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DESIGN AND SIMULATION OF AN OPTIMUM PV-BASED MINI-GRID AT RP-GISHARI COLLEGE

By:

MAJYAMBERE Jean Pierre

Reference number: 220000277

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Supervisor: Ass Prof. BIKORIMANA JMV (PhD)

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KIGALI-RWANDA

DECLARATION

I hereby declare that this thesis is a result of my own work and has not been submitted to the University of Rwanda or any other institution under consideration for a degree.

Name: MAJYAMBERE Jean Pierre

Signature:

APPROVAL SHEET

This thesis work has been submitted for examination with my approval as a university advisor

Ass Prof. BIKORIMANA JMV(PhD)

Thesis supervisor Signature:

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ABSTRACT

This thesis presents the design and simulation of a photovoltaic (PV)-based mini-grid for Gishari College, located in the Eastern Province of Rwanda. The primary goal of the study is to provide a sustainable and reliable power solution for the college by harnessing solar energy through a decentralized system. A comprehensive assessment of the solar radiations, load demand, and load profile was conducted. During the design of a mini-grid based on PV-system, the PV system's capacity was optimized using HOMER (Hybrid Optimization of Multiple Energy Resources) software, which helped simulate various configurations, including energy generation and backup power options, to ensure continuous power supply throughout the year. The study also explores the economic feasibility of the proposed system, analyzing cost implications, potential savings of the proposed PV-based solution. The results demonstrate that the PV-based mini-grid can generate 159,869kWh to meet the college's energy needs efficiently and reduce reliance on the national grid by savins 11175$ annually. This work provides a replicable model for other educational institutions in similar contexts aiming to transition towards renewable energy systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

$:	Unite State Dollar
A:	Area covered by PV-array and
AC:	Alternative Current
ACE-ESD:	African Centre of Excellence in Energy and Sustainable Development
AE:	Agricultural Engineering
BB:	Battery Bank
C:	Total Cost of energy
C_{DG}:	Cost of energy generated from diesel generator
CE:	Civil Engineering
C_{grid}:	Cost of energy generated from utility grid
CO2:	Carbon dioxide
C_{PV}:	Cost of energy generated from PV-system
DC:	Direct Current
DER:	Distributed Energy Resources
DG:	Diesel Generator
DG:	Distributed Generation
DMS:	Distribution Management System
E_{DG}:	Energy generated from diesel generator.
EEE:	Electrical and Electronics Engineering
E_{grid} :	Energy generated from utility grid
E_{PV}:	Energy generated from PV-system
ESS:	Energy System Storage
FL:	Future Load
FW:	Flywheel
GC:	Generation Controllers
HOMER:	Hybrid Optimization of Multiple Energy Resources
I:	Solar Irradiance
kW:	kiloWatt
kWh:	kiloWatt hour

LCOE: Levelized cost of energy

LL: Local Loads

ME: Mechanical Engineering

MG: Mini Grid

MGCC: Mini Grid Central Control

MW: Mega Watt

NPC: Net Present Cost

P_{DG}: Power from Diesel Generator

P_{grid} : Power form Utility grid

$P_{load.max}$: Maximum Power consumed by the load

P_{load}: Power consumed by the load

P_{PV}: Power from Photovoltaic system

PV: Photovoltaic

RP: Rwanda Polytechnics

WT: Wind Turbine

η: overall efficiency of PV-system

CHAPTER ONE: INTRODUCTION

1.1. General Introduction

Electrical energy is now required to enhance industrialization, health, education, and water supply in order to eradicate poverty [1]. Consequently, it is estimated that by 2060, the world's electricity demand will have doubled. However, there will be a number of difficulties associated with continuing to rely on conventional power plants, including frequent outages and global warming [1]. In addition, using centralized generation of electrical energy leads to high cost of building transmission lines, and energy loss during transit to the load center which is not the best option. This problem can be solved by using mini-grids, which are separate from the main utility grid, to supply communities in dispersed rural areas with distribution, balancing-of-system, and generation infrastructure. Besides, renewable energy sources are more efficient, dependable, low maintenance, and provide a quieter atmosphere and reduced carbon dioxide (CO_2) emissions. Therefore it is very crucial to use renewable energy sources like solar, wind and others while designing a mini-grid. [2]. A collection of generators that provide a localized customer base with all of their electricity needs is known as a mini-grid and this one can greatly increase the economics of using a photovoltaic system to generate electricity by eliminating the need to transmit electricity from a remote central-station power plant[3]. Through the research, the education sector and universities in particular have taken the lead in ensuring a sustainable energy system, which includes making sure campuses are energy-independent. Additionally, in many college campuses, mini-grid systems have become an affordable and sustainable option. These systems are intended to help universities become self-sufficient in the event of power outages and load shedding[2]. Utilizing all of the energy produced by the solar photovoltaic system can lower the university's electricity costs. Additionally, lowering the excess electricity supplied to the grid will lessen the effect that distributed power has on the public grid[4].

1.2. Background

There is an extensive list of universities with an increasing number of departments, canteens, and hostels on both a national and international level. Although they increased the nation's energy demand, educational institutions have an obligation to set an example for the country in energy conservation and to optimize energy management in terms of consumption by incorporating mini-grid systems that use renewable energy sources[5]. With the case of Rwanda, according to the paper [6], a large number of Rwandan university campuses are equipped with diesel backup generators to power their campuses in the case that the national grid is unavailable. Because these standby systems function independently, there is no chance of economical dispatching, which raises operating and electricity consumption costs. RP-Gishari College is one of the eight different colleges that make Rwanda Polytechnic[7]. With an area of 12 hectares, RP-Gishari College has four departments and those are Electrical and Electronics Engineering (EEE), Mechanical Engineering (ME), Civil Engineering (CE) and Agricultural Engineering (AE) with currently 1346 students in total where boys are 80.1% and girls are 19.9%. The college consumes around 650.3kWh of electrical energy per months for various activities including teaching and administrative activities. This energy comes from national power grid and it obvious that the college spends 1313.8$ for electricity bills on monthly basis. Moreover, the management of RP-Gishari college has a plan of expanding its infrastructure due to increase of 20% of students every year for the period of five years and this increase in students will be proportional to the increase of teaching staff. This plan requires the high-power demand to meet load requirements hence integration of a solar PV mini-grid system can contribute to energy satisfaction of the college. In this context, a design of a mini-grid based on Photovoltaic (PV) technology is suitable solution for not only meeting load demand at RP-Gishari college but also lowering the cost of electricity. The data from meteo-Rwanada shows that Gishari college is located in area with high sufficient solar radiation of 5.4 kWh/m² on average (refer to the table 3.5 in annex).

1.3. Problem statement

As mentioned in background ,schools and universities are among the big consumers of electricity and this lead to low reliability of power supply due to high power demand and high dependance from national grid[8]. Specifically, polytechnical schools consume a huge amount of electricity to conduct practical sessions where different workshops are operational during teaching activities. In this context, RP-Gishari College is facing a frequent interruption of electricity due to high load demand and high dependance from national grid and this affects not only teaching activities but also quality of education in term of research and innovation at this college. In addition, because RP-Gishari College is still growing in term of infrastructure, students and staff, the increase in power demand is expected to be increased in coming 5 years. In addition, the data of three years from logistic office as show that RP-Gishari college spends average of 1313.8$ per month to buy electricity and fuel for the backup generator. The table 1.1 explains how much energy Gishari college consumes as well as money paid.

Table1. 1.Cost of electricity at Gishari college for three years

Year	Total annual cost of electricity($)	Annual consumed electricity (kWh)	Cost of elecrticity($/motnh)	Cost of elecrticity($)/ motnh	Vaverage cost of elecrticity($)/motnh
2022	13328.6	65984.5	0.202	1110.7	1313.851176
2023	16607.3	82215.9	0.202	1383.9	
2024	14469.0	71630.2	0.202	1446.9	

From the table1.1 it is clear that the price of electricity is 0.202$/kWh and it is relatively high because of high cost of diesel fuel where the college spend 224.6$ to run generator in case the utility grid is not available. With the above-mentioned challenges, it necessary to find sustainable solution to mitigate not only the frequent outage of electricity but also reducing the high cost of electricity by designing an optimal PV based mini-grid. During the design, the proposed mini-grid combines solar PV-system, utility grid and diesel generator where the last one acts as a backup generator due to unpredictable nature of solar energy and frequent outage of national grid. The availability of solar radiations at Gishari college is one of the motivating factors of designing a PV based mini-grid. In addition, numerous academic activities that require high power are conducted during sunshine hours. Furthermore, PV based mini-grid does not only optimize the power management by prioritizing the use of power generated from PV-system during sunshine time but also will have capability to switch to other available sources of power (main grid and diesel generator) whenever PV-system does not meet load requirements. By designing PV based mini-grid using Hommer pro, the improvement about economics of generating electricity and reliability of power supply at RP-Gishari college is highly expected.

1.4. Objective of Research

To achieve successfully the goal of this research, the objectives must be set and these ones include main objective and specific objectives.

1.4.1. Main objective

The main objective of the research is to enhance the reliability and economic dispatch of electrical power consumption at RP-Gishari college by designing an optimal PV-Based mini-grid.

1.4.2. Specific objectives

- Conducting Load assessment and load profile at RP-Gishari college.
- Developing mathematical model of PV-based mini-grid of RP-Gishari college.
- Developing an algorithm to control a PV-Based mini-grid.
- Designing a PV-based mini-grid that includes PV-system, power grid and diesel generator.
- Simulating a PV-Based mini-grid referring to design and control requirements.
- Analyzing and discussing about the results from simulation.

1.5. Research question

- What is the connected load of RP-Gishari college?
- What is the load profile and pick demand of Gishari college?
- What is the mathematical model of PV-Based mini-grid of Gishari college?
- How does control algorithm works to optimize the power supply to the load at Gishari College?
- How does the integration and use of solar energy impact economically and academically GISHARI college.

1.6. Scope of the research

This research is limited on design of PV-based mini-grid case study of RP-Gishari College. In this research also, PV-array has been sized basing on load requirements and the optimization of power management has been performed by Hommer pro. Additionally, this research is limited on design and simulation of PV-system, main grid and diesel generator as backup system. A 45kW-PV-system has been sized based on maximum demand at Gishari College.

1.7. Significance of the research

This research contributes not only on reliable power supply to RP- Gishari College and reduction of the load demand on the main grid but also by using renewable energy sources, there is a contribution to net zero carbon emission. Furthermore, a reliable electricity at RP- Gishari College improves the learning environment in terms of research and innovation. Finally, the cost of electricity is reduced since the big part of electricity is generated from solar and hence losses from the main utility grid are significantly reduced as well as grid stability in terms of voltage regulation is improved.

1.8. Research Outline

The research thesis comprises six chapters and each chapter has its own focus. The chapter one highlights the problem of research basing on case study and clarifies the objectives to be achieved during the research project. Chapter two identifies the research gap through the literature review and explain what other researchers have done to address the gap. Chapter three tackles on different methods used to collect the data and makes important analysis on data in order to apply them correctly in the design of PV-based mini grid. The key points of chapter four are mathematical model and algorithm development of PV-based mini-grid based on case study. In chapter five the results from HOMER as a simulating tool have been analyzed and discussed on. Chapter six which is last of this research thesis summarizes the findings from of research and mentions necessary recommendations.

CHAPTER TWO: LITERATURE REVIEW

A mini-grid is a tiny autonomous network that can power entire neighborhoods with hundreds of homes in a single project. It also has the capacity to grow and eventually connect to the national grid. Also, a mini-grid improves the economics of generating electricity by avoiding the cost of transmitting electricity from a distant central-station power plant[9]. This chapter does not only explain classification, principles of operation, and structure of mini-grid, but also a mathematical model of mini-grid is discussed. Finally, the research gap will be identified.

2.1. Classification of mini-grid

To get a better understanding of how a mini-grids are categorized, it is necessary to begin by defining Distributed Generation (DG), from which the term mini-grid is originated. A generating system that is located close to the load center is known as Distributed Generation. Natural gas, photovoltaic (PV), and other technologies are among the generation technologies used in distributed generation and PV technology has a lower cost of electricity than the other options [3]. The range of power produced by a mini-grid system, taking into account generation capacity, is between 10 kW and 10 MW[10]. Depending on the nature and behavior of the supply mini-grid are classified into

- AC mini-grid,
- DC mini-grid and
- Hybrid mini-grid(combination of AC and DC mini-grids) [11].

In AC mini-grid all loads are supplied from AC bus voltage and transformers and converters are the main components of the power system depending on loads requirements. In addition, the control in AC mini-grid is more complicated since it requires both frequency and reactive power control. On the other hand, DC mini-grids generate power from DC sources such as PV arrays and DC batteries, while all loads are supplied by DC buses. Additionally, because reactive power and frequency are absent, control is straightforward furthermore, Unlike in AC mini-grid there is no need for grid synchronization in DC -mini-grid. However, because there is no zero-crossing point for DC currents, protection systems in DC mini-grids are more complex.[12].the figure 2.1 illustrate the comparison between AC mini-grid and DC mini-grid.

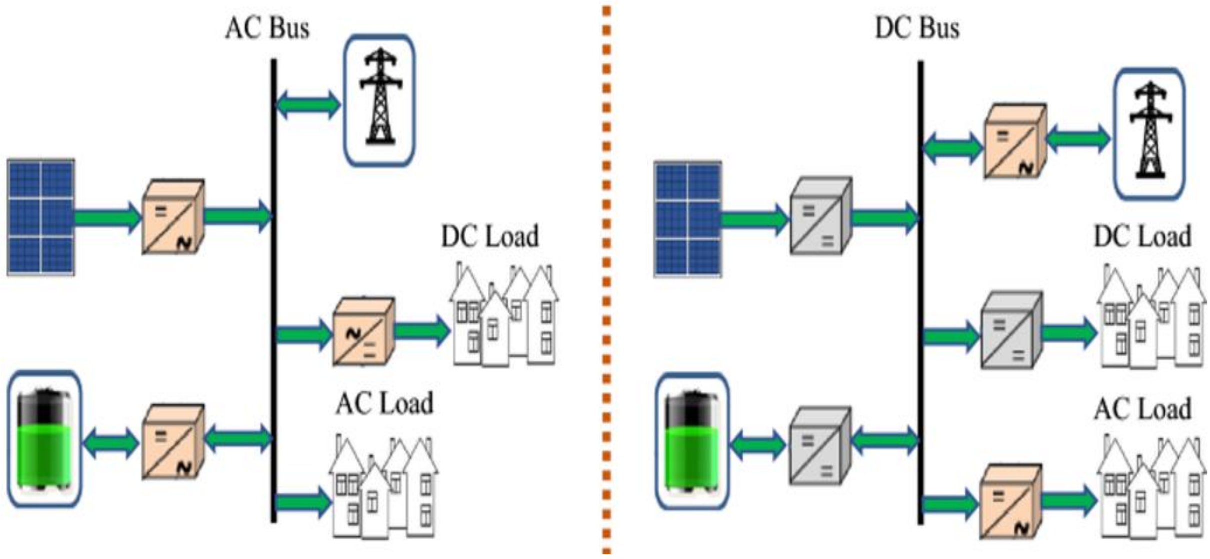

Figure 2. 1. Comparison between AC mini-grid and DC mini-grid.

