth. A clear understanding of the solar potential is vital to making informed decisions for future energy projects.

2.2 Geographical and Climatic Overview of Zimbabwe

2.2.1 Geographical Location

Zimbabwe is a landlocked country located in Southern Africa. It shares borders with South Africa to the south, Botswana to the west, Mozambique to the east, and Zambia to the north. The country stretches between 15° and 23° South latitude and 25° to 34° East longitude, covering a total land area of about 390,757 square kilometers [6].

The physical landscape of Zimbabwe is dominated by a high plateau known as the Highveld, which lies at altitudes between 1,200 and 1,500 meters above sea level. This elevated region runs from the southwest to the northeast and is surrounded by lower-lying areas such as the Lowveld in the south and southeast, which are generally below 900 meters. These variations in elevation play a significant role in influencing the country’s weather patterns and temperatures, which are important factors when analyzing solar energy potential [6].

Figure 2.2.1 Map of Zimbabwe showing its geographical location and neighboring countries

2.2.2 Climate Characteristics

Although Zimbabwe is located within the tropical zone, its relatively high elevation gives it a subtropical climate with moderate temperatures compared to typical tropical areas. Daytime temperatures are generally warm to hot, while nighttime temperatures can be much cooler, especially in higher regions. On average, temperatures range from 18°C to 25°C, depending on the season and altitude [6].

Rainfall in Zimbabwe is highly seasonal and varies significantly across different regions. The eastern highlands receive the highest rainfall amounts, sometimes exceeding 1,000 mm per year, while areas in the southern and southwestern regions may get less than 450 mm annually. This uneven distribution of rainfall affects agriculture, water availability, and also the planning of solar energy systems, as cloudy periods during the rainy season can reduce solar panel output [6].

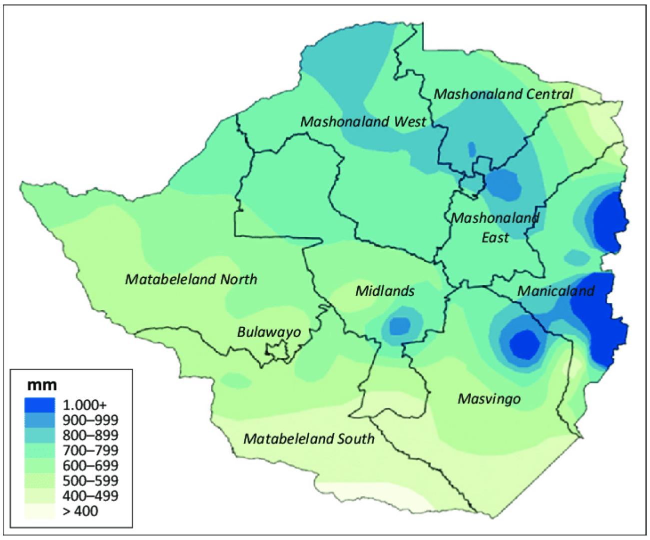

Figure 2.2.2 Zimbabwe average annual rainfall map.

2.2.3 Seasonal Variations and Weather Patterns

Zimbabwe experiences three distinct seasons, each influencing solar energy potential in different ways.

- Rainy Season (November to March): This is typically the hottest and most humid part of the year, characterized by frequent rain and heavy cloud cover, especially in the northern and eastern regions. These clouds reduce solar radiation and affect energy production [6].
- Cool Dry Season (April to July): This period has mild daytime temperatures and cool nights, with clear skies dominating, making it a favorable period for solar energy harvesting [6].
- Hot Dry Season (August to October): Known for very high temperatures and low humidity, this season typically has minimal cloud cover, allowing for maximum solar radiation, which is ideal for photovoltaic systems [6].

In addition to climate patterns, Zimbabwe's solar resource maps indicate that the country has a high solar irradiance potential, with strong levels of Global Horizontal Irradiance (GHI) covering much of the country. This makes Zimbabwe highly suitable for solar energy production, especially during the dry and hot seasons when sunlight is abundant. Understanding these seasonal and solar patterns is crucial for planning reliable solar microgrids that can supply energy throughout the year [7].

2.3 Solar Irradiance Potential in Zimbabwe

2.3.1 Direct Normal Irradiance (DNI)

Direct Normal Irradiance (DNI) measures the amount of direct solar radiation received per unit area by a surface that is always held perpendicular to the sun's rays. DNI is particularly important for concentrating solar power (CSP) systems, but it also gives insights into the strength of direct sunlight available for PV systems that use tracking mechanisms. [8]

On a sunny, clear day, around 95% of the sunlight that reaches the Earth's surface comes as Direct Normal Irradiance (DNI). However, when the sky is cloudy, this value drops to nearly zero. DNI is measured using a pyrheliometer, an instrument designed to capture sunlight within a narrow field of view of about 5°. This device is installed on an automatic sun tracker, which constantly adjusts its position to follow the sun's path from sunrise to sunset, ensuring accurate measurements throughout the day. [9]

In Zimbabwe, DNI levels are moderately high, supporting not only PV but also potential CSP applications. DNI values in Zimbabwe typically range between 5.5 and 6.5 kWh/m^2/day in the sunniest regions, especially in low-lying and dry areas, such as parts of the Lowveld. These values are slightly higher in the dry season when skies are clear, while during the rainy season, cloud cover can reduce DNI significantly . [7]

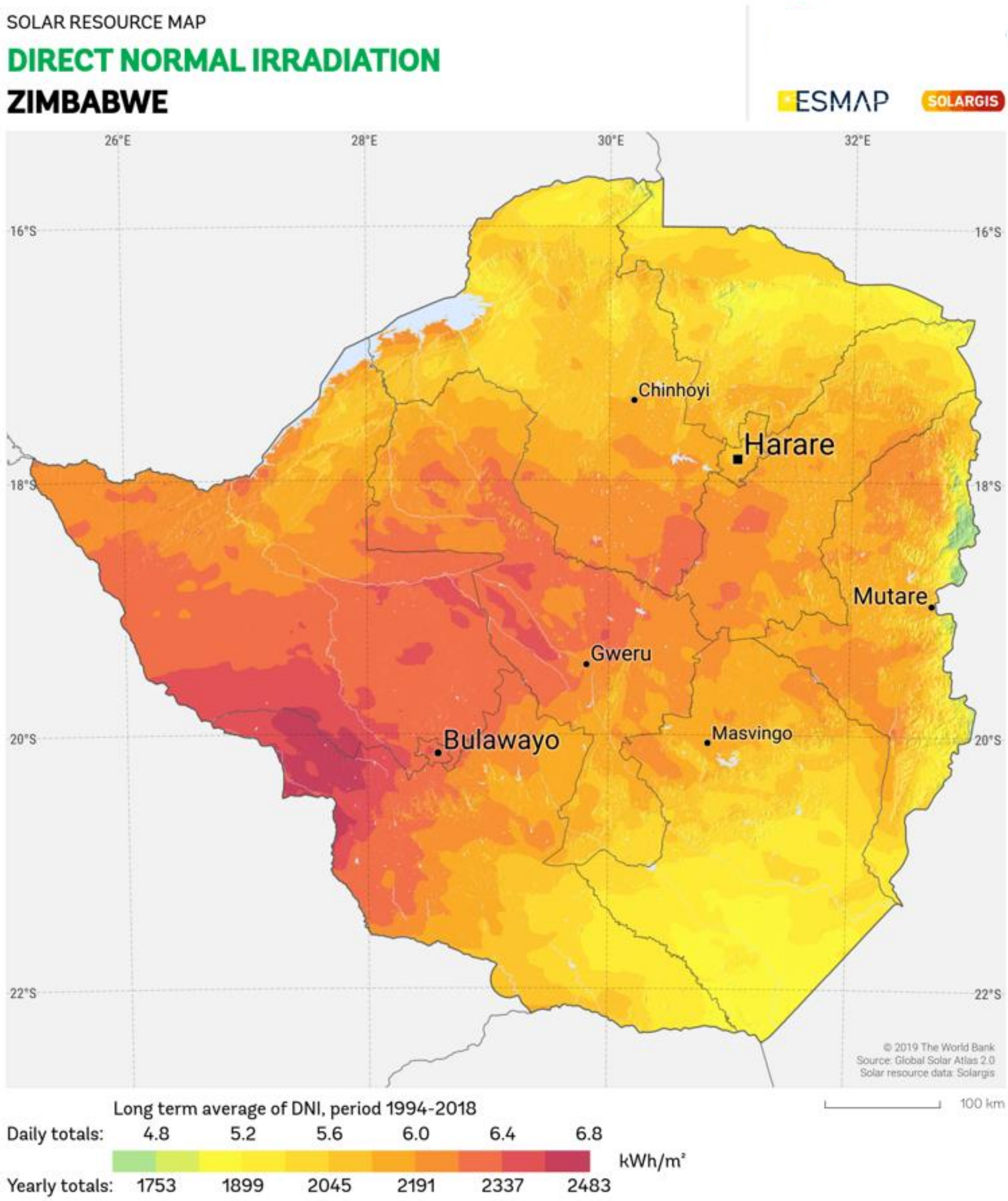

Figure 2.3.1 Direct Normal Irradiation of Zimbabwe

2.3.2 Diffuse Horizontal Irradiance (DHI)

The sunlight that gets scattered by the atmosphere is usually considered as diffuse light, and it is spread almost evenly across the sky above where measurements are taken. On a sunny day, this diffuse light makes up about 5% of the total sunlight reaching the Earth's surface, but on a cloudy day, it can make up nearly 100% of the total sunlight available. Since photovoltaic (PV) panels can capture light coming from many different angles, they are able to generate electricity even when the sky is cloudy by using this diffuse radiation. [9]

When this scattered light from the whole sky hits a flat, horizontal surface, the amount of energy received is called the *Diffuse Horizontal Irradiance (DHI)*. To measure DHI, a horizontal pyranometer is used. It is placed on a sun tracker that keeps it shaded from direct sunlight throughout the day. The shade blocks about 5° of the sky, which is the same narrow angle seen by a pyrheliometer used for measuring direct sunlight. [9]

