UNIVERSITY of RWANDA

COLLEGE OF SCIENCE
AND TECHNOLOGY

ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

MASTER OF SCIENCE IN RENEWABLE ENERGY

TOPIC:

Design and Simulation of a PV-Battery Microgrid System for Murya Village - Gasenyi center

Research thesis done and submitted by

By: **MUHIRE Emmanuel**

REG.NO: **222022408**

A dissertation submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN RENEWABLE ENERGY ENGINEERING at African Center of Excellence in Energy for Sustainable Development (ACE-ESD), College of Science and Technology, University of Rwanda.

Thesis Advisor: **Dr. HAKIZIMANA Eustache**

March 2025

DECLARATION

I, MUHIRE Emmanuel, hereby declare that this research thesis constitutes my original work and has not been submitted for a degree at the University of Rwanda or any other universities. All sources of materials utilized in this work have been fully acknowledged in the appropriate academic format.

Signature: ………………… Date: ………….............

By: MUHIRE Emmanuel
REG.NO: 222022408

This research thesis has been submitted for examination with an endorsement of a university supervisor.

Signature: ………………… Date: ………….............

Approved by the Supervisor:
Dr. Eustache HAKIZIMANA

DEDICATION

This research thesis is primarily dedicated to my wonderful wife, Beathe KAMPIRE, my children, my professors, and my classmates for the encouragement and moral support I received during this journey.

ACKNOWLEDGEMENTS

I want to express my profound appreciation to everyone who has supported me throughout this extensive and fulfilling journey of education. First and foremost, I'm sincerely thankful to my lovely family for their constant encouragement and confidence in my capabilities. I am extremely appreciative of my lecturers, especially Dr. Eustache, Dr. Venant KAYIBANDA, Dr. Innocent, Prof. Biru, Dr. Maxime, Dr. RUGANZU, and Dr. Alice, for their essential guidance and the reassurance they offered during my Master's courses and thesis work. Their mentorship has been crucial in influencing my academic and personal development. I also wish to recognize the University of Rwanda for the excellent support and resources they provided during my studies, which played a significant role in my great achievements. At last, I amplify my appreciation to my classmates for their collaboration, insightful ideas, and unwavering support. Their camaraderie made this journey not only productive but also enjoyable.

ABSTRACT

Reliable electricity access remains a crucial challenge for many rural communities in Rwanda, significantly affecting socio-economic development. Gasenyi center, located in Nzahaha Sector, Rusizi District, currently lacks grid connectivity, necessitating alternative energy solutions. This research explores the design and optimization of standalone photovoltaic (PV) with battery microgrid system as a sustainable alternative to grid extension. The research aligns with Rwanda's National Electrification Plan, which promotes off-grid solutions to enhance rural energy access.

The essential objective of this study is to design an optimized off-grid PV and battery microgrid system tailored to Gasenyi center's energy needs. Key objectives include assessing the village's electricity demand, selecting appropriate solar and storage technologies, evaluating technical and economic feasibility, and applying optimization techniques to improve system performance and cost-effectiveness.

A detailed methodology was adopted, incorporating comprehensive data collection on local electricity consumption patterns, solar resource availability, and meteorological conditions. The study used PVsyst 7.4 software to simulate system performance, ensuring an optimal configuration of PV panels, battery storage, and inverters. The financial assessment was performed by utilizing Net Present Value (NPV) and Levelized Cost of Energy (LCOE) measures to evaluate economic feasibility.

The findings indicate that the proposed microgrid system can generate 74,010 kWh annually, covering 73.09% of the village's energy needs. A 44 kWp solar PV array, supported by a 255.6 kWh lithium-ion battery storage system, ensures a reliable power supply with minimal energy wastage. The system achieves an 81.66% performance ratio, demonstrating high efficiency. The financial analysis confirms long-term economic viability, with significant cost savings compared to diesel-based alternatives.

This study confirms that a standalone PV and battery microgrid system is both a technically and economically viable solution for electrifying Gasenyi center. The findings support broader policy initiatives promoting decentralized renewable energy systems for rural electrification. Future research should explore additional cost reductions and potential hybrid integrations with other renewable sources to enhance system resilience and sustainability.

Keywords: *Rural electrification, Renewable Energy, Off-grid PV Systems, Grid lines, solar home systems, mini-grid systems.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

EDPRS:	Economic Development and Poverty Reduction Strategy
LCOE:	Levelized Cost Of Energy
GoR:	Government of Rwanda
MPPT:	Maximum Power Point Tracker
EICV3:	Third Integrated Household Condition Survey
IED:	Innovation Energy Development
HOMER:	Hybrid Optimization Model for Electric Renewables
NPV:	Net Present Value
ESMAP:	Energy Sector Management Assistance Program
SHS:	Solar Home System
GHG:	GreenHouse Gases
GlobHor:	Global Horizontal Irradiation
PVGIS:	Photovoltaic Geographical Information System
Fiff Hor:	Horizontal Diffused Irradiation
IRENA:	International Renewable Energy Agency
GlobInc:	Global Incident in coll plane
NREL:	National Renewable Energy Laboratory
IPP:	Independent Power Producer
NGOs:	Non-Governmental Organizations
IRR:	Internal Rate of Return
DDP:	District Development Plan
AC:	Alternating Current
DC:	Direct Current
T_Amb:	Ambient Temperature
NPC:	Net Present Cost
GlobEff:	Effective Global, Corr. For IAM and Shadings
PV:	Photovoltaic
EArray:	Effective Energy at the output of the array
E_User:	Energy supplied to the User
E_Solar:	Energy From The Sun

EFrGrid:	Energy from the grid
E_Avail:	Available solar energy
SolFrac:	Solar Fraction (E-used/E-load)
GlobInc:	Global incident Irradiance
EArrMPP:	Array virtual energy at MPP
PV:	Photovoltaic
MPP:	Maximum power point
GHI:	Global Horizontal Irradiation
LCOE:	Levelized Cost Of Energy
E_Grid:	Energy injected into grid
BESS:	Battery Energy Storage System
REG:	Rwanda Energy Group
C&I:	Commercial and Industrial

CHAPTER 1. GENERAL INTRODUCTION

1.1. Introduction

This research addresses the critical issue of energy access in Murya village Gasenyi center, located in the Nzahaha sector of Rwanda's Rusizi District, where the lack of reliable and affordable electricity hampers socio-economic development. The study proposes a standalone photovoltaic (PV) and battery microgrid system as an economical and environmentally friendly substitute for grid extension, leveraging the region's abundant solar resources. The project seeks to contribute to sustainable development goals by promoting renewable energy in underserved rural areas [1].

