College of Science and Technology

Title of the Project: **DESIGN AND SIMULATION OF HYBRID SOLAR PV - DIESEL GENERATOR ENERGY SYSTEM FOR A RURAL OFF GRID TELECOM SITE.**

CASE STUDY: KAYUMBU TELECOM SITE

A Research Project submitted to the African Center of Excellence in Energy Sustainable Development (ACE-ESD), In Partial Fulfillment of the Requirement for the Degree of Master of Science in electrical power systems.

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Submission date:18/10 /2023

DECLARATION

I, the undersigned, confirm that this project work is entirely mine and that it has not previously been submitted for a degree at the University of Rwanda or any other institution. All components of materials used in this work have been fully recognized and cited in accordance with the University of Rwanda's requirements.

Names: BYIRINGIRO Edison Signature

APPROVAL

Date of Submission:8/12/2023

This thesis has been submitted for examination with my approval as a university Supervisor.

Dr. Emmanuel UFITEYEZU

Thesis supervisor Signature

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ABSTRACT

Different challenges arise when cellular mobile services are to be provided in remote or rural areas without access of electricity or where construction of electrical networks is not yet implemented. Because of this, the mobile towers and base transmitter stations that are currently in use but are situated in rural areas rely on traditional diesel generators with backup battery banks to provide the necessary power for all the telecom tower equipment's. More energy sources are needed due to Rwanda's rapidly expanding mobile networks and the rise in cellular base stations in rural areas. Traditional energy sources are expensive due to fuel consumption high cost, and it can lead to pollution of the atmosphere and environmental issues. Additionally, because of Rwanda's rapid development, a variety of services were created, including banks, universities, secondary schools, Irembo services, Electronic Billing Machine services for businesses, and phone conversations. All these services require telecommunication services in rural areas, which has increased demand for diesel-powered off-grid telecom sites. But for these towers to function, they need a steady supply of electricity, which is normally supplied by diesel generators, which can be costly to run because of the high cost of fuel, fuel cost fluctuations, cost of transportation and regular generator maintenance. Diesel generator usage contributes to environmental pollution in addition to high fuel costs. An affordable and sustainable alternative is offered by the hybrid solar PV-diesel generator energy system. The purpose of this study is to design and simulate a hybrid solar PV-diesel generator energy system with lower fuel consumption costs for an off-grid telecom site in a rural area of Rwanda. Additionally, it provides information on how to use the combination of solar Photovoltaic with the diesel generator power system at Kayumbu telecom site, located in rural area, along with a backup battery bank, to supply the site with continuous electrical power. For the Kayumbu site, a stand-alone system is intended to fulfill the necessary power demand. PVSYST software is used for all required modeling and simulation. The fuel cost for this research project has decreased due to the system of design the hybrid power generation of solar photovoltaic and diesel generator.

KEY WORDS

Base Transceiver Station, Off-grid site, hybrid system, diesel generator, photovoltaic, solar, storage battery, and power consumption.

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ABBREVIATIONS

BTS: Base Transceiver Stations

PV: Photovoltaic

G: Giga

RURA: The Rwanda Utilities Regulatory Authority

MNO: Mobile network operators

MW: Mega Watt

GSMA: Global System for Mobile Communications Association

SIM: Subscriber identity module

BSS: Base station subsystem

MSC: Mobile service switching center.

GMSC: Gateway mobile service switching center.

DC: Direct current

RF: Radio frequency

SMPS: Switched-Mode Power Supply/ Switching Mode Power Supply

DG: Diesel generator

V: Volt

AC: Alternating Current

BS: Base station

VRLA: Valve Regulated Lead-Acid

LFP: lithium ferro phosphate

SLA: Sealed Lead Acid Battery

AGM: Stands for Absorbent Glass Mat

RG: Global Solar Radiation

SOC: state of charge

DOD: depth of discharge,

BESS: Battery Energy Storage System

kWh: Killo watt hour

GSM: Global system for mobile communication

CDMA: Code-Division Multiple Access

CSR: Corporate social responsibility

SPV: Solar Photo voltaic

LPG: Liquefied Petroleum Gas

NASA: National Aeronautics and Space Agency

MININFRA: The Ministry of Infrastructure

OPEX: operational expenditure

HOMER: Hybrid Optimization Model for Electric Renewables

HSP: Hybrid solar photovoltaic

PWM: Pulse width modulation

MPPT: Maximum power point tracing

CHAPTER I. INTRODUCTION

The size and use of an off-grid telecom site vary greatly, and it is not linked to the main grid electricity [1].Using a variety of power generation tools, including micro hydropower, photovoltaic systems, wind turbines, conventional generators, and so forth, hybrid power systems seek to produce electricity. It can store electricity and power electronics technology. The benefits of adopting renewable energy sources include having constant, instant access to dependable power, decreasing reliance on changes in oil prices every few months or at any time, and lowering fuel transportation expenses. They also boost economic productivity and combat climate change [2]. Providers of telecommunication network services have significantly impacted positively the activities done by different people in their daily life. Since a large number of people, including those in Rwanda, are connected by mobile networks, telecom operators and service providers constantly have to deal with the challenge of providing these expanding and growing in remote networks with dependable and reasonably priced electrical power solutions. When grid electricity is available, there are times when it is very unpredictable, with frequent and lengthy outages [3].

With wireless voice and data signals becoming more widely available in remote areas, communication services are facing several obstacles [4]. One of the most important issues facing telecom operators when deploying their networks is power supply. Because developed nations have well-developed power infrastructure, this challenge can be easily overcome there. Base Transceiver Stations (BTSs) are powered by national electricity grids, which are the preferred energy source in developing nations. Sadly, its coverage is restricted, and its dependability is not always guaranteed. In developing nations like Rwanda, this is made more difficult by the increasing penetration of mobile communication into rural areas that are not serviced by national grids. Only a tiny percentage of people have access to secondary power plants or grid extensions that electrify rural areas. The electric power infrastructure is negatively affecting mobile telecommunications expansion in terms of network coverage and operating costs due to the absence of grid power supplies.

As a result, the rural population has very little or no mobile network coverage. The mobile tower sites were powered by traditional diesel generators that had a backup battery. These off-grid systems need frequent maintenance, are typically found in hard-to-reach places and are expensive to operate and transport. They burn a lot of fuel as well. In rural areas where renewable energy sources are preferred or most appropriate to realize Rwanda's telecom tower site using renewable energy technologies, this will result in a marked increase in demand for off-grid power supplies. The project's objective is to design an off-grid hybrid PV energy system for the Base Transceiver Station, utilizing a case study of the Kayumbu telecom tower, in order to generate and supply reasonably priced electricity to meet the station's electric load requirement. It's in the Kamonyi District of the South Province of Rwanda. [5].

1.1 **Background**

In developing nations, having access to telecommunication services is essential for promoting entrepreneurship, raising labor productivity, creating jobs, and providing other benefits for consumers, according to the 2016 World Development Report [6].This suggests that people and organizations who have access to mobile telecommunication services enjoy different social and economic benefits from those who do not [7]. It has been acknowledged that the installation of telecom towers infrastructure where electricity is not yet available or very difficult to implement, in particular, is a major factor in raising people's standard of living and eliminating poverty [8] .However, even though mobile telecommunication services are still growing throughout most of Africa and offer significant advantages like 3G and 4G connectivity, many rural areas lack mobile coverage [9].The Rwanda Utilities Regulatory Authority (RURA) is in charge of overseeing the provision of telecommunication services in Rwanda. The majority of Rwanda is covered by the telecommunications network, especially for mobile phones, which has three major competitors in the market.

The last 20 years have seen numerous government-enacted reforms that have fundamentally altered Rwanda's telecom landscape. To establish Rwanda as a worldwide center for telecommunications, the Rwandan government has taken the initiative. The Rwandan telecom industry is still centered on the mobile market. As the operators develop their infrastructure, most local capital expenditures still go toward Rwanda's mobile market. The national telecommunications network of Rwanda is extensive. Network deployment in rural areas has often been seen as uneconomical due to their low population density, low average revenue per user, unstable geographic terrain, and the astronomical costs associated with powering macro site infrastructures in these areas. The most significant of these is the cost of supplying electricity. The base transceiver station of a mobile telecommunication system is an essential part that must be powered on all the time in order to keep mobile network operators (MNO) and end users connected. Additionally, they are believed to be the primary source of energy consumption in communication networks. An MNO's revenue could be significantly impacted by the cost of powering a BTS, depending on the region and energy source. This could be a good reason for MNOs to ignore rural areas [10].

Due to market saturation, mobile network operators have started to see slower revenue growth after a considerable amount of penetration in towns and cities [11]. Simultaneously, increased pressure is being placed on government agencies to ensure that MNO operation licenses include the national coverage area. MNOs need to expand their coverage to previously untapped areas to meet operational demands and grow their subscriber base, as previously mentioned. This makes it imperative to find a dependable and economical solution to the electricity problem [12].

1.2 Problem statement

Across the world, including Rwanda, rural areas lack access to a cost-effective and dependable electrical grid. Therefore, diesel generators are commonly used as the primary power source for off-grid telecom towers located in rural areas. All telecom towers located in rural areas where there is no electricity, diesel generators are dependable sources of electricity power supply, but they have negative impact to telecom tower services provides. Running diesel generators lead to high cost, due to fuel consumption high cost, fuel cost fluctuations, fuel transportation cost and maintenance cost. The high cost of operation for diesel generators is one of the biggest problems with them. By using generators result in high fuel costly and has an adverse effect on the environment because it releases gases that are harmful to human health into the atmosphere. These gases include carbon monoxide, nitrogen oxides, and particulate matter. In general, when generators are running to generate electricity presents several difficulties in many isolated and off grid locations, including high running costs, environmental issues, and a reliance on fossil fuels. Investigating and implementing alternative energy solutions like hybrid systems that combine diesel generators and solar photovoltaic (PV) technology is necessary to address these problems.

1.3. Objectives

1.3.1. General objective

The general objective of this study is the design and simulation of a hybrid solar PV- diesel generator energy system for a rural off grid telecom site**.** “Case study “Kayumbu telecom tower.”

1.3.2. Specific objectives

Specifically, goals of this research are as follows:

- Fuel cost reduction, to achieve significant cost savings in operational expenses related to fuel consumption for telecom tower power generation.
- To calculate the hybrid solar PV-diesel generator system sizing appropriate for that telecom tower (Kayumbu telecom tower).
- Integrate hybrid solar PV/diesel technology to either replace or supplement diesel power during the day to increase the telecom tower's overall energy efficiency.

1.3.3. Research questions

This research project is based in the following questions:

- What are the energy requirements of a typical off-grid telecom site located in a rural area?
- For an off-grid telecom site, how much fuel can be saved by integrating a hybrid solar PV-diesel generator energy system?
- What are the advantages of using a hybrid solar PV and diesel generator energy system for an off-grid telecom site in a rural area in terms of the environment?

1.4 Scope of the study

The design and simulation of a hybrid solar PV-diesel generator energy system for an off-grid rural telecom site, is the main objective of this study. Case study: Kayumbu Telecom tower

1.5. The outcomes expectation and significance of the study

1.5.1. The outcomes Expectation

The outcomes expectation from this research of designing a hybrid solar PV-diesel generator for Kayumbu telecom tower located in Kamonyi District, South - Rwanda are enumerated below:

- Decreased fuel consumption: The main goal of the study is to use less diesel fuel to operate the telecom site at a lower cost.
- Improved energy efficiency: The hybrid solar PV - diesel generator energy system is to provide a clean and efficient source of energy that can be used to power the telecom site.
- Reduced environmental impact: The use hybrid solar PV- diesel generator energy system reduces the environmental impact. This has a result in reducing greenhouse gas emissions.
- Increased reliability: hybrid solar PV- diesel generator energy system, when implemented, improves the reliability of the telecom site's power supply.
- Cost savings: The implementation of hybrid solar PV- diesel generator energy system is resulting in significant cost savings for the telecom company.

1.5.2. Significance of the Study

Owners of businesses in the telecommunications sector suffer greatly from the enormous fuel bills they incur from operating diesel generators for extended periods of time on telecom towers in remote areas with limited access to electricity. Additionally, it is everyone's duty to reduce the number of pollutants they release into the atmosphere, so one important way to do so must be to use hybrid solar PV - diesel generator energy systems on telecom towers. In comparison to other energy sources, solar energy is efficient, renewable, and free of environmental impact. As such, it can lower operating costs while promoting energy conservation and environmental protection. Based on this, it is possible to implement a hybrid solar PV- diesel generator energy system, which will also reduce fuel costs and the harmful effects that these emissions of diesel have on the environment while the generator is operating.

1.6. Methodology used for the Study.

The research methodology involves the following steps:

- Data Collection: The Kayumbu telecom tower's daily energy demand is calculated by gathering data on energy consumption over a predetermined time.
- System Design: Based on the data gathered, a hybrid solar PV and diesel generator energy system is created to meet Kayumbu Tower's energy needs. The design comprises the PV modules' dimensions as well as the battery bank and other passive equipment’s.
- Economic Analysis: Evaluating the generator fuel consumption cost per year before integration hybrid system and fuel consumption cost per year after hybrid solar PV-diesel generator integration.

1.7. Report Arrangement

The goal of this research is to reduce fuel costs by designing and simulating a hybrid solar PV-diesel generator energy system for the off-grid telecom site Kayumbu, which is in a rural area. The main goal is to incorporate solar photovoltaic energy into the site, which presently uses a diesel generator as its main power source and a battery bank as a backup to power BTS equipment.