Another important type of mini-grid is hybrid mini-grid which is a topology combining the configurations of both AC and DC mini-grids, its control strategies become more intricate. As the figure 2.2 shows, such hybrid mini-grids typically have some bus sections that are dedicated DC bus systems and other sections that are AC bus systems[12].

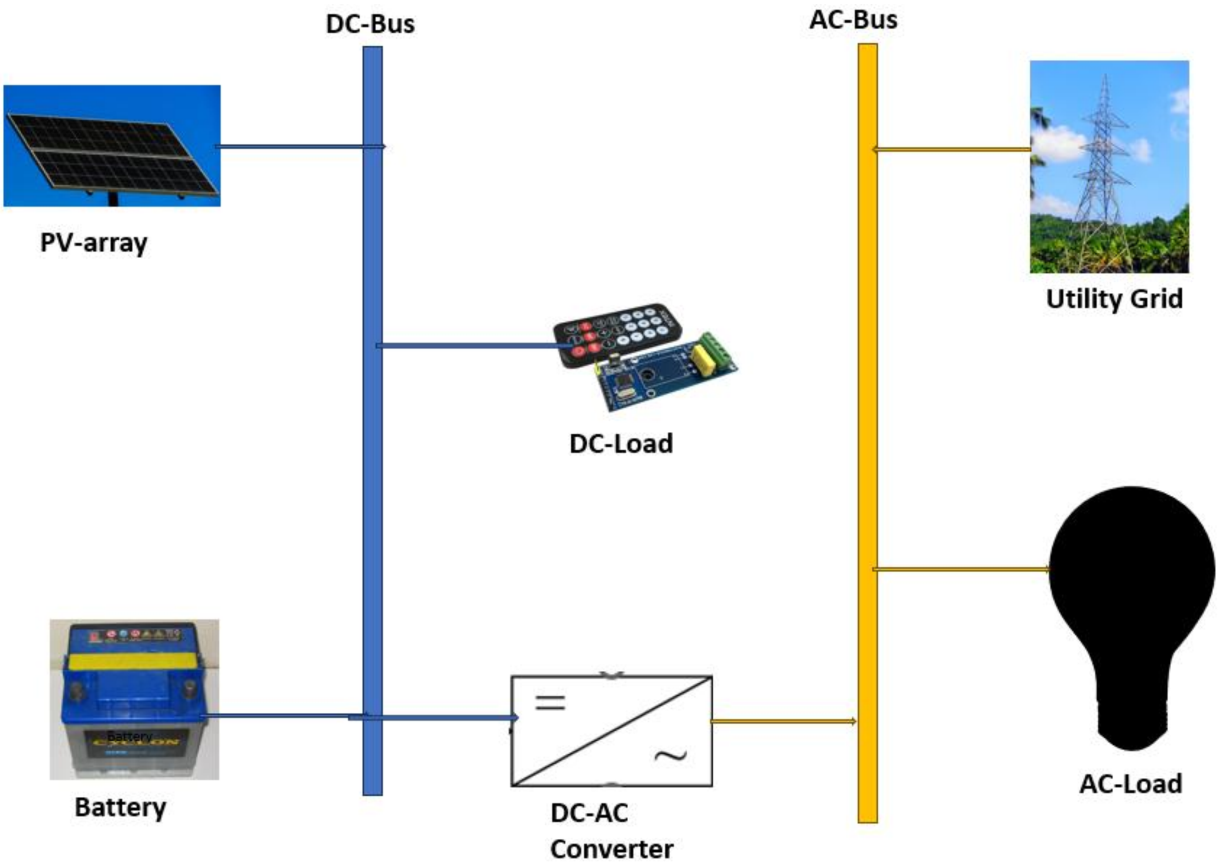

Figure 2. 2.Block diagram of hybrid mini-grid

2.2. Operation of mini-grid

According to the research paper [12] there three working scenarios in which mini-grid can operates and these are : Grid connected mode , Isolating mode and Disconnected mode.

i. Grid connected mode

In this case, the main grid and the mini-grid both function as parallel generators and are connected to each other. They also need to run in the correct phase sequence, at the same frequency, and at the same rated voltage. In this mode of operation, the mini-grid functions as a load when its storage systems use electricity from the main grid.

ii. Isolating mode

In this mode, the microgrid is the only source of power. This scenario arises in the system whenever there is an outage brought on main grid malfunction or when the load is far from the main grid.

iii. Disconnected mode

In order to ensure proper operation mode and power stability, the mini-grid is disconnected from the Point of Common Coupling in specific situations, such as lower power demand or overcurrent.

According to A. Shrestha et al.'s research, mini-grids can operate in two different ways: connected to the grid and isolated from it.

- Mini-grids that are connected to the grid follow the same rules and regulations as the main power grid. Mini-grid systems function as a controllable load or source in this system, which allows them to either receive power from or contribute power to the main grid.
- The units in islanded mini-grids can be managed using a decentralized method that balances the demand and the energy produced. In this mode, the system needs to maintain voltage and frequency while balancing supply and demand with a suitable power quality. Additionally, this mode lowers transmission and distribution costs for the main grid in remote or offshore locations[13].

2.3. Control of mini-grid

Because mini-grids distributed generation (DG) typically makes up the hybrid renewable energy system, these sources of energy are typically intermittent and need to be managed for stable power systems and high-power quality. Multi-task control structure is required for a mini-grid control architecture[12]. The control mechanism in a mini-grid is categorized include Centralized control system and decentralized control system[13]. In order to monitor and regulate everything, a centralized control mechanism requires close communication between the central controller and the controlled units. It also manages loads, Energy System Storage (ESS), and Distributed Energy Resources (DER). Furthermore, centralized control has three control levels: Distribution Management System (DMS), which regulates all other levels of the hierarchy; MG Central Control (MGCC); and Generation Controllers (GC) and Local Loads (LL). However, due to the high computational and communication requirements, this control mechanism is not practical. In remote locations, decentralized control systems are more advantageous. The steady-state frequency is a common quantity that must be the same for all sources in all decentralized control scenarios. The MG control determines the frequency in islanded mode, while the grid determines the frequency in grid-connected mode. The topology of the decentralized radial mini-grid is depicted in figure 2.3. The primary, secondary, and tertiary control levels in the hierarchical control scheme allow for the concession of both centralized and decentralized control frameworks[13].

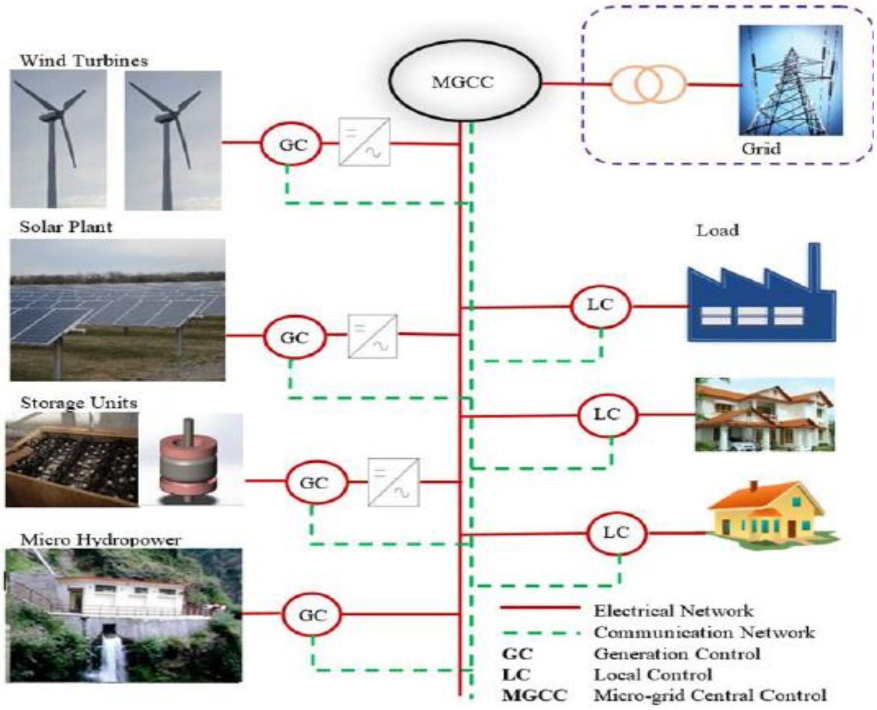

Figure 2. 3 .Decentralized radial mini-grid topology[13]

The primary control makes sure that voltage and frequency stay within their predetermined ranges while reacting to system dynamics. The secondary control, is in charge of the dependable, safe, and cost-effective operation of mini-grids that maintain power quality and reduce long-term voltage and frequency fluctuations. Additionally, it might focus on other key goals to regulate the system for better voltage profiles, power quality, loss reduction, and effective reactive power-sharing. Coordinating the power flow between the mini-grids and ensuring the system' overall health are the main responsibilities of the tertiary level control.

2.4. Description of Hybrid mini-grid.

According to the research paper [14], hybrid mini grids are a concept that arises when mini-grids are made up of multiple energy conversion technologies as it is shown on the figure2.4. By utilizing renewable energy sources like solar, wind, hydro, or biomass, mini-grids can be completely powered by renewable energy. They can also be equipped with a backup diesel generator or storage system and the next paragraph there are some examples of researchers who worked on different scenarios.

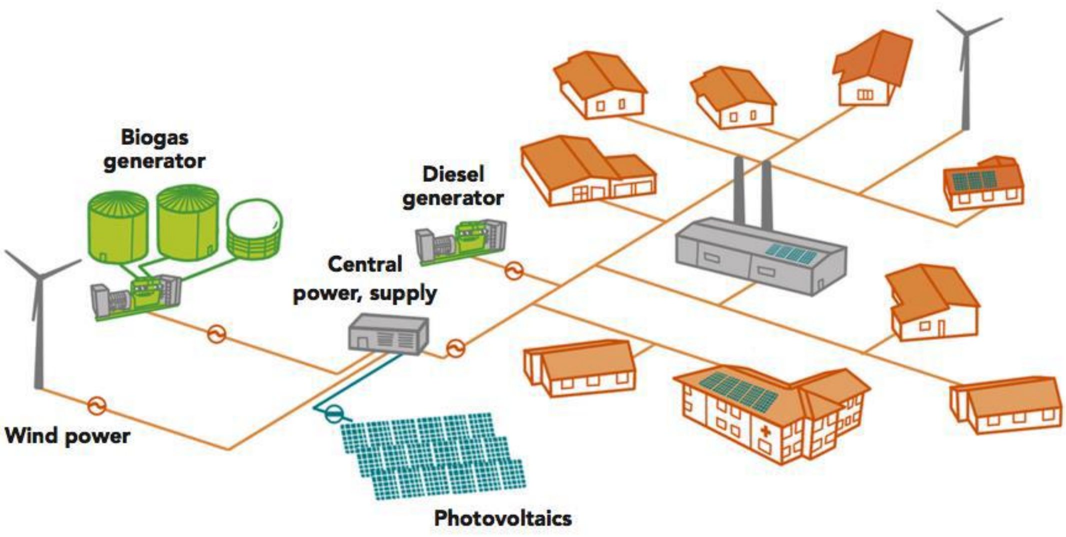

Figure 2. 4 . Hybrid mini-grid scheme[14]

In research paper[15] "Design and Simulation of Photovoltaic, Diesel Hybrid AC Mini-Grid System for Rural Electrification" , Md. Moniruzzaman has focused on a simulated and designed hybrid mini-grid comprising photovoltaic, diesel, and battery power in Simulink/MATLAB for research and analysis needs. In his research, a few home appliances have been designed to explore their various attributes. Furthermore, the researcher sized appropriately PV array and energy storage based on the daily energy consumption and load profile. another aspect that the research worked on is the development of algorithm for power management and simulation of power flow control from PV array, diesel and battery.

In the research work [16]“ Design and optimization of a solar photovoltaic mini-grid: case study of Rwumba village of Nyamasheke district, Rwanda” , the researcher has the objective of designing of mini-grid system for Rwumba village NYAMASHEKE District basing on OFF-grid PV-system and he has referred to the data of existing mini-grid of BANDA Solar mini-grid system. HOMMER is the only program utilized in this study to optimize the mini-grid for Rwumba village. In addition to this software, surveys and questionnaires are employed, and the information gathered falls into three categories which are Data from households to know the load for domestic appliances, Data from community know the common services needed in the village and Data focused on commercial facilities.

Using the traditional formulas for component sizing, the solar PV system's daily energy consumption was found to be 111 kWh, its peak capacity was 34 kW, its pack-back period was 10 years, and its highest and lowest solar radiation levels were 5.278 kWh/m2/day and 4.545 kWh/m2/day, respectively.

2.5. Designing Process of Hybrid mini-grid.

Methods for assessing, sizing, and modeling various parameters are necessary during the mini-grid design process in order to guarantee not only their safety in terms of frequency and voltage but also their ability to meet present and future energy demands. There are several steps in the designing process, such as load assessment, load profile, future load forecasting, mathematical modeling, and the use of simulating tools[14].

2.5.1. Load assessment

It is necessary to perform load assessment in order to match the mini-grid's capacity to the load requirements. PV arrays, batteries, and inverters are among the installation components that are oversized or undersized as a result of inadequate load assessment. The most widely used technique for performing load assessment is a survey form[17].

2.5.2. Load profile

The research paper [18]defines load profile as the amount of power used over a specific period of time, which varies based on the type of customer, temperature, and seasonal effects. Figure 2.5 displays a graphic representation of it. Although many mini-grid installations target consumer groups that have had limited access to electricity, it is crucial to accurately estimate consumer loads.

