“OPTIMAL CONFIGURATION OF SOLAR PV AND BIOMASS-BASED HYBRID SYSTEM WITH BATTERY STORAGE FOR ELECTRIFICATION OF RURAL HEALTHCARE FACILITIES IN RWANDA”.

(CASE STUDY: NTARAMA HEALTH CENTER)

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Kigali-Rwanda

Declaration

I, David TUYIRAMYE do hereby declare the originality of this dissertation as my work and it has not been presented for any academic qualification in the University of Rwanda (UR-ACEESD) or any other university, and all sources of materials that have been used for this dissertation have been fully acknowledged.

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This dissertation is submitted for examination with my approval as a University of Rwanda advisor:

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Dedication

This dissertation is dedicated to:

- Almighty God for his unfailing plan and life grant
- My supervisors, lecturers, and classmates
- My beloved entire family, especially my one and only wife, my children Ryan & Aaron, my beloved sister and my father

Thank you all for your constant encouragement, motivation, and support throughout my academic journey

Acknowledgment

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“This accomplishment would not have been possible without you all”.

Abstract

Reliable electricity access is essential for rural development for enhanced healthcare, education, and economic growth. Expanding the Rwanda national grid is costly and difficult mainly due to geographical location, old network, fund constraints, and even regions with electricity face reliability issues. That is the main reason for this study "Optimal configuration of solar PV and biomass-based hybrid power system with battery storage" aims to extract the local renewable energy resources that remain underutilized at Ntarama Health Center, and to ensure its cost-effective energy production.

The current load profile of Ntarama H.C is 108.540 kWh/day, the time series energy consumption profile results in an annual growth rate of 11.3%, and the forecasted load within five years to accommodate future demand was found to be 185.38 kWh/day. Ntarama health center is located at W27P+CF8, Ntarama, Bugesera, Rwanda (2°5.2'S, 30°2.2'E), with annual averaged solar radiation and biomass potential of 5.04 kWh/m^2*/day and 0.74 ton/day respectively.*

HOMER Pro is used to carry out optimization, simulation, and sensitivity analysis, considering electrical load, climate data, and economic factors whereby maximum daily consumption is 185.38 kWh, and a peak load demand becomes 22.93 kW with a load factor of 0.34.

HOMER Pro provided optimal configuration basing on low total net present cost.

The Simulation revealed the optimal configuration which consists of 50kW photovoltaic array with 88.9% energy contribution, 21 kW biogas generator with 11.1% energy contribution, two strings of 67 batteries each with 451.75 kWh, and 30 kW system converter with HOMER Cycle Charging dispatch strategy. The total Net Present Cost (NPC) is $170,587.90, whereas the Levelized Cost of Energy (LCOE) is $0.194.

The system meets all load demands, without capacity shortage with only an annual electricity surplus of approximately 2,795 kWh (3.37 %) with an annual saving of 446,582.4 Rwf over the national grid, and the initial investment will be recovered within 7.10 years.

Key Words: *Hybrid System, HOMER, Solar PV, Biomass, Biogas, LCOE, NPC*

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ACRONYMS

0^o	Degree Celcius
AC	Alternating Current
AD	Anaerobic digestion
COE	Cost of Energy
D.O. D	Depth of discharge
DC	Direct Current
EAC	East African Community
EDPRS	Economic development and poverty reduction strategy
GHG	Green House Gas
GHI	Global Horizontal Irradiance
GoR	Government of Rwanda
H.C	Health Centre
HOMER	Hybrid Optimization Model for Electric Renewable
HRES	hybrid renewable energy system
HRT	Hydraulic Retention Time
Isc	Short circuit Current
KIST	Kigali Institute of Science and Technology
LCOE	Levelized Cost of Energy
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
NST1	First National Strategy for Transformation
NST2	Second National Strategy for Transformation
OLR	Organic Loading Rate
PADEC	Projet d'Appui au Développement Communautaire
PV	photovoltaic
REG	Rwanda Energy Group
Rwf	Rwandan francs
SAIFI	System Average Interruption Frequency Index
SDG	Sustainable Development Goal

SNV	Stichting Nederlandse Vrijwilligers (Foundation of Netherlands Volunteers)
STC	Standard Test Condition
VFAs	Volatile Fatty Acids
VOC	Open Circuit Voltage
RETs	Renewable Energy Technologies
Eq	Equation

CHAP 1: INTRODUCTION

1.1 Background and Motivation

Globally, the use of distributed renewable energy systems plays a crucial role in the production of electricity, especially in developing countries where the extension of the electrical nation grid to isolated areas is not economically viable due to limited generation capacity, geographic location, fund constraints, and old network which delay the national grid expansion and result in a low electrification rate and a barrier to economic development [1]. This vulnerability of rural areas is the main purpose of this work for providing a typical solution for the electrification of rural healthcare facilities in Rwanda by fully extracting existing natural renewable energy sources to these sites.

Rwanda Energy Group (REG), in its annual report for 2023/2024, reported that there were six blackouts nationwide that led to a total network collapse. The outage duration (SAIDI) was 10.273 hours per year and the average number of disruptions to the customer (SAIFI) was 15.397 times per year [2]. Thus, the above figures highlight the unreliability and uncertainty of electricity supply in Rwanda.

Another motivation to carry out this study is the set target by the Government of Rwanda (GoR) to achieve 100% electricity access by 2028 while current electrification status is only 78.9% (55.9% on-grid and 23% off-grid) by the end of June 2024 [3]. Therefore, the design of this hybridization consisting of PV and biomass-based energy sources integrating battery storage systems for powering Rural Healthcare Facilities in Rwanda could be an ideal solution.

The optimization and simulation of the hybrid system were performed by HOMER Pro. Simply; the objective of this dissertation is to design and optimize hybrid energy systems, comprising Solar PV, Biomass, and Battery storage to address the challenge of unreliable electricity supply for a rural community health center in Rwanda.

1.2 Problem Statement

Rural healthcare facilities in Rwanda face significant challenges due to unreliable electricity which affects critical medical services. This study aims to address this critical issue by designing an economical and sustainable hybrid system based on available local renewable energy sources for reliable electricity, minimizing dependence on diesel-fired generator backup systems, and reducing the amount paid to national utility companies by rural healthcare facilities in Rwanda.

1.3 Research Objectives

1.3.1 Main Objective

The main objective is to design an optimal configuration of solar PV and biomass-based hybrid systems that minimizes total net present cost and maximizes the utilization of available local renewable energy sources while ensuring the continuity of power supply for Ntarama health Center

1.3.2 Specific objectives

The main objectives of the study have been achieved through the following specific objectives:

i. Assessing daily electrical load demand and local energy resources potential for Ntarama Health Center
ii. Designing Hybrid Renewable Energy system
iii. Optimizing and simulating a Hybrid Energy system for validating system operation
iv. To perform technical, economical, and greenhouse gas emission analysis of the hybrid system

1.4 Research Questions

The following questions guided the assessment to achieve the objective of the study:

- How can locally available energy resources be effectively utilized as the primary option for providing reliable and affordable power to rural healthcare facilities?
- How can battery storage be managed efficiently to ensure continuous electricity supply, particularly during periods of low solar generation?

1.5 Justification

Electrification of healthcare facilities is essential for improving public health outcomes, supporting vaccine distribution, and enhancing the quality of medical care. The study emphasizes the provision of reliable, continuous power supply essentially for the critical operations of healthcare facilities. This system minimizes reliance on expensive, polluting diesel generators by leveraging abundant power from renewable resources, enhancing energy security, sustainability, and cost-effectiveness, ensuring long-term resilience in underserved regions.

1.6 Scope

This study involves the design, optimization, and simulation of solar PV and biomass-based hybrid systems integrated with battery storage for Ntarama health center. It also presents and discusses the load, consumption profile and system sizing.

Finally, the project evaluation for economic viability, environmental impact, Conclusion and recommendations based on the findings.

1.7 Significance of the study

The importance of this study is to use available local renewable energy sources effectively, which are already under-utilized for ensuring electricity reliability during peak demand rather than relying on a diesel-fired generator. Hybridization plays a crucial role in addressing reliability issues that arise from the capacity limitations of a single renewable source. It also eliminates the fuel costs associated with standby diesel generators while significantly reducing environmental impacts. Thus, this study minimizes long-term operational expenses and enhances energy resilience and sustainability. It contributes to improved healthcare outcomes and community well-being. In addition, it will support the government to achieve its goal of 100% universal electricity access by 2028 as stated in the background of this section.

1.8 Research Methods

Different research techniques have been used to achieve the objective of this study. Some of the systematic approaches used are detailed below:

Data on solar radiation have been gathered from NASA's surface meteorology and solar energy database at 2°5.2'S Latitude and 30°2.2'E Longitude and analyzed using HOMER Pro software, while biomass potential was assessed from the Health Center's attendance records. The average daily connected load was determined upon the rating and operating hours of the center’s electrical devices/equipment. Load forecasting for 5 years was carried out where the annual growth rate was calculated from the annual consumption for 2023 and 2024 years. Component sizing (solar modules, batteries, biogas generator, and converter) was carried out.

CHAP 2: THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Theoretical Background

Rwanda has significant renewable energy resources, and the government intends to use these resources to meet the country's electricity demand [4]. Solar PV represents a significant potential for rural power supply due to its availability with about 4-6 kWh/m2 /day of solar radiation [4]. However, its wide range of applications is disadvantaged by upfront costs and limitations for large-scale applications. This study aims to maximize the utilization of underused energy resources at the selected site while ensuring a reliable supply of electricity

2.1.1 Concept of Solar Energy and Solar Radiation `

Energy source that utilizes solar radiation for electricity or heat generation is known as Solar energy. It is characterized by its cleanliness and sustainability with negligible environmental impact. Whereby photovoltaic (PV) cell technology is the direct conversion of sunlight into electricity whereas solar thermal technology uses the sun’s heat to generate electricity or provide hot water [5].

Solar radiation is electromagnetic radiation from the sun, utilized as sunlight for various applications. It is measured in Watts per square meter(W/m2) or kilowatt-hours per square meter per year (kWh/m2/year), and it is stated that at optimum conditions, the earth's surface receives 1000W/m^2 of solar radiation.

Key factors influencing solar radiation include geographic location (latitude and longitude of a given area), seasonal variations and weather conditions.

The sun radiation affects the operating conditions of photovoltaic solar modules due to time-to-time variation in solar radiation. The output power from the photovoltaic module rises as the solar radiations increase. Figure 2.1 shows how the output power from a Photovoltaic module rises as the solar radiation increases.

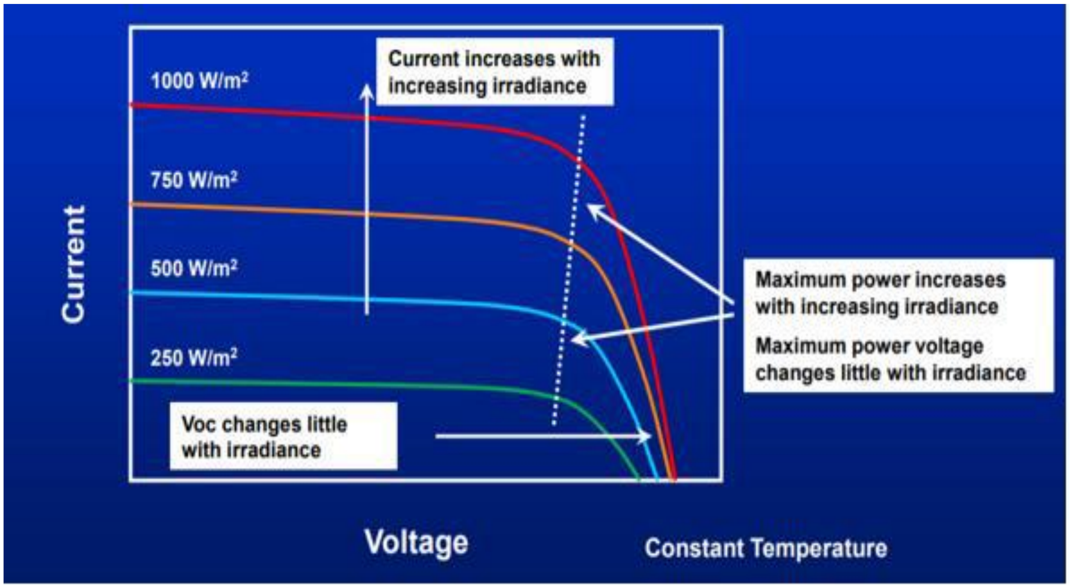


Figure 2. 1: PV current and voltages at different insolation levels [8].

2.1.2 Working principle of Solar PV Systems

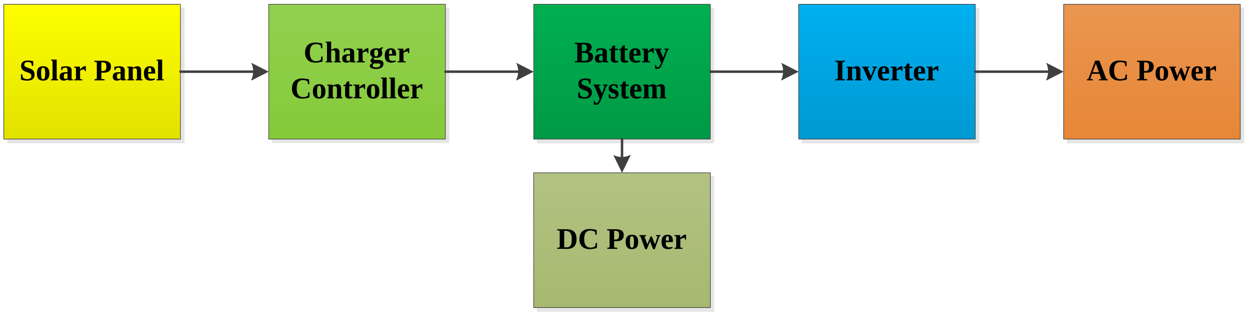


Figure 2. 2: Typical solar PV block diagram

A photovoltaic system converts light into electricity and the whole system consists of solar panels, charger controller devices, battery bank, inverter, and load (DC or AC load). Photovoltaic (PV) cells are responsible for the direct conversion of sunlight into DC (direct current) electricity. The Charge Controller to regulate the power generated by the solar panel, thus preventing any damage due to feedback to the panel. The Battery System comes into play when sunlight is not accessible and serves as a reservoir of electrical power. This entire system is interconnected with an inverter for converting DC into AC [6].

2.1.3 Modelling of Solar photovoltaic Panel

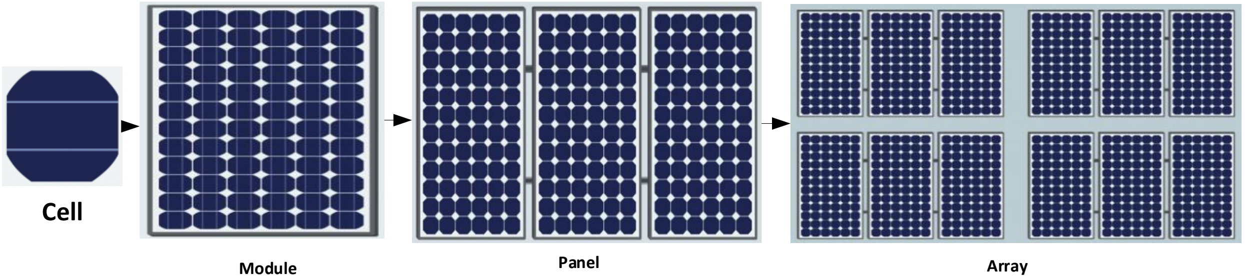


Figure 2. 3: Typical PV Panel system

1. PV Cell

The cells convert sunlight into DC. It is formed by various semiconductor materials, and it is composed of positive and negative charges whenever a cell absorbs photons from sunlight, electrons get released thereby leading to a flow of DC [6].

2. Photovoltaic Module

Modules comprise numerous solar cell strings connected in series within an aluminum framework. The size of cells is proportional to the amperage produced; large cells yield increased amperage [7]. Most solar modules available are of silicon-crystalline type utilized in residential and commercial systems.

3. Photovoltaic Panel

A collection of PV modules mounted together to generate more power

4. Photovoltaic Array

A complete system of multiple photovoltaic (PV) panels are interconnected in series or parallel configurations. This configuration comprises numerous PV cells linked in series and parallel to enhance the voltage and current output of the array, respectively. Consequently, an increase in the array's total area correlates with a rise in the electricity generated by the PV array [6].

2.1.4 Biomass Systems

Biomass refers to any organic material that comes from living organisms and can be converted to energy through various methods whereby each method has its specific advantages and limitations. Different technologies like combustion, gasification, pyrolysis, anaerobic digestion, and mechanical extraction are utilized.

Combustion is common for heat and electricity but less efficient for engine fuels; Gasification produces syngas; pyrolysis creates bio-oil; mechanical extraction makes biodiesel, and anaerobic digestion converts high-moisture biomass into biogas [8].

In this study, Anaerobic digestion technology is selected for energy conversion of human waste as it is the most moisture biomass, high-quality raw material for biogas production with high methane content.

2.1.4.1 Process of electricity generation from biomass

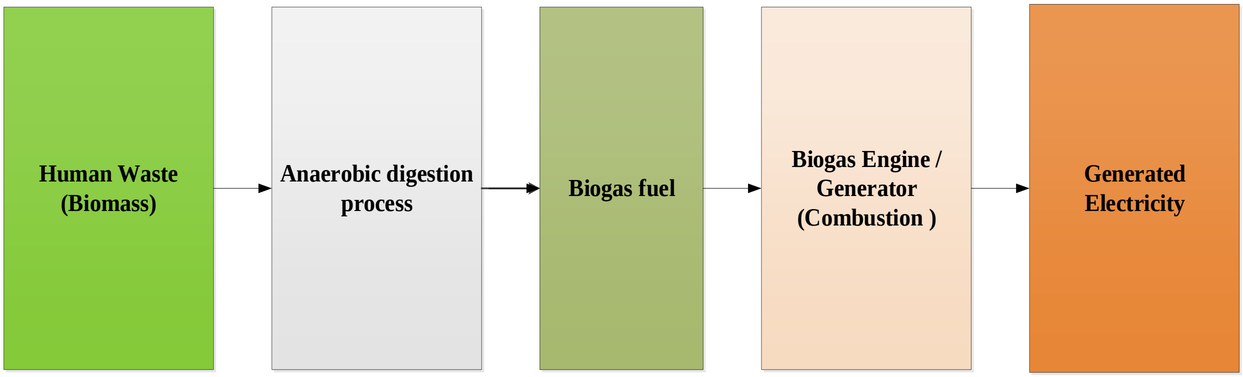


Figure 2. 4: Basic phases of electricity generation from biomass

Human waste Collection, Pre-treatment, and anaerobic digester phases: The process begins with the human waste collection from the toilet, latrines, or other sanitation facilities whereby the collected waste undergoes screening to remove large particles and grinding to create a more homogeneous mixture and then fed into an anaerobic digester where it undergoes in decomposition in absence of oxygen [9].