2.3.3 Global Horizontal Irradiance (GHI)

When both the direct sunlight (DNI) and the scattered sky radiation (DHI) reach a flat, horizontal surface, the combined energy is called Global Horizontal Irradiance (GHI). This total irradiance represents the sum of both components and is calculated using a cosine relationship:

$$GHI = DHI + DNI \times \cos(\theta) \quad \text{------------------------(2.1)}$$

Here, θ represents the solar zenith angle (SZA), which is the angle between the sun and the vertical direction. If the sun is directly overhead, θ is 0°, and if it's right on the horizon, θ becomes 90°. [9]

In Zimbabwe, GHI levels are notably high, making the country suitable for solar photovoltaic (PV) systems. Zimbabwe's GHI values range between 5.0 and 5.7 kWh/m²/day, depending on the region. Central and northern areas of Zimbabwe tend to receive the highest levels of GHI due to clearer skies and favorable climatic conditions. These high GHI levels indicate that most parts of Zimbabwe are well-suited for solar energy generation, and PV panels can produce electricity efficiently throughout the year. [7]

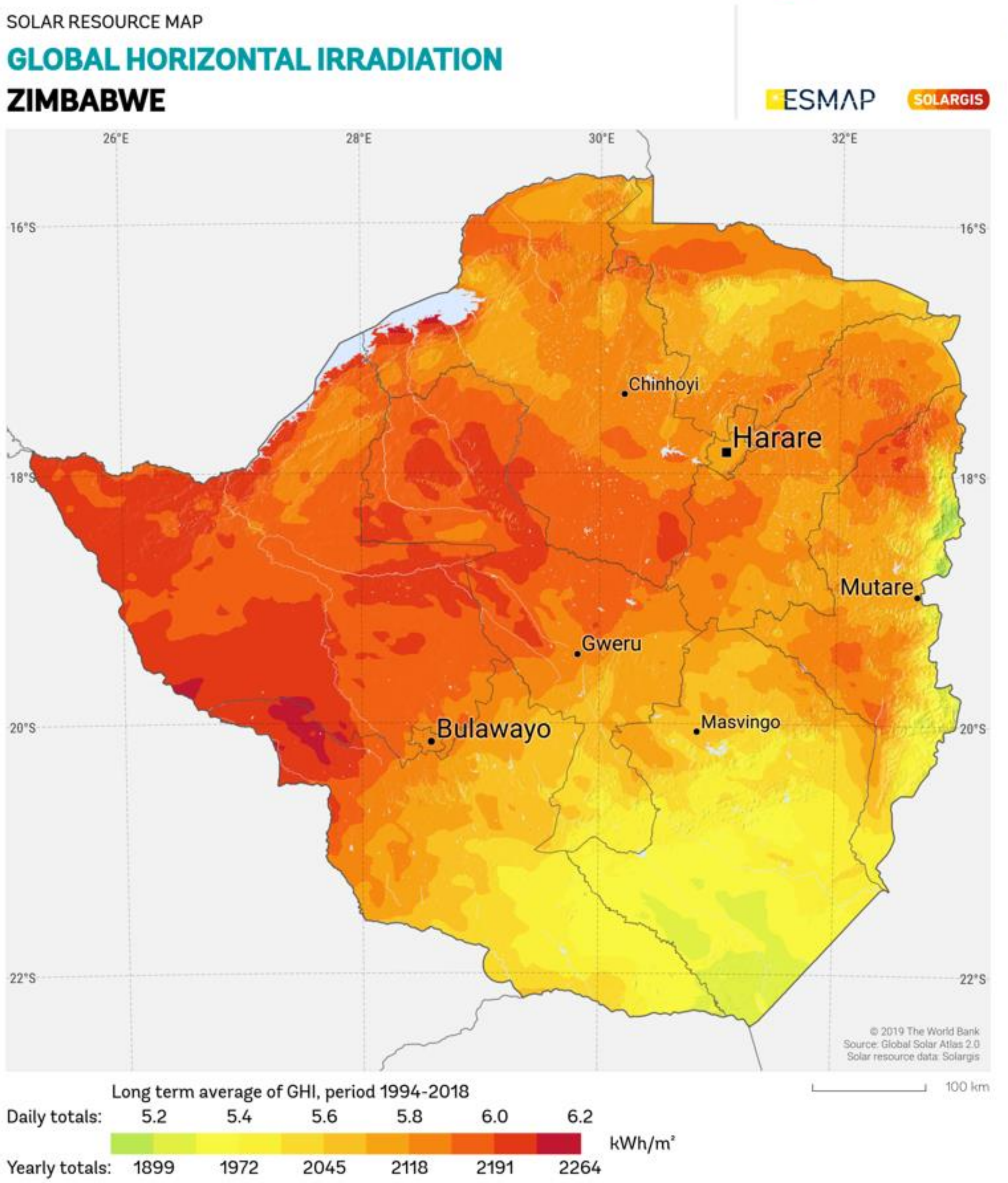

Figure 2.3.3 Global Horizontal Irradiance (GHI) of Zimbabwe

2.3.4 Average Daily and Annual Solar Radiation

Zimbabwe enjoys strong daily and annual solar radiation levels, making solar energy a viable and sustainable resource for addressing electricity shortages, especially in rural areas. The average daily solar radiation across Zimbabwe typically ranges between 5.0 and 5.7 kWh/m²/day, while annual solar radiation levels reach approximately 1,825 to 2,080 kWh/m²/year, depending on the location. [7]

These values indicate that solar systems in Zimbabwe can produce significant energy output all year round, especially if systems are properly sized and located in high irradiance regions. The combination of high GHI and moderate DNI ensures that even fixed-tilt PV systems without trackers can achieve good performance. Moreover, during the cool and hot dry seasons, solar radiation levels peak, offering ideal conditions for maximizing energy production. [7]

Understanding the average daily and annual solar radiation is essential when designing solar microgrids for rural electrification. This information helps in determining the appropriate size of solar arrays and battery storage systems to ensure a reliable and continuous supply of electricity, even during periods of reduced sunlight, such as the rainy season. [6]

2.4 Regional Distribution of Solar Potential

2.4.1 High Potential Regions

Zimbabwe has a favorable solar profile across much of its territory, but certain regions stand out for their exceptionally high solar potential. Areas located in the northern, western, and central parts of the country receive some of the highest solar radiation levels, making them ideal for solar energy projects. [7]

Regions such as Matabeleland North, parts of Midlands, and Mashonaland West consistently record Global Horizontal Irradiance (GHI) values exceeding 5.5 $kWh/m^2/day$, especially during the dry seasons. These areas benefit from clear skies and minimal cloud cover for most of the year, which is critical for achieving maximum solar panel efficiency. [7]

The Highveld plateau, which runs through the center of the country, also offers stable and high solar potential due to its elevation and relatively dry climate. These regions are well-suited for both small-scale rural microgrids and large grid-connected solar farms, offering opportunities for scalable solar energy solutions that can meet growing electricity demands. [7]

2.4.2 Low Potential or Challenging Regions

While much of Zimbabwe has good solar potential, certain areas face challenges that may affect solar energy generation, particularly during specific periods of the year. The eastern highlands, including areas like Mutare and Chimanimani, receive lower solar irradiance levels compared to other regions. This is largely due to higher rainfall, frequent cloud cover, and misty conditions, especially during the rainy season (November to March). [6]

In these regions, GHI values may fall to around 5.0 $kWh/m^2/day$ or slightly lower during peak rainy months, reducing the efficiency of solar panels. Additionally, steep terrain and dense vegetation in these highland areas can present logistical and technical challenges for the installation of solar infrastructure. [7]

Despite these challenges, solar energy remains a viable solution, but it requires careful system design, including proper site selection and backup energy storage to handle periods of low sunlight. [7]

2.4.3 Comparison between Urban and Rural Areas

The distribution of solar potential between urban and rural areas in Zimbabwe shows that both settings receive similar levels of solar radiation, but the application and challenges differ.

Urban areas like Harare, Bulawayo, and Gweru receive comparable GHI values to surrounding rural areas, averaging around 5.2 to 5.6 kWh/m²/day. However, urban solar projects often focus on grid-tied rooftop systems and commercial solar farms, benefiting from existing grid connections that allow easy integration of solar power. [7]

In contrast, rural areas, especially those far from the national grid, are where solar energy can have the greatest social and economic impact. Many rural communities lack access to electricity, and solar microgrids can offer standalone solutions for lighting, water pumping, health services, and small businesses. The solar potential in rural regions such as Matabeleland North and Masvingo is excellent, but the lack of infrastructure and financial constraints remain significant barriers to implementation. [6]

Therefore, while solar potential is high in both urban and rural zones, the urgency and importance of deploying solar systems are greater in rural areas where they can immediately improve livelihoods and drive local development. [6]

2.5 Seasonal Variations and Their Impact on Solar Energy Production

2.5.1 Dry Season and Rainy Season Solar Resource

Zimbabwe's solar energy potential is strongly influenced by its seasonal climate patterns, which affect the availability of solar radiation throughout the year. The country experiences two main climatic periods: the dry season and the rainy season.