Chapter one presents work as an introduction with the problem Statement, Objectives, research questions, scope of the study, significance of the study and expected outcomes.

Chapter two part is concerned with the theoretical background and literature review of the problem formulation, related work and gap from related work done.

Chapter Three focuses on research methodology used in conducting this project, including data collection methods.

Chapter Four presents sizing of hybrid PV-diesel generator energy system, design calculations, mathematical models related to this work, PV syst software results.

Chapter Five represents the Results and discussion on the calculated results.

Then finally, Chapter Six focuses on general conclusion and recommendations for this research project results.

CHAPER II. LITERATURE REVIEW

2.1 Brief Introduction

Telecommunications networks need an electrical power source to function. A large portion of these telecommunication networks' operating costs are attributable to the cost of electrical energy. This is especially true in rural areas where power supply is unpredictable or where energy supply providers still have a lot of work ahead of them in ensuring that people have access to electricity. Operators of telecommunication networks are now skilled at producing their own off-grid power sources. Traditionally, this has been accomplished by using various diesel generators at each location as the main source of power for the BTS. However, a growing number of network operators are now powering their base transceiver stations with renewable energy equipment, like solar and hydroelectric power plants. One drawback of using diesel generators to keep telecom sites powered continuously is that they increase greenhouse gas emissions into the atmosphere, which is bad for the environment and people's health in general. Utilizing renewable energy involves switching out the diesel generators that were previously utilized in rural regions, either entirely or partially, with solar PV panels, wind turbines, or hydroelectric power as the primary source of power for the BTS sites. There are various configurations that have been used for telecommunications, combining convectional and renewable energy sources to try to develop a hybrid working system: Battery and Diesel; Solar and Battery; Wind and Battery; Solar and Wind; Battery and Diesel; Solar and Hydro, Battery, etc [13].

Solar energy is defined as energy that is generated by or comes from the sun; in other words, it is energy derived from sunlight. Because solar energy never runs out and is also referred to as a radiant energy source, it is a form of renewable energy source. These are the various forms of radiant energy that the sun emits. Light in the form of infrared, ultraviolet, and X-rays is the most significant. According to satellite data, Rwanda's territory is currently within the global zone, where the average yearly radiation or daily radiation is between 4 and 6 kWh/m^2/day. Since most of the country receives approximately 4.5 kWh of solar radiation per day on average and has sunshine for part of the day, solar energy is currently economically and practically feasible in Rwanda. To reach 100% electricity availability by 2024, the Rwandan government is promoting the use of renewable energy sources, specifically off-grid and on-grid solar PV systems. As of right now, Rwanda has 12.230 MW of installed solar energy. This comes from 4 solar power plants: the 0.25 MW Jali power plant; the 8.5 MW Rwamagana Gigawatt; the 0.15 MW Ndera Solar power plant; and the 3.3 MW Nasho Solar plant [14].

2.2 Mobile telephone communication network

The mobile telecom industry is growing rapidly globally due to a number of factors, including consumer preferences for new technologies, the accessibility of smartphones, the need for high-speed data connectivity, digitization, and an increase in subscribers. There are billions of active mobile connections worldwide, and the number is increasing every day, according to real-time intelligence data provided by the Global System for Mobile Communications Association (GSMA).

This number of mobile connections includes the number of people who use multiple devices, the availability of dual subscriber identity module (SIM) cards in mobile phones and connected equipment and devices. To satisfy the growing demand from mobile subscribers, the infrastructure network, technology, connectivity, and supporting hardware must be developed and expanded. Both passive and active components make up a mobile phone communication network. Broadly speaking, there are three subsections under which active equipment is generally categorized: (i) base station subsystem (BSS), comprising mobile phones, transcoding rate and adaptation unit, switch arrays, data storage units, central processing unit, and base station controller; (ii) mobile service switching center (MSC), comprising equipment identity register, home location register, and visitor location register; (iii) gateway mobile service switching center (GMSC), comprising identical components as MSC.MSC and GMSC are components of the network switching subsystem. On the other hand, passive equipment includes:(i) structural components like communication towers, antenna mounting structures, antennas, and equipment housing shelters; (ii) power supply systems like battery banks, grid supplies, diesel generator sets, switched mode power supplies, and AC and DC power management systems; (iii) cooling systems like air conditioners, exhaust fans, fan coil units, and passive cooling materials; and (iv) security systems like lighting, alarm monitoring, and lightning protectors [15].

2.3 Telecom towers Type and configurations

Mobile network operators use a variety of telecom towers, each with its own capacity, design, and equipment type. Moreover, these towers' technology is incredibly flexible. The two primary varieties of telecom towers are indoor and outdoor towers. Indoor towers are installed inside of buildings to meet the telecom needs of users, as the name suggests. On the other hand, outdoor towers cover a wider geographic area and are typically mounted on a building's roof or in an open space. Outdoor towers use a range of antenna structures, such as mini poles, rooftops, solar street poles, ground-based towers, slim towers, artificial trees, and sites for decoration or camouflage. Among the various options, ground-based towers and poles placed on the ground and rooftop towers and poles mounted on building roofs are popular [15].

2.4 Electricity requirement of telecom tower

A telecom tower's passive equipment, which includes DC power systems, cooling equipment, radio frequency (RF) loads, and feeder loads (line losses), uses a certain percentage of electricity. Active equipment, which primarily consists of BTS, uses a percentage of the electricity in the tower. It is important to note that the call traffic and number of tenants in a telecom tower determine how the active equipment is configured. A telecom tower that gets power from the grid also frequently needs an automatic transfer switch, SMPS, batteries, and an inverter. Additionally, a DG is included to guarantee telecom towers receive a constant power supply. The telecom tower's BTS is connected to a DC bus and operates at 48 V DC. Through controllers, the DC bus powers every piece of electronic equipment. BTS receives power from the grid or distributed generation (DG) via a DC busbar that uses SMPS. All cooling loads and auxiliary loads are connected to the AC busbar. The critical loads are powered by batteries in the event of a first, temporary power outage. An automatic transfer switch then moves the loads from the energy storage system (battery) to the DG.

As a result, the grid-based conventional power supply system of a telecom tower usually depends on a distributed generator and batteries to keep running in the event of a grid power outage. In telecom towers, both alternating current and direct current loads are utilized concurrently [15].

2.5 Power Supply and Energy Solutions for Off-Grid Base Stations

A telecom tower that runs separately from the main electrical grid is known as an off-grid telecom tower. Off-grid towers are situated in isolated or underserved areas where grid power is either unavailable or inconsistent, in contrast to towers in urban or well-connected areas that are directly powered by grid electricity. These towers need backup power sources in order to keep running. In order to prevent service outages for telecom operators and mobile users, a reliable and continuous power supply arrangement is an essential requirement to take into consideration when powering off-grid base stations (BSs). Historically, conventional power supply options like gasoline and diesel generators have been used to power off-grid battery storage sites. These systems can be used alone or in combination with renewable energy sources like hybrid PV-diesel power supply systems that may or may not have energy storage. These power supply options are particularly helpful in situations where, extending the grid connection to power the BS site would not be financially advantageous or where grid electricity is not always available to ensure a continuous power supply. As the concept of green telecommunication networks gains traction, there has been a discernible surge in interest in the real-world implementation of using sustainable solutions to power base stations. Consequently, a great deal of research and development work has been done to help telecom operators transition from using diesel generators as their primary source of base station power to other options. It's becoming evident that choosing an alternative to diesel generators can help reduce their high operation, maintenance costs, and unreliability issues [16].

2.5.1 Diesel Generators

This study considers a backup generator as part of the hybrid power system configuration. An electrical power supply is produced by a diesel generator, which converts the kinetic energy of combustion engines into electrical power using various energy sources. Due to their low initial capital investment cost, combustion engines are the most straightforward type of oil fuel electricity generators. The primary purposes of a backup diesel generator are to maximize the output of renewable energy sources, to improve the frequency of energy shortages caused by these sources, and to supplement the battery when it is unable to supply the necessary energy to the telecom tower or electrical load, which is the subject of our study. In comparison to renewable energy sources such as solar PV energy, diesel generators have higher operating costs. Fuel availability and engine efficiency are important considerations to consider when considering the integration of a combustion engine into a hybrid system [17].

It is preferable to run the generator only after the energy storage has reached a specific level set of its full charge because the generator runs efficiently at full load. Diesel generators are divided into various categories, such as synchronous and asynchronous generators. These devices are known as synchronous generators, and they transform mechanical power into AC electricity. They offer accurate voltage and frequency control. Runs at synchronous speed and supplies the necessary alternating current. They supply the telecom tower with the electricity it needs. It can be applied to systems that provide power both on and off the grid [18].

Generator modeling

The diesel generator's power output is restricted to what is expressed below the boundaries.

$0 \leq W1(t) \leq W1, max$

$W1, max$ is the maximum power that the generator is capable of producing in an hour.

$W1(k)$, is the output power from the diesel generator(kW)

$$W1 = W1n * \eta W1 \quad 2.1$$

$W1n$: The diesel generator's nominal output power

$\eta W1$: The coefficient that expresses the diesel generator's efficiency

2.5.1.1 Efficiency and Reliability of diesel generator for off grid telecom tower

Diesel generators were among the first technologies used by BSs as a primary or backup power source in locations with poor or no access to the main grid. A number of researchers talked about how sizing a diesel generator for an off-grid BS site application usually involves estimating the generator's final capacity. Thus, a variety of loads, including linear resistive, capacitive, inductive, non-linear, and linear loads, are taken into account when sizing the diesel generator. The primary advantage of diesel system deployment is that it permits system customization according to load demand. However, reliability has never been guaranteed, and the most obvious factor is the diesel generator's high failure rate at startup, particularly in cold climates. A frequently cited failure rate is 5. out of 1000 start attempts, or 0.5%. This is enough to add another set of diesel generators to increase reliability, particularly in circumstances where total reliability is necessary. Reliability can be increased by about 200 times by keeping backup generators on standby; however, the telecom operators may still find this configuration unfavorable economically due to the additional costs involved. Furthermore, there's a chance that the installation of BSs with diesel generators will lead to a significant rise in greenhouse gas emissions.A comparison of the expected greenhouse gas emissions in the telecommunications sector indicates a significant increase in gas emissions from diesel engine operation, according to Webb of SMART 2020: Enabling the low carbon economy in the information age. Furthermore, mobile networks are responsible for the majority of greenhouse gas emissions, according to the same report. The amount of gases predicted to be released into the atmosphere if mandatory action to create green telecommunication networks is not taken [19].

Diesel generators usually have a very low and inefficient performance capability of 30% or less. The heat generated wastes the remaining energy. This raises yet another important concern about using diesel generators to power off-grid BS sites. The high running and maintenance costs of the BSs that these generators power are thus greatly impacted by this. There are further disadvantages to using diesel generators in terms of labor, fuel, and transportation expenses. To ensure that the BS sites receive enough fuel, more trucks are required, and a large number of full-time technicians are required to handle service interruptions. It's also crucial to remember that frequently using diesel generators brings up other issues like oil spills, noise pollution, theft risk, and short shelf lives [19].

2.5.1.2 Environmental Impact of running diesel generator only.

Burning diesel fuel has a major impact on the environment both locally and globally. Formaldehyde, acrolein, polycyclic aromatic hydrocarbons, organic and elemental carbon (soot), toxic metals, nitrogen oxides that form ozone and nitrate particulate matter, volatile organic compounds, carbon monoxide, and carbon dioxide are just a few of the hazardous materials that are released by diesel engines. This implies detrimental effects on the air, water, and soil in addition to immediate health risks for people. Numerous problems with soil contamination are also brought about by diesel exhaust's black carbon particles, sulfur oxides, and heavy metals. Through precipitation, black carbon finds its way into the topsoil where it impacts plant nutrient uptake as well as the soil's capacity to retain and absorb water. This may affect the ability to produce alternative fuels and to cultivate staple crops used as a food source. Rainfall will also deposit the additional toxins present in diesel exhaust into the soil. Plants will then absorb these toxins, and it's possible that animals headed for the slaughterhouse will swallow them as well. As they move up the food chain, some of these toxins, like heavy metals, will concentrate because they do not biodegrade and are not removed. There is serious concern about the implications for the food supply [20].

Figure1: Kayumbu base station site's typical diesel power generating system.

2.5.2 Battery Systems

Energy storage is the primary goal of using a battery bank. A lead-acid battery is the most widely chosen and utilized energy storage device among the various options available. It can be used in standalone systems due to its high performance to cost ratio, moderate cost, and maturity. There are various capacities of battery bank storage that are available, with terminal voltages of 6V, 12V, 24V, and 48V. Based on our research, 48V is the chosen battery system voltage. The depth of discharge, a term used to describe how much of a battery's energy storage capacity is used at any given time, affects the battery's lifespan. The batteries must supply the necessary power during adverse weather conditions.

In addition, if the batteries are depleting more quickly than expected, the diesel generator provides the energy needed while also charging the batteries when the chosen mechanism's power controls need to be cycled. The following are some of the factors that influence battery system sizing:

- Daily energy consumption
- Days of autonomy
- Maximum depth of discharge
- Temperature correction

In order for the battery's rated capacity and battery life to utilize a portion of its total stored energy, it must be large enough, and the DOD is used to determine this [18].

2.5.2.1 Importance of battery in telecom power system

Telecommunications systems should provide a 99.9% site uptime guarantee, or continuous service availability. This includes commercial services offered to the general public, such as emergency services delivered over critical infrastructure networks, microwave signal generation, reception, and transmission for tower-to-tower communication in order to establish a network of telecom towers, and RF signal generation, reception, and transmission for mobile communication.