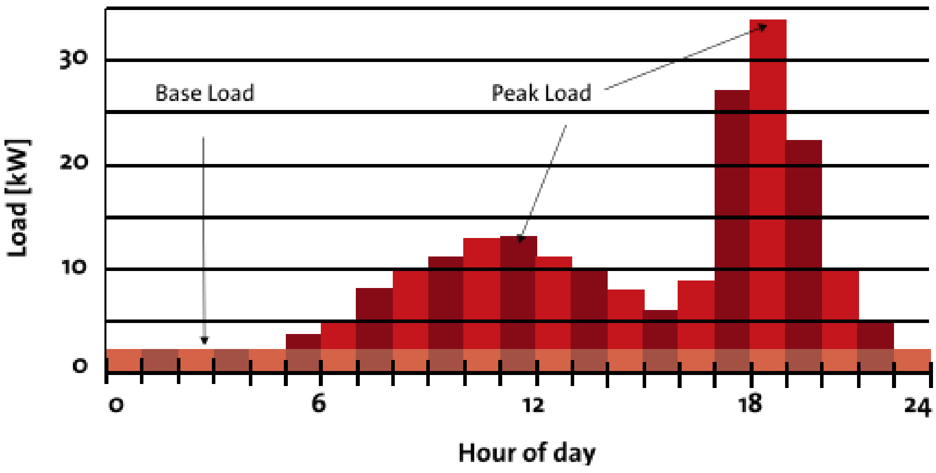

Figure 2. 5 . Typical load curve of a large mini-grid[14]

2.5.3. Load forecasting

For the hybrid mini-grid to be reliable and economically sustainable, it is crucial to take into account the rate at which load demand is increasing over time. This growth is brought on by a number of factors, including population growth and economic expansion in terms of infrastructure. The hybrid mini-grid's size must be optimized by taking into account future load, which can be done by employing a load forecasting technique. [19]. In addition, the load forecasting can be developed in:

- ❖ **Long-term:** Prediction of the load demand for a period of 15 to 25 years,
- ❖ **Medium-term:** Prediction of the load demand for a period of 5 to 15 years.
- ❖ **Short-term:** Prediction of the load demand for a specific day, week, month or year[14].

2.5.4. Mathematical Model of mini-grid

Numerous studies on the modeling and control of mini-grids have been conducted, and consideration must be given to the model's size, accuracy, and validity. Additionally, when modeling a mini-grid for the best distribution of renewable energy, the use of renewables and the dependability of renewable energy systems are crucial considerations [20]. The research paper [21] has examined various modeling approaches for mini-grids, which are categorized into four groups.: (1) Component-wise modelling and thereafter, aggregation; (2) single entity model of the whole mini-grid; (3) Stochastic modelling methodologies and (4) Dynamic equivalence modelling principles.

In accordance with the study by [22], the researcher begins by defining dump load, which is defined as energy wasted as a result of an imbalance between variable RE generation and variable load demand. Additionally, the researcher creates a categorized mathematical model of a hybrid mini-grid based on dump load, taking into account the following four configurations:

System 1. Diesel (DG)

System 2. Wind-Solar-Diesel (WT-PV-DG)

System 3. Wind-Solar-Diesel-Battery (WT-PV-DG-BB)

System 4. Wind-Solar-Diesel-Battery-Flywheel (WT-PV-DG-BB-FW)

$$P_{dump}(t) = P_{re}(t) + P_{dg}(t) + P_{bb.out}(t) - P_{bb.in}(t) - P_{load}(t) \qquad \text{Eq. (1)}$$

Where $P_{dump}(t)$ is the dump load, $P_{re}(t)$ is the power generated by different renewable energy sources $P_{dg}(t)$ is the power from diesel generator, $P_{bb.out}(t)$ is the power from battery bank, $P_{bb.in}(t)$ is the power lost in battery bank and $P_{load}(t)$ is the power consumed by the load. Eq. (2)

Another aspect of mathematical model of mini-grid is economic aspect where the optimal system design with the lowest net present cost (NPC) is determined. In the research study[20], the optimization model was coastwise based and the equation has been developed as follows.

$$C_{ann-tot} = C_{capann} + C_{repann} + C_{O\&Mann} \qquad \text{Eq. (2)}$$

Where $C_{ann-tot}$ is the annual cost of the project in ($/year), C_{capann} is the annual capital cost, C_{repann} is the annual replacement cost and $C_{O\&Mann}$ is the operating and maintenance cost.

2.6. Overview on PV-based mini-grid development.

One of the earliest and most practical methods for electrifying remote locations was the mini-grid, which was powered by a diesel generator. Few solar mini-grids later appeared as a result of the high cost of fuel, which led to the proliferation of decentralized solar home systems (SHS). With funding from international development partners, 50 remote health centers in Rwanda began implementing solar PV/diesel hybrid technology[21]. Referring to various researchers PV-based mini-grids are mini-grid systems where solar energy serves as the primary source of electricity generation, with additional power from storage and other energy sources. In the research paper[22]. As the figure 2.6 shows. PV-based mini-grids can be divided into three categories: standalone PV-system, grid connected PV-system and hybrid PV-system and each of these PV-systems has particular benefits depending on location area and load requirements[23].

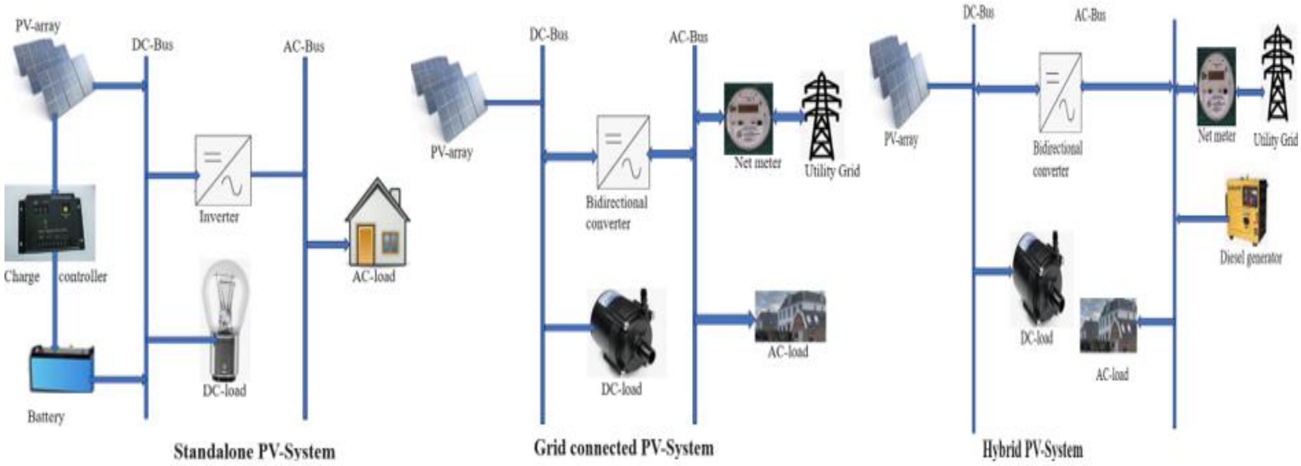

Figure 2. 6 . Classification of PV-based mini-grids

Although batteries are the most commonly used storage devices, the cost of electricity is greatly increased by the fact that they must be replaced frequently, usually every six or eight years. Another aspect that hinders the use of batteries as energy storage systems is their maintenance cost[21].

2.7. Sizing of PV-modules and inverter for PV-based mini-grid

Designing and assessing the performance of a solar PV system requires knowledge of the ratings of the PV modules and inverters. PV modules convert sunlight into electricity (DC current), but the number of modules required depends on the shading factor, module degradation, and desired energy consumption. Several factors must be taken into account when choosing PV modules, including the system's overall daily energy consumption (in Wh/day), site-specific peak sun hours, system efficiency, and the arrangement of modules in series or parallel to meet voltage and current requirements[24]. PV modules' DC is converted into alternating current (AC) via an inverter for grid use sizing. PV array size is another element to be taken into account, where the inverter's rated power should marginally surpass the total PV array output and inverter efficiency. Other factors include total load power, where the inverter should manage peak load power (W), and surge capacity for appliances such as motors[25].

2.8. Challenges of protection system for the PV based mini grid

In addition to having a broad operational range and bidirectional power flow, MG may function as a controlled entity in both grid-connected and islanded modes. The following are the primary issues that call for the reform of traditional protection schemes:

- Relay coordination issues and failures in traditional protection schemes without directional elements might result from high-RES penetration, which can induce reverse power flow or bi-directional power flow [26].
- Because the equivalent impedance changes when MGs switch from grid-connected to islanded mode, and vice versa, this could significantly affect the short-circuit level [27].
- The converter-based DGs' fault current restrictions may result in an undetected fault. issues with frequency and voltage while islanding [28],

2.9. Literature gap

From the literature review and by focusing on the purpose of this research which is to improve the reliability of power supply and economic management of power consumed at university campus by using solar energy, Rwanda as a developing country there is no specific research on integration of renewable energy in university campuses. However, universities are part of big consumers of electricity from utility grid. Additionally , among sub-Saharan African nations, Rwanda has the smallest energy sectors; consequently, extremely unstable electricity supply systems impede research, teaching, and learning on Rwandan university and college campuses[6]. Furthermore , In the research conducted by Augustin et at [16] it is clear that the reliability and efficiency is a big challenge because during the design of the mini-grid only energy from the sun is used without looking for other alternatives. Additionally, the sizing of PV-array and batteries is not optimized. Furthermore, some Solar PV mini-grid system designers do not consider all parameters during sizing hence heavy loads are affected due to the failure of system. To fill the mentioned gap, the aim of this research is to show that with the availability of solar radiations, the university campuses in Rwanda are able to contribute to the generation, reliability and economic management of electricity by integrating solar PV-systems with other available source of power in order to mitigate the shortage of electricity at university campuses and contribute to stability and load reduction on utility grid.

CHAPTER THREE: RESEARCH METHODOLOGY

It is very essential to be clear with the methods and the techniques used while doing research. This chapter focusses on various methods used to collect the useful data for better sizing PV-system and diesel generator.

1.1. Research design

To conduct successfully a research thesis, a research design must be in place and this one is a flowchart that illustrates the main steps of research thesis. The figure 3.1 shows the main steps through which the research thesis was conducted and each step has a specific method that has been used.

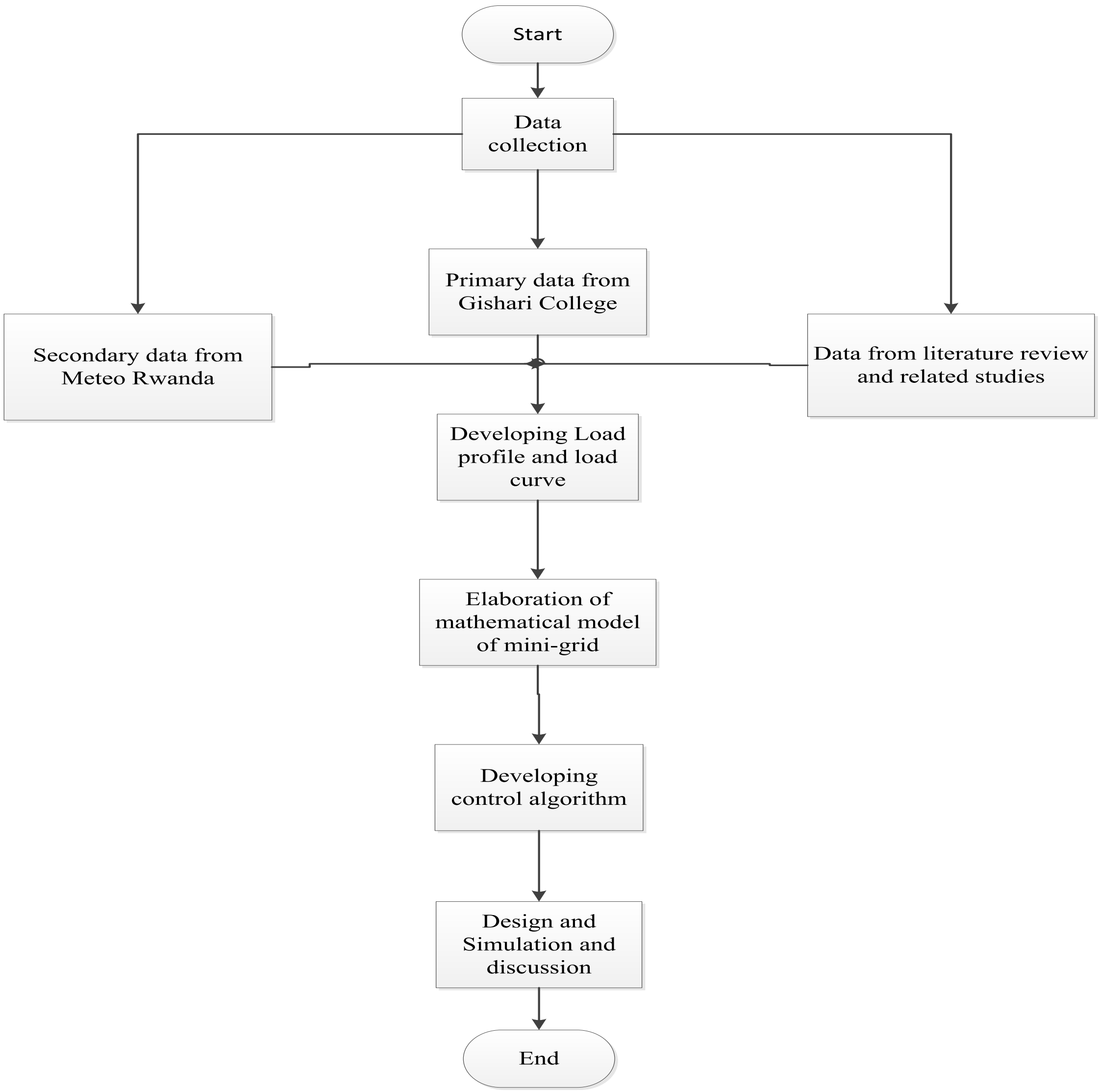

Figure 3. 1. Flow chart for research design

3.2. Data collection

In order to make an optimal size of PV-system that supplies the load demand of Gishari College, the data (both primary and secondary data) have been collected from Gishari college and Meteo-Rwanda and the data sheets are annexed at the last pages of this research report. Total connected load, load profile and load forecasting of Gishari college are the main components of primary data of this research thesis.

3.3. Total connected load of Gishari college

The total connected load has been estimated by conducting site visit and the physical map of the figure 3.2 indicates the various building of the college including departments, classes, workshops and offices where all devices and equipment consuming electricity have been recorded using a survey form.