Anaerobic digestion process: It is a complex organic process in which the generation of biogas through anaerobic decomposition of organic matter without oxygen takes place in four main stages namely Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis [10] [9].

i. Hydrolysis is where the complex compounds are broken into simple molecules.

ii. Acidogenesis where the simpler molecules are converted into volatile fatty acids.

iii. Acetogenesis is where volatile fatty acids are converted into acetic acid, carbon dioxide, and Hydrogen.

iv. Methanogenesis is where acetic acids and hydrogen are converted into methane and carbon dioxide.

Biogas Production: The primary output of the anaerobic digestion process is Biogas, a mixture of methane (50% - 70%), carbon dioxide (30% - 50%), and trace amounts of other impurities [9].

Biogas purification and Energy conversion: The raw biogas is purified to increase its methane content by removing carbon dioxide (CO2) and other impurities whereby the purified biogas can be used to generate heat or electricity [9].

Energy Conversion: The purified biogas used to generate electricity through a biogas engine generator [9].

Fertilizer production: The materials remaining after anaerobic digestion (Digestate) can be processed into liquid and solid fertilizers, providing addition value from the waste treatment process [9].

2.1.4.2 Biogas Energy

The production of electricity from biomass energy sources involves a comprehensive overview of the biogas generation process using biomass feedstock, from collection to energy and fertilizer production. Biogas is a gas produced after organic materials are decomposed by bacteria in the absence of oxygen in anaerobic digestion (AD) process. This process can be controlled and optimized with anaerobic digesters.

The process of biogas production involves raw materials, fuel properties, biogas composition, and anaerobic digestion principles. Biogas contains methane gas and carbon dioxide, with other minor gases like Hydrogen sulfide, hydrogen (H_2), and Ammonia. Biogas has a lower heating value of about 21 MJ/m^3 [10].

2.1.4.3 Overview of biogas production in Rwanda

In 1982, a biogas consultant from Nepal established four initial biogas plants (8 m3 to 20 m3) in Kigali City at Kabuye and initiated relevant training. Additional biogases were constructed in Rwesero and Murambi in the Eastern province under PADEC project, supervised by SNV Rwanda.

However, the program was unsustainable and ultimately failed and the implementation of fixed-dome biogas plants commenced at the end of 1990 [13]. The first biogas plant for a prison was constructed in 2001 and carried out by KIST technicians who expanded biogas projects in prisons. This initiative significantly contributed to alleviating deforestation caused by wood charcoal consumption. In 2006, the Ministry of Infrastructure collaborated with SNV Rwanda to promote biogas, initiating a first phase that continued until 2010. The construction plan aimed to establish approximately 15,000 biogas plants by 2012 [11]. The effectiveness of biogas digesters operating at an average temperature of 20°C resulted in a user satisfaction rate of 97% concerning cooking efficiency.

The utilization and progress of biogas technology have significantly enhanced societal welfare by mitigating carbon monoxide (CO) emissions, generation of energy, the alleviation of environmental challenges associated with the improper disposal of human excreta, and the removal of the necessity for supplementary microbial inoculants. Additionally, it guarantees a consistent supply of microorganisms during the feeding process of raw materials, thereby enhancing the sustainability of biogas production [12].

According to the National Domestic Biogas Program, domestic biogas in Rwanda is generated from the dung of at least two cows, which could reduce wood consumption significantly, amounting to 2,348 kg of firewood annually. Among households utilizing firewood for cooking, 99% possess latrines; 89% express willingness to use energy from animal and human waste for cooking and lighting, and 90% would apply bio-slurry from waste as fertilizer, despite unfamiliarity. Furthermore, 56% report adverse effects from indoor air pollution caused by smoke from firewood and kerosene [11], [13].

2.1.4.4 Key parameters in Anaerobic Digestion (AD) for Biogas Production

Optimal biogas production through AD relies on multiple factors explored in numerous studies which typically focus on digesters, operational parameters, and Biogas production efficiency [9].

Key features influencing the biodegradation process to enhance AD efficiency for biogas production as elaborated on table 2.1 include Temperature, pH, Supply of nutrients (C/N ratio), oxygen omission, volatile substances, the composition of the substrate, retention time, organic loading rate, and mixing ratios. Optimal Temperature, pH, C/N ratio, and mixing ratio significantly enhance microbial activity and biogas production whereas monitoring HRT, OLR, and VFAs is critical for maintaining process stability and balanced feedstock composition with appropriate solid concentration to prevent microbial inhibition [14].

Table 2. 1: key parameters in Anaerobic Digestion for biogas Production [12], [17].

Parameter	Summary
temperature	AD efficiency depends on Temperature, the rate of reaction is directly proportional to the temperature.
pH value	The organic process depends on pH value. Neutral pH (6.8-7.2) is ideal for methanogens. pH affects microbial activity and digestion efficiency.
Carbon/Nitrogen Ratio	The C/N ratio states the relationship between Nitrogen and carbon in a substrate during anaerobic digestion. An optimal C/N ratio of 25-30:1 ensures efficient digestion. Lower ratios (protein-rich feedstock) lead to ammonia inhibition, while higher ratios result in nitrogen deficiency and reduce gas production.
Mixing	Mixing improves substrate exposure to microbes, distributes temperature uniformly, and prevents foaming. Intermittent mixing is generally better for process stability, but overmixing can stress microbial activity.
Hydraulic Retention Time (HRT)	HRT represents the period taken by slurry in the reactor to be completely digested. Longer HRT increases gas yield but requires larger digesters.
Organic loading rate (OLR)	OLR measures the daily mass of organic matter fed per reactor volume. Proper OLR optimizes microbial activity and gas yield while overloading disrupts microbial balance and reduces biogas production.
Feedstock composition and Nutrients	Efficient biogas production requires balanced carbon and essential nutrients (Nitrogen, sulfur, phosphorus, etc.) but imbalanced feedstock composition may increase acid content and delay microbial growth.
Concentration of feedstock	The concentration and composition of the substrate help in the determination of mass balance.
Volatile fatty acids (VFAs)	VFAs are one of the control parameters in AD because VFAs indicate methanogenic activity. Excess VFAs inhibit digestion and biogas yield, while their profile offers insights into microbial community dynamics and potential imbalances.

2.1.4.5 Anaerobic Digestion technology for biowaste

A technology that uses a biogas digester for converting biomass feedstock into Biogas is known as Biogas technology, whereby the biogas digester is the constructed vessel in which biomass feedstocks are broken down by bacteria without oxygen for biogas production in the anaerobic digestion process.

The basic anaerobic digester design choice depends on technical, cost, and local factors. There are numerous types of digesters, but we are going to discuss a few of them according to their viability and have previously been implemented in developing countries. Fixed Dome Digester, Floating Drum digester, and Flexi digester are detailed in the below table 2.2.

They are inexpensive, use local materials, less exposed to failure as they do not have many moving parts [9].

Table 2. 2: Comparison of Biogas Digesters used in developing countries

Features	Fixed Dome Digester	Floating Drum Digester	Flexi Digester
Gas storage	Dome	Floating Drum	Flexible gas holder
Gas pressure	Fluctuates	Consistent	Lower
Construction	Concrete, Masonry	Concrete, Metal	Plastic
Cost	Low	Medium	Low
Maintenance	Low	Medium	Low
Portability	Low	Low	High

2.1.4.5.1 Fixed Dome Digester

A fixed dome digester is a biogas production system with an underground and non-movable Dome structure that stores gas under pressure. It has an inlet for feedstock.

Gas accumulates in the upper section, and increased gas production raises pressure which pushes the digestate into down section. Gas utilization reduces its pressure and causes slurry (digestates) to return from the down section to the digester [9].

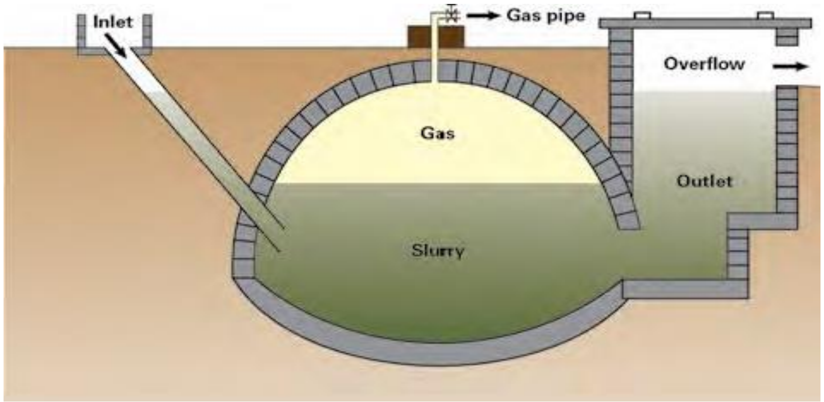


Figure 2. 5: Fixed dome digester [12].

2.1.4.5.2 Floating Drum digester

A floating Drum digester is a type of biogas digester that consists of an underground cylindrical digester and an above-ground floating gas holder. The gas holder adjusts its position based on gas volume, serving as a visual indicator of available gas. Gas is delivered at a steady pressure determined by the weight of the gas holder, and additional weights on the top of the drum can be added to increase the pressure [9].

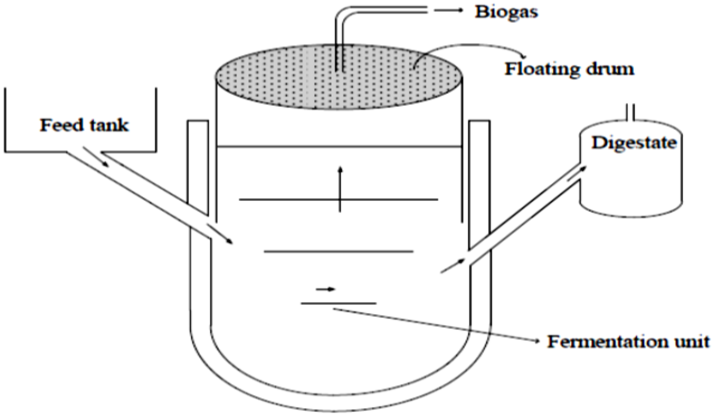


Figure 2. 6: Floating drum digester [12].

2.1.4.5.3 Flexi digester

Flexi digester (flexible biodigester) is a low-cost, portable anaerobic digestion system. It is typically consisting of a flexible, tubular plastic bag or membrane that contains organic materials to be decomposed by bacteria for methane gas production for cooking or electricity generation. Fixed dome systems, common in China and India, are complex and expensive, posing challenges for adoption in developing countries.

In contrast, Kenya's Flexi Biogas is a simpler, cheaper above-ground system using a 6m x 3m PVC tarpaulin bag, which does not require agitation or a sealed tank [15].

Figure 2. 7: Flexi digester [18].

2.1.5 Battery storage

The battery is an energy storage system, and they are serving as a backup for hybrid systems to ensure system reliability. Batteries impact cost, maintenance, reliability, and design. Electrochemical batteries are commonly used for storing electrical power [5].

Batteries provide power during peak load when renewable sources are insufficient. Sizing batteries is crucial for balancing energy production and consumption therefore, the system optimization tools aid in determining the optimal battery size for cost-effective and reliable electricity access [7].

The efficiency of the battery relies on its prior charge, energy demand, and accessible energy from the system. Battery capacity must stay within standard limits, determined by charging/discharging rate, depth of discharge, and energy from the system. The systems operate within specific charge limits to maintain battery health whereby a complete discharge at each cycle negatively impacts battery performance. Discharging by 25% yields more [16].

2.2 Literature review

2.2.1 Previous work

Much research worldwide has been carried out as either a single renewable source or hybrid renewable systems. The hybrid system is designed as either standalone or grid connected, and the findings captured from the reviewed papers are detailed below:

K. C. Chang et al [17]**,** investigated standalone and Mini grid-connected solar PV systems for rural application in Rwanda, with a focus on single household applications versus community-based systems. Their primary objective was to design PV solutions and compare the performance and cost structures of standalone and mini-grid configurations. The simulation results revealed that standalone PV system offered a lowest a lower levelized cost of energy (LCOE) and thus proved more economically viable than mini-grid alternatives. Simply, this study provides valuable insights into the feasibility and economic competitiveness of solar PV technologies in rural electrification across developing countries.

Critically, while the research establishes the cost-effectiveness of standalone systems, its scope is limited to solar PV without integrating complementary renewable resources or storage solutions that could enhance reliability. For rural healthcare facilities in Rwanda where uninterrupted electricity is essential, relying solely on standalone PV may not adequately address intermittency and reliability challenges, especially during low solar irradiation periods. Therefore, the present study builds upon these findings by exploring a hybrid configuration of solar PV and biomass with battery storage, aiming to optimize both cost and reliability. This approach addresses the limitations of this study by ensuring continuous power supply while maintaining economic viability for these critical facilities.

E. Mazimpaka, N. Mandela, A. B. Makokha, J. Kiplakat, H. Ingabire, and B. Ntambara [11], provides a comprehensive sustainability analysis of biogas in Rwanda, highlights its contributions to energy sustainability, reduced CO2 emissions, lower firewood costs, and improved health. Despite these benefits, challenges such as limited feedstock, water scarcity, and inadequate maintenance constraint its full potential. While their study demonstrates the viability of biogas for household and community energy needs, it also reveals its limitations in ensuring continuous and reliable supply. This gap justifies the need for hybrid systems that integrate biogas with complementary resources such as solar PV and battery storage.

By combining these technologies, it becomes possible to overcome the intermittency of solar power and the resource constraints of biogas, thereby providing a more reliable and sustainable energy solution for community healthcare facilities in Rwanda.

S. Bimenyimana et al [18]**,** conducted a techno-economic feasibility study of energy systems in East African Community (EAC) countries, comparing diesel, solar PV, and hybrid options using HOMER software. Their results showed solar PV with battery storage as the most feasible solution across the region, except in South Sudan where diesel appeared cost-effective for standalone systems, though solar remained preferable for environmental reasons. This study underscores the importance of balancing affordability, reliability, and sustainability in technology selection. However, it largely overlooks the role of biomass, which is particularly relevant in Rwanda's rural context where agricultural residues are abundant. Building on this study's findings, the present research extends the analysis by incorporating biomass into solar PV, battery configurations to design an optimized hybrid system tailored for reliable and affordable electrification of rural healthcare facilities in Rwanda.

H. Eustache, D. Sandoval, U. Wali, and K. Venant [4]**,** analyzed Rwanda's Renewable Energy Technologies (RETs) and reported that in 2018, renewables accounted for 52.4% of the energy mix, with hydropower as the dominant source. Despite the country's significant solar potential, solar presented only 2.2% of installed capacity, while biomass was largely confined to traditional cooking uses rather than electricity generation. The study further identified barriers such as high investment costs, limited technical expertise, and somehow weak policy support that continue to constrain renewable energy adoption. These findings reveal critical research gap such as Rwanda's dependance on hydropower makes electricity supply vulnerable to climate viability while the potential of solar and biomass remains underexploited. This gap is particularly pressing for rural healthcare facilities, where unreliable electricity directly undermines service delivery, cold chain management and emergency care. Addressing this challenge provides the rationale for the present study, which investigates the optimal configuration of solar PV and biomass-based hybrid systems with battery storage as a sustainable and reliable solution for rural healthcare electrification.

N. Bolson and T. Patzek [19]**,** in their evaluation of energy resources, provide a critical assessment of Rwanda's current energy landscape and its prospects for future development. Their analysis highlights the availability of resources such as hydropower, methane, peat, solar, biomass and the emerging potential for geothermal and wind energy.

However, they conclude that the present energy mix remains inadequate to support Rwanda's long-term development goals of attaining middle-income status by 2025 and transitioning to high-income status by 2050. Continued dependence on traditional biomass, limited hydropower capacity, and reliance on oil imports present significant barriers to sustainable growth. In this context, authors identify solar PV as a vital resource for bridging the energy deficit and reducing fossil fuel dependency. the present study presents this perspective by emphasizing the integration of solar PV and biomass with battery storage as a hybrid, decentralized solution to enhance reliability and sustainability and ensure sustainable electrification of rural healthcare facilities in Rwanda.

2.2.2 Research Gaps for previous Works

The Summary of gaps in knowledge for the reviewed research papers, especially in Rwanda is presented below:

Standalone PV systems offer lower LCOE but limited scalability, whereas microgrids are costlier but better for community electrification. Hybrid systems that integrate solar PV with locally resources such as biomass remain insufficiently explored in Rwanda, despite their potential to enhance energy security and reduce reliance on fossil fuel. persistent challenges include high upfront investment costs, limited technical expertise, and mismatches between PV technologies and local environmental conditions. Innovative solutions such as advanced battery storage and low maintenance PV modules are essential to ensure reliable, cost-effective and sustainable electricity supply. The gap of lacking focused research on optimized PV-biomass hybrid systems with storage for rural healthcare applications forms the basis of the present study[17].

Biogas has been promoted in Rwanda to address energy deficits, with programs like the National Domestic Biogas Program reducing CO2 emissions, firewood use, and improving energy access. However, socio-economic barriers such as high installation costs, limited feedstock, and lack of technical skills hinder widespread adoption. Many biogas plants struggle with feedstock shortages, water supply issues, and technical faults, leading to underutilization. There is a need for low-cost designs based on available feedstock, robust technologies, and a structured framework for technical support and maintenance services [11].

The challenges of energy access issues in EAC nations have been highlighted focusing on affordability, reliability, and sustainability. While solar energy has great potential, adoption is limited by financial and technical barriers.

PV-Battery systems are viable except in South Sudan, while diesel remains common due to lower initial costs despite environmental concerns. Hybrid system integration is limited, requiring better financial models, regulatory frameworks, and scalability for future energy demands [18].

Rwanda relies heavily on biomass (93.1%) with hydropower as the main renewable source. Hybrid renewable energy systems like solar-biomass or solar-wind remain under explored for rural electrification. Despite Rwanda’s solar potential of 4–6 kWh/m²/day, high costs and limited capacity hinder adoption, contributing only 3% to the energy mix. There is a need to reduce solar installation costs, explore financing models, and integrate modern biomass technologies for large-scale adoption [4]. Rwanda faces an environmental energy crisis due to overpopulation, resource limitations, and land degradation. Inefficient energy use and lack of integrated strategies worsen sustainability challenges.

There is a need for scalable renewable energy solutions and structured policies to balance development with environmental restoration. Regional and international partnerships could help bridge energy gaps and enhance resilience [19].

2.2.3 Renewable energy policies and regulation in Rwanda

Rwanda has progressed in energy policy with a focus on sustainability and efficiency. Rwanda’s latest Energy Policy prioritizes energy efficiency and renewable energy with regulations and incentives. Programs aim to overcome barriers to energy-efficient technologies [20]. Current Energy Sector Strategic Plan (2018/19-2024) of Rwanda aims to expand renewable energy sources and improve energy infrastructure and encourages private sector involvement in renewable energy through regulatory support and economic incentives [20]. Rwanda's energy policy aims for sustainable development, energy security, and environmental management through regulatory frameworks, strategic plans, partnerships, and economic incentives [20],[21].

CHAP 3: RESEARCH METHODOLOGY

3.1 Research Design

The formulation of an optimal hybrid system that integrates photovoltaic (PV) technology and biomass requires the collection of empirical data as an essential preliminary phase to ensure the successful execution of the project. This includes the identification of the geographical site designated for implementation of the project, a comprehensive load profile assessment for the selected community, and an evaluation of solar irradiance and biomass feedstock in the region under consideration [5].