The battery in a telecom power system fulfills two crucial functions, which are as follows:

- As a backup energy source between EB and DG switchover, batteries are essential to telecom cell sites.
- It activates the telecom load (BTS) and keeps the uptime at 100% until EB/DG restores it. [16].

2.5.2.2 Types of batteries used in telecommunication sector.

In an emergency, telecom batteries are the foundation of your system's reliability. It is imperative to have a reliable telecom battery bank to prevent service disruptions during blackouts and other emergencies. To maximize your uptime, your batteries must not only perform the task at hand, but also recharge rapidly and possess a long lifespan. Here are some tips for selecting an excellent telecom battery. Telecom batteries are designed to hold energy in case of an outage. Consider these batteries as your personal internal power supply. For the system to function for as long as possible, they must provide adequate power. In addition, these batteries must be effective, small, and strong enough to survive in some harsh conditions. Compared to standard batteries, telecom batteries are substantially stronger and more long-lasting.

Lead-acid and lithium-ion batteries are the two primary battery types used in telecommunications. There are various types of lead-acid batteries available, such as gel, AGM, sealed or SLA, and wet batteries. While electron transfer is used by all these batteries to store energy, the specific medium that permits it varies. Because lead-acid and lithium-ion batteries are so widely available, it's important to make sure the batteries you purchase are made specifically for use in telecom systems. If not, you may find yourself with a battery made for entirely different power requirements [16].

2.5.2.3 Comparison of technical specifications of LFP and VRLA battery

lithium ferro phosphate batteries offer substantial advantages when compared with Valve Regulated Lead-Acid batteries on the following aspects:

Commercial aspect, when compared to VRLA, the initial investment cost of a lithium-ion battery is higher; however, its operating expenses are lower, meaning that lithium-ion batteries will save money and yield rapid returns on investment. VRLA has a short lifespan compared to LFP lifespan. Therefore, lifetime factor would increase the savings as well.

Operational aspect, While VRLA batteries perform horribly in the conditions, lithium-ion batteries function well at high temperatures.

Environmental aspect, Lead is present in VRLA batteries but not in lithium batteries, which do not contain any materials that harm the environment.

Performance aspect, Lithium-ion batteries are superior to VRLA batteries in terms of charging rate capability, and they are best suited for telecom applications [16].

2.5.2.4 Batteries Capacity and Performance in telecommunication sector

A telecom base station is a type of radio station and an interface device for mobile devices to access the Internet. A radio transceiver station that uses a mobile communication switching center to send data to mobile phone terminals within a specific radio coverage area. One crucial aspect of social security is the building of mobile communication base stations. Communication base stations must guarantee a constant power supply all time throughout the year since their stability is correlated with both national and regional issues. And this is exactly what our lithium battery does. The high waterproof level and robust casing of the lithium battery ensure that it is not easily damaged, and when used safely, it can provide at least ten years of backup cycle. Its requirements as a telecommunication battery include a long lifespan and a high capacity. Telecommunication batteries must have a high voltage and capacity to withstand short-term power outages and offer robust support for repair work because telecommunication base stations are all high-power devices. This is necessary to support the continuous power consumption of such high-power devices [16].

Battery Modeling

The charge or discharge power into or out of the battery is controlled by the load demand at any given time as well as the output power from the hybrid generation system (PV and diesel). The following represents the battery's state of charge (SOC) at any given hour.

SOCmax: The maximum state of charge of the battery, or its nominal capacity.

SOCmix: The battery's minimum state of charge, or the lowest point below which it does not discharge.

DOD: depth of discharge, is used to describe how deeply the battery is discharged.

The output power from the PV and diesel hybrid generation system and the load demand at a specific time control the charging and discharging of power into and out of the battery.

The battery's state of charge (SOC) can be expressed as follows at any given hour:

$$\mathrm{SOC(t)} = \mathrm{SOC(0)} + \eta c \sum_{k=0}^{t} \mathrm{Pc(k)} + \eta d \sum_{k=0}^{t} \mathrm{Pd(k)} \quad 2.2$$

SOC(0): The initial SOC of the battery

Pc: The charged power

Pd: The discharged power

ηc: The charging efficiency,

ηd: The discharging efficiency.

The limitations affect the battery capacity that is available.

$$\mathrm{Bmin} \leq \mathrm{SOC} \leq \mathrm{Bmax}$$

$$\mathrm{Bmin} = (1 - \mathrm{DOD})\mathrm{Bmax} \quad 2.3$$

where DOD is the depth of discharge

The minimum and maximum power limits are denoted by Bmin and Bmax, respectively. The stage of charge at that instant (SOC(t)) is calculated based on the previous instant one SOC (t − 1), the produced power, and the load demand during the time from (t − 1) to t. The state of charge at time t during the charging time could be expressed using the following..

$$\mathrm{SOC(t)} = \mathrm{SOC(t-1)} + \frac{\mathrm{PPV(t)} + \mathrm{Pd(t)} - \mathrm{PL(t)}}{\mathrm{Cref}} \Delta t \quad 2.4$$

PL(t): The load power at time t

PPV(t): The PV system power at time t

Pd(t): The diesel power at time t. In this study, Cref is used to represent the BESS capacity (kWh) and Δt to represent the time interval: Δt = (1 h) [21].

2.5.3 Solar Power in telecommunication sector

Sunlight is one of the best renewable energy sources. Consequently, the use of solar energy for applications such as electricity production, vehicle power, and cellular base station powering is growing in popularity. Solar energy is converted into electrical power using photovoltaic technology. The process of turning solar radiation into electrical power is how a solar photovoltaic cell works. To generate a lot of electricity, a series or parallel arrangement of solar PV cells is used. The amount of solar energy that can be used at the surface of the earth is determined by irradiance, which averages about 1000 watts per square meter.

If solar cells are exposed to full sun, their typical crystalline solar cell efficiencies of 14–16% should yield a yield of 140–160 W per square meter. The amount of energy that is available from the sun is measured by insolation, which is expressed in terms of full sun hours [22].

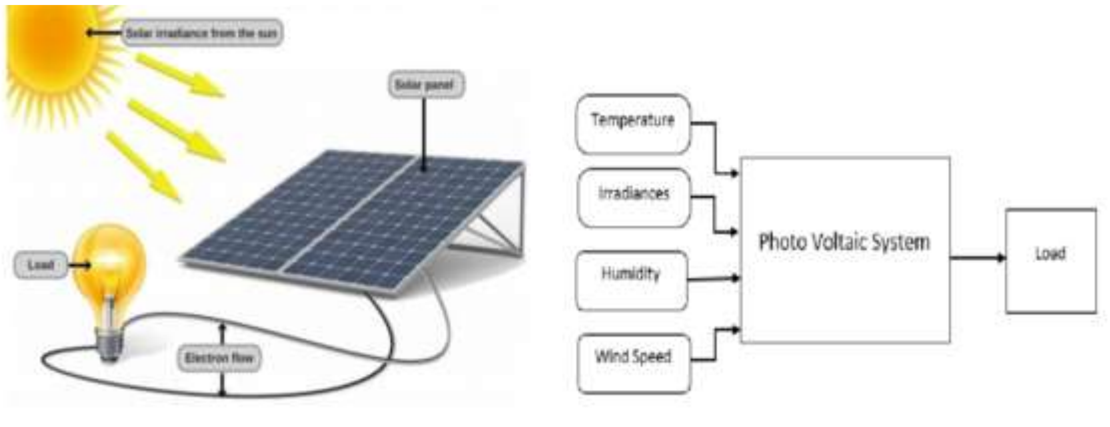

Figure 2: Solar panel converting the sun's energy into electricity.

2.5.3.1 Solar Cell Technology

A solar cell, also known as a PV cell, is an electrical device that uses the photovoltaic effect to turn light energy into electricity. It's a photoelectric cell that produces electricity without the need for an external voltage source when exposed to light. The three stages of the photovoltaic cell's operation:

- Photons from the sun strike the solar panel and are taken up by semi-conducting materials like silicon, germanium, and so forth.
- An electric potential difference results from the atomic loss of negatively charged electrons. Because of the potential difference, current begins to flow through the material; however, because of the structure of solar cells, electrons are only permitted to travel in one direction.
- Direct current electricity is produced from solar energy using a collection of solar cells.

Electricity is produced when electrons move from a negative layer to a positive layer. All the holes on the P-type are suddenly visible to the free electrons on the N-type, and electrons begin to flow to fill the holes. Nevertheless, electrons and holes combine at the PN junction to create a sort of barrier that hinders the migration of N-type electrons to P-type electrons. We eventually arrive at an equilibrium state where the two sides are separated by an electric field. Like a diode, the electric field permits electrons to move from the P-type to the N-type but not the other way around. Light energy disassembles electron-hole pairs in the solar cell when photons of light strike it. Normally, a photon will liberate one electron, which also creates a free hole. The electric field will transfer electrons to the N-type and holes to the P-type if this occurs near enough to it. More electrical neutrality is altered as a result, and if an external circuit path is available, electrons will follow it to the P-type where they will combine with holes that the electric field has sent there, producing beneficial work in the process. The current is produced by the flow of electrons, and the electric field of the solar cell produces voltage. The useful solar power is obtained by multiplying the current by the voltage [22].

2.5.3.2 Types of Solar Powered Systems

Cellular base station PV power systems can be designed using one of four general types of electrical designs: Systems that interact with the utility power grid and include battery backup, standalone systems, hybrid standalone systems, and systems that are connected to the grid but lack battery backup capability.

Grid-Connected without Battery Back-up System

This kind of system only functions when there is utility available. Nonetheless, the system is built to shut down in the case of an outage and wait for utility power to be restored.

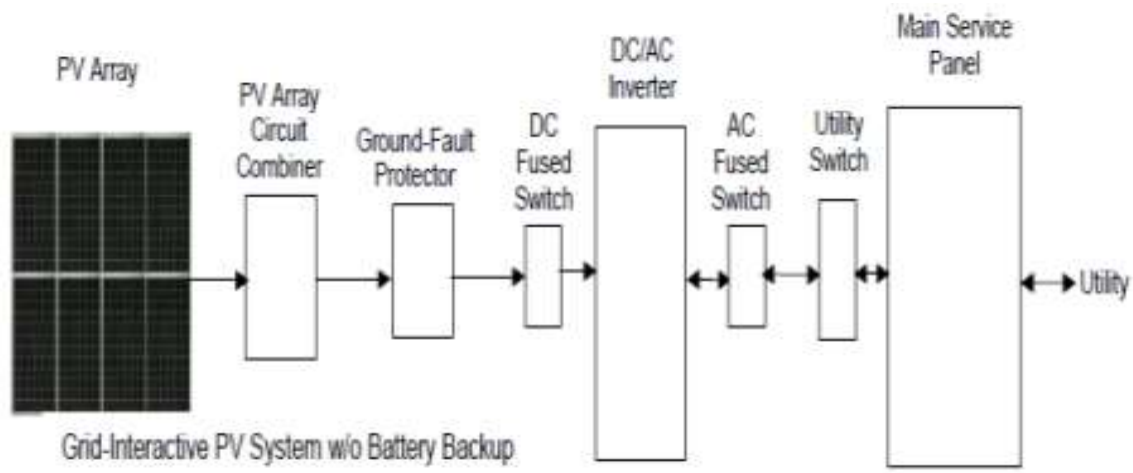

Figure 3: Diagram of a Grid-Connected without Battery Back-up System [23]

Grid-Connected Systems with Battery Back-Up

When there is a power outage, this kind of system uses an energy storage battery to keep vital load circuits running. The device turns off the utility and powers a designated circuit during an outage. The PV array can help the battery supply the critical loads in the event of a daytime power outage. The battery powers the load if the outage happens at night.

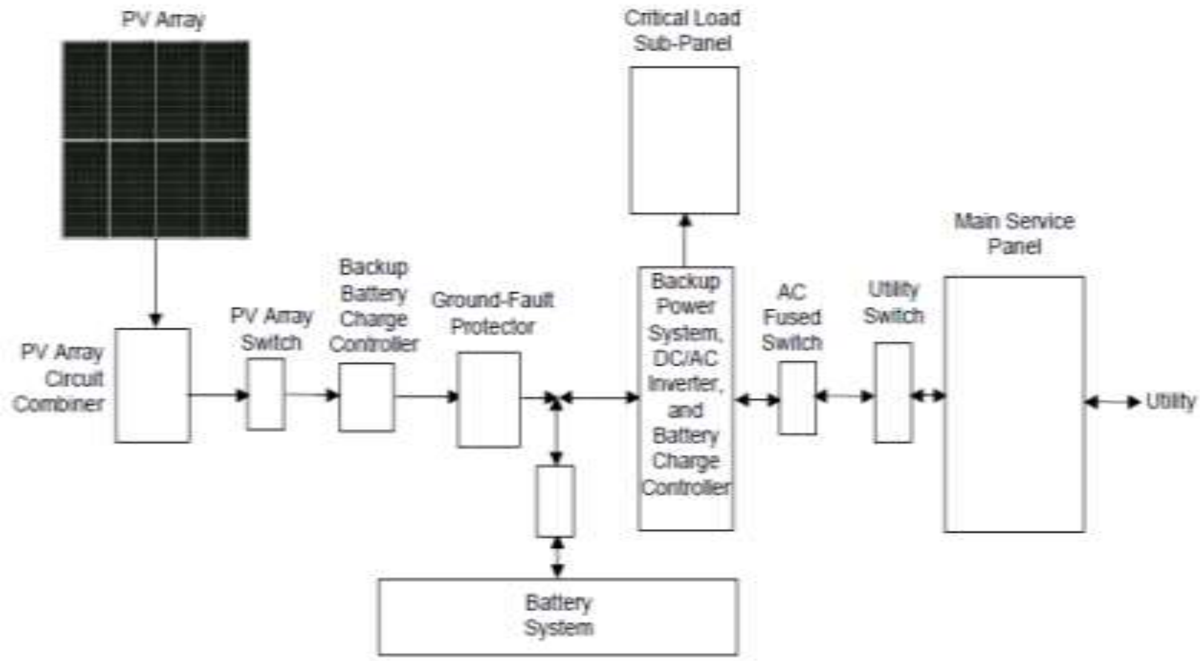

Figure 4: Diagram of a Grid-Connected with Battery Back-up System [23]

Stand Alone Solar Power Systems

These solar power units are isolated from the utility grid. They are constructed from a solar array, switches, batteries, and an inverter. PV radiation energy is converted to DC by an inverter, which then passes the energy from the batteries to the batteries. The base station receives power from the inverter. This is the type in this research project that is powering off grid telecom tower in rural areas. Inverter is used to power AC load available at the site like, Air conditioners, lighting etc while the output power from batteries is directly connected to telecom tower equipment's that use DC power.