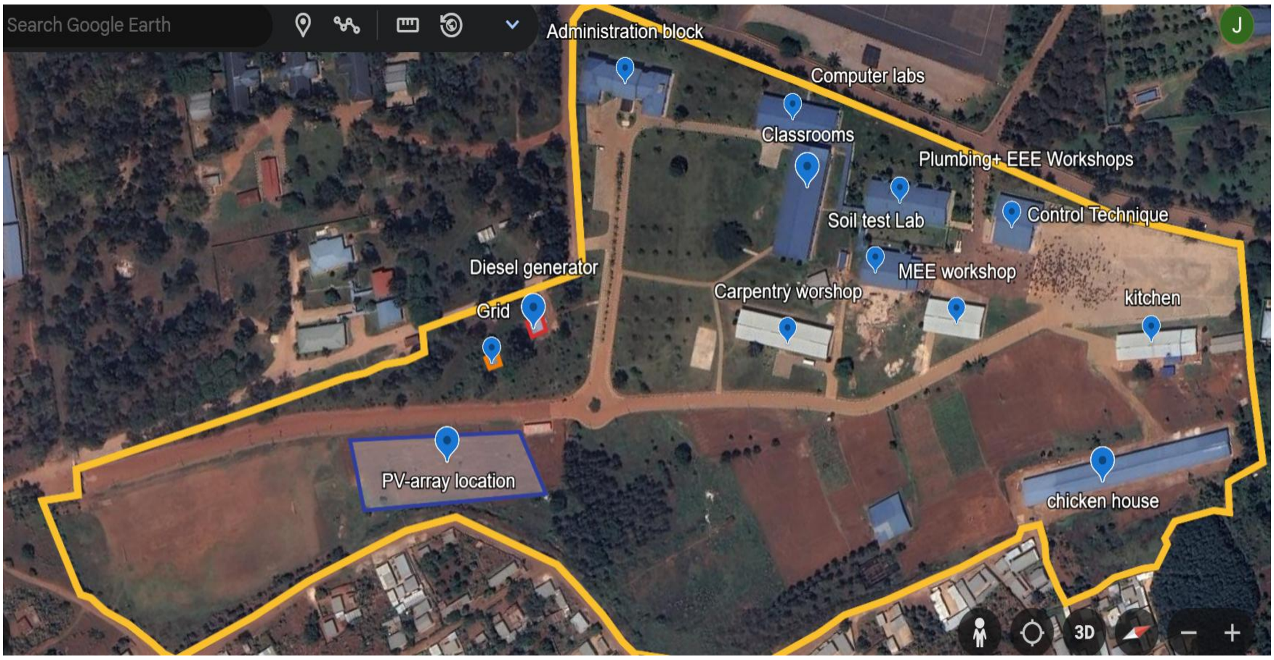

Figure 3. 2. Physical map of Gishari college with building location

After gathering all data by the use of recording form (to find the survey form on appendix annex.1) the total connected load has been estimated and summarized as it is indicated by the table.3.1.

Table 3. 1.Total connected load of Gishari college

Device name	Total power(kW)	Total energy(kWh)
Computers	66.7	389.38
Projectors	1	38.88
Printers & TVs	11.6	37.878
Electrical machines in workshops	199.9	535.029
Electrical lamps	42.5	178.497
Total Power	**321.7**	**1179.664**

To understand the contribution in term of percentage each type of load is presented on diagram of the figure 3.3. and it is clear that workshops have 45% of the total connected load which is the highest percentage compared to other loads.

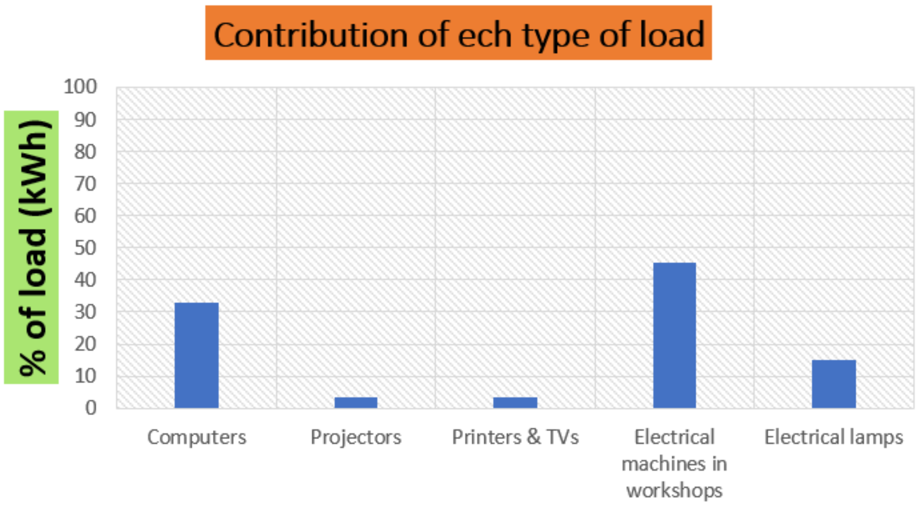

Figure 3. 3. Distribution of connected load

3.4. Load profile of Gishari college

Daily load profile and yearly load profile have been plotted using different technics. To obtain the data for daily load profile, the approach of recording of energy consumed every 60 minutes by reading energy meter for two different days has been used and the load curve has been plotted as it is illustrated on the figure 3.4.

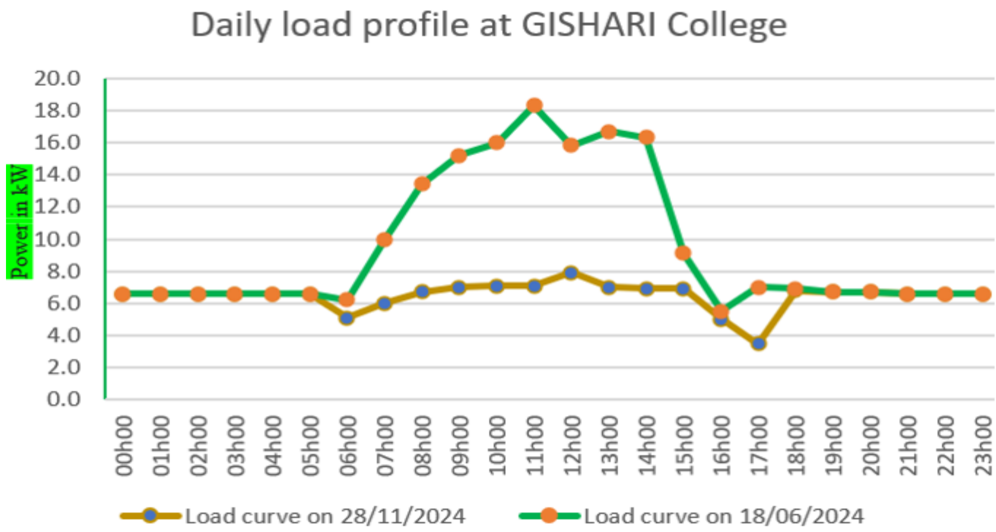

Figure 3. 4. Daily load curve at Gishari college

As the figure 3.5 shows, the daily load curve of only one day is not enough to determine the real maximum load demand because of inconsistency of daily consumption at Gishari college. This inconsistency is due to the fact that does not host regularly the same number of students and staff even the activities demanding high energy consumption are not consistent through the year. Hence it has been required to assess load curve for different days to obtain a real pick demand of the college by considering a day with highest consumption. Furthermore, as it is shown on the figure 3.11 the yearly load curve has been drawn from the monthly report of electricity payment and this report has been provided by Gishari college office of finance.

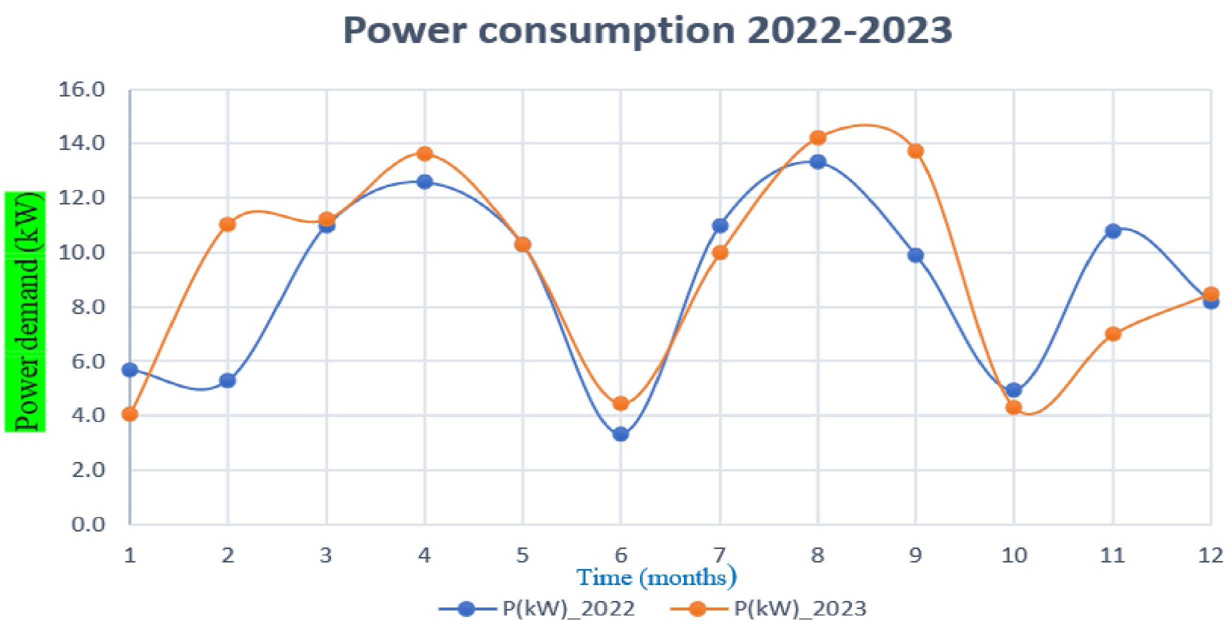

Figure 3. 5. Yearly load curve 2022-2023

3.5. Load forecasting of Gishari college

As discussed in chapter 2 of literature review, it is mandatory to include future load while designing an optimum PV-based mini-grid. The future load must base on current load from daily load curve and by including losses due to inductive load especially electrical machine from different workshops. From the background of the first chapter, future plan of the college to increase the number of students and staff by 20% every year for 5 years. Additionally, the daily load curve (refer to the figure3.4) the current maximum demand is 18kW and by using compound growth approach the future load of GISHARI college in five years ahead is calculated as follows:

$L = L_0 * (1+r)^n$ Eq. (3) Where **L** is Future Load **L_0** is Current Load **r** is rate of increase **n** is the number of years

$FL = 18*(1+0.2)^5 = 44.78kW$ therefore, the optimal size of PV-system with load forecasting of five years is 44.78 kW and by applying approximation the future load at Gishari college within five years is 45kW it means that the optimal sizing of PV-system and diesel generator will base on maximum demand of five years. The figure 3.6 clarifies the evolution of the load from 2024 to 2029.

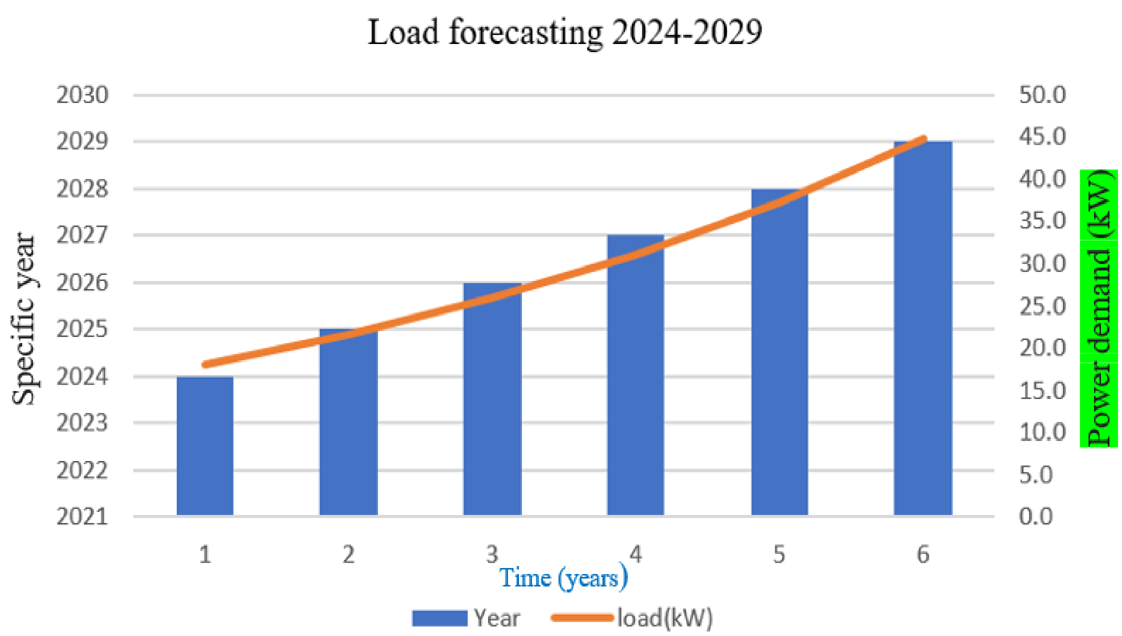

Figure 3. 6. Load forecasting of GISHARI college

3.6. Meteorological dada of Gishari college

Meteorological data make another aspect to consider while designing a PV-system at Gishari college. These data are solar irradiance, temperature and wind speed and have been provided by Meteo-Rwanda. The analysis of these data is shown by the figures (3.7, 3.8 & 3.9).