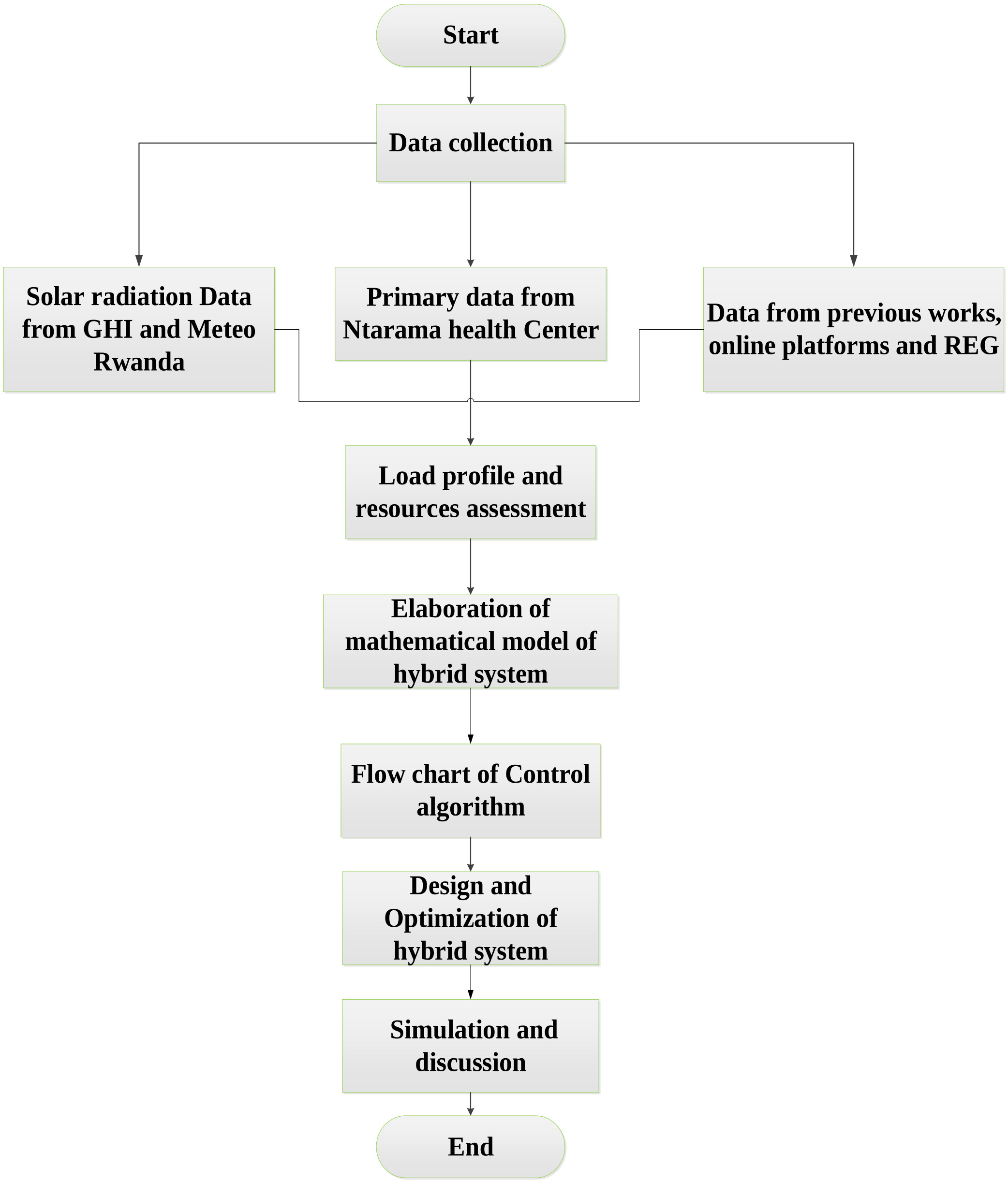


Figure 3. 1: Flow chart of research design

3.2 Primary and Secondary data

This hybrid system for Ntarama health center relies on available renewable energy resources and their respective potentials along with the site-specific load demand [22].

To achieve an optimal configuration, the data collection process site visit and interview with the center's staff and data analysis techniques were carried out.

Data collection provides insights into energy consumption patterns, critical power needs, and operational challenges. Data analysis techniques involve statistical analysis and simulation modeling to interpret collected data.

The sizing of the hybrid system requires primary data collected directly from Ntarama H.C , including the total connected load obtained through survey techniques and the load profile based on power consumption records from the existing transformer on a daily, monthly, and yearly basis. Secondary data collection involves gathering information on solar radiation, temperature, and other climatic conditions. These datasets were obtained from various literature sources, HOMER Pro software and online platforms.

3.2.1 Load assessment for Ntarama health Center

Ntarama Health Center is currently supplied by the National Grid with a 100 KVA 30/0.4 KV three-phase transformer.

Table 3.1 and 3.2 presents main connected electrical loads whereas Table 3.2 presents monthly power and energy consumed by Ntarama health center within two years.

3.2.1.1 Load profile for Ntarama health center

Table 3. 1: Connected Load for Ntarama Health Center as of February 2025

No	Equipment	Power rating (W)	Quantity	Total Power (W)	Operating hours (h)	Energy Consumption (Wh)
1	LED bubbles lamp	12	6	72	9	648
2	LED tube Light for office	9	9	81	8	648
3	Corridor Fluorescent Lamp	36	7	252	12	3,024
4	LG Smart TV 43 inches	70	1	70	14	980

5	hp Laser jet 700color MFPM775	250	3	750	3	2,250
6	Electric Fan	65	4	260	8	2,080
7	Refrigerators (for vaccines, medications)	250	3	750	24	18,000
8	Washing Machine	300	1	300	1	300
9	Automatic hand drier	1200	1	1200	3	3,600
10	Laptop	65	8	520	12	6,240
11	Desktop	80	4	320	9	2,880
12	Outdoor LED Luminaries	100	9	900	13	11,700
13	Ultrasound machine	1,000	1	1000	4	4,000
14	ECG machine (Electrocardiogram)	210	1	210	5	1,050
15	Water pumps	300	1	300	2	600
16	Laboratory equipment	300	1	300	13	3,900
17	Operating table	150	1	150	6	900
18	Surgical lights	750	2	1500	4	6,000
19	Electrosurgical unit	800	1	800	4	3,200
20	Ventilator	750	2	1500	6	9,000
21	Infusion pump	90	1	90	6	540
22	Patient monitor	300	2	600	17	10,200
23	Incubator (for newborns)	240	2	480	5	2,400
24	Server room	600	1	600	24	14,400
	Total			**13,005**		**108,540**

3.2.1.2 Consumption profile for Ntarama health center for 2023-2024

Table 3. 2: Yearly Power and Energy consumption for 2023 and 2024 at Ntarama H.C

Months	**Power (kW) and Energy (kWh) Consumption for 2023 and 2024 at Ntarama H.C**			
	Power(kW)_2023	**Power (kW)_2024**	**Energy(kWh)_2023**	**Energy (kWh)_2024**
1	4.03	8.08	2,998.32	6,010.42
2	4.70	7.75	3,158.40	5,394.60
3	5.03	8.18	3,742.32	6,088.60
4	4.40	8.50	3,168.00	6,122.80
5	4.95	8.29	3,682.80	6,171.05
6	5.42	8.69	3,902.40	6,255.99
7	5.71	9.17	4,248.24	6,822.74
8	5.91	7.60	4,395.46	5,657.01
9	7.74	6.71	5,576.36	4,831.89
10	11.39	6.96	8,473.01	5,181.60
11	12.57	6.85	9,049.25	4,929.90
12	12.96	7.62	9,640.43	5,672.76
Average	**7.07**	**7.87**	**5,169.58**	**5,761.61**

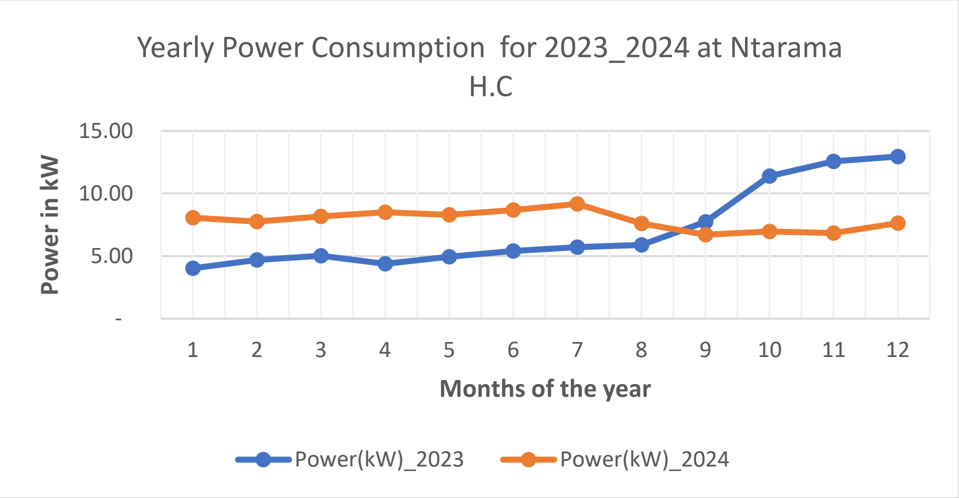


Figure 3. 2: Power consumption profile for 2023 and 2024 at Ntarama H.C

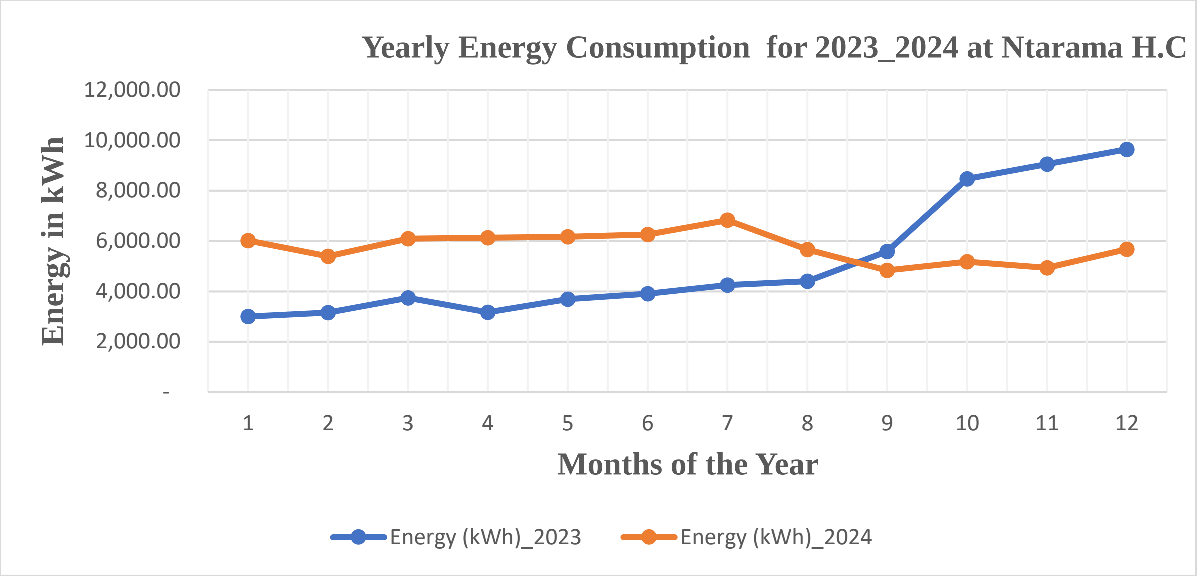


Figure 3. 3: Energy consumption profile for 2023 and 2024 at Ntarama H.C

From table 3.2, the average consumed power in 2023 is 7.07 kW and 7.87 kW in 2024 respectively. Hence, we can calculate the rate of increase or growth rate of power demand as follows:

$$\boldsymbol{Annual\ Growth\ rate}\ (\boldsymbol{r}) = \frac{\boldsymbol{P2-P1}}{\boldsymbol{P1}} \qquad \text{Eq (3.1)}$$

Where:

r = Annual Growth rate

P1 = Power consumed in previous year (2023)

P2 = Power consumed in the following year (2024)

Hence, from Eq (3.1) the annual growth rate **(r)** will be**:** $\boldsymbol{r} = \frac{\mathbf{7.87-7.07}}{\mathbf{7.07}} \approx \mathbf{0.113}$

Table 3. 3: Daily Power consumption (kW) for Ntarama health center for September 2024

Time (hr)	Daily power consumption (kW) of the September 2024 (From 1st to 30th September 2024)																													
	01-Sep	02-Sep	03-Sep	04-Sep	05-Sep	06-Sep	07-Sep	08-Sep	09-Sep	10-Sep	11-Sep	12-Sep	13-Sep	14-Sep	15-Sep	16-Sep	17-Sep	18-Sep	19-Sep	20-Sep	21-Sep	22-Sep	23-Sep	24-Sep	25-Sep	26-Sep	27-Sep	28-Sep	29-Sep	30-Sep
0:00	6.67	6.61	6.68	5.55	5.76	5.36	5.94	7.13	6.36	6.45	6.50	6.17	6.34	6.36	6.30	6.49	6.17	6.03	6.54	6.16	6.16	6.75	6.43	6.01	6.11	6.52	6.04	6.76	6.28	6.01
1:00	5.79	5.58	5.53	5.02	4.97	5.36	5.26	5.81	5.88	5.99	5.94	5.59	6.24	6.03	5.72	5.58	5.54	5.68	5.83	5.89	6.03	5.97	5.88	5.58	5.73	5.71	5.60	6.21	5.72	5.65
2:00	5.38	5.20	5.24	4.62	4.75	4.71	5.16	5.57	5.53	5.74	5.74	5.46	5.29	5.33	5.53	5.34	5.59	5.56	5.33	5.30	5.31	5.80	5.57	5.44	5.34	5.31	5.20	5.40	5.26	5.63
3:00	5.61	4.90	4.97	4.49	4.87	4.95	4.90	5.29	5.53	5.45	5.79	5.11	5.40	5.37	5.33	5.30	5.49	5.35	5.19	5.09	5.30	5.54	5.52	5.25	5.17	5.34	11.07	5.71	5.32	5.23
4:00	4.61	4.80	4.94	4.59	4.60	4.66	4.90	5.13	5.19	5.44	5.54	5.55	5.46	5.36	5.76	5.39	5.06	5.04	5.25	4.93	5.29	5.25	5.76	5.21	4.98	5.31	10.22	5.17	5.21	5.10
5:00	4.54	4.83	4.74	4.46	4.97	4.91	4.63	5.23	5.67	5.29	5.00	5.22	5.20	5.06	5.17	5.38	5.51	5.29	5.69	5.42	5.07	5.15	5.92	5.38	5.04	5.29	5.01	5.23	5.16	9.12
6:00	4.40	5.35	5.20	4.30	5.70	4.62	4.65	4.69	6.04	7.31	7.31	6.00	6.21	4.83	4.31	6.33	5.80	6.79	6.04	6.54	4.96	5.05	7.01	6.44	6.78	7.01	6.11	4.68	4.62	5.25
7:00	4.06	4.87	3.99	4.85	3.64	4.50	3.59	4.60	5.10	4.83	5.20	5.35	5.88	4.54	4.01	5.24	5.72	5.25	4.99	6.06	5.24	4.38	6.61	6.50	6.70	5.52	11.38	4.10	3.90	7.34
8:00	3.84	4.33	3.74	3.22	4.29	4.59	3.47	4.39	4.03	4.37	4.54	4.91	4.29	4.90	4.23	4.64	5.97	4.30	5.44	4.26	5.71	4.37	4.66	4.27	5.01	5.01	10.75	8.20	4.25	9.23
9:00	5.22	4.31	4.59	3.94	3.90	4.55	3.41	4.36	4.35	4.17	4.48	4.26	4.27	7.66	5.68	5.16	4.51	4.70	4.77	5.35	4.69	5.64	4.39	5.20	4.77	4.53	9.74	4.85	5.33	5.35
10:00	5.25	5.13	5.29	4.13	3.84	4.08	4.70	7.56	4.26	4.35	6.08	6.10	5.40	5.05	5.92	5.82	4.97	5.98	6.66	4.77	4.65	5.02	4.79	5.85	5.81	5.98	5.09	5.47	6.04	5.20
11:00	6.23	6.30	4.33	4.42	5.81	4.21	6.13	8.75	4.31	5.72	5.22	4.42	6.42	5.16	5.81	6.25	5.20	6.00	6.91	7.35	6.23	6.34	5.42	5.77	4.93	5.40	9.51	4.99	9.30	8.45
12:00	5.80	5.66	6.17	4.57	6.10	3.95	5.47	5.67	6.25	6.28	6.21	4.78	4.92	5.25	5.46	5.44	4.89	5.34	4.70	5.33	4.54	5.82	4.85	6.93	5.77	5.93	4.84	8.94	10.73	4.87
13:00	5.41	7.03	5.28	3.97	4.61	4.35	5.03	8.49	5.23	5.46	5.35	6.77	5.53	7.17	6.47	5.08	5.60	7.13	5.04	5.88	6.75	6.63	4.86	5.14	5.13	5.32	5.80	10.44	8.67	6.71
14:00	5.42	6.70	-	4.35	6.16	3.73	6.60	7.97	4.91	5.15	5.65	4.65	5.85	4.75	6.07	5.57	5.72	5.20	5.45	7.47	6.14	5.89	5.72	7.64	4.94	11.62	4.93	9.68	10.23	5.74
15:00	5.37	5.30	-	3.52	5.63	3.66	5.33	6.35	5.42	6.27	7.63	5.20	5.33	8.20	5.81	5.93	5.47	4.92	5.05	6.01	5.10	5.97	5.50	6.77	4.65	6.07	6.95	10.99	3.51	5.97
16:00	4.92	6.08	5.63	3.52	7.57	4.74	7.26	7.87	7.23	5.68	6.07	5.26	8.72	8.05	6.50	6.36	6.34	5.69	5.84	5.63	5.59	8.09	5.83	6.14	5.89	9.86	5.21	9.55	4.65	8.19
17:00	7.20	6.15	5.61	4.33	8.92	7.61	6.38	6.70	9.29	6.94	6.82	4.97	6.98	9.83	4.95	6.89	7.81	6.51	7.04	6.02	6.44	8.84	6.02	7.85	5.76	7.63	6.67	9.29	6.36	6.71
18:00	8.70	8.55	6.15	5.41	7.28	5.61	10.35	8.74	7.23	8.58	6.82	6.78	7.01	10.16	6.46	6.95	8.00	9.64	6.42	-	8.97	9.99	6.38	10.36	10.17	14.79	6.51	9.66	10.90	8.38
19:00	10.23	11.08	8.98	10.84	9.73	9.55	13.64	11.54	10.78	11.03	11.42	10.67	10.53	12.65	11.76	11.03	10.89	11.25	11.35	11.74	13.57	11.90	11.00	11.45	10.98	11.46	12.47	10.98	14.66	11.10
20:00	10.50	10.92	10.82	10.32	10.02	9.95	11.48	11.13	11.70	11.48	11.13	10.89	11.24	11.33	12.13	11.45	10.85	11.84	10.63	10.98	11.77	11.07	12.62	11.03	11.22	11.77	10.59	10.79	11.43	11.86
21:00	10.37	10.45	9.28	10.13	9.51	9.85	11.24	10.20	11.75	11.06	10.38	11.54	10.98	11.52	10.78	10.96	10.67	11.05	10.59	10.62	11.49	11.34	11.18	10.97	10.55	10.85	10.43	10.62	9.82	10.89
22:00	9.54	10.42	8.14	8.55	8.90	8.55	9.55	9.29	9.34	9.33	9.20	8.73	9.51	9.96	10.56	9.07	9.08	8.83	8.96	9.25	10.00	8.83	9.00	9.39	9.02	9.20	9.15	9.58	8.48	8.82
23:00	7.81	7.19	6.58	7.28	7.16	6.89	8.30	7.48	8.07	8.20	7.56	7.28	7.39	7.85	7.67	7.02	7.35	7.46	7.52	7.29	8.09	7.36	7.06	7.45	7.14	7.12	7.75	7.34	7.37	7.90