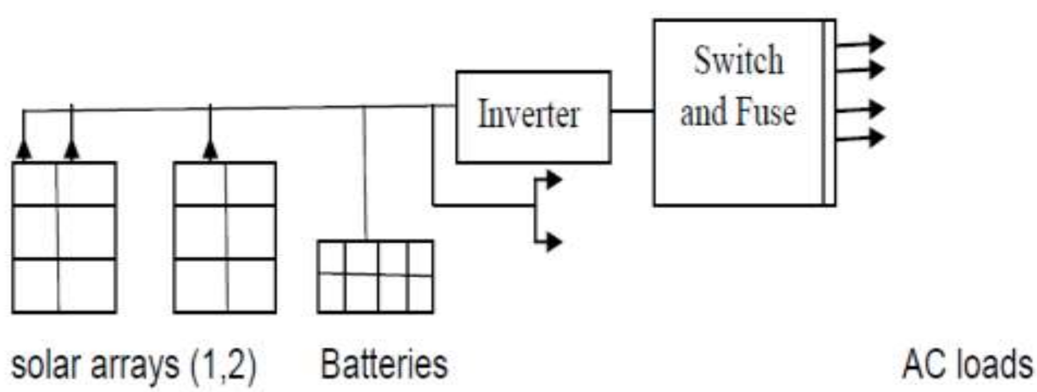

Figure 5. Diagram of a Stand-Alone Solar Power System [23]

2.6 Solar Powered telecom base station

A base station, as used in radio communication, is a wireless communication station that is fixed and utilized as a component of a wireless telephone system, such as a GSM or CDMA cell site. These base stations consist of an electronics house located at the base of the tower and multiple antennas affixed to a metallic tower. In developing nations, a large population resides in rural areas with little access to the electrical grid. The fact that mobile phone base stations depend on a reliable power source creates a major obstacle to increasing network coverage in these locations. The cost and instability of the power supply can exist even in grid connected areas. Diesel generators are costly to operate, require frequent maintenance, and pollute the air when they power base stations. Deeper penetration of mobile networks is made possible by operators being able to lower their operating costs by using solar power to power the base stations.

The telecom industry has become more interested in using solar technology to power cellular base stations in recent years. More remote cellular base stations typically use solar power, especially in developing nations where base stations are frequently off grid and dependent on their own power sources. In these isolated off grid locations, solar energy presents a competitive alternative to diesel generators [22].

Figure 6: Telecom tower powered by solar PV energy.

2.7 Feasibility and Integration of solar energy in telecommunication sector

It is becoming more and more common practice to integrate solar energy into the telecommunications industry. The telecommunications sector can reap numerous advantages from solar power, such as reduced expenses, enhanced dependability, and ecological sustainability. The following are important factors to think about when evaluating the viability and integration of solar energy in the telecommunications industry:

Remote Site Powering, Remote locations that are not connected to the grid, like cell towers, are a common component of telecommunication infrastructure. For these isolated locations, solar power combined with energy storage devices, such as batteries, can offer a dependable and independent power source.

Reduced Operational Costs, because solar energy can replace or even eliminate the need for grid power or diesel generators, it can drastically lower operating costs. For off-grid and rural telecommunication installations, this is especially advantageous.

Environmental Sustainability, one clean, renewable energy source that helps maintain environmental sustainability and lower carbon emissions is solar power. To meet their CSR objectives, telecommunications companies are embracing green energy practices more and more. [23]

Hybrid Systems, Solar energy is combined with other power sources, like diesel generators or grid power, in hybrid power systems. This guarantees a steady supply of electricity, even at night or during times when the sun isn't shining as much. Use of the energy sources that are available can be optimized by intelligent energy management systems.

2.8 Energy Storage Solutions in telecommunication sector

When solar panels are combined with energy storage devices, like batteries, more energy produced during sunny days can be stored for use during times when solar radiation is low or energy consumption is high. This contributes to a steady and continuous power supply.

Customized Solutions: solar solutions can be tailored to meet the unique energy needs of telecom equipment at various locations. It is possible to customize battery capacity and solar installation size to match the requirements of every site.

Reduced Dependency on Grid Power, particularly in areas with inadequate or unstable grid infrastructure, solar power can lessen the reliance of communications infrastructure on grid power. This strengthens the telecom network's resilience.

Government Incentives, Governments provide tax breaks, subsidies, or other incentives to encourage the use of renewable energy sources, such as solar energy. This may increase the viability of incorporating solar energy into the telecommunications industry from an economic standpoint.

Technological Advances, the viability of solar integration in the telecommunications industry is growing due to ongoing advancements in solar technology, such as cost and efficiency reductions.

2.9 Options based on renewable energy to meet telecom towers' electricity needs.

The telecom industry's need for electricity is constantly rising, and because of the grid's unreliability, there is an increasing reliance on alternative energy sources, primarily distributed generation. Utilizing renewable energy sources makes a lot of sense given the growing energy needs of telecom towers and the significance of decarbonizing the power source for them. Other environmental regulations, in addition to those governing the frequency of electromagnetic radiation emissions, aim to reduce carbon emissions by establishing targets, limiting the use of distributed generators in urban areas, mandating the purchase of renewable energy, outlawing the use of diesel in some environmentally sensitive areas, requiring telecom tower operators to disclose their carbon footprints, star labeling equipment used in telecom towers, and so on. Such regulations also promote the adoption of low-carbon power supply options. Recent technological advancements in solar, wind, biomass energy-based options, and storage technologies are encouraging the penetration of renewable energy-based powering solutions in the telecom sector. Because renewable energy sources are widely available worldwide and have minimal to no operating costs, they have been the go-to option for supplying telecom towers with electricity [15].

2.10 Solar Energy Reliability in Remote Locations

Telecom companies are beginning to accept solar energy as a dependable electrical source. Solar energy is a financially viable option in remote areas that are either off-grid, have an unstable grid, or struggle with high diesel consumption to run Diesel Genset to supply dependable power to distant telecom infrastructure, such as repeater stations, towers, Base Transceiver Station equipment, etc. A battery-powered system can reduce expensive electricity costs and offer a reliable supply of electricity all day long. In remote areas without a grid or in areas where the grid is unstable, solar energy dramatically lowers diesel consumption. It lowers the cost of maintaining DG sets and prevents you from relying solely on them for power generation. It lowers the cost of delivering diesel to the BTS location. It contributes to a decrease in both noise pollution and greenhouse gas emissions. It also expands the companies' operational reach [22].

2.11 A hybrid energy system on telecom tower

A hybrid energy system is one that uses two or more renewable energy sources, as well as non-renewable energy sources, as its primary energy generation sources. This allows for the replacement of any power shortages from one source with other readily available sources, ensuring the supply of sustainable power. It is a suitable way to supply electricity from locally accessible energy sources in places where grid extension would require a significant investment, such as remote locations where it would be difficult and expensive to transmit electricity from a centralized utility. A solution to the issue of the electrical power supply's dependability and affordability can be found by combining a conventional diesel generator with an unconventional energy source [24]

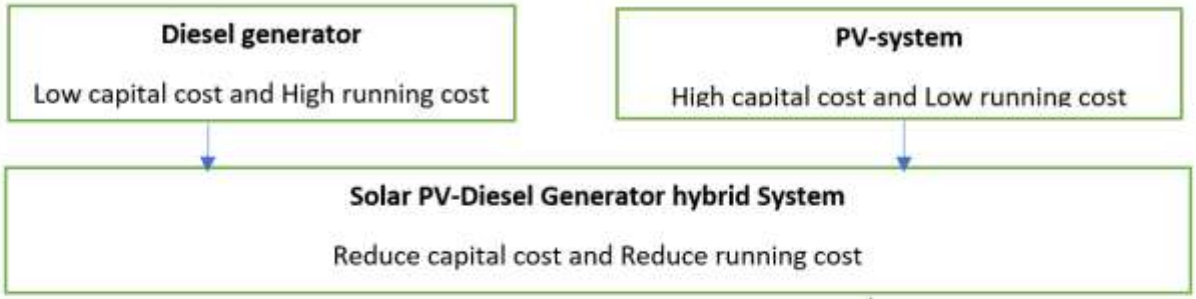

Figure 7: Comparison of Hybrid systems with stand-alone systems

2.11.1 Advantages of using Hybrid Solar PV-Diesel generator

There are different advantages of using hybrid solar PV-diesel generator and here below are some, when implemented:

- Diesel generator fuel usage and greenhouse gas reduction
- Resourceful use of locally available resources
- Deducts/avoids power shortfalls, increases sustainability power supply.
- It provides electricity access in short periods than waiting for grid extension and ease to scale-up at any time.
- Hybrid standalone systems have power control flexibility and merits of environmental protection than diesel generator alone.

Hybrid systems can expand their capacity when load demand is getting higher in the future, from renewable systems, diesel generator rated power or both.

2.11.2 Classification of Hybrid Configuration

The following technical topologies serve as the foundation for the hybrid power systems' design, which aims to meet the necessary energy demand while utilizing the available renewable sources. There are various configuration options available, with voltage and load demand serving as the key determinants. Configurations are categorized into the following forms based on power system configurations: Centralized AC-coupled hybrid system, DC-coupled configuration systems, and AC-coupled hybrid power systems [25]

Due to the issues raised by the production of diesel power, such as the impact of carbon dioxide particulates on the climate, environmental protection has become a top priority. As a result, calls have been made to implement environmentally friendly green energy solutions. A hybrid energy system is one that combines two or more electrical energy sources. The various hybrid power systems that are available are listed below:

Photovoltaic-Battery-Diesel Systems: The main electrical power source in these systems is solar photovoltaic. If the PV power is insufficient to power the load and charge the batteries, the battery bank provides the necessary power to operate the tower. If the battery depth of discharge is reached, or if the battery's exit voltage is set by the designer, the design generator kicks in and supplies power as needed. These systems are the ones under investigation and are utilized in areas with inadequate grid coverage.

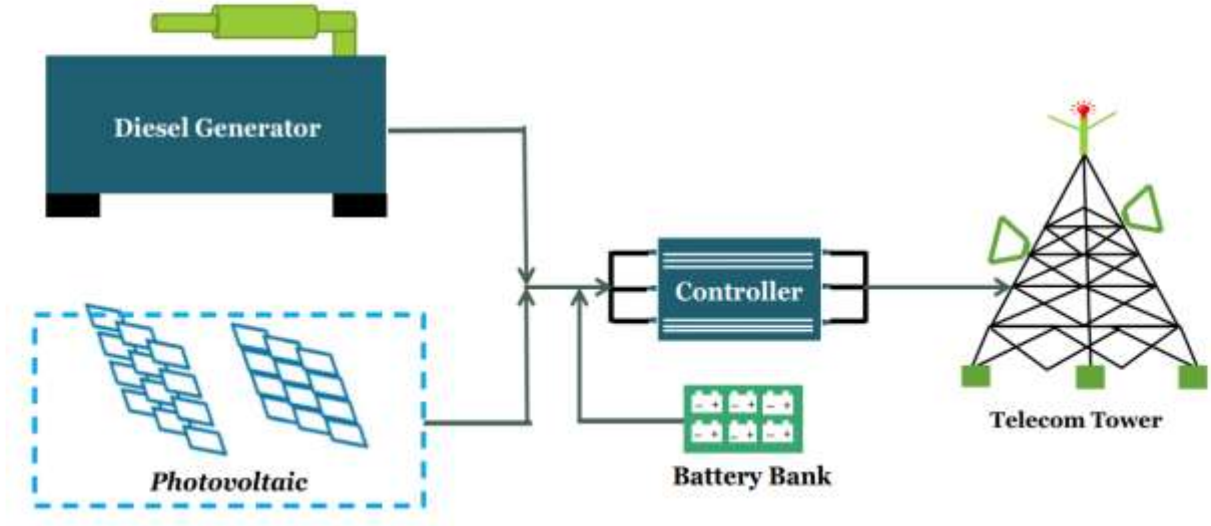

Figure 8: An illustration of how a power supply setup using photovoltaic, distributed generation, and battery storage [15]

Wind-diesel Hybrid Systems One difficult to implement renewable power source for remote locations without access to the grid is wind energy. While the diesel generator ensures a consistent supply of electrical power, the use of wind energy sources reduces the need for diesel fuel. An energy producing wind turbine can be installed in an area with a good wind resource at a reasonable cost.