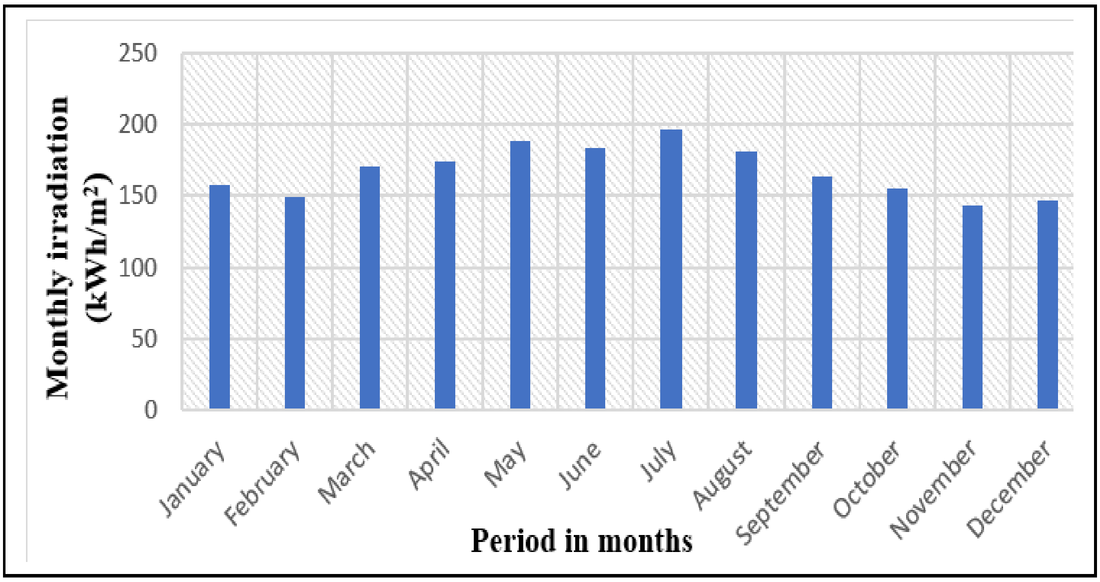

Figure 3. 7. Irradiance at Gishari college

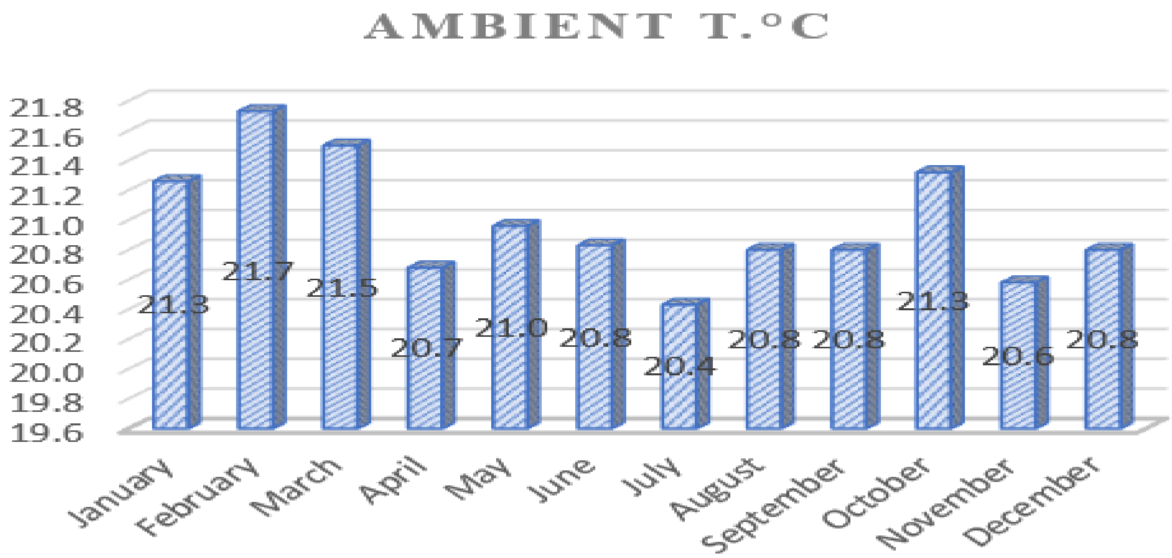

Figure 3. 8. Ambient temperature at Gishari college

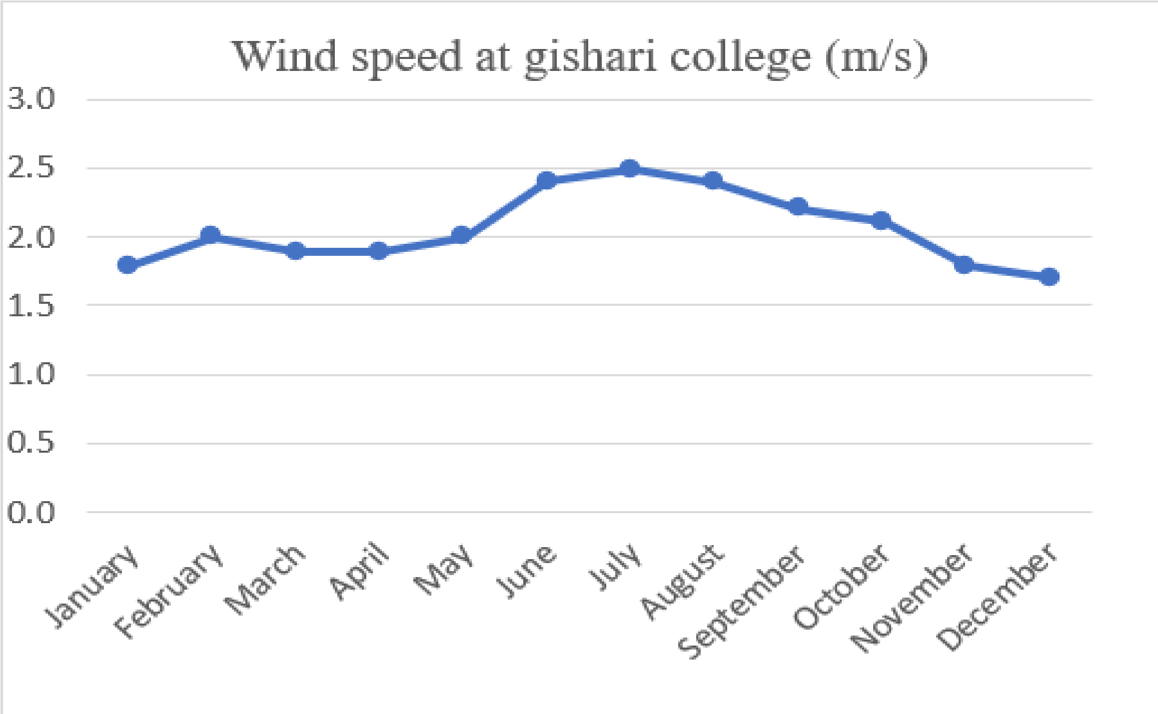

Figure 3. 9. Wind speed at Gishari college

CHAPTER FOUR: MATHEMATICAL MODEL AND ALGORITHM DEVELOPMENT OF PV-BASED MINI-GRID

Creating a mathematical model that integrates a photovoltaic (PV) system, utility grid, diesel generator based on load profile involves several steps. By referring to the proposed mini-grid topology (refer to the figure 4.17) and daily load profile (refer to the figure 3.10) at Gishari college in, this chapter focusses on equation that not only to optimize the power generation and distribution from these resources to meet the load requirements but also to develop the objective function that minimizes the cost of mini-grid in term of generation and consumption. At the end of chapter, the algorithm to control the both power generation and consumption is built.

4.1. Topology of PV-based mini-grid at Gishari college

The architectural design of PV-based mini grid comprises three sources of power and these are PV-system, utility grid and diesel generator and each power source is sized to supply the maximum load of the college (refer to the figure 4.1). In addition, by using control algorithm, three power sources are controlled in a such way that PV-system is prioritized supply the main load of the college.

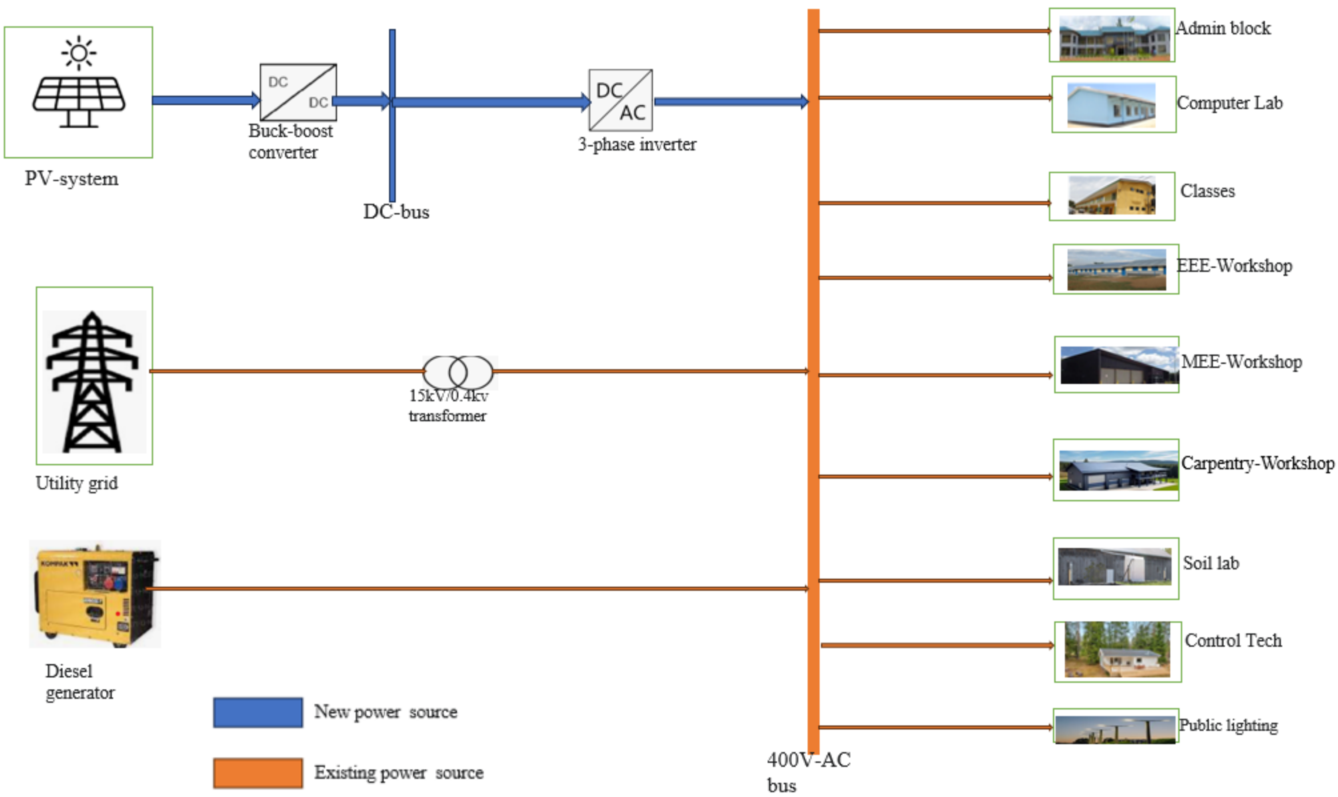

Figure 4. 1. Mini-grid topology at Gishari college

4.2. Mathematical model of mini-grid at Gishari college

This section focusses on mathematical equations that govern the electrical power from PV-system, utility power grid and diesel generator. From load profile, current maximum load demand (refer to the figure 3.10) ($P_{loadmax}$) of Gishari college is 18kW. However, according to future projection of 5 years of the GISHARI college, this maximum load demand will vary with time in a range of 18kW and 45kW due to different factors and load demand at any time is noted as $P_{load}(t)$. Therefore, the mathematical model of PV-based mini grid at GISHARI college must always satisfy the load demand requirements on daily basis and considering the contribution of each and every power source among three power sources. By noting the power from PV-system as ($P_{PV}(t)$), power form Utility grid as ($P_{grid}(t)$) and power from Diesel generator as ($P_{DG}(t)$), the following equations are developed.

$P_{PV}(t) = \eta AI(t) = 45kW$ Eq. (4) [26] where **I** is the solar irradiance at time **t** and **t** represents time in hours throughout the day, ranging from t = 0 (midnight) to t=24 (next midnight) or [0hr,=24hrs]. **A** is useful area covered by PV-array and **η** is the overall efficiency of PV-system. The utility grid can either supply or absorb power depending on the system's net demand and power from utility grid is given by the Eq. (5)

$P_{grid}(t) = P_{load}(t) - P_{PV}(t)$ Eq. (5) it is clear that the utility grid will supply the remaining load from PV-system in case this one does not satisfy the total load.

Diesel generator will supply the power only if the PV and grid cannot meet the load demand and power generated by the Diesel generator is given by the Eq. (6)

$P_{DG}(t) = P_{load}(t) - P_{PV}(t) - P_{grid}(t)$ Eq. (6)

In all cases the power generated must balance the load demand and the equation for load balance is given by the Eq. (7)

$P_{load}(t) = P_{PV}(t) + P_{grid}(t) + P_{DG}(t)$ Eq. (7)

In addition, to optimize the PV-based mini-grid implies generation of energy that meet load requirements at minimum cost and this is expressed by the objective function in the Eq. (8)

$$Minimize C = \sum_{t=1}^{T} (C_{PV}E_{PV}(t)) + C_{grid}E_{grid}(t) + C_{DG}E_{DG}(t)) \text{ Eq. (8)}$$

Where C is the total cost of energy generated in $/kWh, C_{PV} is the cost of energy generated from PV-system, C_{grid} is the cost of energy generated from utility grid, C_{DG} is the cost of energy generated from diesel generator, E_{PV} is the energy generated from PV-system in (kWh), E_{grid} is the energy generated from utility grid and E_{DG} is the energy generated from diesel generator.

Constraints of the model

The total power generated at any time t must meet the load demand

$$P_{PV}(t)+P_{grid}(t)+P_{DG}(t)\geq P_{load}(t)\quad \forall t\in[0,24]\quad \text{Eq. (9)}$$

Referring to the availability of solar energy and priority of supplying the load by among three generators, the constraint equations below show the time allocation for each generator.

The power supplied by the PV-system cannot exceed it maximum generation capacity and PV-system can generate only during sunlight hours.

$$\begin{cases} 0\leq P_{PV}(t)\leq P_{PV,\max}\forall t\in[6,18] \\ P_{PV}(t)=0 \quad \text{Otherwise} \end{cases}\quad \text{Eq. (10)}$$

The utility grid is used as second priority and jumps in at any time to supply the remaining load whenever the PV-system cannot cover the total load demand.

$$0\leq P_{grid}(t)\leq P_{load}(t)-P_{PV}(t)\quad \forall t\in[0,24]\quad \text{Eq. (11)}$$

The diesel generator is only used when the PV system and the utility grid are insufficient and the power supplied by generator must meet the remaining load.

$$P_{DG}(t)=P_{load}(t)-P_{PV}(t)-P_{grid}(t)\forall t\in[0,24]\quad \text{Eq. (12)}$$

4.3. Development of algorithm for PV-based mini grid at Gishari college

As it has been mentioned in chapter one (problem statement section) the PV-based mini grid avails three power sources (PV-system, utility grid and diesel generator). To design an algorithm for controlling power and cost in a PV-based mini-grid system, it is very important to make a balance between three power sources as it is illustrated on the figure 4.2. The key goal is to maximize the power generation from the PV system (which is free once installed) while minimizing the use of the diesel generator and managing the cost associated with purchasing power from the utility grid.

The conditions for control algorithm are:

The maximum load demand of the college varies up to 45 kW depending on college activities for instance, the pick is at minimum point of 8 kW in the holidays and increases when offices workshops and classes are full of staff students and staff. The control strategy should dynamically decide when to use each source based on the availability and priority of power sources and the load demand. The variables used in the algorithm are defined as follows:

P_pv is the power generated by the PV system (in kW), P_utility is the power drawn from the utility grid (in kW),P_diesel is the power generated by the diesel generator (in kW), P_load is the maximum load demand (45kW), P_pv_max is the maximum power capacity of the PV system, P_utility_max is the maximum available power from the utility grid and P_diesel_max is the maximum power capacity of the diesel generator.

Control Strategy:

1. **First, check the PV generation**:

If P_pv ≥ P_load, the PV system can satisfy the demand. Set P_pv = P_load. If P_pv < P_load, calculate the remaining load that needs to be fulfilled: P_remaining = P_load - P_pv.