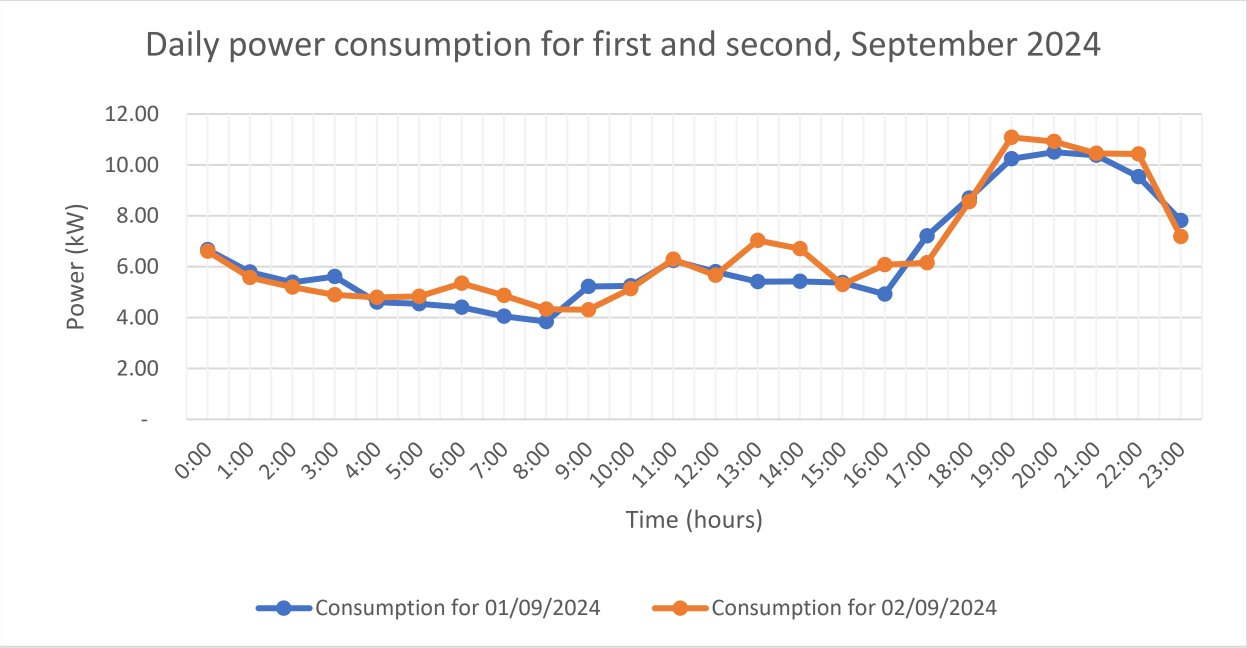


Figure 3. 4: Daily consumption (kW) for 1st and 2nd September 2024 at Ntarama H.C

The power consumption from Ntarama Health Center varies from time to time whereby the monthly averaged maximum and minimum consumptions were 9,640.43 kWh in December 2023 and 2,998.32 kWh in January 2023 respectively as shown in table 3.2, and from daily consumption, the demand varies hourly as represented on above figure 3.4 and table 3.3

3.2.3 Site description

This research project has been conducted in Kanzenze cell, Ntarama Sector, Bugesera District in the Eastern Province of Rwanda. This site has been chosen because it is an urban area with a high population (currently 47,424 people in Ntarama Sector, as of 18th Feb 2025) growth which overloads an existing electrical infrastructure and negatively affects the electricity reliability, especially at Ntarama health Center, which is only one health center available in this sector. Ntarama H.C has currently a total daily connected load of 13.005 kW and an energy demand of 108.54 kWh which is not static but dynamic and expected to be increased within the following next 5 years due to the population growth and any new technology that may be adopted in H.C. This current and future demands of Ntarama health center must be fully supplied by available solar and biomass renewable energy sources with battery storage as backup.

3.2.4 Resource Assessment

The hybrid systems of renewable energy resources are effective in remote areas for electrification purposes, providing sustainable and cost-effective energy solutions. They generate electricity from various sources that complement each other, increasing electricity reliability and reducing carbon emissions. There is a necessity to evaluate and estimate the potential of available local Renewable energy sources in the selected areas before moving forward in further process for successful projects. Therefore, the solar PV and Biomass feedstock have been assessed, and the findings are detailed for each resource.

3.2.4.1 Solar resource assessment

Solar energy, an abundant and cost-free source of energy possesses a unique advantage over traditional power sources because sunlight energy is directly converted into energy through PV cells.

Rwanda is located near the equator where the solar potential is high, and this location enables Rwanda to have averaged daily solar radiation ranging from 4 kWh/m2/day to 6 kWh/me/ day [4]. The global horizontal irradiation (GHI) map data further classifies Rwanda as highly suitable for solar energy exploitation [23].

The monthly averaged values of global horizontal solar radiation and clearness index and averaged temperature of Ntarama health center from NASA Surface Meteorology and solar energy database at 2°5.2'S Latitude and Longitude of 30°2.2'E are shown below in Table 3.4 and figure 3.5.

The monthly values of solar radiation vary from 4.63 (Gmin) in November to 5.49 (Gmax) in August with an annual average solar radiation (Gav) of 5.04 kWh/m2/day. Due to the variations in solar radiation, solar energy will vary too, and therefore biomass-based energy will support generation during the low solar generation period.

The clearness index (CI) shows the portion of solar radiation from the sun that reaches the Earth in each area. The clearness index (CI) at Ntarama H.C varies from 0.45 in November to 0.589 in July.

Table 3. 4: Clearness index, Temperature and Solar radiation for Ntarama H.C

Month	**Clearness index**	**Temperature (^{0}C)**	**Daily radiation kWh/m2/day**
January	0.485	19.59	4.98
February	0.506	20.36	5.32
March	0.484	19.95	5.09
April	0.484	19.64	4.88
May	0.495	20.94	4.67
June	0.552	21.13	5.01
July	0.589	20.99	5.44
August	0.56	22.06	5.49
September	0.521	22.47	5.37
October	0.47	20.62	4.91
November	0.45	19.23	4.63
December	0.467	19.19	4.74
Annual Average		**20.51^{o}c**	**5.04 kWh/m^2/day**

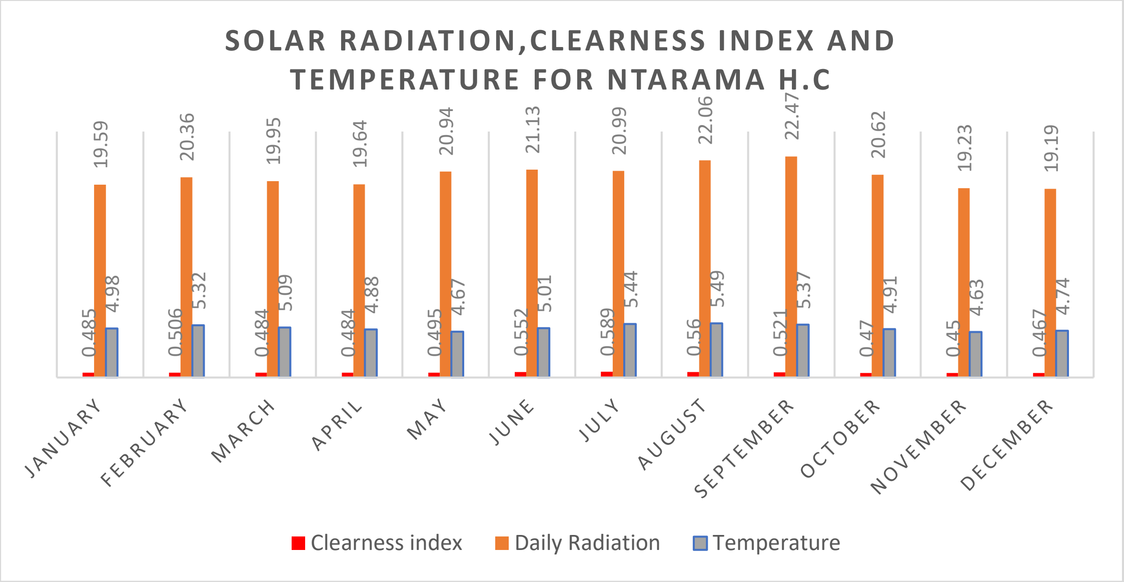


Figure 3. 5: chart of Solar radiation, clearness index for Ntarama H.C

The clearness index (CI) shows the portion of solar radiation from the sun that reaches the Earth in each area. The clearness index (CI) at Ntarama H.C varies from 0.45 in November to 0.589 in July

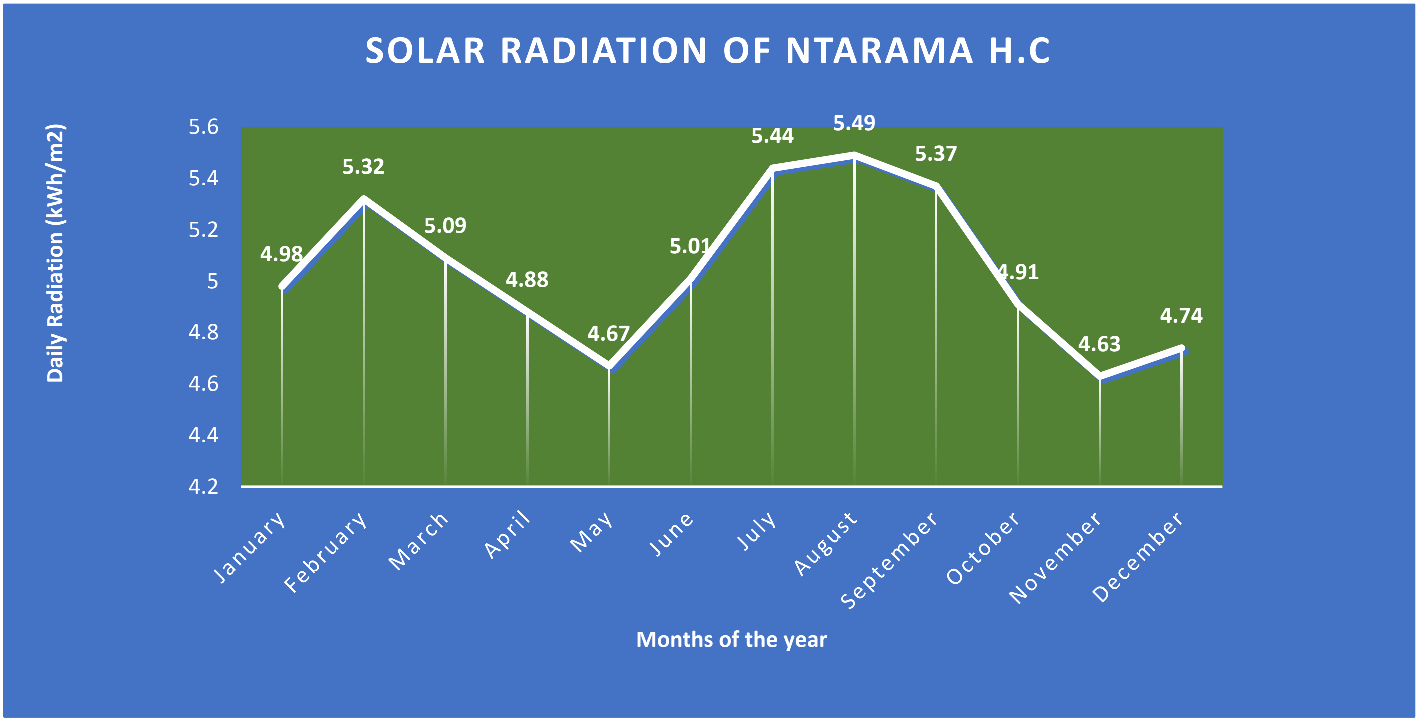


Figure 3. 6: Solar radiation Curve for Ntarama H.C

Table 3. 5: Ntarama health center Temperature data

Month	**Temperature (ºc)**
January	19.59
February	20.36
March	19.95
April	19.64
May	20.94
June	21.13
July	20.99
August	22.06
September	22.47
October	20.62
November	19.23
December	19.19
Annual Average Temperature	**20.51**

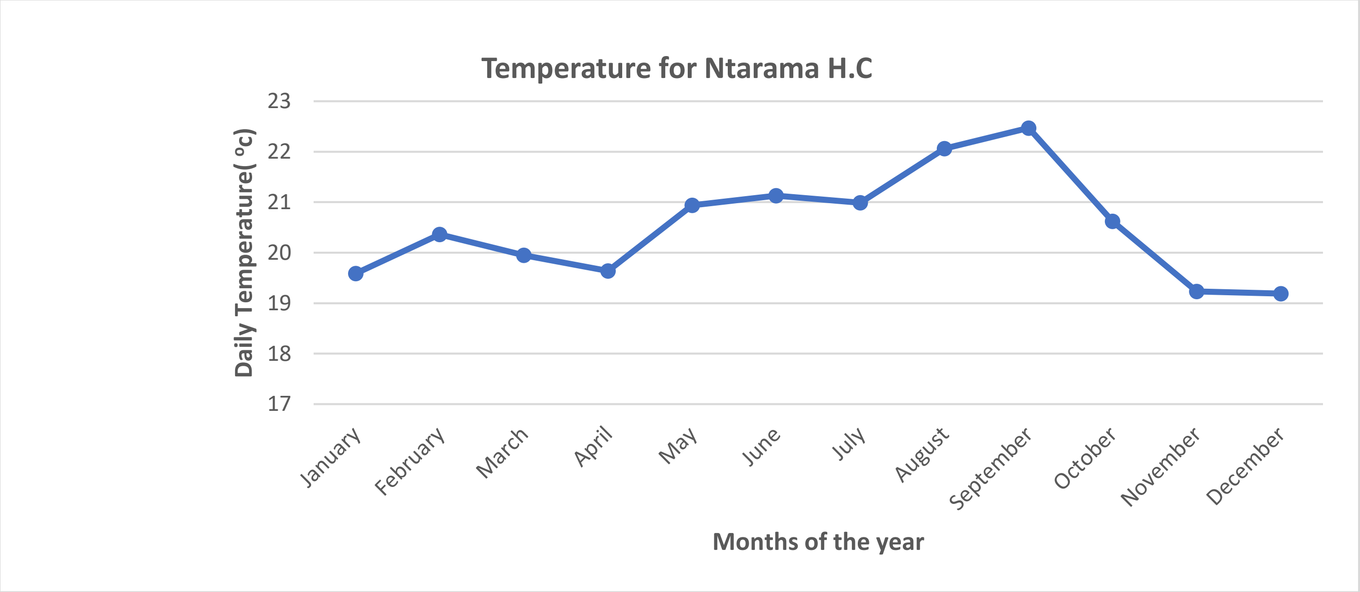


Figure 3. 7: Graphical representation of Temperature data for Ntarama H.C

3.2.4.2 Biomass Resources assessment

Biomass serves as a significant energy resource in Rwanda, especially in rural community regions. The country has various biomass resources available, such as agricultural residues, forestry products, municipal solid waste, animal waste, and human waste.

The biomass input for this study is Human waste from patients, staff, and other daily casual workers of Ntarama health center.

Biomass can be converted to energy through various methods whereby each method with specific advantages and limitations. This study does specifically use an anaerobic digestion technology for converting human waste into energy (biogas energy). Anaerobic digestion technology is selected for energy conversion because human waste is the most moisture biomass, high-quality raw material for biogas production with high methane (CH4) content of about 67.6%. The high portion of methane content in biogas makes it more flammable, higher energy generation as a result [8][9].

The researchers indicated that an adult can be expected to produce an average of 1-1.3 kg of urine and 0.2-0.4 kg of feces per day and the energy content or energy density of biogas is about 6 kWh/m³ [9].

Therefore, if we assume that one person is expected to produce 1.2 kg of urine and 0.4 kg of feces per day and the total average number of people attending at health center is equivalent to 500 as per the health center’s records of April 2024 Hence; the total averaged quantity of biomass can be calculated as follow:

- Average quantity of feces production: 0.4 kg/person/day
- Average quantity of urine production: 1.2 kg/person/day

Daily waste generation (in kg) = $(500 * 0.4) + (500 * 1.2) = 800\ kg$ Eq (3.2)

The averaged maximum quantity of biomass produced daily is 800 kg equivalent to 0.8 tons/day.

Daily biomass production is not constant for all months as the attendees to the health center vary and it leads to the increase and decrease in the total biomass quantity as the attendance increases and decreases accordingly.

This is why a solar PV and biomass-based hybrid system was designs to ensure the reliability of power supply to the health center. Table 3.6 and figure 3.8 show the average quantity of biomass generated per day in each month.