During the dry season (April to October), Zimbabwe enjoys clear skies, low humidity, and minimal cloud cover, making this period ideal for solar energy production. Global Horizontal Irradiance (GHI) values during the dry season can reach up to 5.7 kWh/m²/day, allowing solar panels to generate electricity at maximum capacity. These months provide stable and predictable solar resources, making them highly favorable for photovoltaic (PV) system operation. [7]

In contrast, the rainy season (November to March) is characterized by frequent rain, thunderstorms, and heavy cloud cover, particularly in the eastern and northern regions of the country [6]. These conditions significantly reduce the amount of sunlight reaching solar panels, causing a drop in electricity generation. GHI levels during the rainy season may fall to around 4.5 to 5.0 kWh/m²/day, depending on the region. Therefore, while Zimbabwe has strong overall solar potential, solar energy production fluctuates with seasons, and systems must be designed to handle these variations. [7]

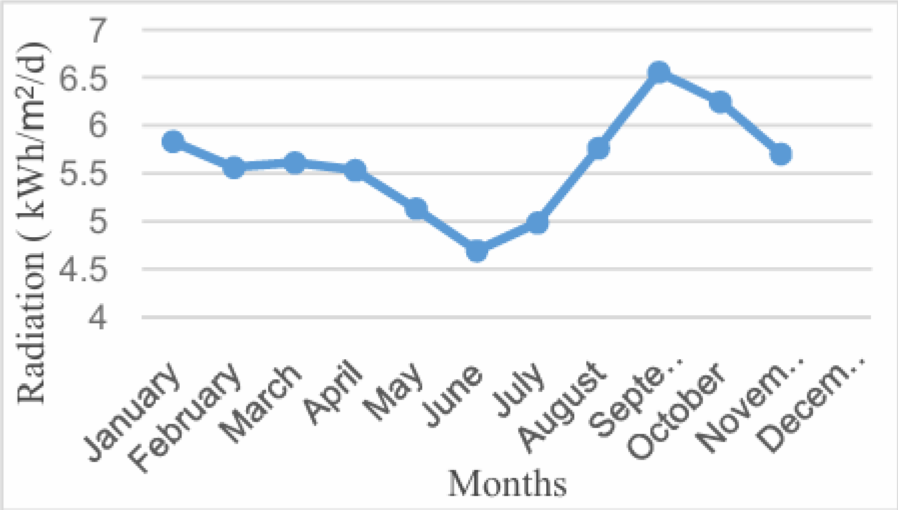

Figure 2.5.1 Graph for monthly variation of solar radiation in Harare, Zimbabwe.

2.5.2 Impact on System Sizing and Storage

The seasonal variability of solar resources in Zimbabwe has important implications for the design and sizing of solar microgrid systems, especially for rural electrification. Since solar energy production decreases during the rainy season, it is essential to size both the solar array (number of panels) and battery storage capacity to ensure that electricity supply remains reliable throughout the year.

During the dry season, when solar radiation is abundant, solar microgrids may generate more electricity than needed, which can be stored in battery banks for later use. Properly sized storage systems are critical to balance supply and demand, especially to cover nighttime use and cloudy days.

However, the challenge arises during the rainy season, when reduced solar generation might not meet daily consumption needs if the system is not well-designed. In such cases, larger battery storage or hybrid solutions (e.g., combining solar with diesel backup or wind energy) may be required to maintain power supply reliability. [6]

Furthermore, understanding the seasonal variation of GHI helps engineers and planners to optimize solar system sizes, preventing both under-sizing, which could cause frequent power shortages, and over-sizing, which increases costs unnecessarily. By analyzing solar radiation data across seasons, systems can be designed to ensure year-round operation, even under challenging weather conditions. [7]

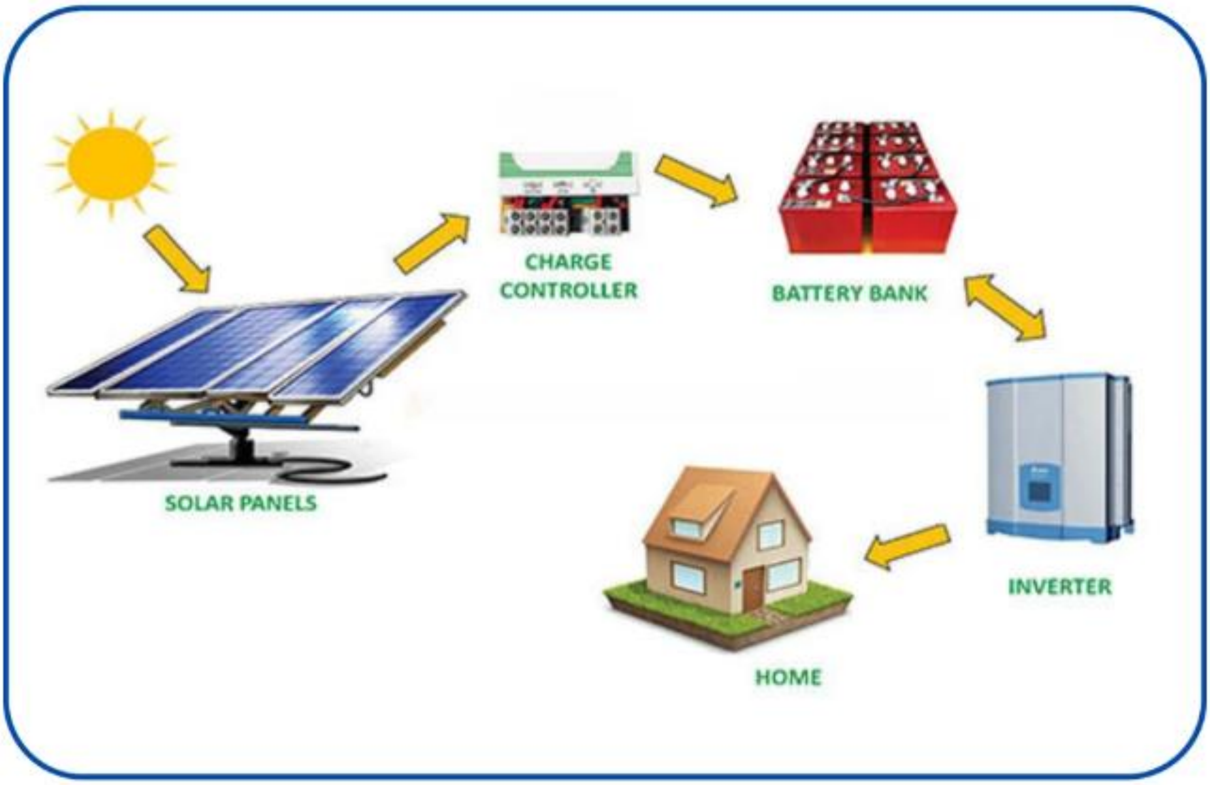

Figure 2.5.2 Basic structure of a solar microgrid with battery storage for rural electrification

2.6 Conclusion

This study has explored the solar energy potential in Zimbabwe, focusing on geographical, climatic, and seasonal factors that influence the design and implementation of solar microgrids for rural electrification. The analysis confirms that Zimbabwe is richly endowed with solar resources, receiving an average Global Horizontal Irradiance (GHI) ranging between 5.0 and 5.7 kWh/m²/day. These high irradiance levels are available throughout most of the year, especially during the dry season, making solar energy a viable and sustainable solution for addressing the country's energy access challenges. [7]

The geographical assessment revealed that while most regions of Zimbabwe, such as Matabeleland North, Midlands, and Mashonaland West, have high solar potential, some areas, particularly the eastern highlands, face lower irradiance levels and climatic challenges due to frequent cloud cover and rainfall. Nevertheless, even these regions maintain sufficient solar resources to support well-designed photovoltaic systems, provided that seasonal variations are properly accounted for in system sizing. [6]

The seasonal analysis further demonstrated that solar energy production is highly dependent on Zimbabwe's climatic cycles. During the rainy season, solar energy output may decline due to increased cloud cover, while in the dry season, solar systems can operate at peak performance. Therefore, accurate system sizing and adequate battery storage solutions are essential to ensure a reliable and continuous energy supply, especially for rural communities that rely solely on solar microgrids.

Overall, solar microgrids represent a practical and scalable solution to electrify rural areas in Zimbabwe, where traditional grid extension is neither economically feasible nor sustainable. By leveraging Zimbabwe's abundant solar resource, rural communities can gain access to clean, affordable, and reliable electricity, improving quality of life and supporting local economic development

3.0 Chapter 3: System Design

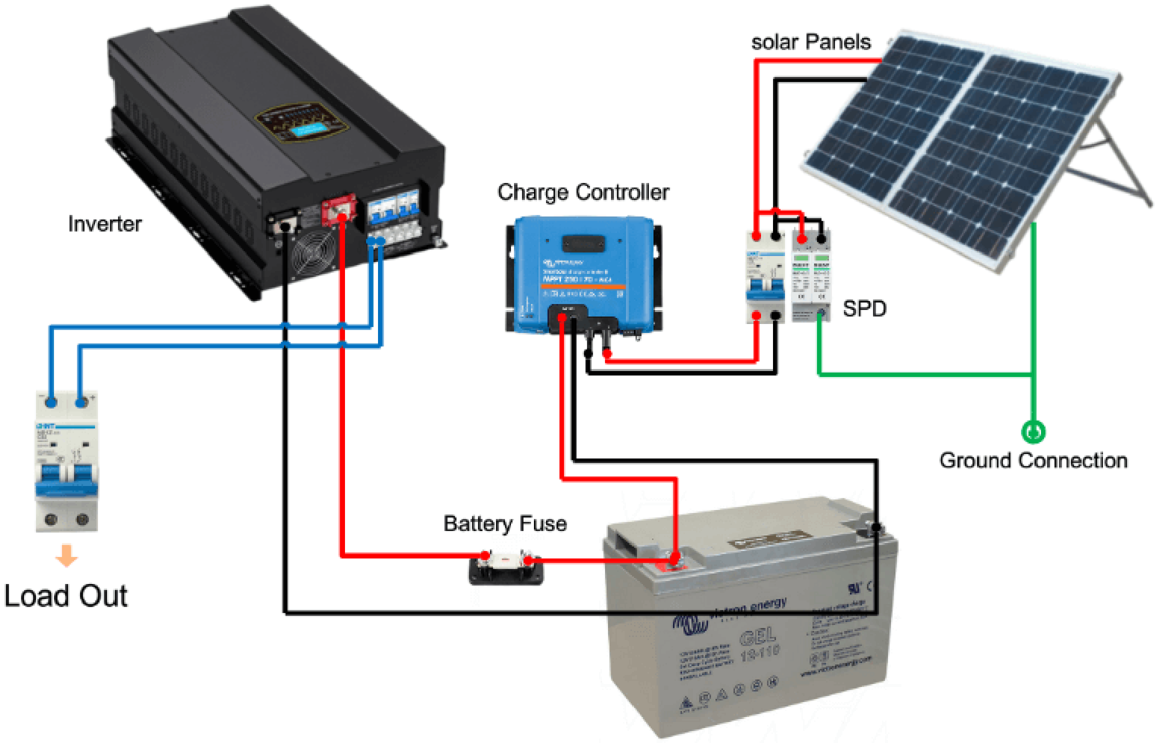

Figure 3.0 Off-grid solar system

3.1 Introduction

Designing a solar microgrid means choosing the right components to match the energy needs of a specific community. In rural Zimbabwe, where electricity is often unavailable, a solar-based solution must be reliable, simple to maintain, and affordable. Since the system will not be connected to the national grid, it must be able to supply power throughout the year even during cloudy or rainy days. This requires careful planning to make sure the solar panels, batteries, and other equipment are properly sized. Other factors like sunlight levels, daily energy use, system losses, and the number of backup days also influence the design. It's important to select components that are efficient and compatible with each other. A strong design helps avoid power shortages, reduces maintenance issues, and ensures that the system supports daily life in the village without frequent breakdowns.