2. **Second, use the utility grid**:

If P_remaining ≤ P_utility_max, the utility grid can provide the rest. Set P_utility = P_remaining and P_diesel = 0. If P_remaining > P_utility_max, use the maximum available from the utility grid: P_utility = P_utility_max and calculate the remaining load to be supplied by the diesel generator: P_diesel = P_remaining - P_utility_max.

3. **Finally, if needed, use the diesel generator**:

If there is still unmet demand after using both PV and utility grid, the diesel generator supplies the remaining power.

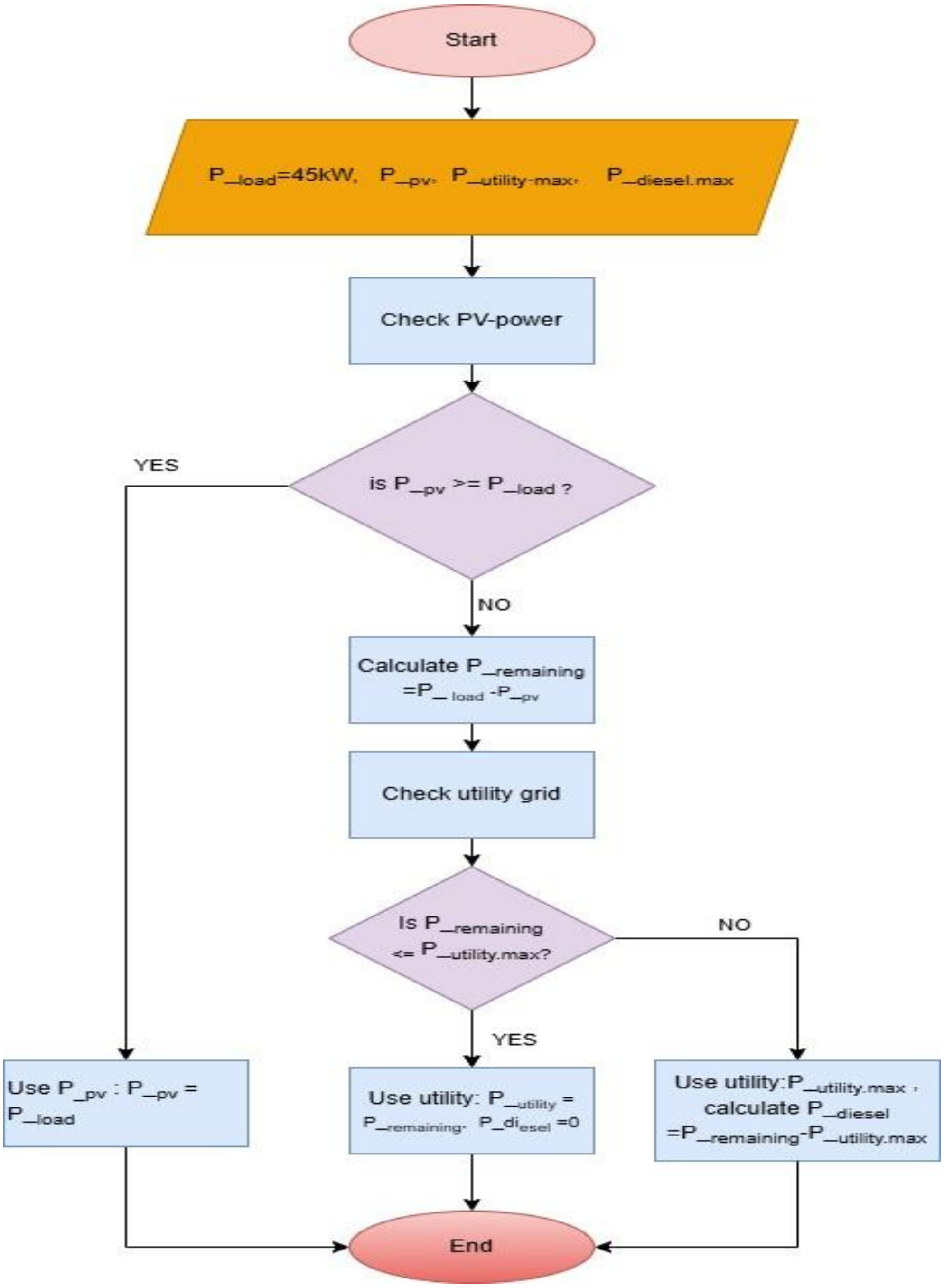

Figure 4. 2. Flowchart of PV-based mini grid control algorithm

CHAPTER FIVE: DESIGN AND SIMULATION

To design and simulate a PV-based mini-grid helps to analyze the its performance over time. This chapter focusses not only on sizing of PV-system where PV-Syst software is used to determine the size of PV-modules in term of series-parallel solar panels and inverter, but also diesel generator will be needed for simulating the whole mini grid that helps in evaluating System Performance and Cost-Effectiveness of mini-grid as well. HOMMER Pro has been used for Simulation, optimization, and sensitivity analysis of this mini-grid [14]. Furthermore, the main components of designed mini grid are PV-array, inverters and diesel generator and HOMER contains all these components with their specifications needed for sizing and simulation. Cost, efficiency and reliability are among criteria of components selection form HOMER Pro software library and the software arranges the optimized results according to the lowest Levelized Cost of Electricity (LCOE).

5.1. Sizing and cost estimation of PV-based mini grid components.

Referring to the long-term plan of Gishari college in term of increase in number of students and staff to the rate of 15.7% every year (see the background of the college), the future load demand at RP-Gishari college in five years is **45 kW**. In order to design single line diagram using PV-Syst, the specification of design parameters of PV-system are shown in the table.5.1 and table.5.2:

Table.5.1. Specification of PV-module[27].

Attribute	Specification
Model	AS-6P30-ET/EW
Rated Power (Pmax)	285 W
Cell Type	Polycrystalline silicon
Number of Cells	60 (6×10 configuration)
Open Circuit Voltage (Voc)	~38.2 V
Short Circuit Current (Isc)	~8.00 A
Maximum Power Voltage (Vmp)	~31.0 V
Maximum Power Current (Imp)	~7.40 A
Module Efficiency	~17.5%
Dimensions	~1650 × 992 × 40 mm

Attribute	Specification
Operating Temperature	−40°C to +85°C
Maximum System Voltage	1000 V DC
Warranty	10 years product, 25 years performance

Table.5.2. Specification of inverter[28].

Parameter	Specification
Nominal AC Power	60 kW
Max AC Power	~66 kW (short-term peak)
Max DC Input Voltage	~1000 V
MPPT Voltage Range	~600–850 V
Max DC Input Current	~120 A
Number of MPPTs	Typically, 2
Max Efficiency	~98.5%
Euro Efficiency	~98.0%
Nominal Grid Voltage	400 V (3-phase)
Frequency	50/60 Hz
Cooling Method	Forced air
Protection	Overvoltage, overcurrent, anti-islanding
Communication	RS485 / Ethernet / Wi-Fi (varies by model)
Weight	~60–70 kg
Dimensions	~700 × 600 × 300 mm

For simplification purpose of circuit diagram, a single line diagram that contains PV module strings and inverters are shown in the figure.5.1. and the important parameters of PV-system design to meet the load and inverter input requirement are the following:

- Required DC Power $= \frac{\text{Total power}}{\text{system efficiency}} = \frac{45\text{kW}}{0.95} = 45.7kW$
- Number of Panels Needed $= \frac{\text{Required DC power}}{\text{Rated power of the module}} = \frac{45700\text{W}}{285\text{W}} = 160.35 \simeq 160\ panels$
- Panels per string $= \frac{\text{Maximum System Voltage}}{PV-module\ voltage} = \frac{1000}{38.2} = 26\ panels$

- Number of strings $= \frac{\text{Total modules}}{\textit{Modules per string}} = \frac{160}{26} = 6.2\ strings \ \simeq 7\ strings$

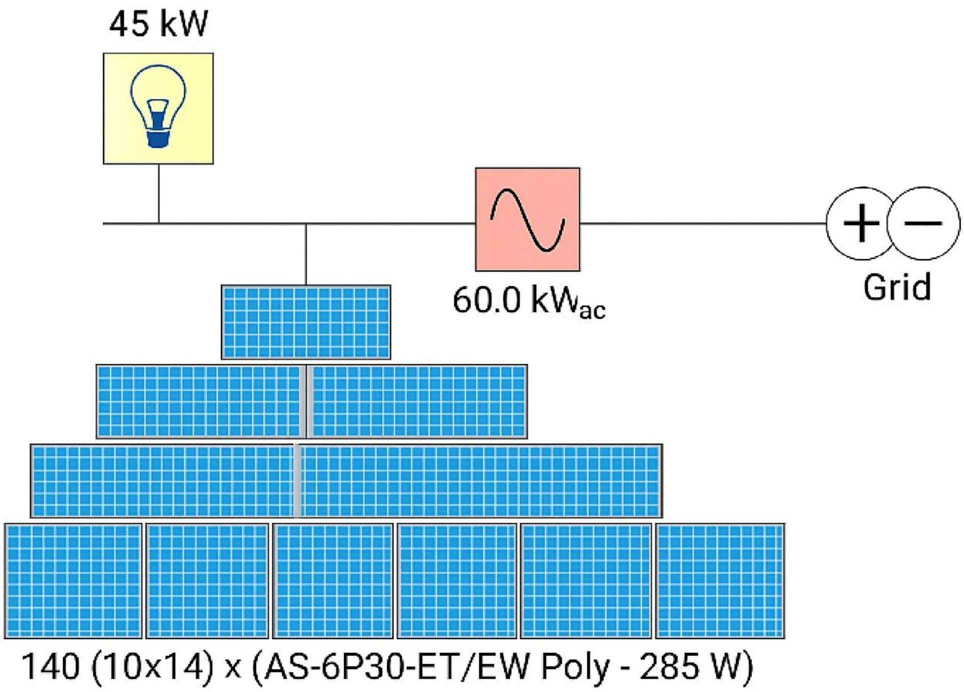

Figure.5.1 Single diagram of PV-system

The primary components that need to be sized using HOMER software are the diesel generator, inverter, and PV system. To prevent oversizing or under sizing, the size and cost of these components are optimized based on the load profile and peak load. the PV-system size is 45kW with capital cost, replacement cost, operating cost, and maintenance costs are 30,000$, 30,000$, and 100$ annually, respectively. Using the Homer Optimizer algorithm, the inverter's size is determined to be 56 kW, its cost is set at 10000$, and its efficiency is assumed to be 98.5%. With a minimum load ratio of 5%. The diesel generator is used as a backup component. Its capital cost and replacement cost are 250$/kW, 250$/kW, and operating and maintenance cost is 0.07$/hour. Furthermore, in case of high renewable energy penetration, the generator works as a backup system, this means that it could be used to supply little amount of power.

5.2. Discussion of results

Numerous important outcomes, such as system performance, economic viability, and environmental impact, have been examined following the execution of a simulation in HOMER Pro. Additionally, a number of parameters have been tested, including annual energy production, levelized cost of energy (LCOE), and total net present cost (NPC). A schematic diagram of Gishari College's PV-based mini-grid from a simulating tool is displayed in figure 5.2. Due to unexpected system losses, simulation by HOMER Pro, proposes 112kW as a new rated capacity of PV-array, 54kW as capacity of diesel generator, 999,999kW as utility grid capacity and inverter rating of 60kW.

Figure 5.2. Schematic diagram of PV-based mini-grid at Gishari college

The results from HOMER indicate that even though the PV-based mini grid avail three power sources, only PV-System and utility grid provide an optimal energy generation where 69.1% of the energy is produced by PV system and utility grid generates 30.9% of the total energy generated. In addition, HOMER Pro generates a list of feasible solutions where the solution on the top is the best one as shown in the table 5.3.

Table 5.3. Categorized optimization with renewables penetration

ET 285 (kW)	Gen (kW)	Grid (kW)	Chi60 (kW)	Dispatch	NPC ($)	COE ($)
112		999,999	60.0	CC	$128,506	$0.0495
112	54.0	999,999	60.0	CC	$138,853	$0.0535
		999,999		CC	$141,556	$0.0800
	54.0	999,999		CC	$151,903	$0.0858

According to table 5.4, the annual total energy generated from PV-system is 159,869kWh of the load energy consumption. The PV plant generates excess energy of 28,682kWh of excess energy or 17.9%, which is sold to the utility grid.

Table 5. 4.Energy management summary (report from HOMER Pro).

Excess and Unmet

Quantity	Value	Units
Excess Electricity	28,682	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
ET Solar New Energy 285ET-P672285WWG	159,869	69.1
Grid Purchases	71,556	30.9
Total	231,426	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	136,875	68.2
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	63,900	31.8
Total	200,775	100

As the pick load of GISHARI College occurs during sunshine hours (refer to the figure 3.4), it is evident that maximum generation of PV-system coincides with the maximum demand as it is shown in figure 5.3.

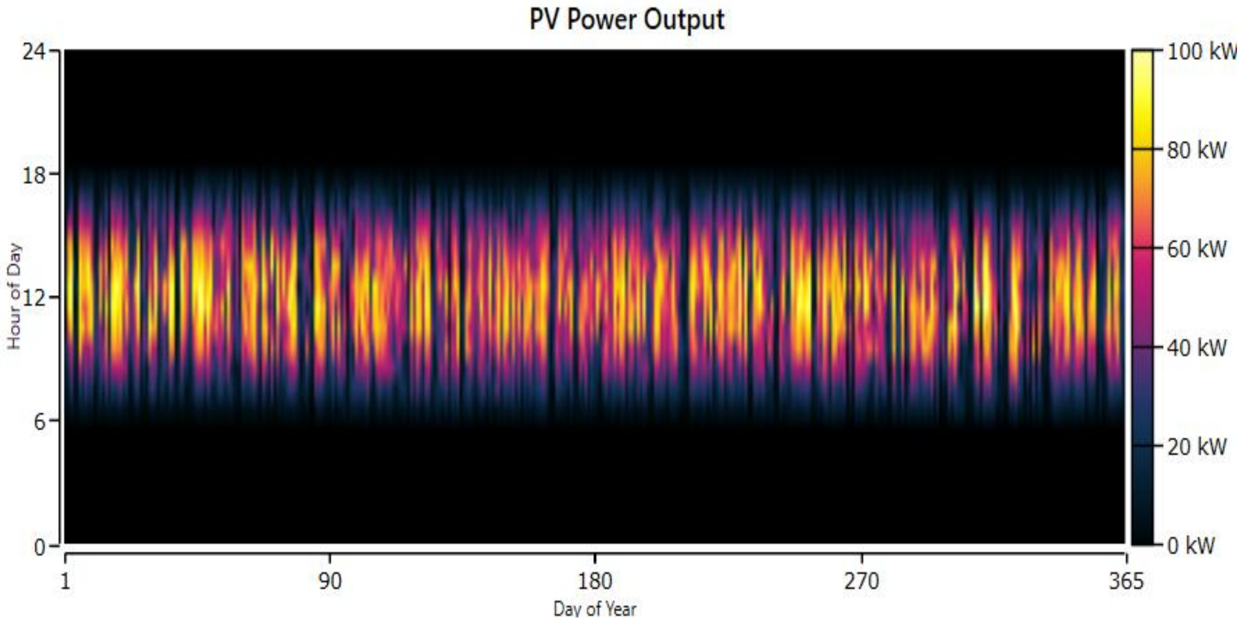

Figure 5. 3. Penetration of renewable energy

Although this research thesis had planned to use diesel generator as backup generator, HOMER Pro optimization omits this one for two reasons. For economic reason due to the high-cost fuel and another reason is that since the presence of utility grid, load is supplied from it during night hours and cloudy days (refer to the figure 5.4).