Table 3. 6: Monthly Average biomass data for Ntarama H.C for 2024

Month	**Available Biomass (t/d)**
January	0.74
February	0.77
March	0.76
April	0.8
May	0.72
June	0.73
July	0.67
August	0.69
September	0.71
October	0.72
November	0.79
December	0.78
Average	0.74

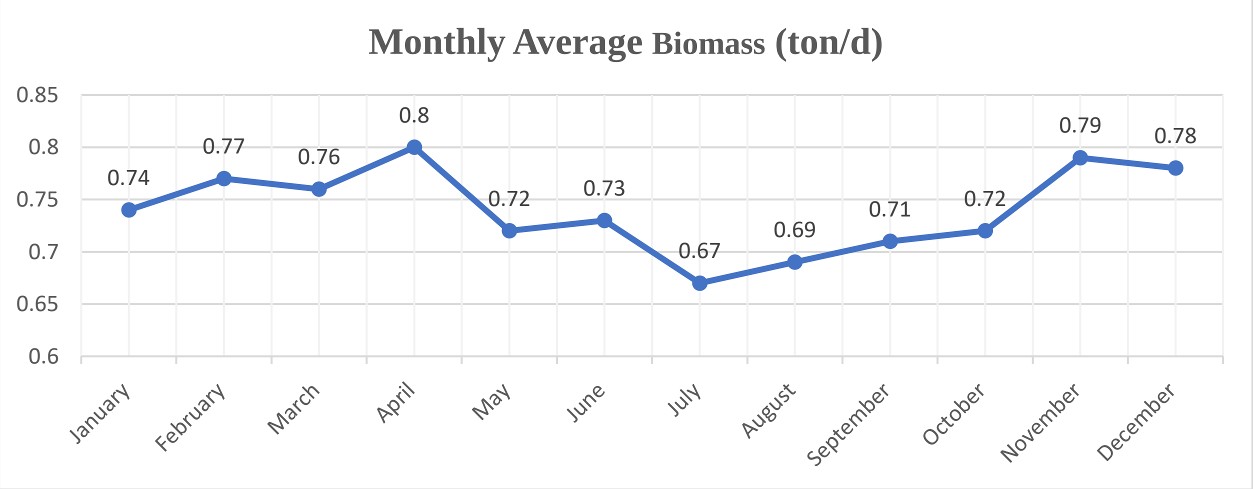


Figure 3. 8: Monthly Average biomass data for Ntarama H.C_2024

3.2.4.4 Architecture design of Hybrid system with battery storage for Ntarama H.C

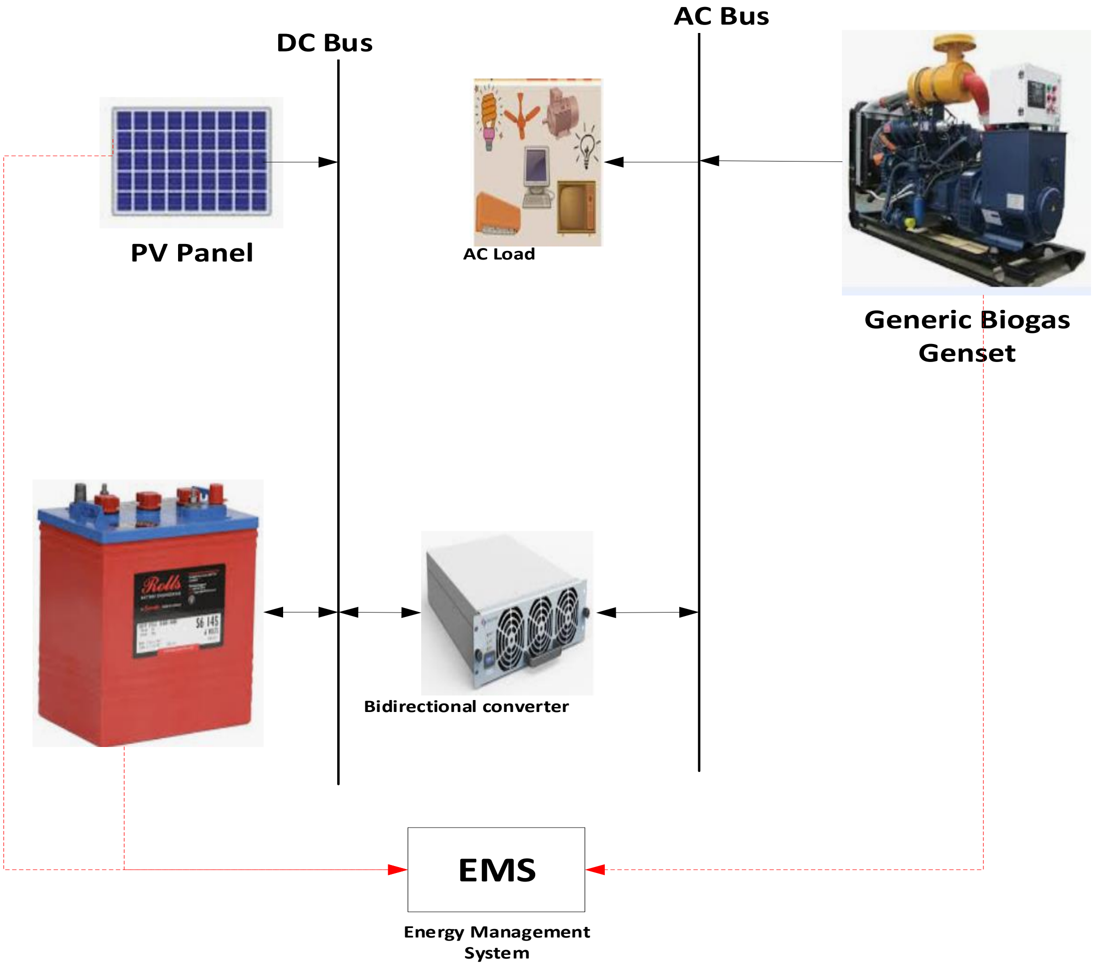


Figure 3. 9: Architecture design of PV and biomass-based hybrid system with battery

3.3 Mathematical Modeling of a hybrid system for Ntarama health center

The mathematical modeling and simulation techniques are crucial for energy system design and optimization.

The mathematical equations that will govern the electrical power from solar PV, biomass, and battery storage will be discussed in this section, and the flow chart of a control algorithm to supply the load will be developed.

3.3.1 Equation of power generated by solar PV System

The power generated by PV systems depends on solar radiation and the efficiency of PV panels.

$$\mathbf{Ppv} = \frac{Eload}{G * \eta system} \qquad \text{Eq (3.3)}$$

For Epv ≥ Eload

Where:

- E_{load} is Daily energy required by load from PV
- E_{pv} is Daily energy produced by PV
- P_{pv} is power of solar PV arrays (kW) at standard test condition (STC: 1kWh/m^2/day)
- G stands for solar radiation (kWh/m^2/day), Acting as effective peak sun hours
- η_{pv} stands for the PV panel efficiency
- η_{system} stands for an Overall System efficiency

3.3.2 Equation of Power Generated by Biogas generator

The power generated when the generator is operating **(**Pbio**)**

$$\mathrm{Pbio} = \frac{\mathrm{Erequired}}{\mathrm{t}} \qquad \text{Eq (3.4)}$$

Where:

- Pbio = Power generated by the biogas generator (kW)
- $E_{required}$ = Yearly energy produced by biomass source
- t = Operating time (hours)

3.3.3 Equation of Power from Battery Storage System

1. Discharging equation

The battery discharges when the PV and biomass generation do not meet the load demand.

$$Pbattery = (\eta battery * \frac{Ebattery}{\triangle t}) \qquad \text{Eq (3.5)}$$

Where:

- $P_{battery}$ is the power delivered by the battery
- $\eta_{battery}$ is the battery efficiency. Let's use 80%
- $E_{battery}$ is the available battery energy (kWh)
- Δt is the time step (hours)

2. Charging equation

$$Pcharge = \frac{Eexcess * \eta charge}{\triangle t} \qquad \text{Eq (3.6)}$$

Where:

- E_{excess} is the surplus energy to the load from solar and biomass available for charging the battery
- P_{Charge} is the power consumed by the battey during charging
- $\triangle$t is the time step (hours)

3.4 Optimization problem Formulation

3.4.1 Objective functions

The main goal is to minimize total net present cost (NPC) and maximize renewable energy utilization while ensuring reliable power supply

$$1.\ \mathbf{min}\, \boldsymbol{NPC} = \sum_{t=1}^{T} \left(\frac{\boldsymbol{Xcapital+XO\&M+Xreplacement-Xsalvage}}{\boldsymbol{(1+d)^\wedge t}} \right) \qquad \text{Eq (3.7)}$$

- NPC = Net Present Cost
- $X_{capital}$ = Capital cost of PV, biomass generator, batteries, and converters
- $X_{O\&M}$ = Operation & Maintenance cost
- $X_{replacement}$ = Replacement cost of components
- $X_{Salvage}$ = components salvage value at the end of the project
- d = Discount rate
- T = System lifetime (years)

$$2.\ \mathbf{max}\, \boldsymbol{REU} = \frac{\boldsymbol{Epv+Ebio}}{\boldsymbol{Eload}} \qquad \text{Eq (3.8)}$$

- REU = Renewable energy utilization
- E_{pv} = Energy generated by solar PV
- E_{bio} = Energy generated by biomass generator
- E_{load} = Total load demand

3.4.2 Decision variables

These are the decision variables to be optimized:

- X_{pv}= PV system size (kW)
- X_{bio} = Biogas generator capacity (kW)
- $X_{battery}$ = Battery storage capacity (kWh)
- $X_{converter}$ = Converter size (kW)

3.4.3 Constraints

i. Power balance constraint

The generated power must always meet the load demand:

$$\mathrm{Ppv(t)} + \mathrm{Pbio(t)} + \mathrm{Pdischarge(t)} \geq Pload(t) + Pcharge(t) \qquad \text{Eq (3.9)}$$

Where:

Ppv(t), Pbio(t), Pdischarge(t), Pload(t), and Pcharge (t) are PV, Biomass, battery discharge, load power, and battery charge power at the time (t), respectively.

ii. Battery state of charge (SOC) Constraints

$$\mathrm{SOC,min} \leq SOC(t) \leq SOC, max \qquad \text{Eq (3.10)}$$

Where:

- SOC, min: minimum allowable battery state of charge =40%
- SOC, max: maximum allowable state of charge =80%

Battery charge/discharge equation:

The state of charge (SOC) of the battery at the time (t) depends on charging and discharging power flows. The SOC represents the amount of energy stored in the battery relative to its total capacity.

$$SOC(t+1) = SOC(t) + \frac{Pbattery,in(t) * \eta charge - Pbattery,out(t)/\eta discharge}{Cbattery} \qquad \text{Eq (3.11)}$$

Where:

- SOC(t) = battery state of charge at time (t), (kWh)
- SOC(t+1) = Battery state of charge at next time step
- $P_{battery,\ in(t)}$ = Power stored (charging) in the battery at time (t), (kWh)

- $P_{battery,\ out\ (t)}$ = discharging power from the battery at time (t), (kWh)
- $\eta_{charge,\ discharge}$ = Battery charging and discharging efficiencies, respectively (typically 80%)
- $C_{battery}$ = Total battery capacity (kWh)

iii. Biomass Fuel availability constraints

The annual biomass consumption should not exceed available biomass:

$$\sum_{t=1}^{T} \frac{Pbio(t)}{\eta bio} \leq Available\ biomass\ Energy \qquad \text{Eq (3.12)}$$

Where:

- $P_{bio(t)}$: Biomass Power at time t
- η_{bio}: Biomass generator efficiency
- T: time in years

iv. Component Capacity Constraints

$$\mathrm{Xpv,min} \leq Xpv \leq Xpv, max$$

$$\mathrm{Xbio,min} \leq Xbio \leq Xbio, max$$

$$\mathrm{Xbattery,min} \leq Xbattery \leq Xbattery, max$$

$$\mathrm{Xconverter,min} \leq Xconverter \leq Xconverter, max$$

Where:

- $X_{pv,min}$, X_{pv} and $X_{pv,max}$ = Minimum, Nominal and Maximum PV system size (kW) respectively
- $X_{bio,min}$, X_{bio} and $X_{bio,max}$ = Minimum, Nominal and Maximum Biogas generator capacity (kW) respectively
- $X_{battery,min}$, $X_{battery}$ and $X_{battery,max}$ = Minimum, Nominal and Maximum Battery storage capacity (kWh) respectively
- $X_{converter,min}$, $X_{converter}$ and $X_{converter,max}$ = Minimum, Nominal and Maximum Converter size (kW) respectively

3.4.4 Control algorithms of hybrid system for Ntarama Health Center

As discussed in Chapter one; this study prioritizes local renewable energy sources for supplying Ntarama health center, Solar PV, biomass-based hybrid with battery storage and by applying the cycle charging dispatch strategy, the priority is Solar which will provide 88.9% and Biomass system which is designed for providing 11.1% of total forecasted load respectively, while the battery storage system has been designed for backing up entire system at 100% for ensuring its reliability.

When the power from PV is above the load demand, the surplus power will be used to charge the battery, otherwise; the power from Biomass will support PV for meeting the load. If the power from both PV and biomass is below the power demand, therefore; the stored energy in the battery will be used to meet the demand.

3.4.4.1 Flow chart Algorithm of a hybrid system for Ntarama H.C

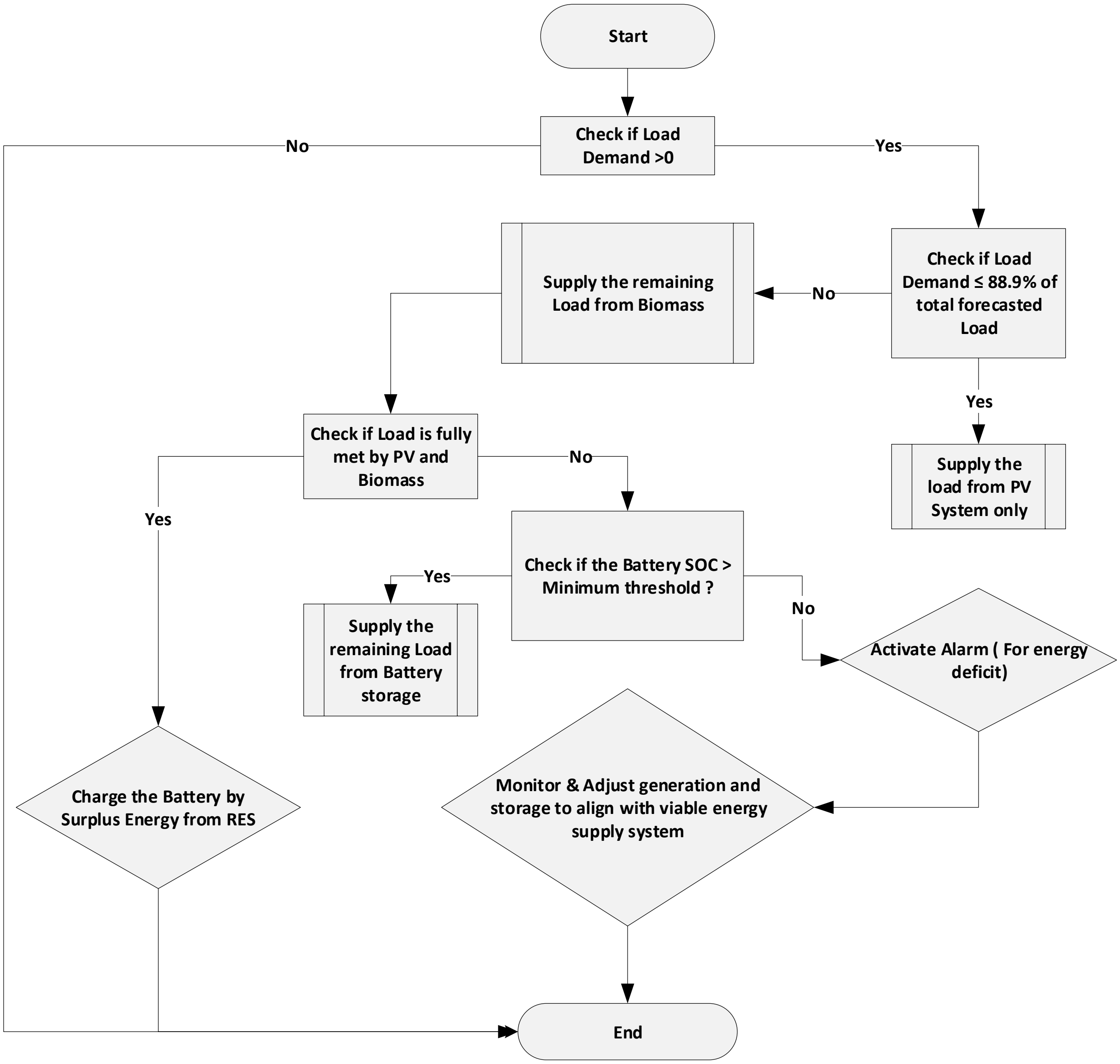


Figure 3. 10: Flow Chart of Algorithm for Ntarama H.C Hybrid power System

CHAP 4: SYSTEM DESIGN, SIMULATION AND DISCUSSION

4.1 Introduction

The design and Optimization of a Hybrid power system integrating Solar photovoltaic and biomass with Battery Storage have been carried out upon the gathered input data and the development of a systematic approach for ensuring reliability, and cost-effectiveness of the hybrid power system from the available local Renewable Energy Sources to satisfy the load demand of Ntarama health Center.

This chapter discusses the maximum capacity of PV Systems, Biomass generator capacity, and battery capacity as well as their technical specifications. HOMER Pro will facilitate technical, economic, and Environment analysis. An essential component of the hybrid system is solar-PV system (Converts solar radiation into electricity), Biomass generator (Converts biomass feedstock into electricity via anaerobic digestion), Battery storage system (Stores excess energy from renewable sources for later use for ensuring system reliability), and System converters (Convert DC to AC or vice versa and regulate power flow). Additionally, maximum load demand and future load forecasting also are important considerations when determining the optimum hybrid system. Reference is made to the augmentation in power consumed within two years 2023-2024 as discussed in chapter three, whereby the annual growth rate from Eq (3.1) was found to be 11.3%. therefore, the forecast for the following five years is computed as follow:

$$FL = CL(1 + r)^n \qquad \text{Eq (4.1)}$$

Where:

- FL: Future Load
- CL: Current Load = 13.005 kW/day power and 108.540 kWh/day Energy
- r: Growth rate = 11.3%
- N: Number of years =5

and $FL = 108.540\ (1 + 0.113)^5$ = 185.38 kWh

$FL = 13.005\ (1 + 0.113)^5$ = 22.21 kW

Therefore, the daily power and energy consumption within 5 years are 22.21 kW and 185.38 kWh respectively.

4.2 Design of system components

The primary load of Ntarama health center is AC type and it requires a three-phase energy supply system. Then, the configuration of solar modules and batteries will be based on the required input voltage range for the DC-AC voltage converter.

The voltage level for a three-phase AC system is 380 V, whereby a DC-AC converter with 400 Vdc input and 380 Vac output voltage was selected. The DC bus and AC bus of 400 Vdc and 380 Vac respectively have been used in this design.

4.2.1 Solar PV System sizing

Solar PV will provide 88.9 % of the total load, whereby the total daily consumption is 185.38 kWh.

Therefore, the solar PV contribution is $= \frac{Total\ demand * PV\ Contribution\ in\ \%}{100}$ Eq (4.2)

PV contribution $= \frac{88.9 * 185.38}{100}$ = 164.8 kWh/day

The PV output will be:

$E_{load} = \frac{PV\ contribution}{Derating\ factor}$ Eq (4.3)

Where:

- E_{load} is PV power output
- Derating factor is measuring factor of how produced power from PV array will be reduced due to dirt, snow, or other foreign matter falling on the solar PV surface.

If we consider the derating factor of 80%.

E_{load} = 164.8/0.8= 206 kWh/day.