One important factor in the fight against greenhouse gas emissions and global warming is the usage of renewable energy sources. In actuality, the widespread benefits of protecting natural resources have propelled significant advancements in solar system development in recent years. Given their finite supply and proven role in climate change, it is also obvious that fossil fuel-based energy sources will ultimately run out. Clean and sustainable energy sources like solar power, captured by photovoltaic systems, may be very beneficial to protect our environment and provide access to electricity in isolated areas. [1]

1.2. Background and motivation

The global energy challenge of unequal energy access, especially in developing countries' rural areas, remains significant. There are over 770 million people without electricity, mostly in South Asia and Sub-Saharan Africa, hindering economic and social development. The reliance on fossil fuels exacerbates climate change, making the shifting transition to renewable energy sources like solar essential. In Rwanda's Murya Village Gasenyi center, a hybrid solar and battery storage system was proposed to meet the energy needs of the rural population. Despite being more expensive than hydroelectricity, the long-term investment is justified, considering Rwanda's energy policies and programs promoting renewable solutions. Despite progress, about 40% of Rwanda's rural population still lacks electricity, but the government's National Electrification Program (NEP) aims to close this gap by promoting off-grid solutions like mini-grids and solar home systems, achieving 81.4% household electricity access by August 2024 [2].

1.3. Problem Statement

Electricity access in Rwanda has significantly improved, rising from 28.6% in 2016 to 63.9% by mid-2022, with rural electrification increasing from 17.5% to 57.9% over the same period. Despite this progress, a notable gap persists, as rural areas still lag behind urban areas, where 91.6% of homes have access to electricity [3]. While the traditional grid dominates in urban regions, off-grid solutions like solar technologies are crucial in bridging the energy gap in rural communities.

By the end of November 2024, 81.4% of households in Rwanda had access to electricity, with 56.5% connected to the national grid and 24.9% utilizing off-grid solutions, mainly solar. During the formulation of EDPRS II, the Rwandan government implemented a policy to diversify electricity sources by extending beyond the conventional grid. Consequently, households situated far from the proposed national grid were urged to consider more affordable options, like mini-grids systems and solar photovoltaic (PV) systems, to bring down the cost of electricity access and alleviate the pressure on traditional government subsidies. [2].

Gasenyi center in the Nzahaha Sector of Rusizi District is included in this problem and the residents still rely a lot on traditional energy sources such as charcoal, firewood, and kerosene. These energy options are also environmentally unfriendly, and they restrict the socioeconomic development of the community as they are not able to acquire information, education, and other productive activities.

The lack of a stable energy supply worsens poverty and curtails the potential for rural development. This is because extending the national electricity grid to remote villages such as Murya is logistically difficult and costly, thus there is a need for decentralized and sustainable energy solutions. A significant gap in rural energy access has been identified, prompting an evaluation of the feasibility of implementing a standalone photovoltaic and battery microgrid system for Gasenyi center. This environmentally friendly system is designed to provide reliable energy, empowering the community to enhance its quality of life and achieve sustainable development. This research emphasizes on assessing the economic and technical viability of a PV-Battery Microgrid System tailored to Gasenyi center, contributing to efforts to bridge this critical energy gap.

The NST1's energy Sector Strategic Plan (ESSP), which included plans to supply power to every Rwandan home by 2024, was unsuccessful.

The ESSP states that both off-grid and on-grid electrification modalities will be implemented to achieve universal access. The off-grid electrification in remote area in more feasible as grid extension is likely to happens for the areas less than 5km from existing grid in next 10 years. [4] As Gasenyi center located in remote area with distance above 5km from existing grid, solar system is the best solution to connect electricity to the village.

1.4. Objectives of the study

1.4.1. General objectives

The main target of this research project is to design and optimize a standalone photovoltaic (PV) and battery microgrid system that meets the energy needs of Gasenyi center, ensuring reliability, sustainability, and economic feasibility.

1.4.2. Specific objectives

1. Assess the current and projected energy consumption at Gasenyi center to guide microgrid system design.
2. Design a PV-battery microgrid tailored to Gasenyi's needs, specifying components, system configuration, and integration.
3. Simulate the system using appropriate software to evaluate technical performance under local conditions.
4. Analyze the technical and economic feasibility of the system, including capital costs, operational costs, and sustainability.

1.5. Research Questions

1. What are the current and projected energy needs at Gasenyi center?
2. What PV-battery system design best fits these needs?
3. How does the system perform under local conditions based on simulation results?
4. Is the proposed system technically feasible, cost-effective, and environmentally sustainable?

1.6. Hypothesis

A properly designed and simulated PV-battery microgrid system can reliably meet the energy needs of Gasenyi center in a technically feasible, economically viable, and environmentally sustainable manner.

1.7. Justification

Gasenyi Center, located in a remote or underserved area, likely lacks reliable access to the national electricity grid. Extending the grid to such regions is often economically unfeasible and logistically complex due to challenging terrain, long distances, and high infrastructure costs. In this context, a standalone photovoltaic (PV) and battery microgrid offers a practical and sustainable alternative. It provides a decentralized energy solution capable of meeting local electricity demands while ensuring reliability and cost-effectiveness. Implementing such a system can significantly improve energy access, support socio-economic development, and reduce dependence on fossil fuels or costly grid expansion.

1.8. Research thesis outline

Chapter 1: Introduction: Introduces the research problem, objectives, and significance of the research, providing the context for the research.

Chapter 2: Literature Review: Reviews relevant literature on off-grid solar systems, renewable energy, and energy access challenges, highlighting gaps in existing studies.

Chapter 3: Methodology: describes the research approach, data collection procedure, and the tools used to model and simulate the off-grid system.

Chapter 4: System Design and modeling: Details the design methods of the off-grid PV system, including the technical specifications and performance analysis. Analyzes the cost-effectiveness, financial feasibility, and economic viability of the designed system.

Chapter 5: Research findings and Discussion: Presents and discusses the results of the system's simulation and analysis, comparing them with expectations and objectives.

Chapter 6: Conclusion and Recommendations: summarizes key findings, draws conclusions, and provides recommendations for future research and implementation.

References: - Lists all sources and citations referenced throughout the research.