3.2 Load estimation

The term *load* refers to any device or appliance that draws power from a photovoltaic (PV) system. At this stage of the design, it's important to calculate the total energy the load will require for daily operation. This is done by multiplying the power rating of the appliance by the number of hours it's used in a day. The result is expressed in watt-hours (Wh).[3]

If multiple identical appliances are used, their total energy demand is found by multiplying the watt-hours of a single unit by the number of units. To make this process easier, it's common to organize the information into tables showing the energy needs for each type of load both for DC and AC appliances. Typically, homes use mostly AC loads, but with the rise of LED lighting, which runs on DC, the use of DC appliances is becoming more common.[3]

3.3 Sizing of solar PV array

The solar PV module needs to generate sufficient energy to charge the battery, which in turn must provide enough power to the inverter to meet the energy demands of the connected load.[3]

3.3.1 Power Output of Solar PV Array

The electrical power produced by the solar photovoltaic array (P_{pv}) can be determined using the following formula:

$$P_{pv} = \frac{E_t \times PSI}{\eta_b \times K_{losses} \times H_{tilt}}$$
-------------------------(3.1)

Where:

- E_t is the total daily energy load
- PSI is the Peak Solar Intensity at the earth surface = 1kW/m^2
- η_b is the Efficiency of the System
- K_{losses} is the determination factor due losses on the system such as dust, change in temperature
- H_{tilt} is the average solar irradiance falling on the specific tilt angle.

[10]

The efficiency of the system is found using the following formula:

$$\eta_b = \eta_{inverter} \times \eta_{connection\ losses}$$ -------------------------(3.2)

Where:

- $\eta_{inverter}$ is the efficiency of the inverter
- $\eta_{connection\ losses}$ is the efficiency of the system connection

[10]

The determination factor is found using the following formula:

$$K_{losses} = t_{manuf} \times F_{temp} \times F_{dirt}$$ -------------------------(3.3)

Where:

- t_{manuf} is the manufacturer's tolerance in %
- F_{dirt} is the de-rating due to dirt which is in %

[10]

F_{temp} is the temperature de-rating factor which can be found using the following equation:

$$F_{temp} = 1 - [\gamma(T_{cell,\ eff} - T_{STC})]\text{ --------------------(3.4)}$$

Where:

- γ is the power temperature coefficient in %/ ^{0}C
- T_{STC} is the standard temperature of the collector

$T_{cell,\ eff}$ is the average daily temperature which is given by:

$$T_{cell,\ eff} = 25 + T_a\text{---------------------------------(3.5)}$$

Where: Ta is the ambient temperature. [10]

3.3.2 Modules configuration

The solar modules are interconnected using both series and parallel configurations making up an array.[10]

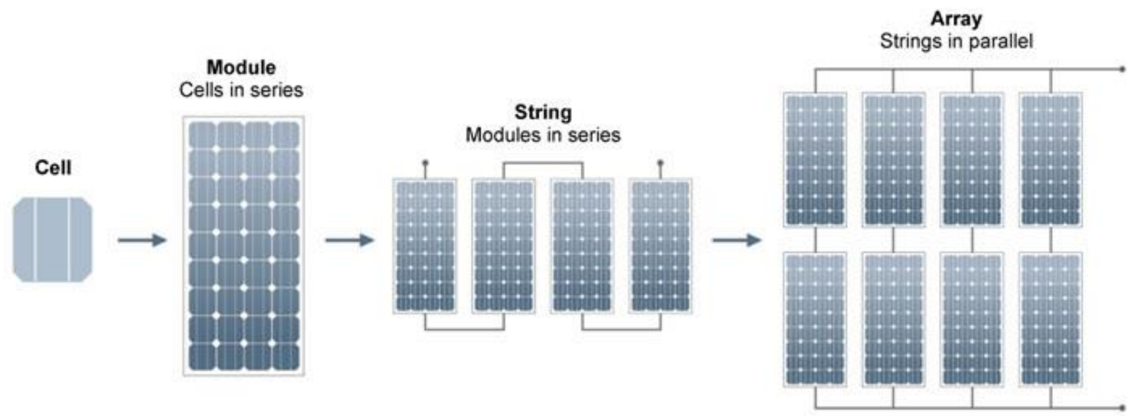

Figure 3.3.2 Modules configuration

3.3.2.1 Series configuration

This represents the number of modules in each row or string. To determine how many PV modules are needed to be connected in series, divide the desired system voltage by the voltage rating of a single module:

$$N_{ms} = \frac{V_{system}}{V_{module}}\text{ ------------------------(3.6)}$$

Where:

- V_{module} is the nominal voltage of the module
- V_{system} is the designed system array voltage

This setup makes sure that the total voltage from the connected modules matches the system's required array voltage. [10]

When PV modules are connected in series, their voltages add together while the current (amperage) flowing through the string remains the same across all modules. This setup ensures that the system meets the inverter's required operating voltage range. Modules are connected in series primarily to match the inverter's input voltage window. [2]

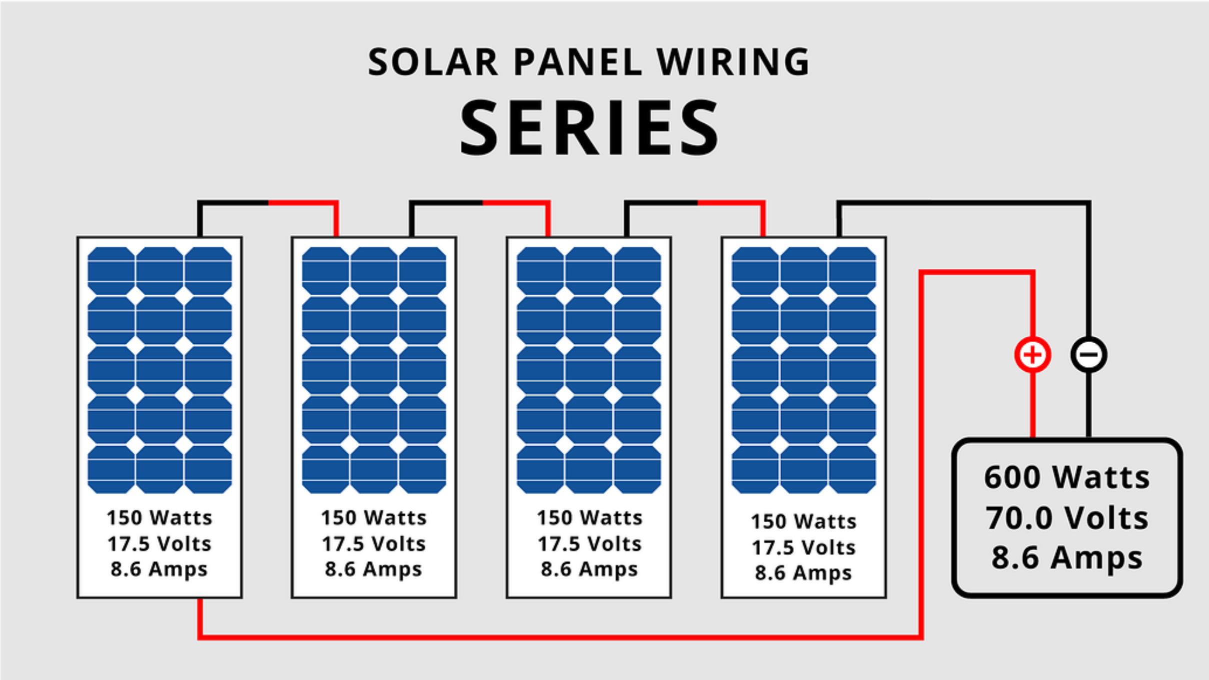

Figure 3.3.2.1 Series configuration of moduless

3.3.2.2 Parallel configuration

This is the number of parallel strings in the array. The number of modules connected in parallel can be calculated using the formula

$$N_{mp} = \frac{P_{PV}}{N_{ms} P_{module}} \quad \text{-------------------------(3.7)}$$

This setup makes sure that the total current from the connected modules matches the system's required array current. [10]

When PV modules are connected in parallel, the total current increases while the voltage stays the same across all modules. This setup allows for adding more modules to generate additional energy without surpassing the inverter's voltage limit. Since inverters also have current (amperage) limitations, connecting modules in parallel helps stay within those limits while maximizing energy production.[2]