Photovoltaic-Grid-Battery-Diesel Hybrid Systems: To supply electricity to the load, this system primarily consists of four parts: PV, grid, diesel, and battery. The SPV system in these systems supplies the necessary power. If the SPV system is not available, the grid supplies the power; if the grid is not available, the supply comes from the battery; and if the battery limits are reached, the required power is supplied by DG. The cheapest source of electricity is the grid.

Photovoltaic-Battery-LPG Hybrid Systems In standalone remote applications, this LPG system (full-time LPG generator) is also employed. It is powered by a portable LPG engine. Because LPG is easy to purchase, store, and transport, and it emits significantly less pollution than gasoline or diesel, it is a wise choice. Systems like these are employed in low power applications. Here, a portable engine powered by LPG is used in place of DG. Additionally, the SPV serves as the primary power source. If SPV power is scarce, batteries step in to supply power. When the battery bank reaches its exit voltage, an LPG-powered engine powers the load [18]

2.12Telecom site resources with Source of solar energy

Completing a site study is a crucial step in designing the best power supply system for a BTS. Estimating the energy resources at the site under consideration for the project in question is part of the site study process. The climate and topography of a site affect the energy resources that are available there. The study prioritized the utilization of natural site resources over auxiliary energy resources, specifically diesel fuel. Solar energy is the primary site resource for the micro BTS, as previously stated. The following subsections include details on the solar energy resources that are available at the locations that are under consideration.

To precisely size and optimize its components, a power supply solution utilizing one or more renewable energy sources needs meteorological data. Typically, this data is derived from historical records for the location under consideration. Alternatively, it may be predicted using high-precision estimations or experimental measurements [26]. based on literary works [26]The chronological approach and the stochastic approach are the two ways to estimate the meteorological data for a site. The chronological approach is a popular and simple data collection technique. It entails gathering data through computations or information from online sources. This method's drawback is that it can't be used to precisely forecast future data.

2.13 Potential of Solar Energy in Rwanda

Rwanda is a tiny nation in East Africa that lies slightly below the equator in Sub-Saharan Africa. As of March 2018, its population was 12,089,72 [27] population on 26,338 square kilometers of land. The land makes up 94.7% of the total surface, with the remaining 5.3% being occupied by water [28]. Geographically, it is bounded by longitudes 28.860 and 30.900°E and latitudes 1.050 and 2.840°S. [29] The two annual rainy seasons that Rwanda typically experiences provide water for the numerous river systems throughout the nation. Solar radiation and solar resources in Rwanda have been measured by the University of Rwanda and the US National Aeronautics and Space Agency (NASA). The report states that Rwanda's Eastern Province has the most potential for solar energy-based electricity production. Research carried out in cooperation with the MININFRA Department of Meteorology indicates that the approximate mean monthly solar irradiance, which is largely unexploited, ranges from 4.3 to 5.2 kWh per square meter per day throughout the entirety of Rwanda. Based on research done in Rwanda for the estimation of global solar radiation, the data gathered indicated that the maximum value of global solar radiation (RG = 5721/ m^2 /day, RG = 5738 Wh/m^2 /day) occurs in May, while the minimum value (RG = 4942 Wh/m2 /day, RG = 4960 Wh/m^2 /day) arises in May for the Kigali station [30]

2.14 Electrical load for a BTS site

The load experienced by a BTS site is contingent upon its geographical location and the time of day. Typically, base station transceiver equipment, base station RBS, microwaves, loads for lighting, and air conditioning for cooling make up the BTS site load [31]Based on the amount of usage, the load for this particular site which is situated in a remote area without grid power is split into three categories: small hour load, medium hour load, and occupied or busy hour load. [32]A radio antenna, a transmission antenna, and a module that serves as a transmitter and receiver to provide services to a mobile station or a mobile phone are some of the components that make up the BTS tower. Rectifiers are required when using AC voltage from the utility grid because BTS devices have direct current voltage characteristics.

2.15 Operation and Control strategies of solar/DG hybrid system

Prioritizing the order in which the various energy sources meet the load demand is crucial for any hybrid energy system to function more effectively. The system designer must specify and indicate this choice. Following the complete utilization of the freely accessible renewable energy resources, the stored energy (i.e., battery bank) is used through the operation and control strategies.

Since the primary goal of a hybrid system is to provide a continuous and stable power supply at the lowest possible cost, prioritizing energy supply sources has the advantage of ensuring effective energy flow management. The control strategy for this study considers the battery bank as an energy supplement, solar PV power output as the primary energy source for the BTS load, and diesel generator power as a backup power source [33].

2.15.1Dispatch strategies of Solar/DG hybrid system

The battery bank and the chosen diesel generator are managed by a set of rules that make up the dispatch strategy. The following describes the two dispatch strategies that are available:

2.14.1.1 Load following strategy.

The only energy sources that can charge the battery bank in this load-following dispatch strategy are renewable ones; generators cannot do this. To keep the cost of battery charging at zero, the battery bank is charged with excess electricity [33].

As a result, anytime the difference between the energy output of the renewable sources and the load demand at a specific time t (hours) is greater than zero, the battery bank is charged until it reaches its maximum state of charge. The continuous energy produced when the battery reaches its maximum state of charge is referred to as an excess load. On the other hand, if the net difference between the energy from the renewable energy source and the load is less than zero, the stored energy in the battery is discharged until it reaches a minimum state of charge or its exit voltage, as determined by the system design, in order to protect batteries from damage. When the battery runs out of power or reaches the exit set voltage level, the diesel generator starts up automatically to serve the load directly [33].

2.14.1.2 Cycle charging strategy.

This kind of cycle charge considers charging the battery with a diesel generator. To generate excess electricity that can be stored in the battery bank, the diesel generator must run at full capacity when using the cycle charge strategy. Because of the high load caused by this, it uses more fuel, which suggests that charging the batteries will cost more than it would in the load-following scenario [33].

2.15 Related works

Other researchers have attempted to work on related projects from this study, "Designing a Hybrid PV -diesel generator Energy System for Powering Off Grid Telecom Tower That Is Located in Rural Area," some of which are listed below:

Dr. Vincent A. Ani" ENERGY OPTIMIZATION AT GSM BASE STATION SITES LOCATED IN RURAL AREAS "The increasing number of mobile base transceiver station locations in Nigeria necessitates addressing the sites' power supply. Sustainability and reducing the negative environmental effects of producing power solely with diesel are very important. The thesis looks at the best way to size, control, and design a hybrid power system to take the place of the site's existing diesel-only option. For improved performance and to avoid the multiple energy conversion that an AC system experiences, the system is sized as DC [34]

Olubayo Moses Babatunde, Damilola Elizabeth Babatunde, Augustine Omoniyi Ayeni, Toyosi Beatrice Adedoja & Oluwas eye Samson Adedoja" TECHNO-ECONOMIC ASSESSMENT OF PHOTOVOLTAIC-DIESEL GENERATOR-BATTERY ENERGY SYSTEM FOR BASE TRANSCEIVER STATIONS LOADS IN NIGERIA “Base transceiver stations are in high demand due to the growing number of mobile users, especially in rural and semi-urban areas. These BTS are linked to the current grid supply and run-on diesel generators. But in most of the isolated places, the grid supply is sporadically available. As a result, diesel generators, which produce a lot of emissions, are mostly used to supply BTS continuously. A hybrid power system based on renewable energy is suggested to meet BTS requirements considering the issues. For remote BTS applications, a hybrid model based on a solar photovoltaic (SPV)/battery/diesel generator set is presented in this work [35].

G. Najafi, B. Ghobadi an, R. Mamat, T. Yusaf, and W. H. Azmi, “Solar energy in Iran: Current “Operators of cellular networks are constantly looking to expand the reach of their networks, enter new markets, and offer services to prospective clients in isolated rural areas. Cellular network operators face significant obstacles due to rising energy consumption, operator energy costs, the possible environmental effects of rising greenhouse gas emissions, and the depletion of non-renewable energy sources (fossil fuel). Utilizing the advancements in renewable energy technology, rural base stations can meet their specific power supply needs, which include affordability, efficiency, sustainability, and dependability. With a hybrid power system that combines solar photovoltaic and diesel generators, this study explores the possibility of reducing both OPEX and greenhouse gas emissions for rural business establishments while ensuring sustainability and dependability. To obtain the ideal model for the BS sites, the systems were simulated using HOMER. Findings indicate that the solar/DG/Battery and the solar/wind/DG/Battery offer the best options for meeting needs [36].

2.16 Literature gap

Many studies on the application of renewable energy sources have been conducted in various nations, such as Rwanda; however, very few have been conducted in the telecommunications industry. Most rural telecom sites are powered by battery-operated generators, which results in high fuel costs for telecom service providers and environmental pollution from atmospheric gas emissions. Due to the high diesel consumption rate of telecommunication sites, which raises the cost of generator maintenance and operation, this study integrates solar photovoltaic systems on hybrid generator sites to address the issues listed above, such as fuel emissions during generator use that harm the environment, the lack of telecommuting services in rural areas due to various generator issues and their unavailability, and power supply instability. In rural areas, telecom operators primarily rely on battery and standby generators; therefore, they need to find alternative, more affordable, and sustainable energy sources. In the telecommunications sector, my project focuses on hybrid solar PV-diesel generator energy systems for rural telecom towers in Rwanda. Due to its availability, solar energy was selected as a renewable source for this investigation.

CHAPTER III: METHODOLOGY

3.1 Introduction

The following explains the principles of integrating a hybrid energy system that use solar PV energy and generator with batteries bank on the telecom site or designing a hybrid solar PV-diesel generator energy system for an off-grid rural telecom site (Kayumbu). This section tries to provide an overview of the strategy and steps used to achieve the desired system with precise results. It is a system of guidelines that directs all structured research and is used to choose and plan studies.

3.2 Design method

By visiting various websites online, electronic sources were taken into consideration for this research project. One helpful resource for information gathering in this research project was the internet. My attempt to obtain access to various publications and e-books via electronic sources helped to refine my concept for this research project. I also used the department library's books, papers, lecture notes, internet searches, and data gathering from several BTS websites, such as KAYUMBU. To enhance the quantitative analyses and acquire sufficient understanding of the circumstances necessary to develop solar energy on BTS sites in remote areas of Rwanda, I conducted a variety of interviews. I managed to visit different Base Station sites to analyze solar insulation, power consumption, generator running hours that correspond to fuel consumption, site total loads (Kw). All enumerated sources of data helped in doing the design. The steps that have been taken to finish the design are listed below, as PV system design is the process of figuring out the size of each component of a photovoltaic power system to meet the load requirements.

Step 1- Site survey or site inspection and power consumption recording

Step 2-Load requirements determination

Step 3- sizing of PV module

Step 4-Sizing of charge controller

Step 5- Sizing of battery bank

Step 6 -Sizing of inverter

step 7- Cable sizing

step 8- Evaluation of the cost

3.3 Electronic sources

By accessing websites, electronic sources were used in this study. The internet proved to be a useful tool in obtaining the information required. I was able to access a variety of journals and online books, technological resources, which significantly enhanced the ideas I had for this study of designing a hybrid solar PV-diesel energy system for Kayumbu off grid telecom site.

3.4. Research Steps

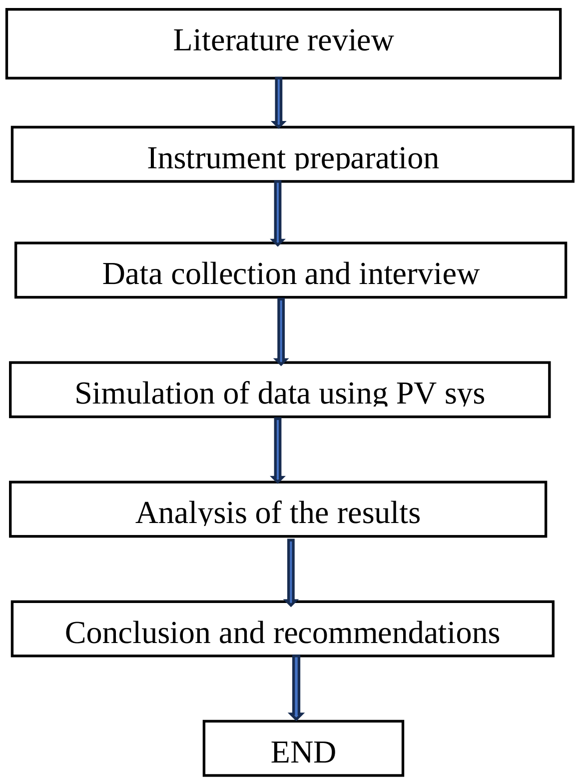

Figure 9: research steps

The benefits of employing a hybrid PV energy system of a solar and generator arrangement with battery bank as an off-grid renewable energy source for Kayumbu telecom site is examined in this study. With the use of PV Syst as a modeling tool, the anticipated cost of PV energy for the BTS was determined. The quantity of PV modules, battery storage capacity, and inverters needed for the BTS power design and other considerations.

3.5 Data collection

Data collection tools are devices that are used to gather various types of data, like a paper questionnaire filled out during a site visit, a personal computer or laptop, or conversations with telecom site field engineers. A variety of approaches were used to collect the data, including questionnaires, field operation observation, checklists, and conversations with site engineers.

The information gathered includes the total load (kW) on the site, the generator's KVA, the amount of fuel used daily by the generator, and various telecom devices. The equipment of two customers (MTN and Airtel) and lighting are the sources of the power consumption at the KAYUMBU site.