Appendices: - Includes supplementary material such as data, calculations, and additional details relevant to the research.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

The literature review provides a comprehensive examination of the existing body of knowledge related to the feasibility study of an off-grid photovoltaic (PV) and battery microgrid system. It highlights the key technical, economic, and environmental aspects necessary for the design and implementation of such systems in rural areas. The chapter also identifies the data requirements and research methodologies relevant to this master's thesis, emphasizing solar resource data, load demand data, system components, and grid-related challenges.

2.2. Technical Data Requirements

2.2.1. Solar Resource Data

Solar resource data is critical for designing an efficient PV system. Parameters such as global horizontal irradiance (GHI), peak sun hours, and seasonal variations must be assessed to determine the solar potential of the location. Studies indicate that regions with consistent solar irradiation above 4 $kWh/m^2/day$ are suitable for PV systems [5]. For Gasenyi center, specific data on daily and seasonal solar variations guided the system's energy production estimates and equipment sizing.

2.2.2. Load Demand Data

Understanding the community's electricity demand is essential for system design. This involves collecting data on:

- Current electricity usage: Daily and seasonal variations in energy consumption.
- Peak and off-peak patterns: Identifying hours of high demand to optimize system performance.
- Household and commercial needs: Differentiating between residential and business energy requirements.

These insights help in creating an accurate load profile, which is crucial for determining battery and inverter capacities [6].

2.2.3. Energy Storage Systems

Batteries are a vital component of off-grid microgrids. The literature explores different types of batteries suitable for rural energy systems, such as lead-acid, flow batteries and lithium-ion.

Lithium-ion batteries are favored for their upper energy density, prolonged lifespan, and better charge-discharge efficiency, despite higher costs [7], [8]. Key metrics include:

- Cost per kWh of storage.
- Lifespan (measured in charge-discharge cycles).
- Efficiency and depth of discharge.

These factors directly impact the system's reliability and economic feasibility.

2.2.4. Solar Panels and Balance of System (BOS) Components

Solar panel selection is critical for system efficiency. Factors like panel efficiency, degradation rates, and cost per watt guide the choice of PV modules. Monocrystalline panels are often recommended for their eminent efficiency and durability (Al-Addous et al., 2017). Additionally, other BOS components such as inverters, charge controllers, and wiring must be considered for overall system performance. Inverter efficiency is particularly important to minimize energy losses during the conversion of DC to AC power.

2.2.5. Grid Availability and Constraints

Grid access in remote areas like Gasenyi center is limited. Extending the national grid involves high costs, ranging from $10,000 to $20,000 per kilometer (World Bank, 2019). Additionally, the reliability of grid power in such areas is often low, making off-grid systems a more viable alternative. This highlights the importance of assessing the cost and technical constraints associated with grid expansion.

2.3. Economic and Grid-Related Considerations

2.3.1. Grid Extension Constraints

The cost and logistical challenges of extending the national grid to remote areas like Gasenyi center are well-documented. Studies suggest that grid extension costs can be prohibitively high, ranging from $10,000 to $20,000 per kilometer in rural settings ([9]. Off-grid solutions, including solar microgrids, offer a cost-effective alternative by providing localized energy generation.

2.3.2. Financial Metrics for Off-Grid Systems

Economic feasibility involves analyzing metrics such as:

- Initial installation costs.
- Levelized cost of energy (LCOE).
- Payback period and return on investment (ROI).

Rural energy systems often benefit from government subsidies or international funding, making them financially viable in the long term [10]

2.4. Theoretical background of electricity generation in Rwanda

23.9% of Rwandan homes have off-grid access as of the end of August 2024. The Rwandan government made a clear strategic decision to diversify its power sources from the conventional dominating grid to incorporate off-grid connections during the elaboration of the EDPRS II. In order to detrude the cost of energy access and remove restrictions on previous government subsidies, homes and businesses located far from the intended national grid coverage have been urged to adopt alternative, reliable and less expensive connections such solar photovoltaics (PVs) and mini-grids.

The Rwandan government has pledged to electrify the country entirely by 2024 in an attempt to further strengthen its economy. Rwanda Energy Group (REG) announced a revised electrification strategy that decreased the percentage of targeted houses to be electrified using off-grid options from 48% to 30% while increasing the percentage of households linked to the grid from 52% to 70%. [11]

2.4.1. Domestic generation, imports and regional shared energy

As presented in Table 2-1 the energy generation data from various power plants in Rwanda highlights fluctuations in production across quarters and years. Hydropower plants (HPP) such as Nyabarongo, Mukungwa, and Rukarara consistently contribute significantly to the domestic grid, with Nyabarongo showing a marked increase from Q4 2023 to Q1 2024. Thermal power plants (TPP) like Jabana and So Energy showed a sharp decline or complete cessation of operation in later quarters, indicating a shift away from fossil fuels. Solar plants like Nasho and GigaWatt Global maintain steady but relatively low outputs, while smaller micro-hydro power plants (MHPP) like Giciye III and Rukarara V-Mushishito show steady contributions, with some plants such as Shema Power demonstrating a substantial increase in generation [11].

In addition to domestic generation, imports and shared regional hydropower plants played a vital role in meeting national demand, with a noticeable spike in imports during Q3 2023, likely addressing shortfalls. Overall, Rwanda's total energy generation shows an upward trend, growing from 301 GWh in Q1 2023 to 342 GWh in Q1 2024, indicating increased capacity and better utilization of renewable resources. This growth reflects progress in diversifying the energy mix and expanding reliance on domestic renewable energy sources.

Table 2-1: Domestic generation, regional share and imports (kWh) from Q1 2023 to Q1 2024