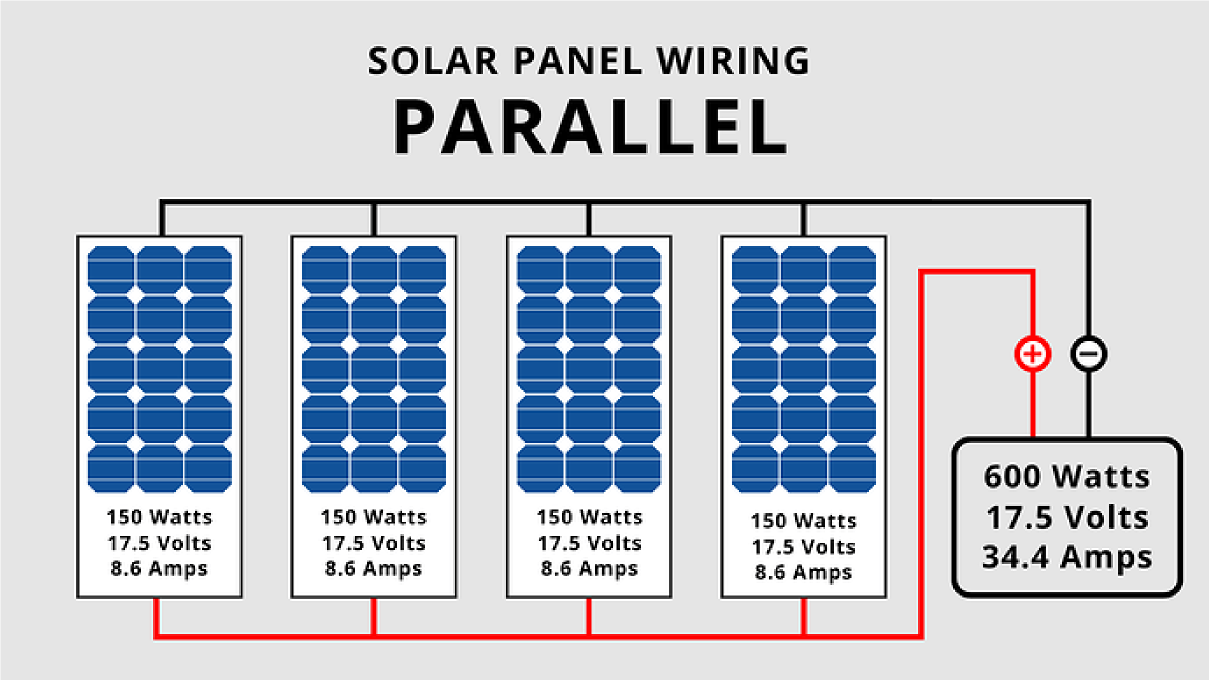

Figure 3.3.2.2 Parallel configuration of modules

3.3.2.3 Total number of modules in an Array

The total number of modules in an array can be obtained by multiplying number of modules in series and that in parallel.

$$N_{mt} = N_{ms} \times N_{mp} \text{------------------------(3.8)}$$

[10]

3.4 Sizing of the battery bank

Battery sizing should be done after the inverter has been sized for AC loads, and after the appropriate DC-DC converter has been selected for DC loads. The design of PV systems proceeds in the opposite direction of energy flow. The inverter and DC to DC converters will have some losses because they will have less than 100% efficiency. Therefore, we have to choose batteries in such a way that they should not only supply the power and energy required by the load, but also be able to supply the loss of energy in inverter and/or DC to DC converters, i.e., the loss occurring at converter has to be compensated by the battery. [3]

Figure 3.4 battery bank

3.4.1 Battery Bank Capacity

The battery bank plays a crucial role in smart grid systems, serving as the storage unit for the solar energy captured by the photovoltaic modules. Its capacity can be determined using the following:

$$C_b = \frac{E_t N_c}{\eta_{inv}.V_n DOD_{max.}}$$
-------------------------(3.9)

Where:

- N_c is the number of the autonomy days (Autonomy days refer to the number of consecutive days a solar system's battery storage can provide energy to the load without additional input from solar panels, typically used to ensure reliability during cloudy or rainy periods.)
- η_{inv} is the efficiency of the inverter
- V_n is the battery nominal voltage
- DOD_{max} is the maximum depth of discharging (The maximum depth of discharge (DoD) is the highest percentage of a battery's capacity that can be safely used without reducing its performance or lifespan)

[10]

3.4.2 Batteries configuration

Just like solar PV modules, batteries can also be arranged in both series and parallel configurations. [10]

3.4.2.1 Series configuration

The number of batteries connected in series can be determined using the following formula:

$$N_{b_{series}} = \frac{V_{system}}{V_{battery}} \quad \text{-------------------------(3.10)}$$

This setup makes sure that the total voltage from the connected batteries matches the system's required battery bank voltage. [10]

When batteries are connected in series, their voltages add together while the current (amperage) flowing through the string remains the same across all batteries. This setup ensures that the system meets the inverter's required operating voltage range. Batteries are connected in series primarily to match the inverter's input voltage window. [3]

Figure 3.4.2.1 Series configuration of batteries

3.4.2.2 Parallel configuration

This refers to the number of parallel strings of batteries within a battery bank. Similarly, the number of batteries connected in parallel can be calculated using the following formula:

$$Nb_{parallel} = \frac{Cb}{Nbseries \times Cselected} \quad \text{-------------------------(3.11)}$$

This setup makes sure that the total current from the connected batteries matches the system's required battery bank current.[10]

When batteries are connected in parallel, the total current increases while the voltage stays the same across all batteries. This setup allows for adding more batteries to generate additional energy without surpassing the inverter's voltage limit. Since inverters also have current (amperage) limitations, connecting batteries in parallel helps stay within those limits while maximizing energy production.[3]

Figure 3.4.2.2 Parallel configuration of batteries

3.4.2.3 Total number of batteries in battery bank

The total number of batteries in a battery bank can be obtained by multiplying number of batteries in series and that in parallel.

$$N_{b\,total} = N_{b\,series} \times N_{b\,parallel} \quad (3.12)$$

[10]

3.5 Inverters and Charge Controllers

3.5.1 Inverter selection

An inverter is required in systems where AC power output is needed. Its input capacity should always be equal to or greater than the total power consumption of the connected appliances. Additionally, the inverter's nominal voltage must match that of the battery bank. For off-grid setups, the inverter must be capable of handling the total power demand expected at any given moment. To ensure reliable performance and account for potential surges, it's recommended that the inverter's size be 25–30% higher than the combined power of all appliances.[10]

Figure 3.5.1 Inverter

Fig 3.5.1 Inverter

3.5.2 Charge controllers

The charge controller manages the flow of electricity from the solar panels to the battery, ensuring that the batteries are charged efficiently and safely. It prevents overcharging, deep discharging, and also helps extend battery life.[3]

There are two main types of charge controllers commonly used:

1. PWM (Pulse Width Modulation):
   PWM controllers are simpler and more affordable. They work by slowly reducing the amount of power applied to the batteries as they approach full charge. However, their efficiency drops significantly when the solar panel voltage is much higher than the battery voltage, leading to potential energy loss. [3]
2. MPPT (Maximum Power Point Tracking):
   MPPT controllers are more advanced and efficient. They continuously track the maximum power point of the PV array, adjusting the input voltage and current to extract the maximum possible energy. MPPT controllers are especially beneficial in systems where the panel voltage is substantially higher than the battery bank voltage. [3]

Given their superior performance, MPPT charge controllers are generally recommended for modern off-grid systems, particularly in environments with variable solar irradiance or when using high-voltage PV arrays. [3]

Figure 3.5.2 MPPT

3.5.2.1 Distinctions between MPPT and PMW

Feature	PWM	MPPT
Cost	Lower	Higher
Efficiency	Moderate (up to ~75-80%)	High (up to ~98%)
Best for	Small/simple systems	Larger or more efficient systems
Voltage Matching	Requires panel voltage to match battery voltage	Can work with higher panel voltage
Performance in Cold/Cloudy Weather	Lower	Better – extracts more power
Technology	Simpler	More advanced

Table 3.5.2.1 Distinctions between MPPT and PMW

[3]

3.5.2.2 Charge controllers configuration

A voltage regulator controls the flow of current in a system. To perform effectively, it must be able to handle both the maximum current produced by the array and the maximum current required by the load. The proper sizing of the voltage regulator can be determined by multiplying the short-circuit current of the modules connected in parallel by a safety factor (f_{safe}). This calculation yields the rated current required for the voltage regulator

$$I_{rated} = N_{mp} \times I_{sc} \times f_{safe} \text{------------------------(3.13)}$$

Where:

- N_{mp} is the number of PV modules connected in parallel
- I_{sc} is the short circuit current of the module and
- f_{safe} is the safety factor which is usually taken to be 1.25

The required number of voltage regulators can be determined using the following equation.

$$N_{v_{reg}} = \frac{I_{rated}}{I_{selected}} \text{------------------------(3.14)}$$

Where:

- $I_{selected}$: The current capacity of a single selected charge controller

This method is essential when the system current exceeds the rating of a single controller. In such cases, multiple controllers are connected *in parallel* to share the load evenly. [10]

3.6 Distribution: Low-voltage AC grid.

The proposed solar microgrid utilizes a low-voltage alternating current (LVAC) distribution system to supply power to end-users. This approach is suitable for rural and institutional settings, as it aligns with the standard 230 V, 50 Hz power requirements of most household and laboratory appliances. The inverter delivers this AC voltage directly to the distribution board, from which electricity is routed to various loads through protected circuits.

Given the small scale of the system rated at 2.5 kW and the relatively short cable runs within the site, voltage drops are expected to remain minimal and within recommended limits. Electrical conductors are sized appropriately to ensure efficiency and safety, maintaining a voltage drop below 5%.

The system incorporates key protective components such as circuit breakers, fuses, and an earthing system. These are essential for preventing damage to equipment and ensuring user safety in the event of faults. The centralized distribution board simplifies the organization of circuits and allows for future load expansion if the energy capacity is increased.