No	Question	Answers
1	At the Base Transceiver Station site, what is the load?	In any mobile network, a fixed radio transceiver is called a base transceiver station. Mobile devices are connected to the communication network via the BTS. Its responsibilities include digital signal conversion, network-based signal routing to other network terminals or the Internet, and radio signal transmission and reception to mobile devices
2	What is the load at Base Transceiver Station site?	The total power used by all the telecom site's equipment. The location of the site determines the BTS site's load (urban or rural). The reason for the higher load on an automatically urban site is that it has more traffic (i.e., users connected to it) than a rural site, which has less traffic because of fewer users. We have three loads at the Kayumbu site as examples for our study (MTN tenant, Airtel tenant, and lighting).
3	What components make up a Base Transceiver Station site?	The base transceiver station is composed of various components such as the antenna and tower, sectorial antennas, microwaves, waveguide cables, rectifier, generator, radio base station, duplexers, data distribution frame rack, transceiver unit, trucking, TX cabinet, and shelter. The transmission radio, radar, grid system, cooling system, batteries, generators, lighting fixtures, aviation lights, and rectifier are the BTS components for the generation and use of electrical power.
4	What are the primary obstacles facing telecom providers in rural areas?	High Fuel consumption cost when there is usage of generator only and it is due to fuel cost fluctuation, fuel transportation cost, High maintenance cost and network outage due to the generator failure due to different causes.

5	What is the monthly cost and average generator fuel consumption?	Fuel usage is influenced by the site's load and the number of hours the generator runs each day. Fuel consumption varies based on load, but it averages 3.5 liters per hour. The monthly fuel consumption determines the cost, which is determined by the cost of fuel in Rwanda
6	What is the Kayumbu generator's KVA and why was it chosen?	Generator KVA, at Kayumbu is 20KVA, it was selected based on the load estimation of this site
7	What are the obstacles to using renewable energy sources, such as wind and solar power, in Rwanda's telecommunications industry?	It is not reliable. It has high initial cost It occupies a lot of space. From the market DC equipment's are expensive. It is also not applicable for all sites.
8	What are the difficulties in applying solar photovoltaic energy in the telecom industry?	It has a high implementation cost. It is Weather-dependent. Although solar energy can be collected on cloudy or rainy days, the efficiency of the solar system decreases. Solar energy storage is costly. Big space.
9	What benefits do PV systems offer the telecommunications industry?	Pure and quiet electri3city is produced by the sun. Because photovoltaic systems run exclusively on sunshine, they do not deplete natural resources, release harmful air or water pollution, or pose a health risk to humans or animals. Photovoltaic systems are silent and do not obtrude visually. It also requires little upkeep and operation. The network managers have access to their own power supply.

Table 1: Different questions asked during site visit.

The power consumption at Kayumbu telecom site is given in table 2.
Static Generator size: 20KVA
Rectifier Module Quantity :18
Rectifier Battery Type: GEL BATTERY
Rectifier Battery Quantity :18
DG running hour per day:18hours.
Fuel consumption per day:63 liters/day

Figure 10: Kayumbu telecom site

Figure 11: The diesel generator model at Kayumbu site

HOURS	MTN equipment's(W)	AIRTEL equipment's(W)	LIGHTING	TOTAL(W)
00-01	1355.34	2014.89	25	3395.23
01-02	1252.28	1973.44	25	3250.72
02-03	1176.78	2023.64	25	3225.42
03-04	1288.21	1966.08	25	3279.29
04-05	1360.02	1989.91	25	3374.93
05-06	1423.4	2076.15	25	3524.55
06-07	1423.4	2148.37	0	3571.77
07-08	1502.38	2202.03	0	3704.41
08-09	1512.29	2073.47	0	3585.76
09-10	1624.05	2179.25	0	3803.3
10-11	1403.85	2223.86	0	3627.71
11-12	1592.39	2170.82	0	3763.21
12-13	1592.39	2363.71	0	3956.1
13-14	1693.14	2132.84	0	3825.98
14-15	1655.81	2108.55	0	3764.36
15-16	1708.06	2112.28	0	3820.34
16-17	1705.39	2275.82	0	3981.21
17-18	1638.82	2129.88	0	3768.7
18-19	1597.76	2222.16	25	3844.92
19-20	1597.0	2522.47	25	4145.23
20-21	1662.6	2274.79	25	3962.39
21-22	1662.32	2351.16	25	4038.48
22-23	1627.79	2073.8	25	3726.59
23-00	1249.79	2047.8	25	3322.59

Table 2: Hourly total load variation at KAYUMBU telecom site.

CHAPTER 4: DESIGN AND SIMULATION

This chapter presents the hybrid solar PV-diesel generator energy system design for Kayumbu telecom site. The hybrid solar PV-diesel generator energy system design requires detailed knowledge of the load behavior on the Kayumbu telecom tower. Table 2 shows the daily variation of power consumption. In addition, the design must put in place the functionality algorithm of the hybrid solar PV-diesel generator energy system to show the unit commitment for each individual generation unit. The hybrid system has PV and diesel with battery bank storage.

4.1 The total equipment's energy consumption

The total equipment's power is equal to 4145.23W and it is shown in table 2. The total solar PV panels energy required per day is equal to the total energy consumption per day times 1.3(loss factor of the system). Table 3 shows the total approximated energy, it is equal to 99197Wh/day. The energy consumption of the tower is based on different factors like available power equipment, traffic or number of users connected to the site etc. These calculated results are simulated using PV syst software. The amount of energy required from the solar PV system is equal to 128.9561kWh per day. It is calculated by using electrical energy formula (Energy is equals to Power times time). The selected system Voltage is 48 V DC.

No	Equipment Name	No	Power(W)	Running hours/day	Energy(wh/day)
1	MTN tenant equipment's	1	1598	24	38352
2	Airtel tenant equipment's	1	2522	24	60528
3	Lighting	1	25	12	300
4	Others				24
	TOTAL				99197

Table 3: Energy consumption per day at Kayumbu telecom site

4.2 Solar Photovoltaic component sizing

4.2.1 Solar Photovoltaic modules sizing

To find the size of solar PV module, the total watt-peak rating needed from the PV panels is calculated to operate the available load at the Kayumbu. The number of solar PV modules for the system is equal to the total watt-peak rating required to operate the tower equipment's divided by watt-peak of the PV module available.

$$\text{Number of PV modules} = 1 \text{ PV module} * \frac{\text{Watt–peak rating}}{\text{Rated output peak of the solar PV available}} \quad 4.1$$

$$\text{The watt peak rating required to operate the tower load} = \frac{\text{the total enery required}}{\text{Sunshine hours}} \quad 4.2$$

The watt peak rating required to operate Kayumbu tower load $= \frac{128.956\text{kWh}}{5\text{h}} = 25.791\text{kWp}$

The number of PV module required $= \frac{25791\text{W}}{500} = 51.1\text{panels}$

From the system design, there is a multiplier of the total energy required from the total PV modules, then the total number of PV required can be 50 PVs Panels of 500Wp.

ITEMS	Formulas	results
Number of solar PVs module	Total watt peak rating over the rated PV output power	50
Number of solar PVs in series	Voltage of the system(48V) divided by voltage of a Module(24V)	2
Number of solar PVs in Parallel	number of total PVs modules divided the number of PVs in series	25

Table 4: The total number of solar PV panels, series or parallel connected

4.2.2 Estimation of the Battery Bank

The Solar battery sizing is the one of the most important considerations based on the basic components required to implement the integration of hybrid solar PV-diesel generator energy at Kayumbu tower. The battery bank is sized, and the main objectives in sizing this battery bank is to get the energy that can handle the load coming from our PV panels array and to provide enough stored power our tower needs when there is no sunshine or when it a cloudy day. In system design the preferred battery bank capacity should be large enough so that it can store sufficient energy to operate the tower load needs at night or at cloud day.

$$\text{Size of battery} = \frac{\text{C}*\text{n}}{0.85*0.95*\text{Voltage of the system}} \qquad 4.3$$

0.85= battery loss

0.95=depth of discharge

System voltage=48V

C=battery bank capacity or energy required per day in wh

n=autonomy days

$$\text{The Battery size} = \frac{99197 * 3.5}{0.89 * 0.95 * 48} = 8514\text{AH}$$

The capacity of the selected battery is 52AH, Lithium Series 48V 2.4 kWh Technology Lithium-ion, LFP.

Items	Formulas	
NO. of total batteries	battery bank capacity over the capacity of the battery selected	165
NO. of batteries in series	Voltage of the system divided Voltage of the selected battery (48)	1
NO. of batteries in parallel	Total number of batteries divided by Total batteries in series	165

Table 5: Total number of batteries, parallel and series connected.

4.2.3 The Solar charge controller sizing

This charge controller is required to control the amount of energy that the solar panel array charges the batteries, prevent overcharging, and reverse current flow at night. This study project takes into account the most widely used charge controllers, which are Maximum Power Point Tracing (MPPT) and Pulse Width Modulation (PWM). When it comes to the series charge controller type, the controller's size is determined by the total PV input current that is supplied to it as well as by the arrangement of the PV panels: parallel or series arrangement. Another way to think of the charge controller is as the brains of the photovoltaic system. It makes it possible to safeguard and manage the battery bank. The charge controller in this study protects batteries from deep discharges and overloads while also enhancing the energy transfer from PV array to load. The PV SYST App selects or modifies the universal controller's operating parameters automatically based on the system's properties.

4.3 Generator-battery site configuration

From the generator -battery power topology configuration, the generator plays a role of primary source of power, the batteries storage is used as backup. Enumerated points are taken into consideration: to analyze the generator running hours per day, to analyze and calculate the fuel consumption per day and per month that impacts fuel cost in function of time.

4.3.1 Manual calculation of fuel consumption cost before hybrid solar PV-diesel generator integration

The analysis done at KAYUMBU off grid site, demonstrates that it uses the generator as primary source to power equipment's and batteries as backup. The data for generator running hours has been recorded in 1 day(24hours) as shown in table 6.

Start time	End time	Duration(hours)
10/25/2023 00:00	10/25/2023 2:15	2:15
10/25/2023 3:15	10/25/2023 5:15	2:15
10/25/2023 6:15	10/25/2023 8:15	2:15
10/25/2023 9:15	10/25/2023 11:15	2:15
10/25/2023 12:15	10/25/2023 14:15	2:15
10/25/2023 15:15	10/25/2023 17:15	2:15
10/25/2023 18:15	10/25/2023 20:15	2:15
10/25/2023 21:15	10/25/2023 23:15	2:15
Total generator running hours /day		18

Table 6: The generator running hours per day at Kayumbu site.

No	Items	
1	Generator fuel consumption	3.5 liters/hour
2	Generator running hours	18hours/day
3	The total fuel consumption per day equals to 18hours times 3.5liters/hour	63 liters/ day
4	The total fuel consumption year equals 63 liters per day times 365days	22,995 liters/year
5	The average cost for diesel fuel in Rwanda from 10-July-2023 to 16-October-2023	1,630.87 per liter
6	1Rwanda Franc equals	1.32USD/liter
	The total fuel cost before HSP diesel per year equals 1.32USD/liter times 22,995 liters/year	30,353.4USA /year

Table 7: Fuel consumption cost per year before Hybrid solar PV diesel integration

4.3.2 Manual calculation of fuel consumption cost after hybrid solar PV-diesel generator integration

After hybrid solar PV-diesel generator energy integration, the solar PV energy plays a role of the primary source of power. It supplies the load and charging batteries bank at the same time. During the night or when it is cloudy, the battery bank takes place and supplies the power to the load. When the battery bank reaches the exit voltage that is set at a certain battery voltage level, the controller system sends the command to the generator, and it starts running and supplying the power to the load. Table 8 provides Power supply availability of solar PV, batteries and diesel generator in normal conditions. Table 8 shows the working principle of this hybrid system in normal conditions, when there are no cloudy days.

Hours	**Solar status**	**Batteries status**	**Generator status**
06AM	ON	charging	OFF
07AM	ON	charging	OFF
08AM	ON	charging	OFF
09AM	ON	charging	OFF
10AM	ON	charging	OFF
11AM	ON	charging	OFF
12PM	ON	charging	OFF
01PM	ON	charging	OFF
02PM	ON	charging	OFF
03PM	ON	charging	OFF
04PM	ON	charging	OFF
05PM	ON	charging	OFF
06PM	OFF	Discharging	OFF
07PM	OFF	Discharging	OFF
08PM	OFF	Discharging	OFF
09PM	OFF	Discharging	OFF
10PM	OFF	Discharging	OFF
11PM	OFF	Discharging	OFF

00AM	OFF	Discharging	OFF
01AM	OFF	Discharging	OFF
02AM	OFF	Discharging	OFF
03AM	OFF	No Discharging, No charging	ON
04AM	OFF	No Discharging, No charging	ON
05AM	OFF	No Discharging, No charging	ON

Table 7: Solar, generator and batteries power supply status per day

No	Items	
1	The generator is supposed to run	3 hours / day
2	Fuel consumption after HSP-diesel DG integration =3 hours times 3.5 liters/hour	10.5liters/day
3	Total fuel consumption after HSP-diesel DG energy integration=10.5lites times 365 days	682.5liters/year
4	The total fuel cost after HSP-diesel DG integration=1.32USD/liter times 682.5 liters/year	900.9 USA / year
5	The fuel cost reduction per year=30,353.4USA-900.9 USA	29,452.5 USA / year
6	Rate of fuel cost reduction= (29,452.5 x 100)/ 30,353.4	97%

Table 8: Fuel consumption cost per year after Hybrid solar PV diesel integration

An integrated solar power system and a traditional diesel generator are combined in a hybrid solar PV-diesel generator, which solves issues with fuel flexibility, dependability, emissions reduction, efficiency, scale, and cost. Because the diesel generator only runs, when necessary, a hybrid fuel saver offers a practical least-cost supply option while also lowering fuel bills and maintenance expenses.