Plant name	**Quoter-1 2023 [kWh]**	**Quoter-2 2023 [kWh]**	**Quoter-3 2023 [kWh]**	**Quoter-4 2023 [kWh]**	**Quoter-1 2024 [kWh]**
Nyabarongo HPP	32,099,100	36,537,200	17,035,400	27,262,300	43,287,600
Ntaruka HPP	8,488,674	8,186,000	6,233,000	4,858,000	6,481,000
Mukungwa HPP	16,924,380	17,302,150	18,265,527	17,004,242	14,328,249
Jabana 1 TPP	1,989,310	479,300	-	-	-
Jabana 2 TPP	22,038,400	8,408,982	3,957,920	1,881,280	2,462,240
Nasho solar	1,133,127	1,229,807	1,301,855	1,031,865	1,021,237
Nyabahanga MHPP	197,124	246,462	200,320	176,997	222,396
Jali Solar	28,281	26,171	29,999	25,077	24,587
Gisenyi MHPP	2,484,803	2,062,717	1,785,411	2,040,343	2,218,780
Gihira MHPP	2,236,321	2,283,408	1,602,329	1,966,370	2,532,457
Rukarara 1 HPP	14,083,908	15,549,032	11,321,436	14,948,920	15,827,515
Rukarara 2 MHPP	3,941,919	4,301,104	3,232,681	3,934,988	3,474,722
Murunda MHPP	164,537	52,984	-	-	-
Rugezi MHPP	2,475,858	3,735,744	1,630,647	2,464,319	3,528,104
Keya MHPP	0.0	1,873,686	2,419,869	2,908,168	3,328,667
Cyimbili MHPP	457,820	437,200	345,850	391,010	425,960
Mazimeru MHPP	715,638	889,192	783,553	889,858	876,775
Nkora MHPP	891,120	887,420	641,980	762,410	904,000
Musarara MHPP	827,617	830,286	518,038	911,108	877,731
Mukungwa 2 HPP	5,697,125	6,175,521	5,503,292	5,614,542	4,756,103
Giciye I HPP	2,973,734	3,722,410	2,449,990	4,019,743	4,993,984
GigaWatt Global	3,169,110	3,164,800	3,568,790	3,130,010	3,070,540
Janja MHPP	220,622	291,598	314,456	306,935	300,439
Kivuwatt	50,055,287	55,025,413	56,544,338	48,455,536	55,908,155
Giciye II HPP	3,260,368	4,159,300	2,584,571	4,538,264	5,259,977
Mutobo MHPP	409,439	410,742	406,937	415,020	379,684
Gaseke MHPP	230,086	223,081	-	-	-
So Energy Mukungwa 1	8,961,060	5,911,100	384,560	-	-
So Energy Masoro	11,137,340	8,247,830	315,650	-	-
So Energy Birembo	7,369,160	5,126,200	298,380	-	-
Gashashi	237,658	357,962	210,465	270,097	338,121
Rwaza-Muko MHPP	5,054,111	4,953,769	4,823,455	4,251,384	4,462,241
Rukarara V-Mushishito	8,206,448	9,089,132	6,562,542	8,677,529	8,830,940
Rubagabaga MHPP	437,516	255,036	12,623	229,219	233,368
Agatobwe MHPP	497,248	473,399	257,783	427,570	465,967

Plant name	Quoter-1 2023 [kWh]	Quoter-2 2023 [kWh]	Quoter-3 2023 [kWh]	Quoter-4 2023 [kWh]	Quoter-1 2024 [kWh]
Nyirantaruko MHPP	1,290,242	1,921,096	1,168,980	1,706,133	1,574,273
Kigasa MHPP	293,503	329,948	263,974	307,238	294,769
Giciye III	6,948,966	8,637,052	6,336,386	12,407,105	12,912,138
Nyirabuhombohombo	751,559	1,045,370	862,281	1,051,092	254,873
Hakan QP	28,666,305	14,096,726	38,595,150	36,547,200	8,065,500
Gishoma PPP	18,728,820	21,324,270	12,771,990	-	-
Kavumu Mwange	68,560	443,147	272,058	469,423	489,151
Shema Power	248,490	16,851,110	23,485,420	48,590,080	60,486,800
Ntaruka A HPP	25,411	181,071	4,053,838	4,605,739	4,240,713
Total domestic generation	**276,116,106**	**277,735,928**	**243,353,725**	**269,477,114**	**279,139,758**
Regional shared HPP	18,452,000	21,268,000	20,820,844	37,683,425	40,850,839
Imports	7,353,011	15,387,690	61,000,830	26,049,663	22,082,219
Total	**301,921,117**	**314,391,618**	**325,175,399**	**333,210,202**	**342,072,816**

2.4.2. Percentage Contribution of Rwanda’s Electricity Generation

The Regional Shared facilities generated 11.9% of the total electricity, with imports accounting for 6.5% of the electrical output. The first quarter of 2024 had a 13.3% rise in overall electricity generation compared to the same quarter in 2023, mirroring Rwanda's expanding energy industry [12].

Domestic generation consistently provided most of the Rwanda's energy supply, contributing between 74.85% in Q3 2023 and 91.43% in Q1 2023, underscoring the country's reliance on local renewable energy sources, particularly hydropower. Meanwhile, regional shared hydropower steadily increased its share, peaking at 11.94% in Q1 2024, reflecting enhanced regional energy cooperation. Imports, while generally lower, reached their highest contribution of 18.75% in Q3 2023, indicating a dependence on external sources during periods of domestic shortfalls or maintenance as shown in Figure 2-1.

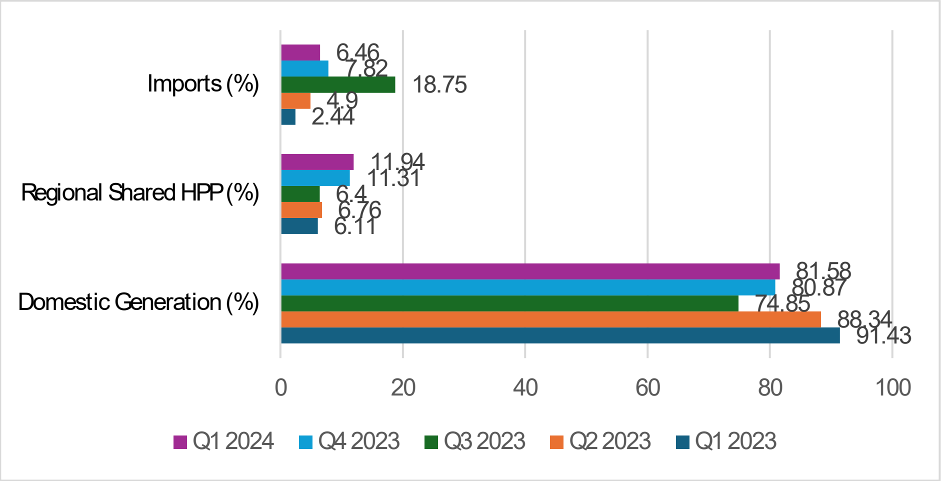


Figure 2-1: Contribution Percentage of Domestic Generation, Regional Shared HPP, and Imports [12]