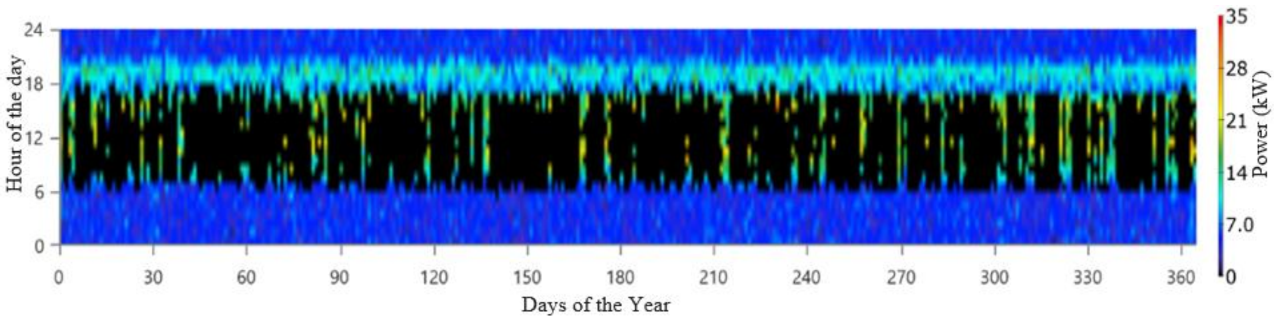

Figure 5. 4. The energy purchased from the grid

Hence no fuel consumption is in the results from simulation. It clear on the figure .5.5 when solar energy is not available especially during night hours the load is supplied from utility grid. Furthermore, the simulation results indicate that total load is covered rather, the PV-system draw 17.9% excess energy.

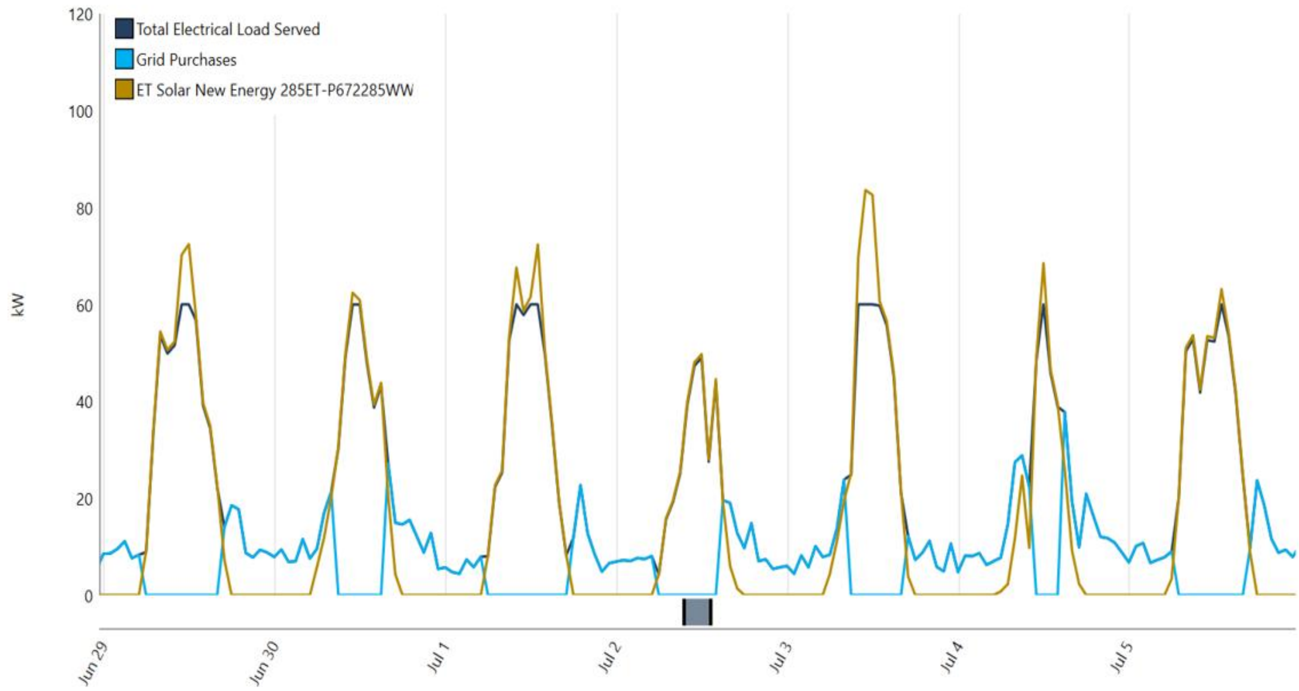

Figure 5. 5. Hourly generation and consumption

5.3. Economic Evaluation

Referring to the optimal solution, the economic evaluation indicates that Net Present Cost (NPC) of 128,506.50$ and low levelized cost is 0.0495$/kWh. In comparison with 0.202$/kWh as the cost of electricity at GISHARI college, it clear that with penetration of renewable energy the cost of energy has been reduced and the college can save 0.15$/kWh. With this saving, the college can save 30116.25 $ per year. Additionally, the investment of the project will be covered in 10 years as payback period while the lifetime of the project is 25years. Cumulative cash flow in function of base cost and lowest cost parameters of this solution are economically attractive as is shown on the figure5.6.

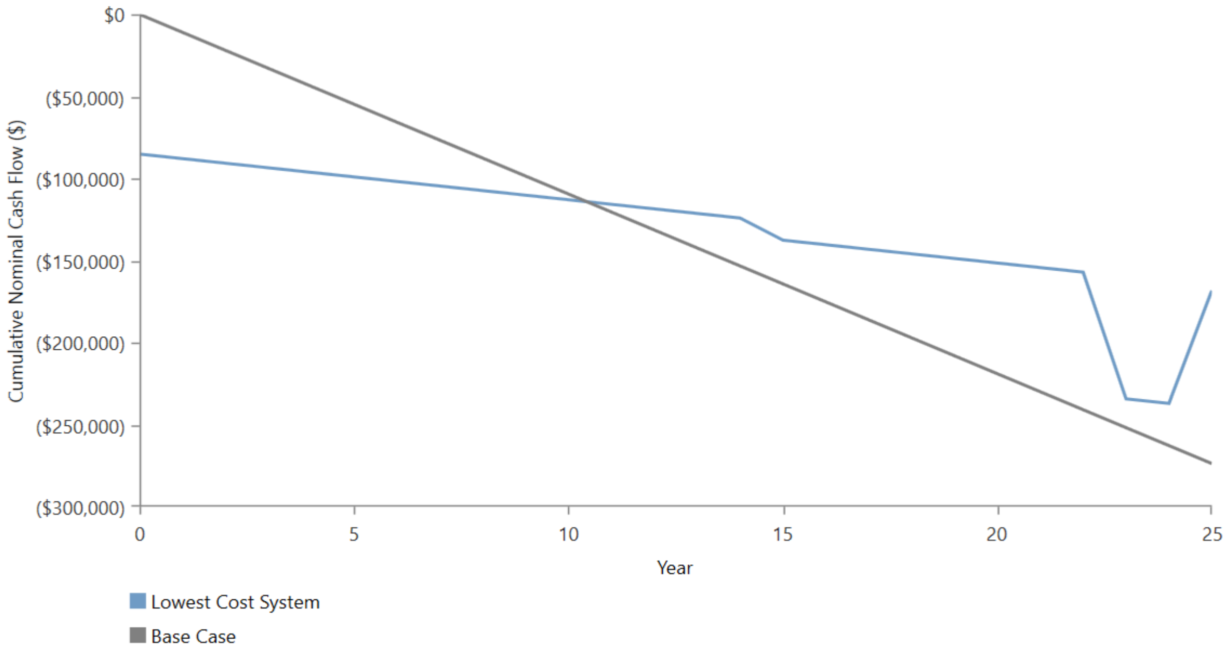

Figure 5. 6. Diagram for economic evaluation

5.4. Sensitivity analysis

This section focuses on how a change in one design parameter affects the behavior and performance of a PV-based mini grid. The simulation's levelized cost of energy (LCOE) and net present cost (NPC) are affected by the PV system's lifespan change. As seen in figure 5.7, both LCOE and NPC actually increase when the PV system's lifetime is decreased.

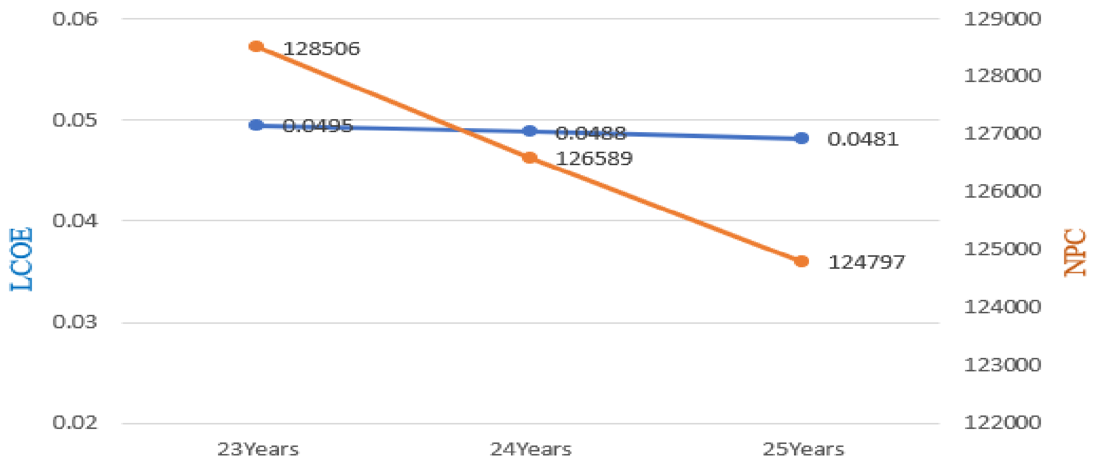

Figure 5. 7. Change of LOCE & NPC with PV-system lifetime

In addition, due the fact that HOMER Pro does not consider diesel generator in the optimal solution, the change in price of fuel does not impact neither on LCEO nor on NPC of PV-based mini grid as it is shown on the figure 5.8 Furthermore, the figure 5.9

indicates that the increase of electricity price from utility grid increases also LCOE and NPC

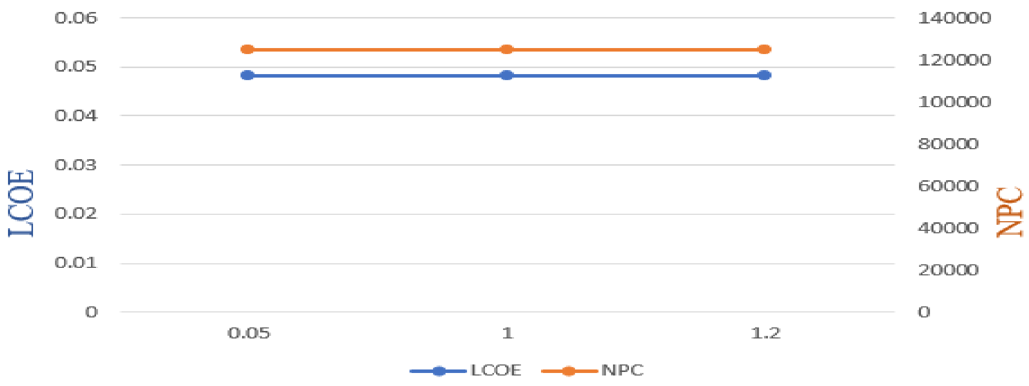

Figure 5. 8. Impact of fuel price on LCOE&NPC

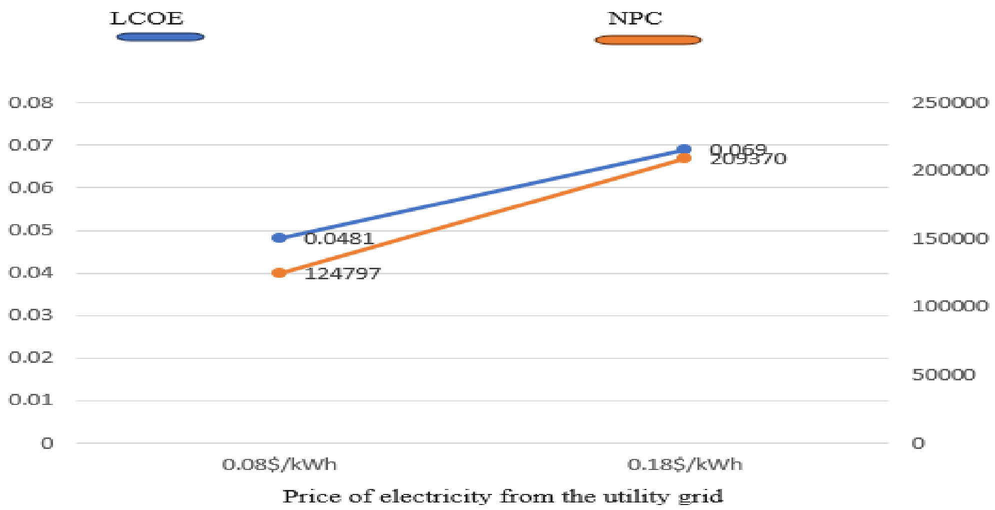

Figure 5. 9. Impact of price of electricity on LCOE and NPC

Another important parameter to test in term of sensitivity analysis is the impact of load variation on solar energy contribution to supply the total load and excess of solar energy that is sold to the grid. Referring to the figure 5.10, when the load increases, the contribution of solar energy reduces as well as the excess of energy generated from solar. This reduction in both solar energy contribution and excess of energy is justified by the limited capacity of PV-system as well as the weather conditions. On another hand, the figure.5.11 shows that the rise in load demand causes the increase of the total energy generated from the whole mini grid.