4.4 Modelling of hybrid solar PV- diesel generator system with battery

An off-grid hybrid solar PV, diesel, battery, and power system is being modeled and optimized for the Kayumbu telecom tower. The main goal is to create a stand-alone hybrid energy system with low excess power, low fuel costs, and low overall energy consumption to meet the required electric load.

4.4.1 Mathematical model of the hybrid solar PV-diesel generator energy system

4.4.1.1Solar Photovoltaic module Model

The output energy per hour of solar module is given by below expression:

$$EPV = \eta m * Aarr * Iarr \qquad 4.4$$

EPV: The output energy per hour of solar module

Aarr: The solar PV array area

ηm : Module efficiency

Iarr : Hourly solar irradiance incident per hour on PV array in kWh/m^2

The module efficiency is calculated by the following expression.

$$\eta m = \eta RT\left(1 - 0.9\alpha\frac{Iarr}{Iarr,NT}\right)(Tc,NT - TA,NT) - \alpha(TA - Tref) \quad 4.5$$

ηm= The module efficiency

ηRT= The PV module efficiency at reference cell temperature of 25°C

α : Temperature coefficient for solar cell efficiency (0.004-0.005/ °C)

$Iarr,NT$: Average hourly solar irradiance incident on the array at standard nominal operating temperature(45°C)

Tc,NT : Cell temperature at normal test condition

TA: Ambient temperature

TA,NT: Ambient temperature (20°C) at normal test conditions.

Iarr:Actual solar irradiance

Tref: reference cell temperature (°C)

4.4.1.2 Battery bank model

Output power of the solar PV array at a given time in hours(t) determines the charge power into the battery storage. It determines again the power discharge out of the battery storage. The state of charging of battery storage at any hours t, C(t) depends on the state of charging at the previous hour C(t-1)

Then from (t-1) up to (t): The state of charging is given by the following expression:

$$C(t) = C(t-1) + \eta charging(W3(t)) - \eta discharging(W4(t)) \quad 4.6$$

This gives the battery dynamics equation.

$$C(t) = C(0) + \eta charging\sum_{\tau=1}^{t} w3(\tau) - \eta discharging\sum_{\tau=1}^{t} w4(\tau) \quad 4.7$$

$C(0)$:The initial state of discharge of the battery

$\eta charging\sum_{\tau=1}^{t} w3(\tau)$: The acceptable power of the battery at time "t"

$\eta discharging\sum_{\tau=1}^{t} w4(\tau)$: The power discharge out by the battery at time "t"

The battery bank capacity cannot be less than the minimum acceptable capacity $Cmax$ and must not be greater than maximum acceptable capacity $Cmin$ this is expressed as follows.

$$Cmin \leq C(t) \leq Cmax$$

$$Cmin = (1 - DOD)Cmax \quad 4.8$$

DOD: Percentage depth of discharge of the battery bank

4.4.1.3 Diesel generator model

DGs are used as a backup in hybrid power supply systems and are typically needed to take over the load when the PV and battery are unable to do so. Usually, the DG's manufacturer advises using the least amount of diesel. A distributed generator's maximum efficiency is directly correlated with its rated power; hence, the DG must be operated within the range of its rated power and a minimum value that that is specified, as illustrated by the following constraint:

$$W1min \leq W1(t) \leq W1max$$

$W1,$ max is considered as the maximum power that can be produced by the generator in 1 hour.

$W1(t)$, is the output power from the diesel generator(kW)

$$W1 = W1n * \eta W1 \qquad 4.9$$

$W1n$: The nominal output power of a diesel generator

$\eta W1$: The coefficient describing the efficiency of diesel generator.

4.5 Optimization model for the hybrid system

The solar PV power plant satisfies the load demand. The battery discharges to meet the load requirements when the solar PV plant is insufficient to meet the demand. Batteries store energy until they are fully charged if the PV output is higher than the load. The diesel generator fills in the power gap if the solar PV and batteries are unable to meet the load demand, but it can be turned off once the loads are met by the solar PV plant or the batteries. Finding the hybrid system's ideal operating point to meet load demand while minimizing fuel costs is an economic challenge.

The objective function

$$\text{Minimize } Kf \sum_{t=1}^{N} (a\,W^2 1(t) + bW1(t)), \text{all } t = 1 \ldots N \text{ and } N = 24\text{hours} \qquad 4.10$$

Where Kf is the fuel price, a and b are fuel cost coefficients.

Subject to the following constraints:

$$\begin{cases} W2(t) + W3(t) \leq Wpv(t) & (1) \\ W1(t) + W2(t) + W4(t) = WL(t) & (2) \\ W1(t) \geq 0, W2(t) \geq 0, W3(t) \geq 0, W4(t) \geq 0 & (3) \end{cases}$$

$$Wimin \leq Wi(t) \leq Wimax$$

$$Cmin \leq C(0) + \eta charging \sum_{\tau=1}^{t} w3(\tau) - \eta disch \sum_{\tau=1}^{t} w4(\tau) \leq Cmax \qquad 4.11$$

W1(t), W2(t) and W4(t) are control variables which represents energy flows from the diesel generator, solar PV plant and the battery storage to the load at any time(t) respectively while W3(t) represents the energy flow to charge the battery during t=24hours period, WL represents the load demand and $Wpv(t)$ represents the power from PV panels.

According to the first constraint (1), the power used to directly supply the load from the solar Photovoltaic plant and charge the batteries is either the same or less than the installed capacity of the solar Photovoltaic. .

The diesel generator, photovoltaic array, and battery all supply enough power to meet the demand at the same hour, as shown by constraint (2).

The power available for charging, the power from the diesel generator, the power from the battery, and the power directly from the solar PV array to the load are all greater than zero, as shown by the third constraint (3).

The diesel generator is impacted by the dispatch strategy. The generator is turned on when the hourly PV output is less than the hourly load and the load cannot be met by the combined output of batteries and solar PV.

The quadprog solver in Matlab is used to simulate the nonlinear quadratic programming for the models mentioned above.

In this case study of the Muyumbu site, the solar PV system must provide =9000Wp to meet the site's maximum demand of 4145.23W and charge the batteries.

Ƞcharging: The battery charging efficiency (85%) and the battery discharging efficiency (Ƞdish=100%)

The fuel cost coefficients are given as a=3.465USD/hour and b=7.92USD/kWh

The fuel cost per liter is 1.32 USD /liter. By replacing the parameters in objective function by their corresponding values, the objective function becomes the generator running the 24hours of the day.

Minimize $1.32 * 24(3.465W^2 1(t) + 7.92W1(t)$ which is

Minimize $109.77W^2 1(t) + 250.9W1(t)$

Subject to the constraints:

$$\begin{cases} W2(t) + W3(t) \leq 9000 \\ W1(t) + w2(t) + W4(t) = 4145.23 \\ W1(t) \geq 0, W2(t) \geq 0, W3(t) \geq 0, w4(t) \geq 0 \end{cases}$$

$$Wimin \leq Wi(t) \leq Wimax$$

$$Cmin \leq 0.85 \sum_{\tau=1}^{t} w3(\tau) - \sum_{\tau=1}^{t} w4(\tau) \leq Cmax$$

For quadratic programming

$$\text{Minimize}\,\frac{1}{2}x^THx + f^T = 109.77W^21(t) + 250.9W1(t)$$

$$\frac{1}{2}x^THx = 109.772W^21(t)$$

$$x^THx = 219.54W^21(t)$$

$$f^T = 250.9W1(t)$$

$$\text{Minimize}\,\frac{1}{2}x^THx + f^T \begin{cases} Ax \le b \\ Aeq.x = beq \\ lb \le x \le ub \end{cases}$$

where H, A, and Aeq are matrices, and f, b, beq, lb, ub, and x are vectors.

$$\text{Minimize}\,\frac{1}{2}x^THx + f^T \begin{cases} W2(t) + W3(t) \le 9000 \\ W1(t) + w2(t) + W4(t) = 4145.23 \\ W1(t) \ge 0, W2(t) \ge 0, w3(t) \ge 0, w4(t) \ge 0 \end{cases}$$

$$\text{Wimin} \le \text{Wi}(t) \le \text{Wimax}$$

$$\text{Cmin} \le 0.85\sum_{\tau=1}^{t} w3(\tau) - \sum_{\tau=1}^{t} w4(\tau) \le \text{Cmax}$$

4.6 Design of solar PV-diesel design with PV syst software

While the site was using generators and batteries to power the BTS equipment, solar PV is to be integrated and is believed to be the primary source of energy. The hybrid energy system that is being studied consists of a diesel generator for electricity production and solar photovoltaic cells. In most cases, this kind of system consists of the balance of equipment (charge controller, batteries, converter) plus wiring and supporting structures. A screenshot of a layout from the PV SYST software is shown in Figure 11. According to the PV system design, the current from the diesel generator is fed into the AC bus, where a rectifier converts it to DC. It is then combined with other DC bus components to meet the load demand. The project lifetime is 25 years because that is the lifespan of the solar PV system.

4.6.1 Simulation using PV syst software.

The results from the PV system simulation software used to design an off-grid solar PV -diesel generator with battery storage.

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	181.3	155.7	3343	74.4	0.00	3075	3075	1.000
February	162.4	146.3	3131	361.4	0.00	2778	2778	1.000
March	175.0	167.0	3565	407.4	0.00	3075	3075	1.000
April	165.4	167.5	3554	496.6	0.00	2976	2976	1.000
May	167.4	177.8	3789	577.6	0.00	3075	3075	1.000
June	156.0	169.1	3624	488.2	0.00	2976	2976	1.000
July	166.4	179.3	3845	797.0	0.00	3075	3075	1.000
August	164.9	169.2	3626	378.7	0.00	3075	3075	1.000
September	160.3	156.4	3328	234.0	0.00	2976	2976	1.000
October	163.6	150.2	3229	77.6	0.00	3075	3075	1.000
November	165.0	142.8	3081	106.2	44.39	2932	2976	0.985
December	175.3	147.0	3165	0.0	0.00	3075	3075	1.000
Year	2002.9	1928.4	41279	3999.1	44.39	36162	36207	0.999

Legends

GlobHor Global horizontal irradiation
GlobEff Effective Global, corr. for IAM and shadings
E_Avail Available Solar Energy
EUnused Unused energy (battery full)
E_Miss Missing energy
E_User Energy supplied to the user
E_Load Energy need of the user (Load)
SolFrac Solar fraction (EUsed / ELoad)

Table 9: Global Horizontal Irradiation, Balances and main results

4.8 Working principal of solar PV/Diesel generator hybrid power system.

The hybrid system under consideration for this study consists of solar PV panels, a diesel generator, and battery backup. The system modeling and energy management strategy are covered in this section. The site currently runs on a generator and batteries; the study incorporates solar PV energy. After solar PV energy is integrated, solar energy serves as this site's primary power source. During the day, when solar power is supplying the load, batteries will be charged. The battery bank powers the load at night and during overcast days or seasons, acting as a backup power source. To avoid damaging the batteries, this system has an automation feature that will help send a signal or instruct the generator to start running at the preset voltage. The generator is configured to operate without needing to charge the batteries; solar PV energy will be used to power the batteries instead.

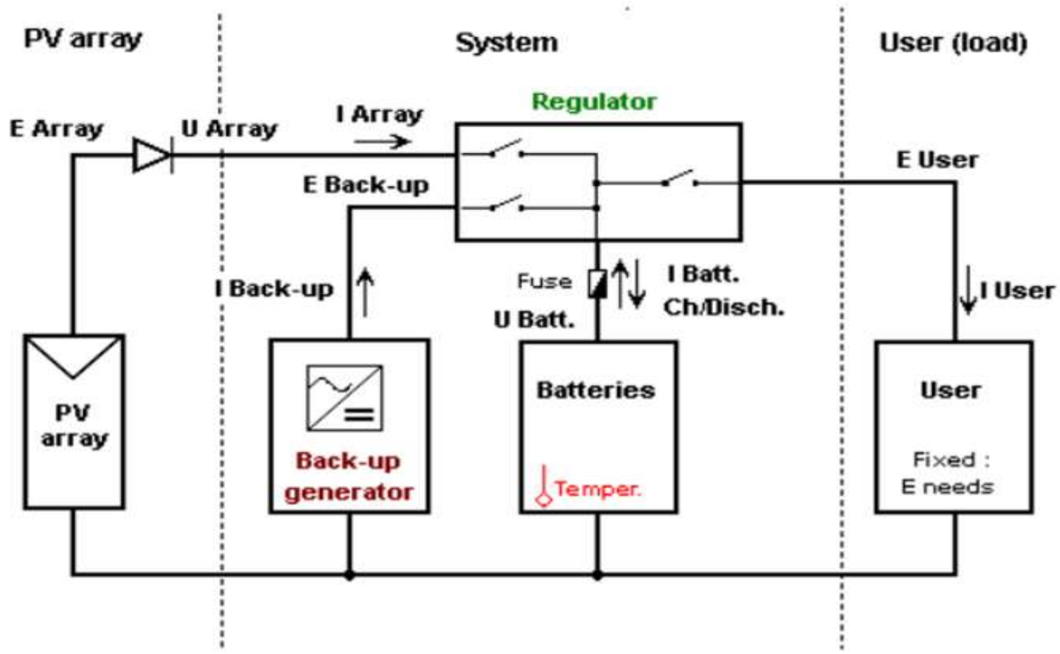

Figure 12: Typical layout of a stand-alone system

4.9 The system data specifications

Figure 12 displays the condensed technical data for the PV energy system equipment that was utilized. PV Syst software is used to design and calculate all used equipment.