2.4.3. Integration of Renewable Energies in Rwanda

In order to meet its goal of boosting total capacity by 100% by 2024, the government of Rwanda intends to use a variety of autochthonous resources that complement one another in the energy mix. Because fossil fuels are expensive to generate, this will help diversify away from them. The physical potential of the current renewable energy resources is described in the section that follows. As of right now, Rwanda has 332.6 MW of installed capacity for electricity generation from various power plants. Thermal sources account for 51% of the generation technology mix, with hydro sources coming in second at 43.9% and solar sources at 4.2% [12]. The graph below shows how these initiatives are anticipated to alter the generation technology mix and significantly reduce the use of costly sources (fuel):

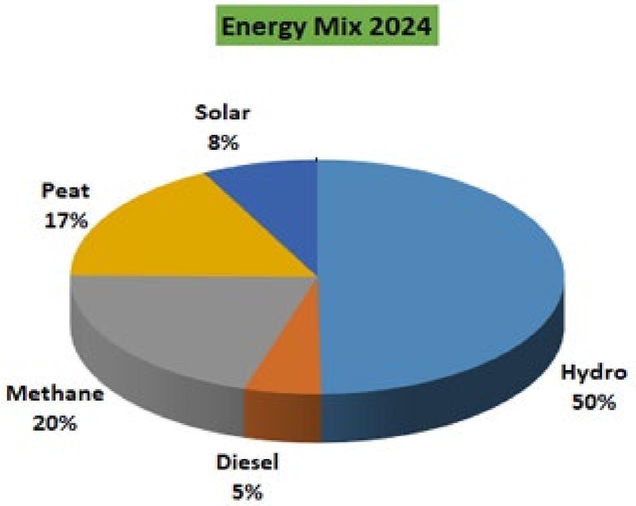


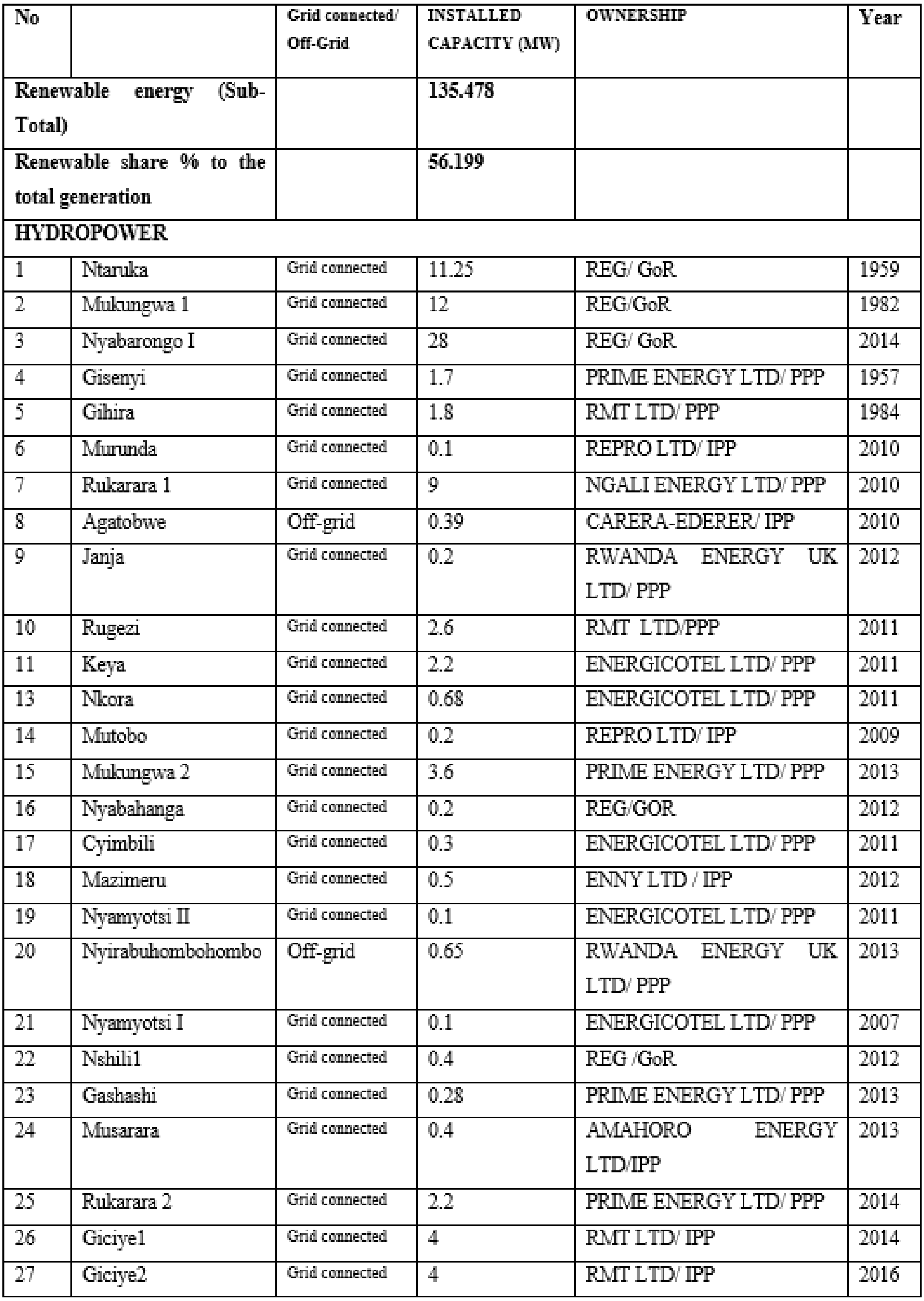
Figure 2-2: Energy mix 2024 [12].

2.4.4. Contribution of off-grid power plant in Rwanda

As presented in the Table 2-2, the off-grid power plants play a significant role in Rwanda's energy landscape, especially in addressing electricity access in remote and rural areas where the national grid may not be feasible. The off-grid systems, primarily small hydropower and solar power plants, contribute to the diversification of energy sources. Notably, the Agatobwe hydropower plant (0.39 MW) and the Nyirabuhombohombo hydropower plant (0.65 MW) are key contributors to off-grid renewable energy capacity. Additionally, the Mukugu Pico power plant (0.016 MW), though smaller in capacity, also provides crucial localized electricity. The total installed renewable energy capacity of 135.478 MW, of which a share of 56.199% is renewable, includes these off-grid plants that complement the larger grid-connected hydropower plants. [12].