Importantly, the system does not require the use of transformers, as the inverter output already matches the local low-voltage standard, and the power is distributed over short distances. Eliminating the transformer reduces both system complexity and cost.

3.7 Off-Grid PV system numerical design question for Zimbabwe Rural Electrification

Numerical Design Question:

A solar photovoltaic (PV) system is to be designed for an off-grid rural electrification project in Zimbabwe, targeting an ICT training center. The estimated energy demand of the center is 30 kWh/day. The system should operate at 48 V DC and provide autonomy for 2 full days without sunlight.

Given:

- Peak Solar Intensity (PSI): 1 kW/m^2
- Average solar irradiance on tilted surface: 5.5 kWh/m^2/day
- Ambient temperature: 28 °C
- STC temperature: 25 °C
- Power temperature coefficient (γ): 0.0048 /°C
- Inverter efficiency (η_1): 90%
- Connection efficiency (η_2): 85%
- Manufacturer tolerance: 97%
- Dirt derating factor: 90%

PV Module:

- Power: 300 W
- Voltage: 24 V
- Short-circuit current: 9.6 A

Battery:

- Voltage: 12 V
- Capacity: 150 Ah
- Max Depth of Discharge (DOD): 50%

Regulator:

- Max current: 90 A
- Safety factor: 1.25

Questions

A. PV Power Output

1. Calculate the total PV array output required to meet the load demand, taking into account system efficiency and losses.

B. PV Module Sizing

2. How many PV modules are required in series to match the system voltage?
3. How many PV modules are required in parallel to meet the energy output?
4. What is the total number of PV modules needed?

C. Battery Bank Design

5. Calculate the total required capacity of the battery bank in Ah.
6. How many batteries should be connected in series to match the system voltage?
7. Calculate the number of batteries required in parallel.
8. Determine the total number of batteries required.

D. Voltage Regulator Design

9. Calculate the total current generated by the PV array.
10. Determine the number of voltage regulators needed.

E. Inverter Selection

12. Suggest a suitable type and size of inverter that would support the system load reliably.

[10]

Solution

1. Required PV Power Output

System efficiency:

$$\eta_b = \eta_1 \times \eta_2 = 0.90 \times 0.85 = 0.765$$

Effective cell temperature:

$$T_{cell,eff} = 25 + T_a = 28 + 25 = 53^{\circ}C$$

Temperature derating factor:

$$F_{temp} = 1 - [\gamma(T_{cell,eff} - T_{STC})] = 1 - 0.0048(53 - 25) = 0.8656$$

Total system loss factor:

$$K_{losses} = t_{manuf} \times F_{temp} \times F_{dirt} = 0.97 \times 0.90 \times 0.8656 = 0.755$$

Required PV output:

$$P_{pv} = \frac{E_t \times PSI}{\eta_b \times K_{losses} \times H_{tilt}}$$

$$P_{pv} = \frac{30 \times 1}{0.765 \times 0.755 \times 5.5} = \frac{30}{3.173} \approx 9.45\text{kWh/day}$$

2. PV Modules in Series

$$N_{ms} = \frac{V_{system}}{V_{module}}$$

$$N_{ms} = \frac{48}{24} = 2$$

3. PV Modules in Parallel

$$N_{mp} = \frac{P_{PV}}{N_{ms} P_{module}}$$

$$N_{mp} = \frac{9.45 \times 1000}{300 \times 2} = \frac{9450}{600} = 15.75 \approx 16$$

4. Total Number of PV Modules

$$N_{mt} = N_{ms} \times N_{mp} = 2 \times 16 = 32$$

5. Required Battery Capacity

$$C_b = \frac{E_t N_c}{\eta_{inv.} V_n DOD_{max.}}$$

$$C_b = \frac{30 \times 1000 \times 2}{0.90 \times 0.50 \times 12} = \frac{60000}{5.4} = 11111.11\text{Ah}$$

6. Batteries in Series

$$N_{b_{series}} = \frac{V_{system}}{V_{battery}}$$

$$N_{bseries} = \frac{48}{12} = 4$$

7. Batteries in Parallel

$$Nb_{parallel} = \frac{Cb}{Nbseries \times Cselected}$$

$$Nb_{parallel} = \frac{11111.11}{4 \times 150} \approx 18.52 \approx 19$$

8. Total Number of Batteries

$$Nb_{total} = Nb_{series} \times Nb_{parallel}$$

$$Nb_{total} = 4 \times 19 = 76$$

9. Total Array Current

$$I_{array} = I_{rated} = N_{mp} \times I_{sc} \times f_{safe}$$

$$I_{array} = I_{rated} = 16 \times 9.6 \times 1.25 = 192A$$

10. Number of Voltage Regulators

$$N_{v_{reg}} = \frac{I_{rated}}{I_{selected}}$$

$$N_{vreg} = \frac{192}{90} \approx 2.13 \Rightarrow 3 \text{ regulators (rounded up)}$$

11. Inverter Selection

Total load = 30 kWh/day → average power = $\frac{30 \times 1000}{24}$ = 1250W

Add 25% margin:

$$1250 \times 1.25 = 1562.5W \Rightarrow 2kW \text{ pure sine wave inverter}$$

The 25% margin is a safety buffer to ensure the inverter can handle real-world conditions like surges and future expansion and is a best practice in professional solar system design.

[10]

3.8 Conclusion

This chapter outlined the complete system design of the proposed solar microgrid for rural electrification, tailored to the specific requirements of the Laboratory LSELM. Key components including the photovoltaic modules, battery storage system, charge controller, inverter, and low-voltage AC distribution network were selected and dimensioned based on the site's energy demand and local environmental conditions.

The design prioritizes simplicity, efficiency, and reliability, ensuring that the system remains cost-effective while meeting the laboratory's energy needs. The use of a low-voltage AC distribution approach eliminates the need for transformers, further reducing installation and maintenance complexities. This foundational design serves as the blueprint for implementation, enabling a transition to clean, off-grid electricity. [11]

4.0 Chapter 4: Case Study: Laboratory LSELM.

Implementation of 1.4 kW system serving Lab LSELM.

4.1 Introduction

This chapter presents the implementation and performance analysis of an off-grid photovoltaic system designed to power a laboratory environment. The system integrates key components such as PV modules, an MPPT charge controller, a battery bank, an inverter, and an AC load (a laboratory motor controlled via a VFD).

The aim of this case study is to demonstrate the practical viability of using solar energy for small-scale laboratory applications, with a focus on system setup, operation under various load conditions, and analysis of performance data. The chapter provides a detailed description of the system installation, configuration of components, and monitoring procedures, followed by a critical assessment of the system's operational behavior under both no-load and load conditions.

By analyzing this system in a real-world context, this chapter contributes valuable insights into the challenges and opportunities of deploying off-grid PV systems for specific applications like laboratory equipment.

4.2 Installation and System Setup

4.2.1 Site assessment

Figure 4.2.1 Site assessment

4.2.1.1 Location

The photovoltaic (PV) system was installed on the rooftop of the Laboratory LSELM at Badji Mokhtar University, located in Annaba, Algeria. The choice of this location was based on both accessibility and its suitability for solar energy applications in a university environment. The rooftop offers a controlled, observable environment ideal for practical learning and technical evaluation.

4.2.1.2 Climate and Solar Potential

Annaba is situated in north eastern Algeria and benefits from a Mediterranean climate, characterized by hot, dry summers and mild, wet winters. According to climatological data, the city receives an average of approximately 2,675 hours of sunshine annually, which makes it a favorable location for solar energy generation. This high solar potential supports the feasibility and expected efficiency of photovoltaic systems, especially in academic or demonstration-scale setups.

[12]

4.2.1.3 Shading Conditions

The selected rooftop is free from shading obstructions such as tall buildings, trees, or other physical structures. A full shading assessment was carried out before installation, both visually and using manual angle checks throughout the day. No significant shadowing was observed during peak sunlight hours (09:00 to 16:00), which is crucial for maintaining consistent solar irradiance and avoiding performance degradation in the PV modules.

4.2.1.4 Site Orientation and Tilt Angle

For optimal solar energy capture in the northern hemisphere, photovoltaic (PV) modules should be oriented to face true south. This orientation ensures maximum exposure to sunlight throughout the day, enhancing the system's overall efficiency.

Regarding tilt angle, a common guideline is to set the angle equal to the site's latitude. In Annaba, Algeria, which lies at approximately 36° latitude, this would suggest a tilt angle of 36°. However, studies have shown that slightly adjusting the tilt angle can further optimize energy production. For instance, research conducted in Algiers and Ghardaia found that the angle maximizing annual energy production is close to the local latitude, with optimal angles around 32° and 33°, respectively

Therefore, for the installation in Annaba, a tilt angle of approximately 32° to 36° is recommended to maximize annual energy yield. This adjustment accounts for the sun's path and seasonal variations, ensuring the PV modules receive optimal sunlight exposure throughout the year.

[13]

4.2.1.5 Structural Suitability

The rooftop was assessed for its load-bearing capacity and structural stability. It was deemed suitable to support the mounting structures and PV modules without reinforcement. The installation area provided ample space and secure anchoring points for a stable and safe system setup.