PV module		**Battery**	
Manufacturer	Maysun Solar	Manufacturer	Turbo Energy
Model	MS-500-MB-50H-100cells	Model	Lithium Series 48V 2.4 kWh
(Original PVsyst database)		Technology	Lithium-ion, LFP
Unit Nom. Power	500 Wp	Nb. of units	165 in parallel
Number of PV modules	50 units	Discharging min. SOC	10.0 %
Nominal (STC)	25.00 kWp	Stored energy	359.0 kWh
Modules	25 Strings x 2 In series	**Battery Pack Characteristics**	
At operating cond. (50°C)		Voltage	48 V
Pmpp	22.88 kWp	Nominal Capacity	8514 Ah (C10)
U mpp	52 V	Temperature	Fixed 20 °C
I mpp	439 A		
Controller		**Battery Management control**	
Universal controller		Threshold commands as	SOC calculation
Technology	MPPT converter	Charging	SOC = 0.96 / 0.80
Temp coeff.	-5.0 mV/°C/Elem.	Discharging	SOC = 0.10 / 0.35
Converter			
Maxi and EURO efficiencies	97.0 / 95.0 %		
Total PV power			
Nominal (STC)	25 kWp		
Total	50 modules		
Module area	120 m²		

Figure 12: The condensed technical data for the PV energy system equipment

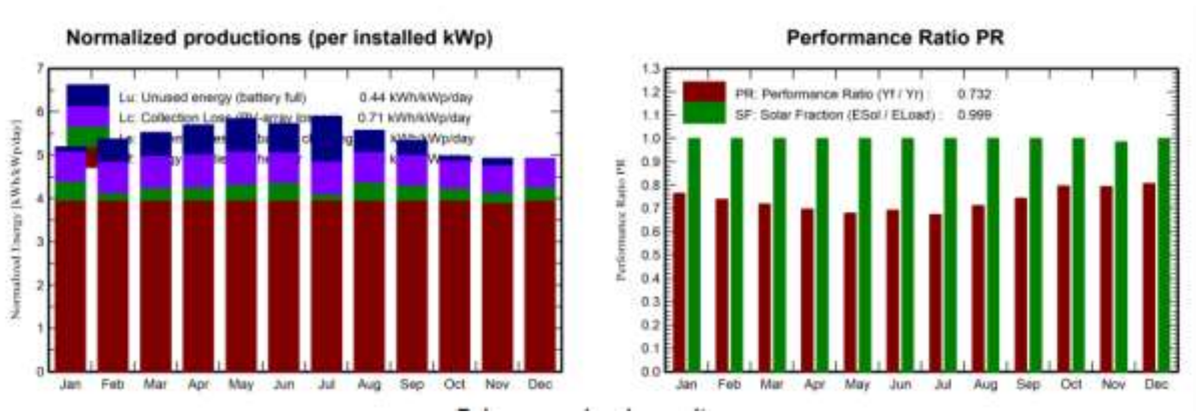

Figure 13: Normalized productions (per installed kWp and Performance ratio PR)

4.10 The cost of the system

Item	Quantity units	Cost USD	Total USD
PV modules			
MS-500-MB-50H-100cells	50	152.00	7,600.00
Supports for modules	50	13.48	674.00
Batteries	165	140.00	23,100.00
Controllers			213.00
Other components			
Accessories, fasteners	1	10.00	10.00
Wiring	1	50.00	50.00
Combiner box	1	2.00	2.00
Monitoring system, display screen	1	600.00	600.00
Surge arrester	1	100.00	100.00
Studies and analysis			
Engineering	1	1,000.00	1,000.00
Installation			
Global installation cost per module	50	5.00	250.00
Global installation cost per inverter	1	5.00	5.00
Global installation cost per battery	165	2.00	330.00
Transport	1	5,000.00	5,000.00
		Total	38,934.00
		Depreciable asset	31,597.00

Table 10: Installation costs

Item	Total USD/year
Maintenance	
Salaries	900.00
Repairs	200.00
Cleaning	50.00
Total (OPEX)	1,150.00

Table 11: Operating costs

System summary	
Total installation cost	38,934.00 USD
Operating costs	1,150.00 USD/year
Excess energy (battery full)	4.0 MWh/year
Used solar energy	36.2 MWh/year
Used energy cost	0.075 USD/kWh

Table12: system summary

4.11 Financial analysis

Simulation period

The project's start year is 2024, and its duration is 25 years. The PV syst software simulation's result after 12.2 years demonstrates that the project is profitable.

Financial analysis

Simulation period

Project lifetime 25 years Start year 2024

Income variation over time

Inflation	0.00 %/year
Production variation (aging)	0.00 %/year
Discount rate	0.00 %/year

Depreciable assets

Asset	Depreciation method	Depreciation period (years)	Salvage value (USD)	Depreciable (USD)
PV modules				
MS-500-MB-50H-100cells	Straight-line	25	0.00	7,600.00
Supports for modules	Straight-line	25	0.00	674.00
Batteries	Straight-line	25	0.00	23,100.00
Controllers	Straight-line	25	0.00	213.00
Accessories, fasteners	Straight-line	20	0.00	10.00
		Total	0.00	31,597.00

Financing

Own funds 38,934.00 USD

Electricity sale

Feed-in tariff 0.1200 USD/kWh

Return on investment

Payback period	12.2 years
Net present value (NPV)	40,803.48 USD
Internal rate of return (IRR)	6.50 %
Return on investment (ROI)	104.8 %

Table 13: Financial analysis

Financial analysis

Detailed economic results (USD)

Year	Electricity sale	Own funds	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amorti.
0	0	38,934	0	0	0	0	0	-38,934	0.0%
1	4,339	0	1,150	1,264	1,926	0	3,189	-35,745	8.2%
2	4,339	0	1,150	1,264	1,926	0	3,189	-32,555	16.4%
3	4,339	0	1,150	1,264	1,926	0	3,189	-29,366	24.6%
4	4,339	0	1,150	1,264	1,926	0	3,189	-26,176	32.8%
5	4,339	0	1,150	1,264	1,926	0	3,189	-22,987	41.0%
6	4,339	0	1,150	1,264	1,926	0	3,189	-19,797	49.2%
7	4,339	0	1,150	1,264	1,926	0	3,189	-16,608	57.3%
8	4,339	0	1,150	1,264	1,926	0	3,189	-13,418	65.5%
9	4,339	0	1,150	1,264	1,926	0	3,189	-10,229	73.7%
10	4,339	0	1,150	1,264	1,926	0	3,189	-7,039	81.9%
11	4,339	0	1,150	1,264	1,926	0	3,189	-3,850	90.1%
12	4,339	0	1,150	1,264	1,926	0	3,189	-660	98.3%
13	4,339	0	1,150	1,264	1,926	0	3,189	2,529	106.5%
14	4,339	0	1,150	1,264	1,926	0	3,189	5,719	114.7%
15	4,339	0	1,150	1,264	1,926	0	3,189	8,908	122.9%
16	4,339	0	1,150	1,264	1,926	0	3,189	12,098	131.1%
17	4,339	0	1,150	1,264	1,926	0	3,189	15,287	139.3%
18	4,339	0	1,150	1,264	1,926	0	3,189	18,477	147.5%
19	4,339	0	1,150	1,264	1,926	0	3,189	21,666	155.6%
20	4,339	0	1,150	1,264	1,926	0	3,189	24,856	163.8%
21	4,339	0	1,150	1,263	1,926	0	3,189	28,045	172.0%
22	4,339	0	1,150	1,263	1,926	0	3,189	31,235	180.2%
23	4,339	0	1,150	1,263	1,926	0	3,189	34,424	188.4%
24	4,339	0	1,150	1,263	1,926	0	3,189	37,614	196.6%
25	4,339	0	1,150	1,263	1,926	0	3,189	40,803	204.8%
Total	**108,487**	**38,934**	**28,750**	**31,597**	**48,140**	**0**	**79,737**	**40,803**	**204.8%**

Table 14: Detailed economic results (USD)

CHAPITER FIVE: RESULTS AND DISCUSSION

Hybrid solar Photovoltaic-diesel generator energy system is thought to be the best substitute option for supplying electricity to BTS sites in rural areas. Due to the high-cost of fuel consumption or fuel usage that resulted in high fuel costs paid by the telecom towers operators, the integration of hybrid solar PV-diesel generator energy system into the site that was using generator as the primary source of energy and batteries as backup has played a significant role in reduction of fuel cost paid per year by the telecommunication companies owners. Prior to the integration of hybrid solar PV-diesel energy system, the generator at the Kayumbu site ran for eighteen hours a day, or 6570 hours annually, using 22995 liters of fuel based on the amount of fuel used per hour. Prior to the integration of hybrid (solar/diesel generator), the annual fuel cost amounts to $30,353.4 USD. The total fuel cost after hybrid solar/diesel generator integration per year is equal to 1.32USD/liter times 682.5 liters/year= 900.9 USA per year.

$$\text{The fuel cost reduction per year} = 30353.4\text{USD} - 900.9\text{USD} = 29452.5 \text{ USD per year}$$

$$\text{Rate of fuel cost reduction} = \frac{29452.5 * 100}{30353.4} = 97\%$$

The fuel cost per year has been reduced by 97 % after integration of solar PV.

According to the study's output results, using solar PV energy for off-grid telecom sites is more economically feasible than relying solely on diesel generators.

From MATLAB simulation the minimum cost for the hybrid system battery, solar PV and diesel generator to meet load demand is val is $7.8227e^{-02}$ and this is USD 0.078227/liter

By considering the cost

Diesel generators are generally preferred by telecom tower service providers over solar PV because of the initial costs associated with system design, implementation, and installation. However, if investors take their time and consider potential revenue streams or expanses, they will decide to install a hybrid diesel generator/photovoltaic system to power telecom towers situated in remote, off-grid rural areas. According to PV sys software results, this project has a 25-year lifespan, and the payback period is 12.2 years.

About Pollution

The installation of a hybrid solar PV-diesel generator system not only helps to save fuel costs, but it also reduces the pollution of the environment. Utilizing hybrid solar PV-diesel generator energy system to power telecom towers rather than diesel generators lowers atmospheric emissions of greenhouse gases, such as carbon dioxide. Running diesel generators release greenhouse gases. When operate multiple diesel generators, they contribute to climate change and global warming. In this research the generator running hours per year have been reduced after integration of hybrid solar/diesel generator, and due to this reason, the quantity of pollutant gases emitted by running diesel generator long time have also been reduced.

CHAPTER 6. CONCLUSION AND RECOMMENDATION

6.1 conclusion

This study aims to design and simulate a hybrid solar PV-diesel generator energy system for an off-grid telecom location in a rural area (Kayumbu site). The study incorporates solar photovoltaic energy into the location where a diesel generator was previously used. The outcomes of the manual computation and the PV SYST software simulation clearly show that, in comparison to the current generator-with-batteries power topology, the integration of a hybrid solar PV-diesel generator energy system is advantageous for powering the BTS site. As the project will last for 25 years, and the payback period is12.2 years, it is discovered that the hybrid solar PV-diesel energy integration is profitable. The manual calculation method reduced the fuel cost by 97%, making this research project both financially and technically feasible. In order to connect with their potential customers, telecom mobile network operators in Rwanda require a dependable, economical, and environmentally sustainable power solution for off-grid BTS situated in rural areas. This study will assist them in deploying telecommunication infrastructures in remote locations where access to electricity is difficult. It has been demonstrated by this study that a hybrid power system with solar PV, DG, and battery is the best power option when compared to the current setup, which only used a diesel generator and battery bank.

6.2 Recommendation

Based on the findings from the simulation software PV SYST, I recommend that service providers of telecommunication towers to use a hybrid system of solar PV and diesel generator for powering base transceiver stations located in rural areas rather than diesel generators. I advise them to implement this hybrid system on all off-grid towers located in rural where grid is not available since it helps lower fuel transportation cost, generator fuel consumption costs, maintenance cost etc while also lowering the amount of pollutants gases released into the atmosphere.

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APPENDICES

Matlab programming codes using quadprog solver.

```
f= [2509e-1 0 0 0];
H= [21954e-2 0 0 0;0 0 0 0;0 0 0 0;0 0 0 0];
A= [0 1 1 0];
b= [9000];
Aeq =[1 1 0 1];
Beq =[4145.23];
Lb =[0 0 0 0];
ub=[inf inf inf inf];
[x,fval,exitflag,output]=quadprog(H,f,A,b,Aeq,beq,lb,ub)
```

SIMULATION RESULTS

```
x =

   1.0e+03 *

    0.00001

    2.0579

    0.0690

    2.0873

fval =

   7.8227e-02

exitflag =

     1

output =

           message: 'Minimum found that satisfies the constraints.…'

         algorithm: 'interior-point-convex'

     firstorderopt: 7.8227e-02

    constrviolation: 9.0949e-13

        iterations: 4

      cgiterations: []
```

From the above results it is clear that the minimum cost for the hybrid system battery, solar PV and diesel generator to meet load demand is val = 7.8227e-02 and this is USD 0.078227/litre