These off-grid systems are essential in meeting Rwanda's goal of universal complete electrification by 2024. They provide immediate, cost-effective, and scalable solutions for rural households, significantly improving the energy access rate in underserved regions. With off-grid solar power plants, such as the Mukugu Pico power plant, Rwanda can extend energy access quickly and sustainably, reducing reliance on centralized grid systems and alleviating pressure on government subsidies. In combination with grid-based hydropower and thermal plants, off-grid systems contribute to Rwanda's energy mix, enhancing the nation's energy security and ensuring equitable access to electricity across all regions.

Table 2-2: List of Power Plants ON grid and OFF grid in Rwanda 2024



No		Grid connected/ Off-Grid	INSTALLED CAPACITY (MW)	OWNERSHIP	Year
Renewable energy (Sub-Total)			**135.478**		
Renewable share % to the total generation			**56.199**		
HYDROPOWER					
1	Ntaruka	Grid connected	11.25	REG/ GoR	1959
2	Mukungwa 1	Grid connected	12	REG/GoR	1982
3	Nyabarongo I	Grid connected	28	REG/ GoR	2014
4	Gisenyi	Grid connected	1.7	PRIME ENERGY LTD/ PPP	1957
5	Gihira	Grid connected	1.8	RMT LTD/ PPP	1984
6	Murunda	Grid connected	0.1	REPRO LTD/ IPP	2010
7	Rukarara 1	Grid connected	9	NGALI ENERGY LTD/ PPP	2010
8	Agatobwe	Off-grid	0.39	CARERA-EDERER/ IPP	2010
9	Janja	Grid connected	0.2	RWANDA ENERGY UK LTD/ PPP	2012
10	Rugezi	Grid connected	2.6	RMT LTD/PPP	2011
11	Keya	Grid connected	2.2	ENERGICOTEL LTD/ PPP	2011
13	Nkora	Grid connected	0.68	ENERGICOTEL LTD/ PPP	2011
14	Mutobo	Grid connected	0.2	REPRO LTD/ IPP	2009
15	Mukungwa 2	Grid connected	3.6	PRIME ENERGY LTD/ PPP	2013
16	Nyabahanga	Grid connected	0.2	REG/GOR	2012
17	Cyimbili	Grid connected	0.3	ENERGICOTEL LTD/ PPP	2011
18	Mazimeru	Grid connected	0.5	ENNY LTD / IPP	2012
19	Nyamyotsi II	Grid connected	0.1	ENERGICOTEL LTD/ PPP	2011
20	Nyirabuhombohombo	Off-grid	0.65	RWANDA ENERGY UK LTD/ PPP	2013
21	Nyamyotsi I	Grid connected	0.1	ENERGICOTEL LTD/ PPP	2007
22	Nshili1	Grid connected	0.4	REG /GoR	2012
23	Gashashi	Grid connected	0.28	PRIME ENERGY LTD/ PPP	2013
24	Musarara	Grid connected	0.4	AMAHORO ENERGY LTD/IPP	2013
25	Rukarara 2	Grid connected	2.2	PRIME ENERGY LTD/ PPP	2014
26	Giciye1	Grid connected	4	RMT LTD/ IPP	2014
27	Giciye2	Grid connected	4	RMT LTD/ IPP	2016

No		Grid connected/ Off-Grid	INSTALLED CAPACITY (MW)	OWNERSHIP	Year
28	Gaseke	Grid connected	0.500	NOVEL ENERGY LTD /IPP	2016
29	Rwaza-Muko	Grid connected	2.600	Rwaza-Muko SPV	2018
30	Ruzizi 1	Grid connected	4.100	SNEL/ IPP	1958
31	Ruzizi 2	Grid connected	12.000	SNELAC/ PPP	1989
32	Rukarara V & Mushishito	Grid connected	5.000	REFAD	2019
33	Kigasa	Grid connected	0.272	LED Solutions	2020
34	Nyirantaruko	Grid connected	1.840	Nyirantaruko Hydropower Ltd	2020
35	Rubagabaga	Grid connected	0.450		2019
36	Mukugu Pico power plant	Off-grid	0.016	Handed over to REG in Jan/2020	2020
37	Giciye III	Grid connected	9.800	RMT-Energy Development Ltd	2020
38	Rusumo Falls Hydropower plant	Grid connected	26	Rusumo Power Company Ltd (RPCL)	2024
Total Hydropower			**149.428**		
SOLAR POWER					
39	Jali	Grid connected	0.250	MAINZ/ IPP	
40	GigaWatt /Rwamagana	Grid connected	8.500	GIGAWATT GLOBAL/ IPP	2015
41	Nasho Solar	Grid connected	3.300	REG/GoR	2017
Total Solar			**12.050**		
Non-renewable energy (sub-total)			**103.590**		
No-renewable energy % to the total generation			**42.971**		
THERMAL POWER					
42	Jabana 1	Grid connected	7.800	REG/GoR	
43	Gishoma	Grid connected	15.000	REG/GoR	2016
44	Hakan PTP	Grid connected	35.000	REG/GoR	2022
45	SoEnergy LTD (SEZ)	Grid connected	10.000	SoEnergy / IPP	2017
46	SoEnergy LTD (MUKUNGWA)	Grid connected	10.000	SoEnergy / IPP	2017
47	Jabana 2	Grid connected	21.000	REG /GoR	
48	SoEnergy LTD (	Grid connected	10.000	SoEnergy / IPP	2017

No		Grid connected/ Off-Grid	INSTALLED CAPACITY (MW)	OWNERSHIP	Year
	Birembo)				
49	KP1	Grid connected	3.600	SYMBION POWER / PPP	2012
50	Kibuye Gaz methane	Grid connected	26.190	KIVUWATT LTD / IPP	2015
51	Shema Power Lake Kivu	Grid connected	56	SPLK: **Shema Power Lake Kivu Ltd**	2023
Total Thermal			**194.590**		
Mixed (not well specified)					
52	UETCL	Grid connected	**2.000**		
Grand TOTAL			**358.68**		

2.4.4.1. High Percentage of Off-Grid Population

A significant portion of Rwanda's population lives in rural areas with bounded or no access to the national grid. This has created a strong demand for off-grid solar solutions. Despite being relatively new technology in Rwanda, over 400,000 homes have already adopted off-grid options. [13].

2.4.4.2. Government Initiatives and Private Sector Participation

The Rwandan government, through various initiatives, has been promoting the adoption of solar home systems (SHS) and other off-grid solutions to increase electricity access.
Over 40 solar companies are active in Rwanda's off-grid solar market, indicating a robust and growing sector [13].