4.2.2 PV Modules Installation

Figure 4.2.2 Modules installation

4.2.2.1 Equipment and Materials Used

The installation involved several essential components selected based on availability, compatibility and system requirements

- Photovoltaic (PV) Modules
  A total of 8 monocrystalline modules, each rated at 175 W, were used. These were connected in series to achieve a total system capacity of 1.4 kW. Monocrystalline panels were chosen for their higher efficiency and space-saving benefits, which are suitable for the limited rooftop area.
- Mounting Structures
  A ballasted, fixed-tilt steel frame system was used as the mounting structure for the PV modules. The steel was hollow, which helped reduce the overall weight of the installation while maintaining necessary structural strength. It was also painted to offer basic protection against corrosion. The ballasted design allowed the system to be securely placed on the rooftop without drilling, preserving the roof's integrity.
- DC Cables
  Proper sizing of the cables was ensured to minimize voltage drop and maximize current-carrying capacity. Cable Duct is used to safely route and protect the electrical cables coming from the solar panels on the roof into the lab. It keeps the wiring organized, prevents damage, and reduces electrical hazards. This ensures a neat, safe, and professional solar installation.
- MC4 Connectors
  MC4 connectors were used to connect the PV modules in series. These weatherproof, snap-lock connectors are standard in solar installations and ensure a secure and safe connection between panels. Their design allows for quick installation and disconnection when needed, while maintaining reliable conductivity and resistance to environmental exposure. MC4 connectors are designed to minimize power loss.
- Safety Equipment
  Personal protective equipment (PPE) was used throughout the installation process. This included insulated gloves, safety goggles, and a digital multimeter for voltage and continuity checks. These tools ensured that installation procedures were conducted safely and in compliance with electrical safety standards.

4.2.2.2 Mounting Structure Setup

The PV modules were mounted on a ballasted, fixed-tilt steel frame system positioned on the flat concrete rooftop of the laboratory building. The hollow steel frames were pre-assembled on-site, allowing for efficient alignment and placement.

No drilling or anchoring was required, as concrete blocks were used as ballast to hold the frames securely in place. This method ensured the roof remained undamaged while still providing adequate resistance to wind loads.

4.2.2.3 Implementation of Orientation and Tilt

To maximize solar energy capture, the PV modules were installed with a fixed tilt angle of approximately 36°, matching the latitude of Annaba, Algeria. This angle was selected to ensure optimal year-round performance based on standard solar design guidelines for the northern hemisphere.

The modules were oriented to face true south, determined using a compass corrected for magnetic declination. The tilt angle was measured and verified using a digital inclinometer, ensuring accuracy during setup.

The mounting structure itself was pre-engineered to provide a fixed 36° tilt. Once positioned correctly, the modules were secured to the steel frame using clamps and bolts, while the frame was held in place with ballast blocks to prevent movement or misalignment. The fixed-tilt configuration was chosen over an adjustable one due to its simplicity, durability, and suitability for this off-grid rooftop application.

4.2.2.4 Electrical Interconnection

All eight 175 W PV modules were connected in series via MC4 connectors, resulting in a total system capacity of 1.4 kW. The use of MC4 connectors ensured secure, weather-resistant, and standardized connections between modules. This method also simplified installation and allowed for quick disconnection during maintenance. The series configuration was selected to achieve higher system voltage, improving the performance of the MPPT charge controller

Before making any connections, polarity checks were performed on each module using a multimeter to ensure proper positive and negative orientation. This step was critical to avoid reverse polarity, which could lead to equipment damage or reduced performance.

4.2.2.5 Earthing and Safety Measures

4.2.3 Charge Controller and Battery Setup

4.2.3.1 Type of Charge Controller Used

For this installation, an MPPT solar charge controller, model *SC-M-60A*, was used. This controller is capable of handling multiple system voltages, specifically 12V, 24V, and 48V battery systems. It has a maximum charge current of 60A, making it suitable for medium-scale solar installations. The MPPT tracking voltage range for different battery systems was respected during setup:

- 15V–155V solar input voltage for 12V battery system
- 30V–155V solar input voltage for 24V battery system
- 60V–155V solar input voltage for 48V battery system

The MPPT tracking voltage range means the range of input voltages that the charge controller can handle effectively when it's searching for the maximum power point of your solar panels. If your solar panel voltage falls below the minimum, the MPPT can't track properly, and your system won't harvest maximum power. If your solar panel voltage goes above maximum, it could damage the controller. The controller also limits the series connections of panels for safety: a maximum of 6 panels in series for 18V modules, and up to 3 panels in series for 36V modules.

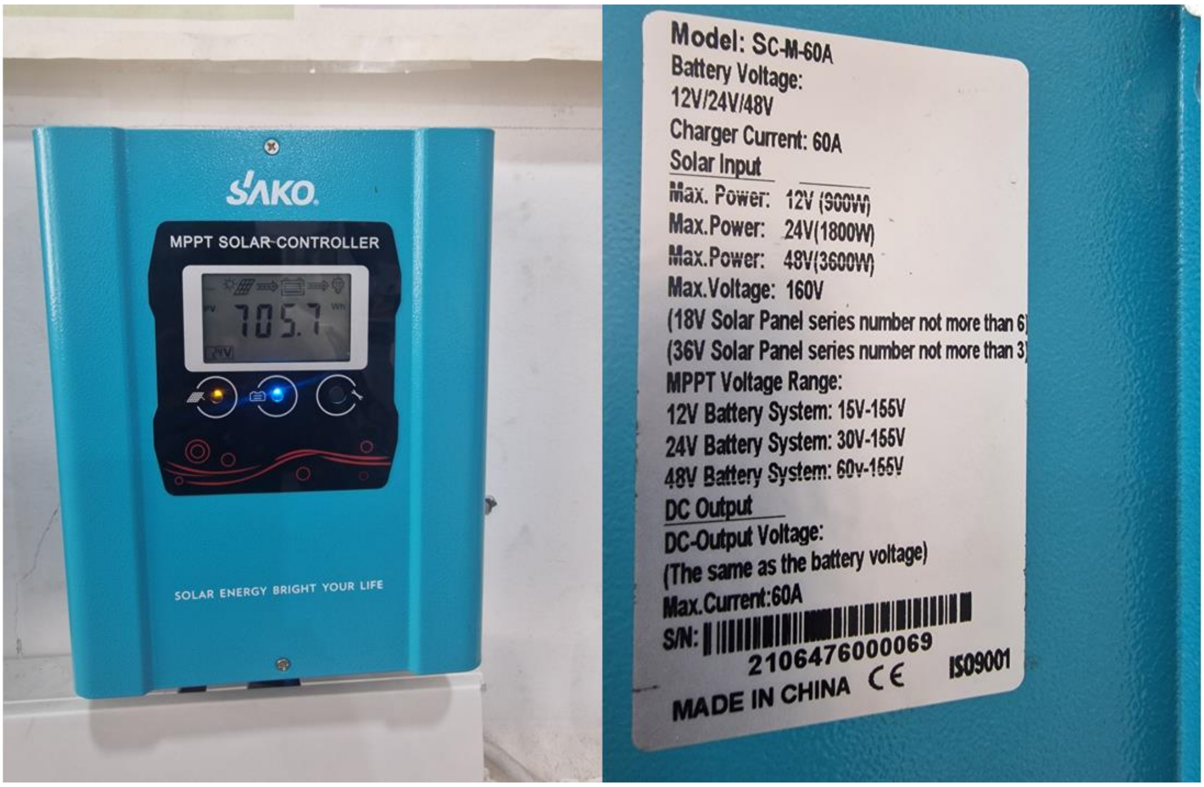

Figure 4.2.3.1 MPPT

4.2.3.2 MPPT Voltage and Current Ratings

The charge controller's input ratings were carefully considered. The maximum solar input power is:

- 900W for 12V battery system
- 1800W for 24V battery system
- 3600W for 48V battery system

The input voltage limit is 160V, which was not exceeded during the system design and installation. The output voltage from the controller is the same as the battery voltage, and the maximum output current is rated at 60A.

4.2.3.3 Battery Specs and Connections

The system uses Valve Regulated Lead-Acid (VRLA) gel batteries, model 6FM150G, rated at 12V and 150Ah each. Two batteries were connected in series to achieve the required system voltage of 24V.

Proper terminal tightening and series interconnection methods were followed to ensure stable and reliable energy storage. The connections were made using appropriately rated cables to handle the expected current.

Figure 4.2.3.3 Battery Specs and Connections

4.2.3.4 Safety Components

To ensure the safety of the system, DC fuses were installed between the charge controller and the batteries, as well as between the solar array and the charge controller. A DC circuit breaker was also included for emergency shutdown and maintenance. All connections were made in compliance with standard electrical safety practices, including proper cable management and grounding where applicable.

4.2.4 Inverter Setup

The system uses a pure sine wave inverter with a continuous power rating of 1200W and a surge power rating of 2400W. The inverter's DC input voltage is 24V, which matches the battery bank voltage (two 12V batteries connected in series). This voltage compatibility ensures stable and efficient power conversion from DC to AC for the system's loads. The 1200W continuous rating was selected based on the estimated maximum load demand in the laboratory, while the 2400W surge rating provides an adequate margin for handling startup currents from devices such as motors. The choice of a pure sine wave output was also critical to ensure compatibility with sensitive laboratory equipment.

Figure 4.2.4 Inverter

4.2.5 Load Connection

4.2.5.1 Type of Load Used

The primary load connected in this setup is a Leybold-Didactic GmbH 732-10 three-phase AC motor. The motor has the following specifications:

- Voltage: 220/380 V
- Current: 1.47/0.85 A
- Power: 0.3 kW (300 W)
- Speed: 2800 RPM
- Frequency: 50 Hz
- Protection Rating: IP54

The motor is controlled through a motor driver (VFD), which allows for varying the motor's speed during operation. This setup simulates a realistic laboratory load scenario, where equipment with variable power demand is used.

Figure 4.2.5.1 Motor

4.2.5.2 Load Connection Method

The motor driver is connected directly to the AC output terminals of the inverter. The inverter receives power from the DC system (battery and MPPT controller) and provides a stable AC voltage suitable for running the motor

4.2.5.3 Approximate Load Power

The motor's rated power is 0.3 kW; however, depending on the motor speed and load conditions, actual power consumption may vary during operation. SPPEEED

4.2.5.4 Monitoring Setup

System performance and load behavior are monitored through:

- The MPPT controller screen, which displays PV input power, battery voltage, and load consumption.
- Digital multimeters, used for measuring voltages, currents, and power directly at different points in the system.