Considering Minimum, Average, and Maximum solar radiation (4.63, 5.04, and 5.49) kWh/m2/day respectively from solar data resources at standard test conditions. the output power from solar PV panels will be:

$$\boldsymbol{Ppv} = \frac{\mathrm{Eload}}{G}$$ Eq (4.4)

Where:

- P_{PV}: PV power rating
- Gmin, Gav, Gmax is Minimum, Average, and Maximum solar radiation respectively

$$\text{Ppv at Gmin} = \frac{206}{4.63} = 44.48 \text{ kW} \approx 45 \text{ KW}$$

$$\text{Ppv at Gav} = \frac{206}{5.04} = 40.87 \text{ kW} \approx 41 \text{ kW}$$

$$\text{Ppv at Gmax} = \frac{206}{5.49} = 37.52 \text{ kW} \approx 38 \text{ kW}$$

Let us consider the output power of PV from the minimum solar radiation for meeting the load for all the time (For Sizing the PV to meet demand under worst-case conditions). The PV modules can be installed in Parallel and Series to increase the system current and voltage respectively.

Some Specifications of the selected Module are listed below:

- Rated peak Power = 380 W
- Open Circuit Voltage (Voc) = 48.8 V
- Short Circuit Current (Isc) =9.94 A

$$\text{Total number of modules (Nm)} = \frac{PV\ array\ size\ in\ kW}{Rated\ peak\ power\ per\ Module} \qquad \text{Eq (4.5)}$$

$$\text{Nm} = \frac{45\ KW}{0.38\ kW} = 117.08 \approx 118 \text{ modules}$$

$$\text{Total number of modules per string (Ns)} = \frac{System\ Voltage\ (Vdc)}{Open\ Circuit\ voltage\ of\ module\ (VOC)} \qquad \text{Eq (4.6)}$$

$$\text{Hence, NS} = \frac{400}{48.8} = 8.19 \approx 8 \text{ Modules}$$

Then, the number of modules in parallel (NP) will be given:

$$Np = \frac{Nm}{NS} \qquad \text{Eq (4.7)}$$

$$\text{Therefore, NP} = \frac{Nm}{NS} = \frac{118}{8} = 14.7 \approx 15 \text{ modules}$$

The total real number of modules is given by:

(Nm,r): NP x Ns Eq (4.8)

Nm,r = 15*8 = 120 modules.

Where:

- Nm: Total number of modules

- Ns: Total number of modules per string
- Np: Total number of modules in parallel
- Nm,r: Total real number of modules

4.2.2 Sizing of Battery Storage

This hybrid system uses batteries for storing energy from solar panels, which will be used for supplying the load in case the power from Renewables (PV and Biomass) is insufficient. The battery storage system ensures continuous power supply and helps in smoothing out fluctuations in energy production and consumption [24].

The size or capacity of a battery depends on the energy consumption (kWh) in each time and the required days of autonomy. The maximum depth of discharge of the battery (representing the limit of energy that is discharged from the battery) is another important factor to consider when carrying out the battery sizing. Some researchers indicate that most of the systems are designed for regular discharges from 40% to 80% [5].

The selected battery (Surrette 6 CS 25P) has 60% of the allowable rate of discharge and 80% efficiency with the following specifications:

Battery nominal voltage (Vb) = 6V

Rated battery capacity (Bc) = 820Ah

$$\text{Battery capacity (kWh)} = \frac{E*DA}{\eta inv*\eta batt*D.O.D} \qquad \text{Eq (4.9)}$$

$$\text{Battery capacity (CAh)} = \frac{E*DA}{\eta inv*\eta batt*Vn*D.O.D} \qquad \text{Eq (4.10)}$$

Where:

- Cah: Battery capacity in Ampere-hour
- E= E_{pv}: Daily energy from PV = 206 kWh/day from Eq (4.3)
- DA: days of autonomy = 1 day
- η_{inv}: Inverter efficiency = 95 %
- η_{batt}: Battery efficiency = 80%
- V_n: Nominal system voltage = 400 V
- D.O.D: depth of discharge = 60%

From Eq (4.9); Battery capacity (kWh) = $\frac{206*1}{0.95*0.8*0.6} = \frac{206}{0.456}$ = 451.75 kWh

From Eq (4.10); Battery capacity CAh, (Ah) = $\frac{206*1}{0.95*0.0.95*0.8*0.4*0.6} = \frac{206}{0.1824}$ = 1129.385 Ah

Battery connected in parallel or Number of string (Bp) = $\frac{CAh}{Bc}$ Eq (4.10)

Bp = $\frac{1129.385}{820}$ = 1.37 ≈ 2 strings

Number of batteries connected in series Bs = $\frac{Vn}{Vb}$ Eq (4.11)

Bs = $\frac{400}{6}$ = 66.67 ≈ 67 batteries

Total Battery (Nb) will be given by: $Bp * Bs$ Eq (4.12)

$$Nb = 2 * 67 = 134\ Batteries$$

Where:

- Bp: Battery connected in parallel or Number of strings
- Bc: Rated battery capacity in Ampere-hour
- Bs: Number of batteries connected in series
- V_n: Nominal system voltage
- Vb: Battery nominal voltage
- Nb: Total number of Battery

4.2.3 Sizing of Biogas Generator

Biomass feedstock, ambient temperature, and other factors considered in biogas production vary from time to time, therefore; biogas production is not constant during the day. That is why the biogas needs to be stored in the gas holder and used for electricity generation when required, biogas is combusted into biogas fueled generator to generate electricity [9].

As the biogas generator will cover only 11.1% of the total load; The energy required from the Biogas generator (**E_{bio}**) will be:

E_{bio} = $\frac{Total\ demand*Biogas\ \ Contribution\ in\ \%}{100}$ Eq (4.13)

$$Ebio = \frac{11.1*185.38}{100} = 20.577\ kWh/day$$

Where:

- E_{bio} = Energy generated by biomass generator

Suppose that the biogas generator will operate only one hour per day due to its limited feedstock. Therefore, it will operate 365 hours per year. The average power output of the generator will be.

$$\text{Pbio} = \frac{Erequired}{t} \qquad \text{Eq (4.14)}$$

Energy required per year = 20.77 kWh/day*365day = 7581.05 kWh

And the yearly operating hours = 365hours

Hence, from Eq (4.13); $\text{Pbio} = \frac{7581.05}{365} = 20.77\ kW \approx 21\ \text{kW}$

Where**:**

- P_{bio} = Power output of Biomass generator

4.2.4 Sizing of Converter

The converter is an electronic device used to convert direct current to alternating current (Inversion) or vice-versa (Rectification). The solar PV and Biomass-based hybrid system consists of both DC and AC buses. The converter transforms the DC power stored in the battery to AC electricity and converts an excess AC power generated by a biogas generator to DC before being stored in batteries. At optimum conditions. the sizing ratio (Rs) must be between 0.8 and 1.8 [25]**.**

Inverter capacity (DC to AC) P-AC,pv = ɳinv*Ppv Eq (4.15)

P-AC,pv = 45 kW*0.95 = 42.75 kW

Where:

- P-AC,pv: Inverter capacity
- η_{inv}: Inverter efficiency
- Ppv: Power rating of Solar PV

Rectifier Capacity (AC to DC) P-AC, biogas = η_{rect}*Ppv Eq (4.16)

P-AC, biogas = 21 kW*0.95 = 19.95 kW

Where:

- P-AC, biogas: Rectifier Capacity
- η_{rect}: Rectifier efficiency
- Ppv: Power rating of Solar PV

Rectification is carried out if we need to convert the generator output for charging the battery.

- P-AC, biogas = 21 kW if the generator output is directly used to supply the load (No conversion Losses)

The total system output (P-total) = P-AC, PV + P-AC,Biogas Eq (4.17)

P-total = 42.75 kW+19.95 kW= 62.7kW (with conversion)

And P-total = 42.75kW + 21 kW = 63.75 kW (if no conversion is required for generator output)

The inverter sizing ratio is given by: Rs = $\frac{Ppv}{Pinv}$ Eq (4.18)

Where:

- Rs: Inverter sizing ratio
- Ppv: Power rating of Solar PV
- Pinv: Inverter input power

Therefore, a system converter of sizing ratio including in predefined range can serve the purpose of this project

Sizing of charger controller:

The charge controller must handle the total current from the solar array.

$$\text{Charger controller capacity (Icc)} = \frac{Actual\ power\ from\ Solar\ PV}{system\ voltage} \quad \text{Eq (4.19)}$$

$$\text{Charger controller capacity (Icc)} = \frac{45}{400} * 1000 = 112.5\ A \approx 113\text{A}$$

Thus, a minimum of 113 A charge controller is sufficient for this system

CHAP 5: SIMULATION AND DISCUSSION

5.1 Introduction

The system has been designed and optimized according to the forecasted load to meet current and future power demands and to ensure the system's reliability. Hence, the validation of this system in HOMER Pro ensures that the system configuration meets energy demand, operates reliably, and minimizes NPC. The validation process includes performance assessment, cost evaluation, and sensitivity analysis.

HOMER Pro facilitated to carrying out of the simulation and setting all the required parameters for achieving a realistic load profile, whereby the adjustment of random variabilities was set to 10 % and 20 % day-to-day and time step respectively.

HOMER Pro estimates daily, seasonal, and yearly load profiles. It generates Average demand (kWh/day), average load (kW), peak load (kW), and load factor for both baseline and scaled [5].

5.2 Overview of HOMER Software

HOMER is defined as the hybrid optimization model for electric renewables. It is a computer model developed originally by the USA National Renewable Energy Laboratory (NREL).

HOMER Pro is the primary tool employed in this study for simulation and optimization.

It autonomously optimizes and determines the most cost-effective and viable system configuration. HOMR’s performance is robust, executed in three phases, namely Simulation, Optimization, and Sensitivity analysis providing a comprehensive evaluation of the system alongside technical and financial design details [5].

During the simulation process, the hourly working operation of a given power system configuration where the model is assessed annually for technical viability and cost over its life cycle.

Optimization involves exploring various system setups to identify the most cost-effective solution that satisfies energy demands and HOMER Pro achieves this by testing different combinations of component sizes and quantities whereas during the sensitivity analysis; HOMER Pro carries out many optimizations by considering a range of assumptions due to uncertainty or changes in inputs parameters like component efficiency, discount rate, etc.

Input data of daily load values for different hours are inputted in HOMER and then HOMER generalizes the yearly load profile.

5.3 System Simulation Options

HOMER software used in the modeling of different hybrid systems performs simulations based on the configuration arrangement of selected components to determine the optimum size and system performance. The optimum system is determined based on optimization and sensitivity analysis[13].

5.3.1 Search space

Optimum variables are chosen in HOMER and inserted in the search space worksheet. Optimization is carried out through variation of capacity and number of the different system components. Therefore, the HOMER Pro input search space of each component is provided for optimization purposes.

5.3.2 Sensitivity variables

Sensitivity variables are variables you can vary across a specified range to analyze their impact on system performance and optimization.

A different number of optimizations is carried out by considering different input assumptions. A sensitivity analysis shows how the selected optimum system configuration is likely to change due to variations in input parameters like component efficiency, load random variability, etc. In this study, the main sensitivity variables used during optimization are Nominal discount rates of 12%, 6%, to 24% respectively where 12% is found to be the best whereby it gives an optimal configuration.

5.3.3 Dispatch Strategy

Dispatch strategies manage battery charging in hybrid systems. Load Following (LF) matches generator output to demand, using PV surplus for Battery charging. Cycle- Charging strategy (CC) runs the generator at its full power, prioritizing battery charging before load supply [13].

In this study, the HOMER Cycle Charging dispatch strategy is used because it serves as a backup strategy to maintain system reliability whereby the uninterrupted power to the Health Center for critical load (like vaccine refrigerator, etc.) is non-negotiable. This means that both solar and biogas generators will supply the load for the Health Center. As PV surplus will charge the battery and whenever PV satisfies the load, the generator will be used to charge the battery and supply the load only when PV is disabled to meet the load.

5.3.4 Economics

During the evaluation of the economic viability of the Hybrid system, analysis of the cost of energy for each optimum system is carried out. Renewable energy systems are associated with high initial costs but low Operation and Maintenance costs within a given system lifetime.

5.3.5 Net Present Cost (NPC)

Net Present Cost (NPC) is the total lifetime cost of a system, discounted to present value, subtracting any salvage value (revenue). It includes initial, O&M costs, and replacement costs, plus fuel and emissions costs [13].

5.3.6 Levelized Cost of Energy (LCOE)

The Levelized cost of energy (LCOE) is used to make a comparison of various energy system configurations to select the optimal system. The system which has the least cost of energy is the optimum one [13].

$$LCOE = \frac{Total\ Annualized\ Cost\ of\ Energy}{Total\ Electrical\ consumption} \qquad \text{Eq (5.1)}$$

5.4 Input data and parameters in HOMER Pro Software

Input data required for HOMER Pro software to carry out the validation process of solar PV and biomass-based hybrid systems with battery storage, are the energy resources, Load profile data of the selected site, and the data of system components.

5.4.1 Inputted Load to HOMER Pro Software

The electrical load for Ntarama H.C. has been entered into the modeling tool and needs to be fully supplied by the Hybrid system. The primary load profile, which was determined in chapter three, has been inserted in HOMER Pro and then it provides a periodic load profile for Ntarama H.C as shown in Figure 5.1, Note that the random variabilities are included in the estimation of load demand for the H.C for having a more realistic electrical load profile.

Name: Ntarama H.C Electric Load

January Profile

Hour	Load (kW)
0	2.000
1	2.000
2	2.000
3	2.000
4	2.000
5	3.000
6	5.000
7	7.000
8	8.000
9	8.000

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/d)	165.44	185.38
Average (kW)	6.89	7.72
Peak (kW)	20.46	22.93
Load Factor	.34	.34

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

Scaled Annual Average (kWh/d): 185.38

Figure 5. 1: Inputted primary load profile for Ntarama Health Center in HOMER Pro

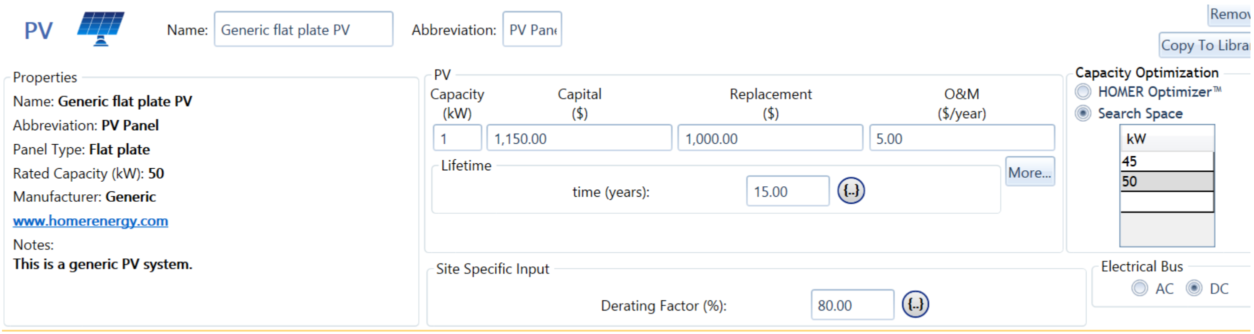
The baseline column shows the real load values without any added variables while the scaled one considers day-to-day and timestep variables and operating reserve of load growth.

5.4.2 Input system components to HOMER Pro Software

The necessary information on system components with corresponding capital, replacement, and O&M costs are inserted into HOMER Pro.

5.4.2.1 Inputted Solar PV data to HOMER tool

The solar PV capacity (kW), derating factor, capital, replacement, Operation, and Maintenances (O&M) cost have been inputted in HOMER Pro as shown in Figure 5.2



Name: Generic flat plate PV

Abbreviation: PV Pane

Properties

Name: **Generic flat plate PV**

Abbreviation: **PV Panel**

Panel Type: **Flat plate**

Rated Capacity (kW): **50**

Manufacturer: **Generic**

www.homerenergy.com

Notes:

This is a generic PV system.

PV

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	1,150.00	1,000.00	5.00

Lifetime

time (years): 15.00

Capacity Optimization

○ HOMER Optimizer™

● Search Space

kW
45
50

Site Specific Input

Derating Factor (%): 80.00

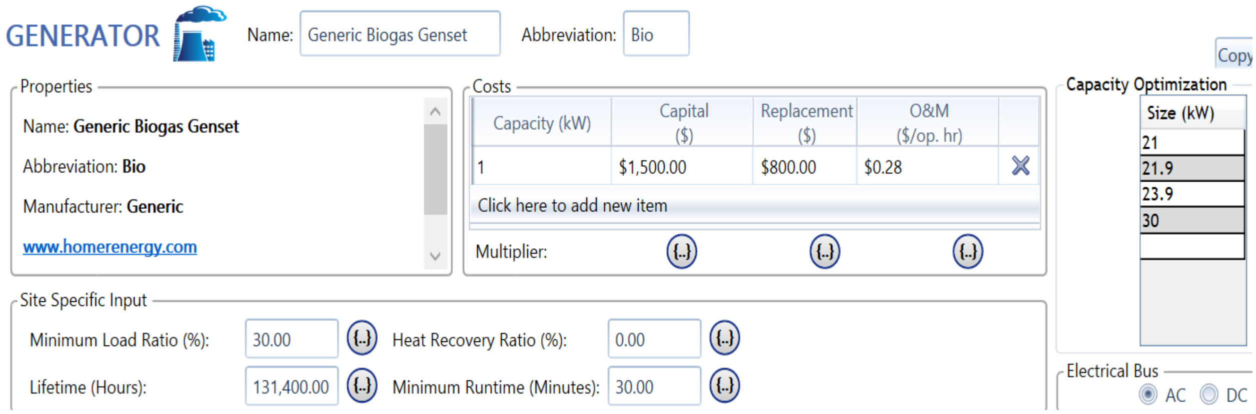
Electrical Bus

○ AC ● DC

Figure 5. 2: HOMER inputted data for Solar PV for Ntarama Health Center

5.4.2.2 Inputted Biogas Generator data to HOMER Pro software

The biomass generator power rating (kW), and costs have been inserted into HOMER



Name: Generic Biogas Genset
Abbreviation: Bio

Properties
Name: Generic Biogas Genset
Abbreviation: Bio
Manufacturer: Generic
www.homerenergy.com

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/op. hr)
1	$1,500.00	$800.00	$0.28

Click here to add new item

Multiplier:

Capacity Optimization

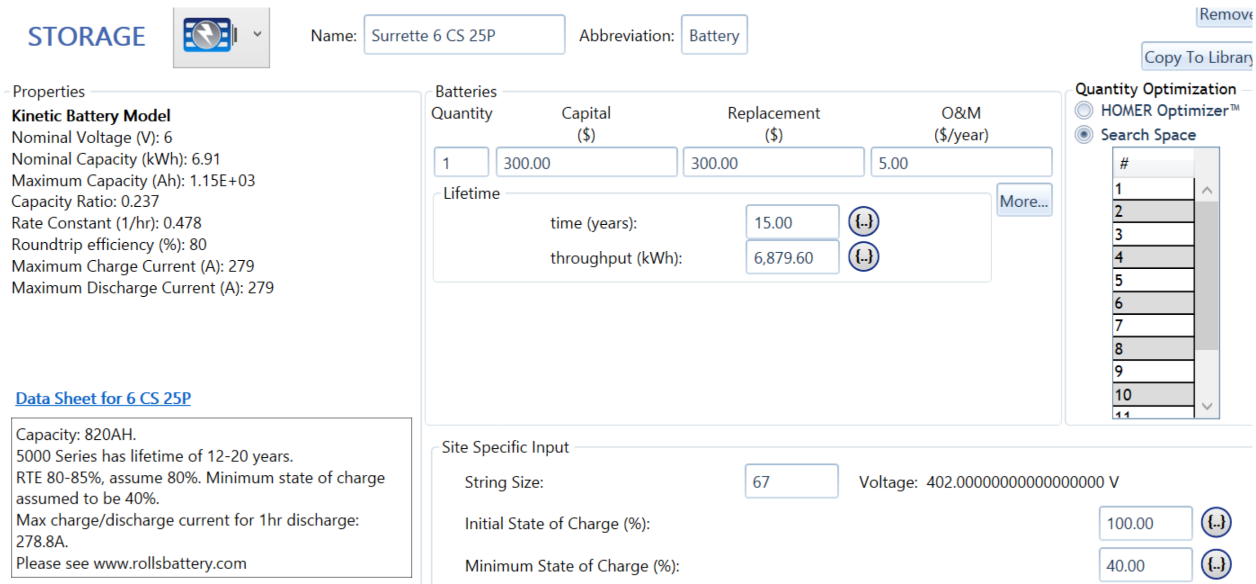
Size (kW)
21
21.9
23.9
30

Site Specific Input
Minimum Load Ratio (%): 30.00
Heat Recovery Ratio (%): 0.00
Lifetime (Hours): 131,400.00
Minimum Runtime (Minutes): 30.00

Electrical Bus ● AC ○ DC

Figure 5. 3: HOMER inputted data for Biogas Generator for Ntarama Health Center

5.4.2.3 Inputted Battery storage data to HOMER tool



Name: Surrette 6 CS 25P
Abbreviation: Battery

Properties
Kinetic Battery Model
Nominal Voltage (V): 6
Nominal Capacity (kWh): 6.91
Maximum Capacity (Ah): 1.15E+03
Capacity Ratio: 0.237
Rate Constant (1/hr): 0.478
Roundtrip efficiency (%): 80
Maximum Charge Current (A): 279
Maximum Discharge Current (A): 279

Data Sheet for 6 CS 25P

Capacity: 820AH.
5000 Series has lifetime of 12-20 years.
RTE 80-85%, assume 80%. Minimum state of charge assumed to be 40%.
Max charge/discharge current for 1hr discharge: 278.8A.
Please see www.rollsbattery.com

Batteries

Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	300.00	300.00	5.00

Lifetime
time (years): 15.00
throughput (kWh): 6,879.60

Quantity Optimization
○ HOMER Optimizer™
● Search Space

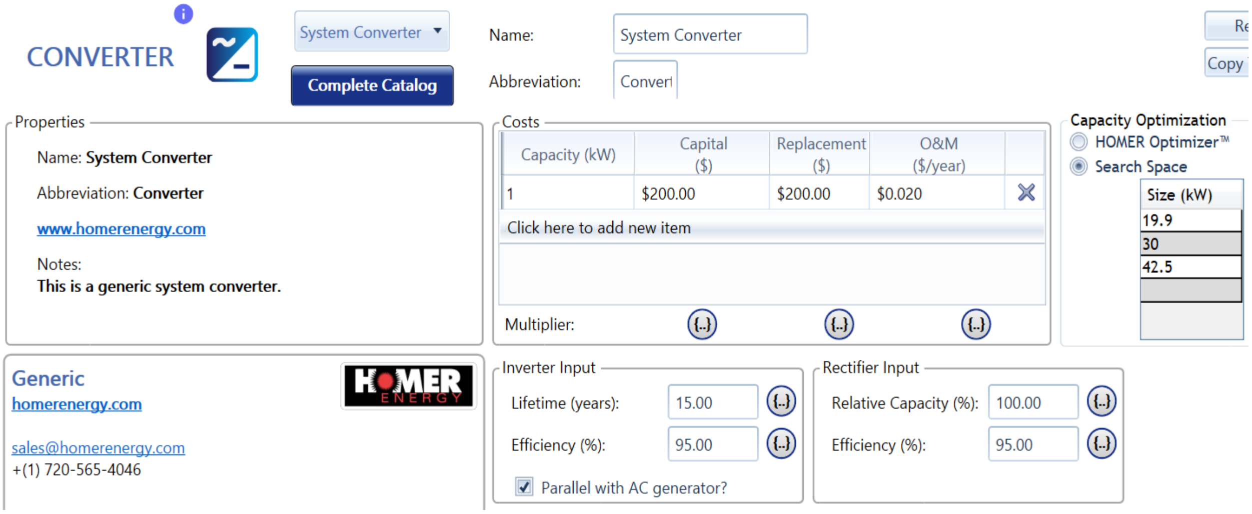
#
1
2
3
4
5
6
7
8
9
10

Site Specific Input
String Size: 67
Voltage: 402.0000000000000000 V
Initial State of Charge (%): 100.00
Minimum State of Charge (%): 40.00

Figure 5. 4: HOMER inputted data for Battery Storage

5.4.2.4 Inputted System Converter data to HOMER Pro software

Converter power rating, efficiency, capital, and replacement costs have also been inserted in HOMER Pro as shown in Figure 5.5



Name: System Converter

Abbreviation: Convert

Properties

Name: **System Converter**

Abbreviation: **Converter**

www.homerenergy.com

Notes:
This is a generic system converter.

homerenergy.com

sales@homerenergy.com
+(1) 720-565-4046

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	$200.00	$200.00	$0.020

Click here to add new item

Multiplier: {..} {..} {..}

Capacity Optimization

○ HOMER Optimizer™
● Search Space

Size (kW)
19.9
30
42.5

Inverter Input

Lifetime (years): 15.00

Efficiency (%): 95.00

☑ Parallel with AC generator?

Rectifier Input

Relative Capacity (%): 100.00

Efficiency (%): 95.00

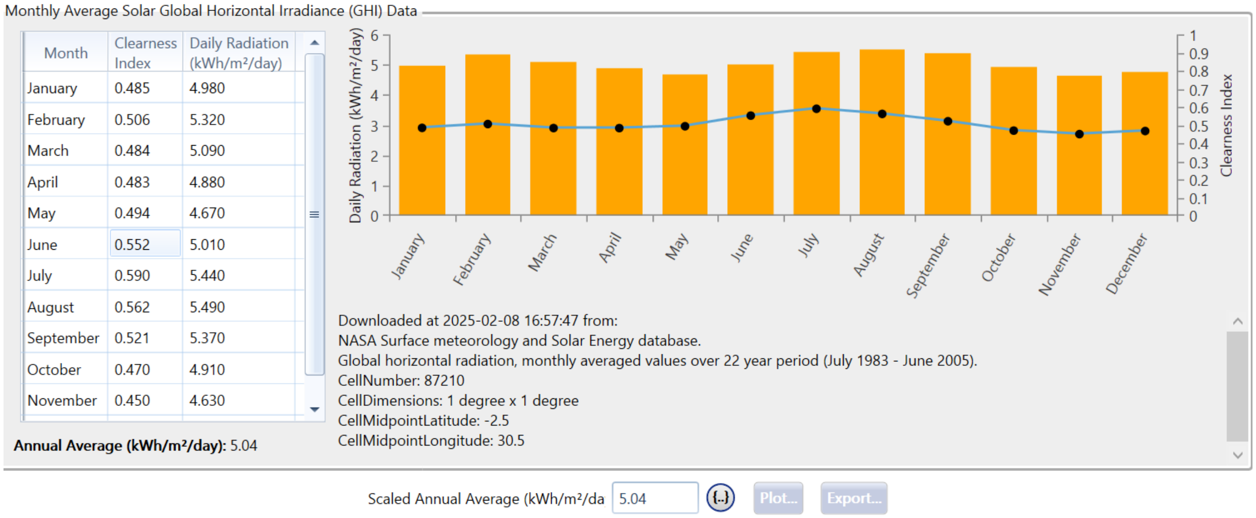
Figure 5. 5: HOMER inputted data for the system converter

5.4.3 Inputted resources to HOMER Pro Software

Energy resources are external inputs driving electricity or heat generation [5]. In this work, Solar radiation and biomass are key inputs. Solar availability is geographically and climatically determined whereas the Biomass yield is tied to local biological waste production.

5.4.3.1 Inputted Solar Resource to HOMER Pro software

The average monthly solar radiation data for the selected location was obtained from NASA as shown in Figure 5.6



Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.485	4.980
February	0.506	5.320
March	0.484	5.090
April	0.483	4.880
May	0.494	4.670
June	0.552	5.010
July	0.590	5.440
August	0.562	5.490
September	0.521	5.370
October	0.470	4.910
November	0.450	4.630

Annual Average (kWh/m²/day): 5.04

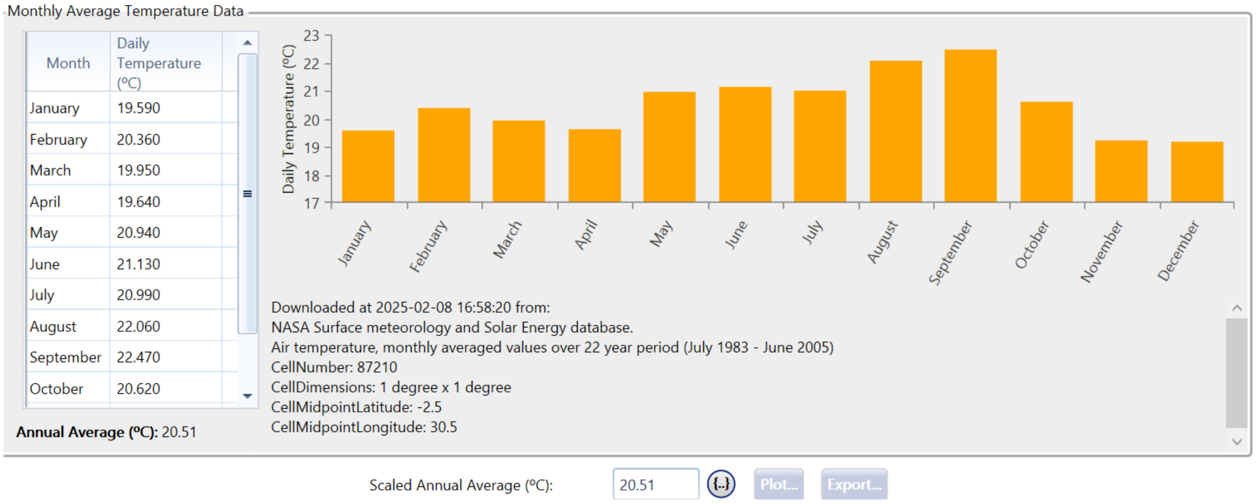
Downloaded at 2025-02-08 16:57:47 from:
NASA Surface meteorology and Solar Energy database.
Global horizontal radiation, monthly averaged values over 22 year period (July 1983 - June 2005).
CellNumber: 87210
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: -2.5
CellMidpointLongitude: 30.5

Scaled Annual Average (kWh/m²/da 5.04

Figure 5. 6: HOMER inputted data for solar resource for Ntarama Health Center

5.4.3.2 Inputted Temperature Resource to HOMER Pro

Monthly average temperature data (◦C) of Ntarama site found on NASA surface meteorology as shown in figure 5.7


Monthly Average Temperature Data

Month	Daily Temperature (ºC)
January	19.590
February	20.360
March	19.950
April	19.640
May	20.940
June	21.130
July	20.990
August	22.060
September	22.470
October	20.620

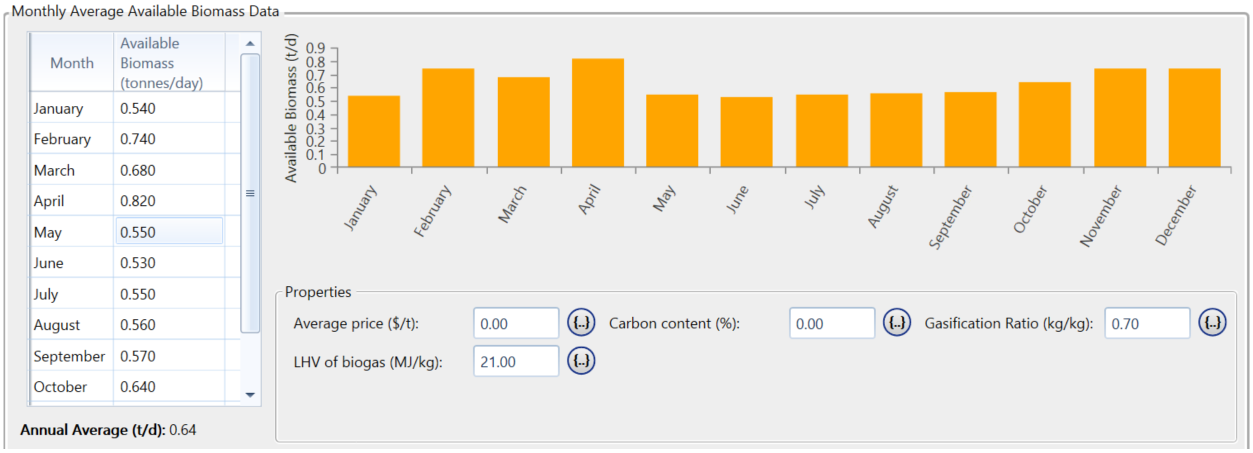
Annual Average (ºC): 20.51

Downloaded at 2025-02-08 16:58:20 from:
NASA Surface meteorology and Solar Energy database.
Air temperature, monthly averaged values over 22 year period (July 1983 - June 2005)
CellNumber: 87210
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: -2.5
CellMidpointLongitude: 30.5

Scaled Annual Average (ºC): 20.51

Figure 5. 7: HOMER inputted data for temperature for Ntarama health center

5.4.3.3 Inputted Biomass Resource to HOMER Pro


Monthly Average Available Biomass Data

Month	Available Biomass (tonnes/day)
January	0.540
February	0.740
March	0.680
April	0.820
May	0.550
June	0.530
July	0.550
August	0.560
September	0.570
October	0.640

Annual Average (t/d): 0.64

Properties

Average price ($/t): 0.00
Carbon content (%): 0.00
Gasification Ratio (kg/kg): 0.70
LHV of biogas (MJ/kg): 21.00

Figure 5. 8: HOMER inputted data for Biomass resources for Ntarama Health Center

5.5 The System Configuration

Hybrid system components supply both Direct and Alternating Electrical energies. Solar PV Panel generates DC which is inverted into AC for supplying AC loads or used to charge the battery as DC power. By using the combination of these components with a converter, AC energy can be obtained and supplied to the health Center’s loads. The converter can be used alternatively for rectifying the AC power from the Biogas generator for charging the battery.

The Hybrid Power System is therefore designed in HOMER Pro using both AC and DC bus couplers as shown in Figure 5.9

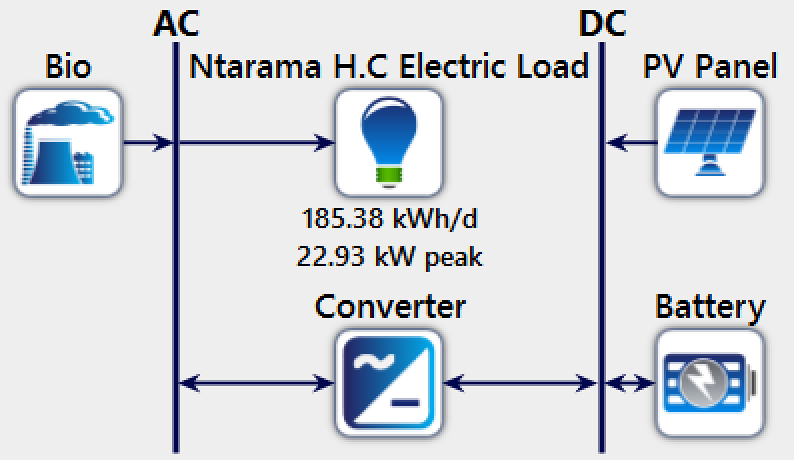


Figure 5. 9: Hybrid system configuration in HOMER Pro Software

5.6 Simulation Results and Discussion

A detailed simulation model was developed using HOMER Pro incorporates various system components and operational plans. This model evaluates system behavior under varying operational conditions based on provided data.

The design and optimization focused on identifying the hybrid power system configuration that satisfies the energy requirements of Ntarama Health Center while minimizing net present cost and levelized cost of energy while maximizing solar and biomass energy utilization.

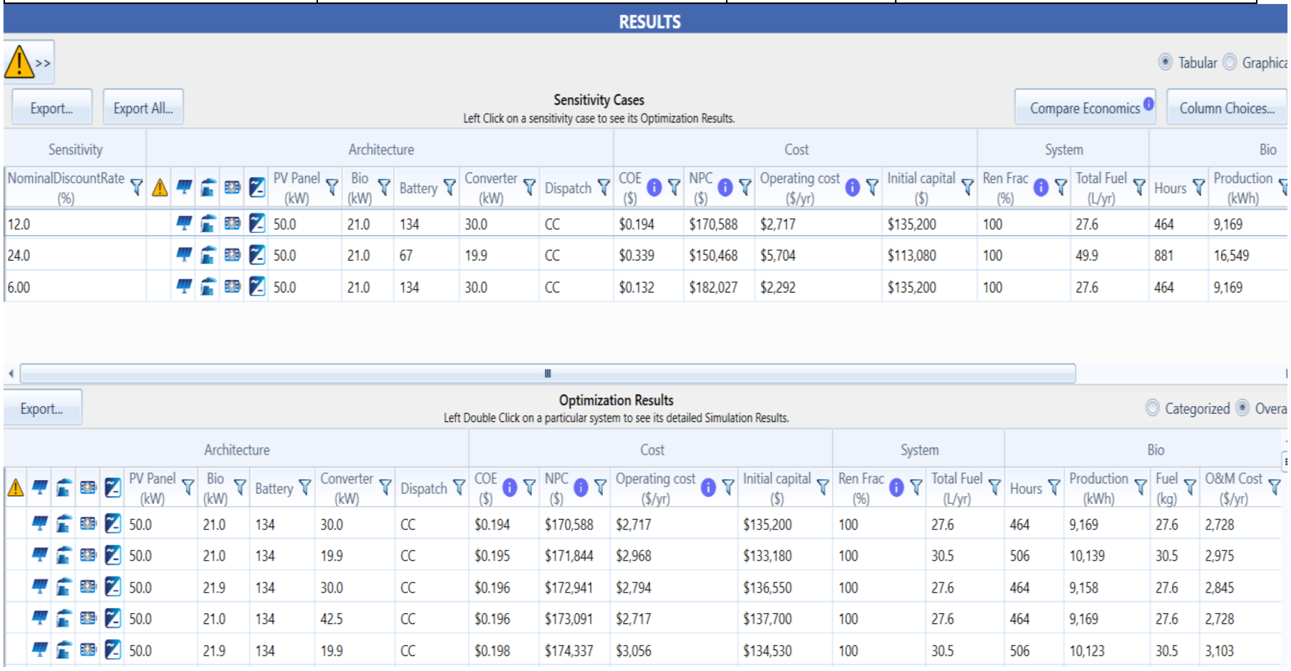
HOMER Pro determines optimal solutions for various system configurations, defining an optimal system as one that satisfies the load at the lowest net present cost. The simulation organizes the different viable system configurations according to Net Present Cost, with the configuration yielding the lowest Net Present Cost considered optimal.