2.4.4.3. Projected Demand

Through the National Electrification Plan, Rwanda aims to achieve complete electricity access by 2024, with a significant portion (48%) expected to be served through off-grid solutions, primarily solar energy.

2.4.5. Solar Energy Exploitation in Rwanda

The daily solar radiation in Rwanda fluctuates between 4 and 5.4 kWh/m². Seasonal variations exist, too, with average daily irradiance levels in the overcast regions reaching around 4.5 kWh/m² [14]. Further information is provided in Figure 2-3

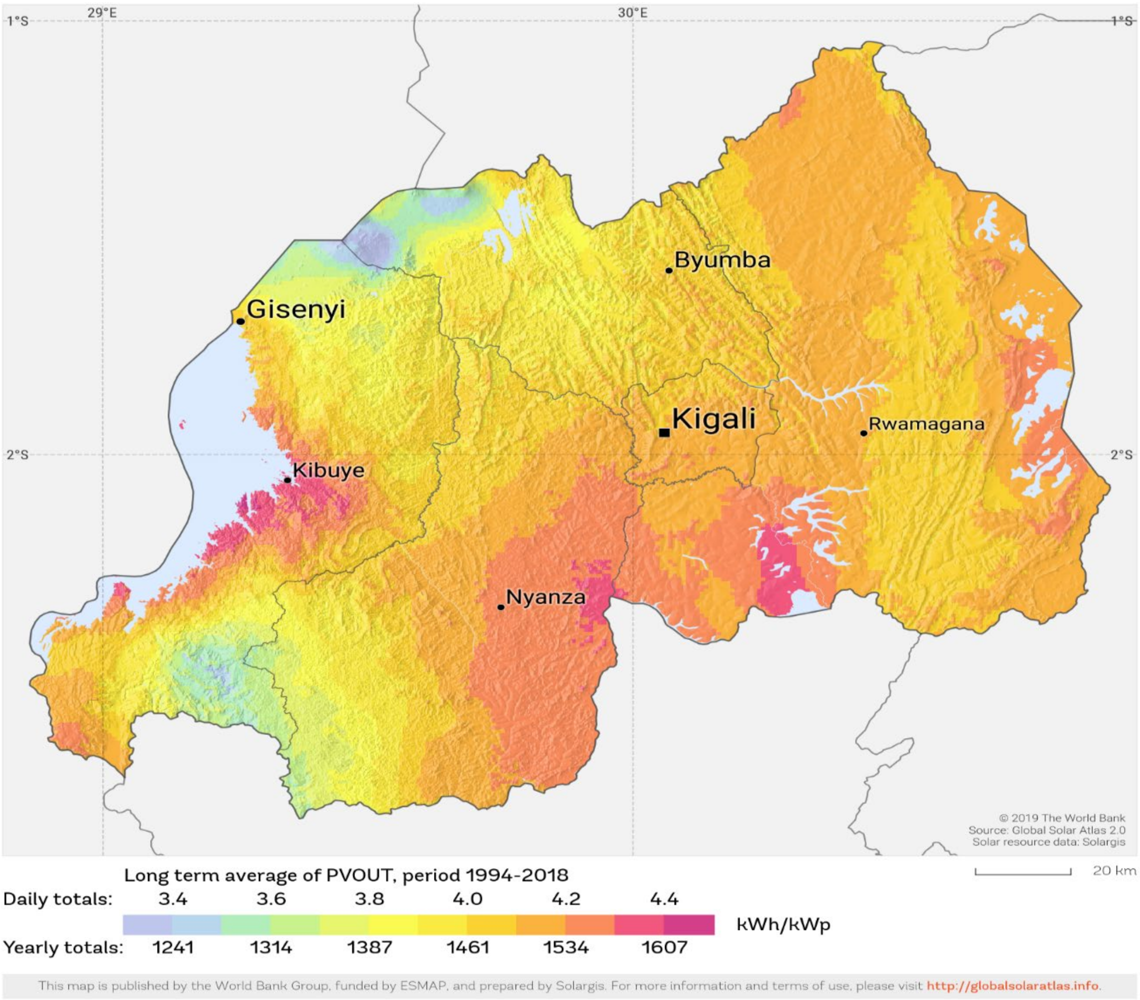


Figure 2-3: Photovoltaic Power Potential for different districts of Rwanda

Rwanda currently has 12.050 MW of installed solar energy on the grid, which comes from three solar power plants: the Jali power plant, which generates 0.25 MW, the Rwamagana gigawatt, which generates 8.5 MW, and the Nasho solar plant, which generates 3.3 MW. The Rwandan government plans to expand the number of solar power plants in order to lower production costs and exploit Rwanda's renewable energy resources.

Figure 2-4: Rwamagana Gigawatt generating 8.5 MW

2.4.5.1. Electricity access through solar

Solar energy offers a practical and sustainable solution for providing electricity to rural households in remote areas. By May 2021, approximately 16% of Rwandan households were accessing electricity through off-grid systems, primarily solar energy as shown in Table 2-3. The country's Energy Sector Strategic Plan aims to achieve universal electricity access by 2024, with nearly half of households (48%) connected via off-grid power systems. This ambitious plan includes electrifying around 500,000 additional households through off-grid solutions. Considering the growing population, the goal is for all 3.72 million households in Rwanda to have access to electricity through a combination of on-grid and off-grid connections [15].

Table 2-3: Cumulative Off and On-grid connectivity 2013-2021

Year	On-grid households	Off-grid households	Cumulative Total N of households connected
2013	364,409	0	364,409
2014	461,323	0	461,323
2015	513,092	0	513,092
2016	542,750	37,250	580,000
2017	545,419	142,194	687,613
2018	851,829	281,806	1,133,635
2019	1,055,174	308,783	1,363,957
2020	1,132,522	418,502	1,560,699
2021	1,278,601	473,744	1,752,345

2.5. Review of other past research projects

2.5.1. Advancements in Off-Grid Renewable Energy Systems

Although the lifespan of renewable resources is immeasurable, their daily energy output is restricted. Renewable energy is energy derived from naturally renewing sources that vary randomly over time. Solid waste, landfill gas and biogas, ethanol, biodiesel, hydropower, geothermal, wind, tidal, thermal solar, solar photovoltaics, and wood and wood waste are among them. [16], [17].

In Jordan Valley, the authors created off-grid photovoltaic installations. The warm climate of the area is one of the main reasons why temperature increases have a detrimental effect on the solar PV system. The authors pointed out that improved efficiency may be achieved by combining temperature control with PV system cooling. In tropical areas like Pakistan's Faisalabad, Ghafoor and Munir identify the appropriate design, viability, finance indicators, and risk factors associated with the off-grid PV electrification system's installation. [18].