4.2.6 Protective devices

Step 1: PV Array → Junction Box → MPPT Controller

1. WSPV-32B (DC fuse holder)
    - Protects the MPPT from overcurrent by fusing if current exceeds the safe level.
2. XLSPD-PV (DC Surge Protection Device)
    - Protects the system from voltage surges (e.g. lightning).
3. CNC YC89-80DM (DC Circuit Breaker)
    - ‣ Provides manual disconnection and automatic cut-off in case of overcurrent.

Step 2: MPPT → Junction Box → Battery Bank

4. GEYA (DC Circuit Breaker)
    - DC circuit breaker between the MPPT output and the battery bank. It protects the wiring and battery system from overcurrent or short circuits.
    - Also provides a means to disconnect the battery safely when needed.

Step 3: Inverter Output → Junction Box → AC Loads

5. RT18-32X (AC fuse holder)
    - It's used here as an AC fuse holder for Live wire protection.
6. DZ47-63 (C6) – AC MCB
    - Giving overcurrent protection

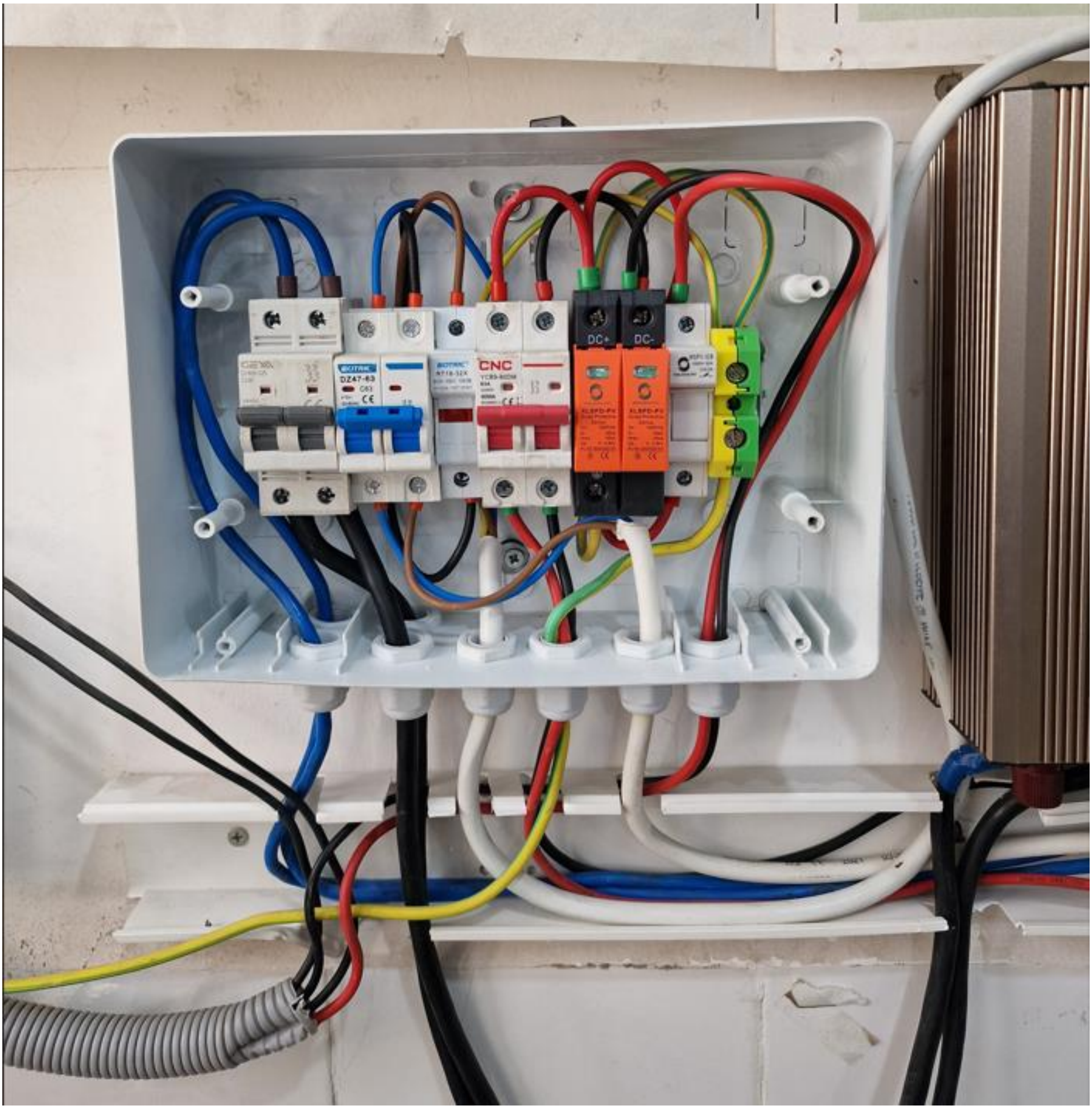

Figure 4.2.6 protective devices

4.3 Performance Observation and Analysis

4.3.1 Test Conditions

The system’s performance was observed under two distinct conditions

1. No Load Test
2. On Load Test

Both tests were conducted under stable environmental conditions (daylight hours, consistent irradiance) and standard ambient temperature. Measurements were recorded over a period of approximately 10–20 minutes using the MPPT controller display and external meters.

4.3.1.1 No Load Test

Conducted for a short period at the start of the testing, where the motor (load) was not connected, and the PV system operated under open-circuit conditions. The primary objective was to monitor the behavior of the PV system and MPPT controller in the absence of load.

4.3.1.2 On Load Test

The Leybold-Didactic GmbH 732-10 three-phase AC motor was connected as the load, controlled through a variable frequency drive (VFD). The test was carried out over multiple intervals, and changes in system parameters were recorded as the load power demand varied

4.3.2 Results of measurements

State	V_{pv}(V)	I_{pv}(A)	P_{pv}(W)	E_{pv}(Wh)	V_{bat}(V)	Motor Speed(RPM)
No load	83.2	1.4	38.8	635.8	27.7	-
On load	82.1	4.1	110.8	669.2	27.7	2772
	81.8	3.9	108.0	674.3	27.7	2510.7
	81.9	3.6	97.0	678.8	27.7	2212
	82.4	3.4	94.2	682.5	27.7	2025.3
	82.3	3.3	91.4	684.7	27.7	1829.3
	82.2	3.1	85.9	688.2	27.7	1652
	82.0	3.0	83.1	690.3	27.7	1484
	82.1	2.8	77.6	692.8	27.7	1250.7
	82.3	2.7	74.8	695.3	27.7	1082.7
	82.0	2.6	72.0	697.3	27.7	942.7

Table 4.3.2 Results of measurements

4.3.2.1 Explanation of Data Collection

Readings were taken at regular intervals directly from the MPPT controller's display, which provided real-time data on PV voltage (Vpv), PV current (Ipv), PV power (Ppv), energy produced (Epv in Wh and kWh), and battery voltage (Vbat)

We measured the motor speed by connecting a digital multimeter to the red and blue terminals of the tachogenerator. The voltage reading is proportional to RPM; using the ratio 3V = 2800 RPM, we calculated the speed with:
RPM = (Measured Voltage / 3) × 2800.

4.3.3 Observations

4.3.3.1 Trends in Voltage, Current, and Power

- PV Voltage (Vpv) remained relatively stable, ranging between 81.8V and 83.2V, indicating a stable MPPT operation.

- PV Current (Ipv) increased significantly when the load was applied, from 1.4A (no load) to 4.1A at peak load, then gradually decreased as the load reduced.
- PV Power (Ppv) peaked at 110.8W under load, confirming higher energy extraction from the PV system when the motor was running.

4.3.3.2 Energy Values

- Epv (Wh) steadily increased from 635.8Wh to 697.3Wh, reflecting continuous energy generation over the testing period. The Epv (Wh) values represent cumulative energy generation over time

4.3.3.3 Battery Voltage Behavior

Vbat remained constant at 27.7V throughout, showing effective charging and regulation by the MPPT controller despite varying load conditions.

4.3.3.4 Motor Speed Variations

As motor speed decreased from 2772 RPM to 942.7 RPM, the electrical power drawn by the motor also decreased, reflecting a typical reduction in power demand at lower speeds for this type of load.

4.3.4 Interpretation

4.3.4.1 System Behavior

The system performed as expected. The PV array supplied higher current under load, and the MPPT controller maintained stable voltage and power extraction. The battery voltage stability indicates that the system is well-regulated.

4.3.4.2 Losses and Efficiency

Minor losses are observed due to the natural decrease in PV voltage under load. The system's efficiency remained acceptable, although the PV array's power output (max ~110W) is lower than the theoretical peak of 1.4kW. This discrepancy is likely due to reduced solar irradiance during testing, wiring losses, and conversion inefficiencies in the MPPT and inverter.

4.3.4.3 Adequacy of Energy Generation

For the connected 0.3kW (300W) motor load, the energy generation is marginally sufficient under good solar conditions. However, sustained operation at full motor power may not be achievable without exceeding the system's generation capacity. The test demonstrates that while the system can support light to moderate loads, careful load management is essential to avoid over-discharge of the battery or system instability.

4.4 Conclusion

This case study demonstrated the practical implementation of an off-grid photovoltaic system for powering a laboratory load. The system was successfully designed, installed, and tested, including PV modules, an MPPT charge controller, a battery bank, and an inverter to supply AC power. The system was able to operate a laboratory motor connected through a variable frequency drive (VFD), demonstrating the feasibility of using solar energy for such applications.

Performance observations showed that the system operated as expected, maintaining stable voltage levels, tracking maximum power point through the MPPT, and supporting the motor's varying speed demands under load. The energy generated by the system was sufficient for the load, with efficiency losses and minor fluctuations in performance remaining within acceptable limits for real-world systems.

Overall, this study highlights the importance of careful system design, component compatibility, and real-world performance analysis in successfully implementing off-grid solar systems. The system provided a reliable and sustainable solution for powering the laboratory load, demonstrating the potential of renewable energy in practical applications.

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