Figure 5. 10. Impact of solar load variation on contribution of solar energy

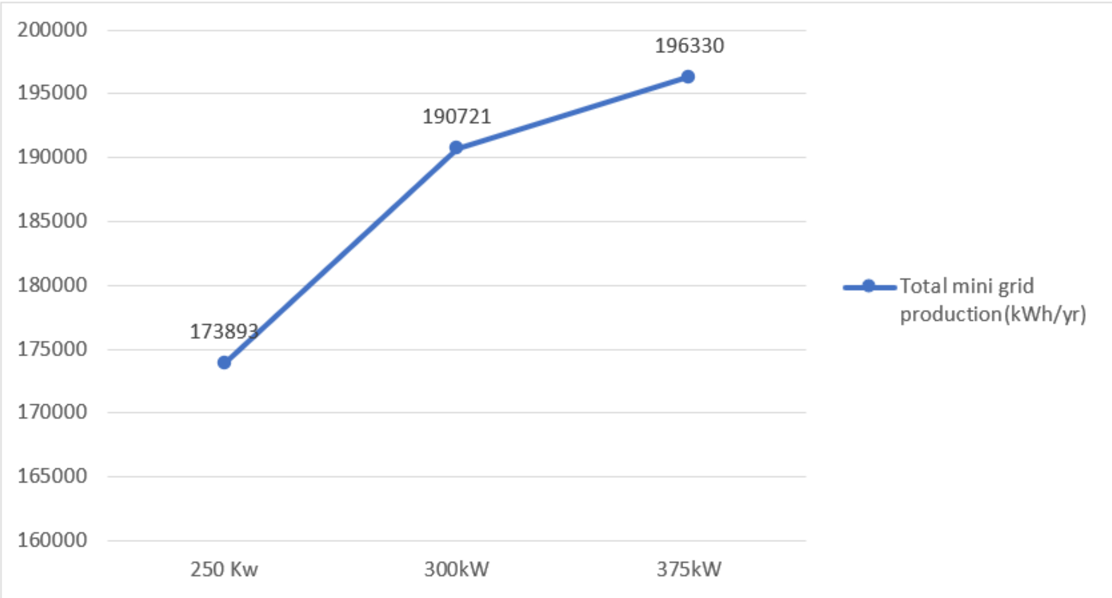

Figure 5. 11. Impact of load demand mini

CHAPTER SIX: CONCLUSION AND RECOMMENDATION

The design and simulation of a PV-based mini-grid at RP-GISHARI college is a major step forward in renewable energy solutions, providing a dependable and sustainable power source. This chapter evaluates the key findings and detailed simulations of PV-based mini-grids to demonstrate their potential to offer economical and ecologically friendly substitutes for traditional power sources.

6.1 Conclusion

The purpose of this study was to design an optimal PV-Based mini-grid to improve the reliability of electrical power supply at RP-Gishari College, improve research and innovation quality in education, and lower college costs associated with fuel and grid electricity payments. The study discovered that the location area of RP-Gishari college is favorable for use solar energy to generate electricity. Additionally, the pick load at GISHARI College coincides with the maximum solar radiation. As a result, GISHARI College can save 30116.25 $ annually by integrating solar energy through the design of a PV-based mini grid, and the college can cover all project expenses within ten years. Basing on the results found in this research thesis, The contribution of solar energy in power reliability, reduction of cost of electricity and high quality of education at Gishari College is no doubt.

6.2. Recommendations

Referring to the outcomes of this research thesis, RP-GISHARI college is recommended to use solar energy by implementing PV-based mini grid project since this would not only reduce the dependance of using electricity from utility but also through the use of solar energy college would save much money. Universities and high schools are recommended to use solar energy for becoming more energy-independent, reducing their reliance on grid electricity and vulnerability to energy price fluctuations. Additionally further research should be conducted about comparison between the cost of electricity purchased from utility grid during night hours and cloud days to the cost of storing solar energy in batteries to see if the college can be totally independent of electricity from the grid.

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APPENDICES

Appendix A: Survey for connected load of GISHARI COLLEGE

No	Load name	Quantity	Power rating (kW)	Total power (Kw)	Cos ø	Apparent power (KVA)	Total power (KVA)	Operating time (Hrs)	Daily energy(kWh)
1	Computers for staff	150	0.065	9.8	1	0.07	9.8	5	48.75
2	Computers for students	445	0.065	28.9	1	0.07	28.9	5	144.63
3	Computers for smart classes	100	0.28	28.0	1	0.28	28.0	7	196
4	Skyworht Smart TV 75 inches	1	0.28	0.3	1	0.28	0.3	3	0.84
5	LG inch 43 Smart TV 43 inches	1	0.07	0.1	1	0.07	0.1	9	0.63
6	EPSON Projectors	20	0.298	6.0	1	0.30	6.0	6	35.76
7	SONY 4K SXRD Home Cinema Projector	1	0.39	0.4	1	0.39	0.4	8	3.12
8	CANON Image Runner 2545i	1	1.5	1.5	1	1.50	1.5	3	4.5
9	KONICA MINOLTA bizhub C364e	1	1.5	1.5	1	1.50	1.5	4	6
10	hp Laser jet 700color MFPM775	1	0.703	0.7	1	0.70	0.7	3	2.109
11	Brother MFC-J2330DW	5	0.029	0.1	1	0.03	0.1	3	0.435
12	CANON Image Runner 20206	3	1.5	4.5	1	1.50	4.5	3	13.5
13	Brother MFC-J5755DW	2	1.344	2.7	1	1.34	2.7	3	8.064
14	hp color Laser jet pro MFPM175n	2	0.3	0.6	1	0.30	0.6	3	1.8
15	Compressor	1	7.5	7.5	0.85	8.82	8.8	3	22.5
16	Drill machine	1	0.7	0.7	0.5	1.40	1.4	2	1.4
17	Changer weel machine	1	1.1	1.1	0.58	1.90	1.9	2	2.2
18	Pump testor machine	1	22	22.0	0.85	25.88	25.9	2	44
19	Hydraulic fault machine	3	1.5	4.5	0.78	1.92	5.8	3	13.5

20	Pneumatic Trainer	1	0.55	0.6	0.85	0.65	0.6	3	1.65
21	Weel balancer	1	0.275	0.3	0.8	0.34	0.3	2	0.55
22	Recharge machine	1	2	2.0	0.8	2.50	2.5	2	4
23	Weel alignment machine	1	0.3	0.3	0.8	0.38	0.4	3	0.9
24	Surface planer machine	1	3.7	3.7	0.76	4.87	4.9	3	11.1
25	Circular saw machine	1	7.5	7.5	0.78	9.62	9.6	3	22.5
26	Thicknesser machine	1	3.7	3.7	0.77	4.81	4.8	3	11.1
27	Spindle moulder machine	1	4.45	4.5	0.85	5.24	5.2	0.5	2.225
28	Dust collector machine	5	1.5	7.5	0.8	1.88	9.4	4	30
29	band saw machine	1	3.7	3.7	0.75	4.93	4.9	0.5	1.85
30	sander machine	1	1.1	1.1	0.85	1.29	1.3	1	1.1
31	Radial Saw Machine	1	2.2	2.2	0.8	2.75	2.8	0.5	1.1
32	Wood laser machine	1	0.75	0.8	0.67	1.12	1.1	0.5	0.375
33	Tenon saw machine	1	3	3.0	0.7	4.29	4.3	0.5	1.5
34	Drilling machine	2	0.75	1.5	0.9	0.83	1.7	9	13.5
36	Fluorescent L offices	50	0.036	1.8	1	0.04	1.8	3	5.4
37	LED tube L offices	198	0.009	1.8	1	0.01	1.8	3	5.346
38	LED bubles bathrooms	36	0.012	0.4	1	0.01	0.4	1	0.432
39	Fluorescent L Corridor	144	0.036	5.2	1	0.04	5.2	10	51.84
40	LED tube L corridor	72	0.009	0.6	1	0.01	0.6	12	7.776
41	LED bubles outsides	12	0.012	0.1	1	0.01	0.1	12	1.728
42	Fluorescent L Classes	155	0.036	5.6	1	0.04	5.6	5	27.9
43	LED tube L Classes	415	0.009	3.7	1	0.01	3.7	5	18.675
44	Street light L	8	0.1	0.8	1	0.10	0.8	12	9.6
45	Street light L	26	0.15	3.9	1	0.15	3.9	12	46.8
46	Soil lab big lamps	4	0.15	0.6	1	0.15	0.6	5	3
47	Automatic hand drier	8	2.2	17.6	0.9	2.44	19.6	2	35.2
48	Water boiler machine	1	3	3.0	0.9	3.33	3.3	8	24
49	Super cooling machine	1	1.5	1.5	0.85	1.76	1.8	8	12
50	Florsa freeser	1	0.16	0.2	1	0.16	0.2	8	1.28
51	Florsa freeser	1	0.16	0.2	1	0.16	0.2	2	0.32

52	Micro-wave	1	1.15	1.2	0.85	1.35	1.4	2	2.3
53	Electrical Kettle	1	1.5	1.5	1	1.50	1.5	2	3
54	Health food processor	1	0.5	0.5	1	0.50	0.5	2	1
55	Blender machine	1	1.3	1.3	1	1.30	1.3	2	2.6
56	Grinder machine	2	2.1	4.2	0.9	2.33	4.7	3	12.6
57	Traeding machine	3	1.7	5.1	0.85	2.00	6.0	3	15.3
58	Chearing machine	1	3	3.0	0.85	3.53	3.5	3	9
59	Rolling machine	1	1.5	1.5	0.8	1.88	1.9	3	4.5
60	Electrical hacksaw	1	1.1	1.1	0.78	1.41	1.4	3	3.3
61	Drilling machine	1	0.75	0.8	0.9	0.83	0.8	3	2.25
62	dc inverter mma welding machine	1	7.8	7.8	0.9	8.67	8.7	3	23.4
63	Welding machine	4	4.163	16.7	0.85	4.90	19.6	2	33.304
64	IGBT and smart inverter welder	1	5	5.0	0.85	5.88	5.9	2	10
65	Soil freezing machine 1	1	6	6.0	0.8	7.50	7.5	3	18
66	Soil freezing machine 2	1	3	3.0	0.8	3.75	3.8	4	12
67	Soil freezing machine:3	2	5	10.0	0.9	5.56	11.1	4	40
68	Electric compaction machine	1	3	3.0	0.9	3.33	3.3	4	12
69	Soil Compressor machine	4	1.35	5.4	0.85	1.59	6.4	2.5	13.5
70	Angeles's single-Cylinder abrasion Machine	2	0.75	1.5	0.92	0.82	1.6	3.5	5.25
71	Electric measuring machine	2	0.75	1.5	0.78	0.96	1.9	4	6
72	Electric demolding testing machine	1	1.5	1.5	0.87	1.72	1.7	2	3
73	Air compressor	1	2.2	2.2	0.85	2.59	2.6	2	4.4
74	3-Phases induction motors type.1	1	2.2	2.2	0.85	2.59	2.6	2	4.4
75	3-Phases induction motors type.2	4	1.1	4.4	0.9	1.22	4.9	3	13.2
76	DC power supply	4	0.375	1.5	1	0.38	1.5	4	6

77	Analogue oscilloscope	2	0.035	0.1	1	0.04	0.1	0.5	0.035
78	al oscilloscope	1	0.02	0.0	1	0.02	0.0	1	0.02
79	Digital IC Trainer	2	0.02	0.0	1	0.02	0.0	3	0.12
80	Discrete component Trainer	2	0.015	0.0	1	0.02	0.0	2	0.06
81	Function generator	1	0.01	0.0	1	0.01	0.0	3	0.03
82	Hot air gun	3	0.21	0.6	1	0.21	0.6	3	1.89
83	soldering iron	4	0.06	0.2	1	0.06	0.2	3	0.72
84	Drilling machines	4	0.7	2.8	0.9	0.78	3.1	3	8.4
85	Battery charger	2	1.8	3.6	1	1.80	3.6	1	3.6
TOTAL POWER (kW)				309.5	**TOTAL APPARENT POWER (kVA)**		346	TOTAL ENERGY (kWh)	1179.664

Appendix B: Daily load profile at GISHARI college

	28/11/2024	18/06/2024
	Load curve(kW)	Load curve(kW)
00h00	6.6	6.6
01h00	6.6	6.6
02h00	6.6	6.6
03h00	6.6	6.6
04h00	6.6	6.6
05h00	6.6	6.6
06h00	5.1	6.2
07h00	6.0	10.0
08h00	6.7	13.4
09h00	7.0	15.2
10h00	7.1	16.0
11h00	7.1	18.3
12h00	7.9	15.8
13h00	7.0	16.7
14h00	6.9	16.3
15h00	6.9	9.1
16h00	5.0	5.5
17h00	3.5	7.0
18h00	6.8	6.9
19h00	6.7	6.7
20h00	6.7	6.7
21h00	6.6	6.6
22h00	6.6	6.6
23h00	6.6	6.6

Appendix C: Yearly load profile at GISHARI college

Energy consumption 2022-2023			Power consumption 2022-2023	
Mothns	kWh_ 2022	kWh_2023	P(kW)_2022	P(kW)_2023
1	4227.4	3006.8	5.7	4.0
2	3554.8	7419.7	5.3	11.0
3	8175.7	8339.7	11.0	11.2
4	9065.5	9821.5	12.6	13.6
5	7657.2	7657.2	10.3	10.3
6	2402.8	3215.6	3.3	4.5
7	8175.7	7419.7	11.0	10.0
8	9905.5	10241.5	13.3	14.2
9	7137.2	9889.7	9.9	13.7
10	3681.5	3214.5	4.9	4.3
11	7771.7	5027.7	10.8	7.0
12	6104	6315.7	8.2	8.5

Appendix D: Solar irradiation at Gishari college

Months	Irradiation (kWh/m²)	Daily irradiation(kWh/m²)
January	157.2	5.1
February	149.3	5.3
March	170.4	5.5
April	173.6	5.8
May	188.2	6.1
June	183.9	6.1
July	196	6.3
August	181.3	5.8
September	163.2	5.4
October	155.2	5
November	143.9	4.8
December	146.8	4.7
Average daily solar irradiation		**5.5**

Appendix E: Ambient temperature at Gishari college

Months	**Ambient T.°C**
January	21.3
February	21.7
March	21.5
April	20.7
May	21.0
June	20.8
July	20.4
August	20.8
September	20.8
October	21.3
November	20.6
December	20.8
Average	**21.0**

Appendix F: wind verbosity at GISHARI College

Months	**Wind (m/s)**
January	1.8
February	2.0
March	1.9
April	1.9
May	2.0
June	2.4
July	2.5
August	2.4
September	2.2
October	2.1
November	1.8
December	1.7
Average speed	**2.1**

Appendix G: Approval E-mail of Data collection at METEO-RWANDA.