5.6.1 Hybrid System Architecture

Table 5. 1:system architecture from simulation results

Component	Name Description	Size	Unit
Generator	Generic Biogas Genset	21	kW
Solar PV	Generic flat plate PV	50	kW
Battery Storage	Surrette 6 CS 25P	2	strings

System Converter	System converter	30	kW
Dispatch strategy	HOMER cycle- Charging		



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Sensitivity	Architecture					Cost				System		Bio	
NominalDiscountRate (%)	PV Panel (kW)	Bio (kW)	Battery	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)
12.0	50.0	21.0	134	30.0	CC	$0.194	$170,588	$2,717	$135,200	100	27.6	464	9,169
24.0	50.0	21.0	67	19.9	CC	$0.339	$150,468	$5,704	$113,080	100	49.9	881	16,549
6.00	50.0	21.0	134	30.0	CC	$0.132	$182,027	$2,292	$135,200	100	27.6	464	9,169

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture					Cost				System		Bio			
PV Panel (kW)	Bio (kW)	Battery	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (kg)	O&M Cost ($/yr)
50.0	21.0	134	30.0	CC	$0.194	$170,588	$2,717	$135,200	100	27.6	464	9,169	27.6	2,728
50.0	21.0	134	19.9	CC	$0.195	$171,844	$2,968	$133,180	100	30.5	506	10,139	30.5	2,975
50.0	21.9	134	30.0	CC	$0.196	$172,941	$2,794	$136,550	100	27.6	464	9,158	27.6	2,845
50.0	21.0	134	42.5	CC	$0.196	$173,091	$2,717	$137,700	100	27.6	464	9,169	27.6	2,728
50.0	21.9	134	19.9	CC	$0.198	$174,337	$3,056	$134,530	100	30.5	506	10,123	30.5	3,103

Figure 5. 10: Overall optimization and simulation results

From Table 5.1 and Figure 5.10, the best optimal configuration is the one with the lowest total net present cost of $170,587.90 with 50 kW photovoltaic, 21 kW Biogas generator, 134 Surrette 6CS25P batteries (2 strings with 67 series connected) and 30 kW system converter

5.6.2 Cost Summary

Table 5. 2: System Cost Summary

Net Present Cost						
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic Biogas Genset	$31,500	$35,538	$0.00	-$12,142	$0.00	$54,896
Generic flat plate PV	$57,500	$3,256	$0.00	$0.00	$0.00	$60,756
Surrette 6 CS 25P	$40,200	$8,727	$0.00	$0.00	$0.00	$48,927
System Converter	$6,000	$7.82	$0.00	$0.00	$0.00	$6,008
System	$135,200	$47,530	$0.00	-$12,142	$0.00	$170,588
Annualized Costs						
Name	Capital	Operating	Replacement	Salvage	Resource	Total

Generic Biogas Genset	$2,418	$2,728	$0.00	-$932.16	$0.00	$4,214
Generic Flat Plate PV	$4,414	$250	$0.0	$0.0	$0.0	$4,664
Surrette 6 CS 25P	$3,086	$670.00	$0.00	$0.00	$0.00	$3,756
System Converter	$460.62	$0.600	$0.00	$0.00	$0.00	$461.22
System	$10,379	$3,649	$0.00	-$932.16	$0.00	$13,096

From table 5.2, it is clear to discuss the component's total NPC. Solar Systems are more cost-effective in the long run due to their low operating costs and no fuel dependency, despite their higher initial capital cost they contribute 88.9%. Biogas generators are cheaper initially but incur high operating costs due to fuel consumption which makes them less economical over time and they contribute only 11.1%

5.6.3 Electrical Summary

Table 5. 3: Summary of production, consumption, Excess and unmet load for Ntarama H.C.

Excess and Unmet		
Quantity	**Value**	**Unit**
Excess Electricity	2,795	kWh/year
Unmet Load	0	kWh/year
Capacity Shortage	0	kWh/year
Production Summary		
Component	**Production (kWh/year)**	**%**
Generic flat plate PV	73,688	88.9
Generic Biogas Genset	9,169	11.1
Total	82,857	100
Consumption Summary		
Component	**Consumption (kWh/year)**	**%**
AC Primary Load	67,644	100
DC Primary Load	0	0
Total	67,644	100

The solar PV system is projected to fulfill 88.9% of energy requirements, whereas the biogas Generator will account for only 11.1%. the system exhibits no unmet load and no capacity shortages, with an annual electricity surplus of 3.37%

5.6.4 Biogas Generator

Table 5. 4: Simulation result for a biogas generator

Electrical Summary		
Quantity	Value	Unit
Production	9,169	kWh/year
Mean output	19.8	kW
Minimum output	6.30	kW
Maximum output	20.5	kW
Fuel Summary		
Quantity	Value	Units
Consumption	27.6	Tons/year
Specific consumption	2.11	Kg/kWh
Fuel energy input	112,658	kWh/year
Mean electrical efficiency	8.14	%
Generic Biogas Genset Statistics		
Quantity	Value	Units
Hours of operation	464	Hours/year
Number of starts	22.0	Starts/year
Operational life	283	year
Capacity factor	4.98	%
Fixed generation cost	6.01	$/hour
Marginal generation cost	0	$/kWh
Biogas consumption Statistics		
Quantity	Value	Units
Total feedstock consumed	27.6	tons
Average feedstock per day	0.0756	Tons/day
Average feedstock per hour	0.00315	Tons/hour

The total feedstock consumed for selected biogas generators is only 27.6 tons per year, the average feedstock is 0.0756 tons/day and 0.00137 tons per hour with specific fuel consumption equal to 2.11 kg/kWh. The mean electrical output is 19.8 KW, the minimum power that can be produced by a biogas generator is 6.30 kW and the maximum electrical output is 20.5 kW.

5.6.5 Photovoltaic PV

Table 5. 5: Simulation results for Solar PV

PV Electrical Summary		
Quantity	value	Units
Minimum output	0	kW
Maximum output	47.3	kW
PV penetration	109	%
Hours of operation	4380	Hours/year
Levelized cost	0.0633	$/kWh
PV Statistics		
Quantity	Value	Units
Rated Capacity	50	kW
Mean Output	8.41	kW
Mean Output	202	kWh/day
Capacity Factor	16.8	%
Total Production	73,688	kWh/yr

5.6.6 Battery Storage: Surrette 6 CS 25P

Table 5. 6: Simulation results for battery storage

Battery properties		
Quantity	Value	Units
Batteries	134	Pieces.
String size	67	batteries
Strings in parallel	2	strings
Bus Voltage	402	V

Surrette 6 CS 25P Result Data		
Quantity	Value	Units
Average energy cost	0	$/kWh
Energy In	45,630	kWh/yr
Energy Out	36,871	kWh/year
Storage depletion	411	kWh/year
Losses	9,169	kWh/year
Annual throughput	41,223	kWh/year
Surrette 6 CS 25P statistics		
Quantity	Value	Units
Autonomy	71.9	hours
Storage wear cost	0.0488	$/kWh
Nominal Capacity	962	kWh
Usable nominal capacity	555	kWh
Lifetime throughput	618,349	kWh
Expected life	15	years

From the simulation results as indicated in Table 5.6, the hybrid power system to operate at its optimum capacity and meet the load reliably at a reasonable cost, the total number of batteries is 134 configured in two parallel strings with 67 batteries for each string with a bus voltage of 402V with an autonomy of about 3 days

5.6.7 Converter: System Converter

Quantity	Inverter	Rectifier	Units
Capacity	30.0	30.0	kW
Mean Output	7.30	0.593	kW
Minimum Output	0	0	kW
Maximum Output	22.9	18.3	kW
Capacity Factor	24.3	1.98	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	8,314	445	hrs/yr
Energy Out	63,961	5,193	kWh/yr
Energy In	67,327	5,466	kWh/yr
Losses	3,366	273	kWh/yr

Figure 5. 11: Simulation results for system converter

At the optimum operating condition of the designed hybrid system, 30 kW converter capacity was selected with inverter and rectifier statistics as shown in Figure 5.11.

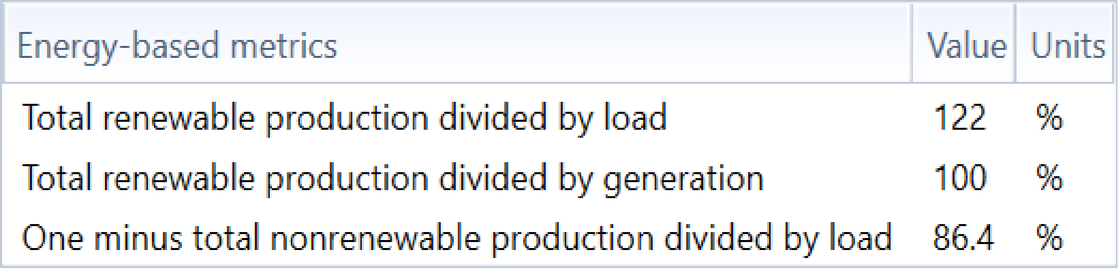
5.6.8 Emissions

Table 5. 7 : Simulation results for Emissions

Pollutant	**Quantity**	**Units**
Carbone Dioxide	-0.0867	Kg/year
Carbone monoxide	0.0552	Kg/year
Unburned Hydrocarbons	0	Kg/year
Particulate matter	0	Kg/year
Sulfur Dioxide	0	Kg/year
Nitrogen Oxide	0.0345	Kg/year

The simulation results show the quantity of emitted gases by this hybrid system as shown in Table 5.7. note that there is a saving of carbon dioxide as it is indicated by its negative value

5.6.9 Renewable penetration

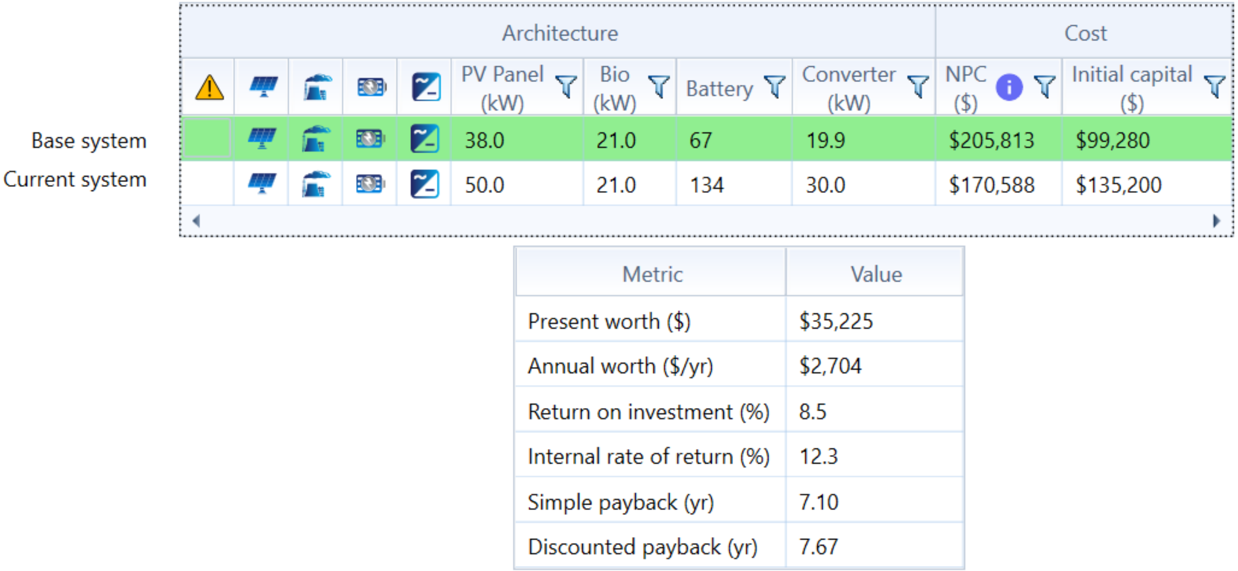


Energy-based metrics	Value	Units
Total renewable production divided by load	122	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	86.4	%

Figure 5. 12 : Simulation results for renewable penetration

From Eq (3.8), the Renewable Energy utilization $= \frac{Epv+Ebio}{Eload} = \frac{82,857}{67,664} = 1.224 \approx 122\%$

5.6.10 Compare Economics



	Architecture									Cost	
	⚠					PV Panel (kW)	Bio (kW)	Battery	Converter (kW)	NPC ($)	Initial capital ($)
Base system						38.0	21.0	67	19.9	$205,813	$99,280
Current system						50.0	21.0	134	30.0	$170,588	$135,200

Metric	Value
Present worth ($)	$35,225
Annual worth ($/yr)	$2,704
Return on investment (%)	8.5
Internal rate of return (%)	12.3
Simple payback (yr)	7.10
Discounted payback (yr)	7.67

Figure 5. 13: Economic comparison

The simulation indicates a return on investment of 8.5% and a payback period is 7.10 years. Thus, the initial investment will be recouped in 7.10 years via cost savings

5.7 Economic Analysis

A comparison was made between the hybrid system's energy cost and Rwanda's national Grid rates. Rwanda's Electricity tariffs, set by Rwanda Utility Regulatory Authority (RURA) since 21st January 2020, are adjusted quarterly to cover operational and Network expansion Costs. The Government provides an annual subsidy amounting to 10.5 billion, and tariffs are further modified to reflect fluctuating external costs like fuel and currency exchange [26].

To date, the tariffs set in 2020 are still in use. Therefore, the archived exchange rate from Rwanda National Bank (BNR) as of 21st January 2020 indicated the average exchange rate of 1 USD = 924.751 Rwf.

From Eq (5.1); $LCOE = \frac{Total\ Annualized\ Cost\ of\ Energy}{Total\ Electrical\ consumption} = \frac{13{,}096}{67{,}644} = \$0.1936 \approx \$0.194$

The levelized cost of energy is \$0.194 corresponds to 0.194*924.751= 179.4 Rwf, and this is an indicator of the potential benefits of full utilization of local underutilized energy s

resources to address and mitigate the problem of energy scarcity in underserved rural regions in Rwanda.

Table 5. 8: Summarized comparison of COE for National Grid and designed Hybrid System

Customer	Energy consumption in kWh	COE as of 21st January 2020 (Rwf)	Hybrid system COE (USD)	Hybrid system COE Refer to Archived exchange rate as of 21st January 2020 (Rwf)
Health facilities	All	**186**	0.194	**179.4**

The estimated primary energy demand as shown in Table 5.3 is 67,664 kWh/year. Therefore, let's conduct an annual cost calculation from both systems for economic evaluation as follows:

- Annual total cost of energy if H.C is supplied by National Grid (A) =186Rwf/kWh* 67,664 kWh/year = 12,585,504 RWF/year
- Annual total cost of energy if H.C uses hybrid system (B) =179.4 Rwf/kWh* 67,664 kWh/year = 12,138,921.6 RWF/year

The cost comparison between the RE hybrid system and the National Grid indicates that the hybrid system is a bit more cost-effective for electricity generation as it has less cost of energy. The annual saving will be calculated as the difference between the cost of energy from the Grid and the cost of energy from the designed RE hybrid system as follows:

$$Annual\ saving = \mathrm{A} - \mathrm{B} \qquad \text{Eq (5.2)}$$

$$\text{Annual Saving} = \ 12{,}585{,}504\ - 12{,}138{,}921.6 = 446{,}582.4\ \text{Rwf}$$

In addition, the digestates are good soil fertilizers, they can be a source of money once sold to the farmers and provide another income to the Ntarama Health Center.

CHAP 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The optimal configuration of solar PV and Biomass-based hybrid system with battery storage was performed for the electrification of Ntarama Health Center. The study aims to determine the most cost-effective hybrid system configuration utilizing local renewable energy sources to ensure reliable electricity access for the Health Center**.**

The study was started by load calculation and conducting energy consumption analysis along with assessing the potential of available local energy resources (solar and biomass) at Ntarama Health Center. The current connected load and energy consumption were found to be 13.005 kW and 108.540 kWh respectively. Load forecasting was conducted over 5 years to accommodate future demand, whereby an annual growth rate of 11.3% was found from time series energy consumption as shown in Eq (3.1) for Ntarama H.C within 2023 and 2024 years. Hence, the forecasted load was found to be 22.21 kW and 185.38 kWh respectively. Monthly averaged solar radiation data and air temperature of Ntarama H.C at Latitude of 2°5.2'S and Longitude of 30°2.2'E, revealing solar radiation values ranging from 4.63 (Gmin) in November to 5.49 (Gmax) in August, with an annual average of 5.04 kW/m²/day and daily averaged biomass production of 0.740 tons have been assessed.

Afterward, HOMER Pro software facilitated validation system operation and to refine the system configuration by optimizing the component's sizes and carrying out an economic analysis for the hybrid system of Ntarama Health Center, yielding various configurations ranked by Net Present Cost, thereby the most optimal configuration was identified as having the lowest Net Present Cost.

The daily baseline energy consumption was 165.44 kWh, while the daily scaled value was 185.38 kWh. The baseline peak demand was 20.46 kW and a scaled peak load demand of 22.93 kW with load factor of 0.34

According to HOMER Pro simulation results, the system is highly renewable utilizing primarily solar energy (88.9%) supplemented by biogas generation (11.1%), achieving complete energy autonomy with 71.9 hours of battery backup. The optimal configuration consists of 50 kW photovoltaic array, 21 kW biogas generator, two strings of 67 batteries for each string, and 30 kW system converter.

This system has no unmet load or capacity shortages, but it has an annual electricity surplus of approximately 2,795 kWh (3.37 %) and this excess will ensure reliability during unexpected demand spikes or generation drops and ensure sustainable operation when biomass availability is low. The system is economically viable with $0.194/kWh LCOE and $170.587.90 total Net Present Cost. The system is an environmentally friendly due to its low CO2 emissions.

Finally, the economic analysis indicates that the cost of energy from hybrid renewable energy sources for the health center is low compared to National Grid, where the annual saving is 446,582.4 Rwf. This system is therefore cost-effective, diminishes dependence on fossil fuels, reduces waste management expenses, and improves healthcare service delivery. It is in this context, that Ntarama Health Center may utilize these findings as foundational research to design its own hybrid power systems.

6.2 Recommendation

Rwanda aims to achieve Universal electricity access by 2028, as initially stated. This target drives the county's energy development strategies. Thus, people are encouraged to use available local renewable energy source to support the government in achieving this goal.

In pursuit of enhancing renewable energy, energy infrastructure, security, and environmental management, various challenges such as limited capacity, geographical constraints, funding issues, and outdated networks hinder grid expansion. To fully realize its renewable energy goals, the Government of Rwanda must create clear incentives for private sector investment via supportive regulatory frameworks, strategic planning, partnerships, and economic incentives. This study examines solar PV and biomass-based hybrid systems at Ntarama Health Center, with recommendations for further research at additional potential sites to align with government objectives for an all-inclusive power management strategy utilizing an intelligent energy control system mechanism.

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