The current advancements in PV systems coincide with a decline in PV costs. For residential home energy solutions, this makes PV technology manufacturing more cost-competitive when compared to traditional energy resources [6]. In addition, the United Nations (UN) set a goal of achieving seventeen Sustainable Development Goals (SDGs), emphasizing the steps that various nations should take to achieve sustainable development by 2030.

The seventh goal is on ensuring that everyone has access to modern, sustainable, economical, and dependable energy. According to studies, the most susceptible regions of the world are rural ones, hence electrification efforts should be concentrated there.

Off-grid hybrid photovoltaic systems developed by Veldhuis and Reinders outperformed diesel gensets in producing energy in the majority of Indonesia's rural areas [19]. Additionally, they conducted a sensitivity analysis by altering the battery and the non-served energy penalty costs. Subsequently, they looked at battery degradation, predicted solar insolation variability, and scheduling impacts [20]. The end-user load choice was a major focus of the recent Nepalese research that enlarged on off-grid alternatives for rural people. In order to feed the load according to the order of desire, their paper contribution employs micro and mini-hydro and solar resources microgrids. Energy services are categorized along two "characteristics" axes, such as storage capacity and user priorities. [21].

Soudan and Darya developed a clever off-grid hybrid PV/battery/diesel power system that uses a well-managed battery and a small amount of diesel gensets to maintain electricity at night using an algorithm with smart switching control [22]. Moreover, Campana et al. concentrated on the impact of system optimization attained using battery energy systems and the cooling impacts of floating PV systems in off-grid mode [23].

2.5.2. Rwanda off-grid overview

As the graph demonstrates, 24.9% of Rwandan homes have off-grid power at the end of November 2024. The Rwandan government made the strategic decision to diversify its power sources during the building of EDPRS II, moving away from dependency on the national grid and towards off-grid connections. By encouraging the use of affordable alternatives like mini-grids and solar photovoltaic (PV) systems by families located far from planned grid coverage, this program decreased the cost of power access while relieving pressure on government subsidies.

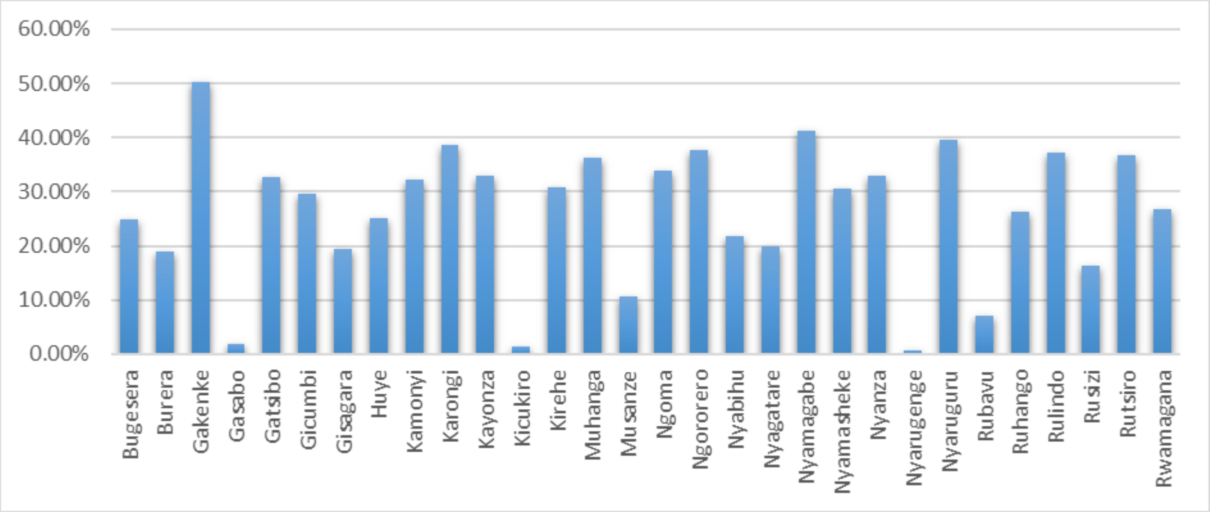


Figure 2-5: Off-grid electricity Across Rwanda's Districts

In order to meet the need for essential energy services like powering homes, small businesses, and phone charging in off-grid areas, Mesh Power Limited, a UK-based company, launched storage solutions for nano-grid solar power projects in Eastern Africa. Mesh Power's nano-grid solutions ensure dependable service even during rainy seasons by managing energy generation and distribution for more than 50 households per base station using extremely efficient electronics. In rural Rwanda, where 75% of families are still off the grid, their experience has brought attention to the urgent need for independent energy solutions [24]. In Rwanda's Eastern District, 17% of rural residents have been serviced by Mesh Power; yet, plans for grid extension would still deprive 1.2 million people of power [25]. Supported by FONERWA, the company highlights the potential of off-grid systems to complement government efforts in achieving reliable, green, and affordable energy access.

This study focuses on a case comparison of off-grid solutions for rural homes, considering economic parameters like LCOE and NPC for 200 homes with similar energy consumption. Standalone solar systems, or off-grid systems, have become a sustainable solution for powering remote and rural areas where extending the grid is logistically and financially challenging. These systems provide reliable electricity by combining solar panels with battery storage.

2.5.3. A Comparative Analysis of off-grid design, Research Contributions, and Gaps

This comparative analysis Table 2-4 highlights the evolution of off-grid design strategies, the research contributions towards sustainable energy solutions, and the existing gaps that require further investigation to enhance the efficiency and effectiveness of off-grid systems.

The off-grid PV models designed for rural homes showcase varying system sizes and complexities, ranging from nano-grid solar home systems for single households to larger PV array systems for communities of 200 households.

As presented in Table 2-4, the recent studies have focused on developing off-grid solar energy solutions for rural areas, emphasizing the importance of technological advancements to address blackout issues and promote renewable energy utilization.

Table 2-4: Gaps in different research about off-grid design and optimization

Title	**Authors**	**Contributions**	**Research Gaps**
The potential of performance targets (imihigo) as drivers of energy planning...." [26]	Bisaga et al. (2019)	Highlights the role of imihigo (performance contracts) in energy planning, raising awareness about off-grid energy, and encouraging private sector involvement.	Lack of effective dissemination of imihigo frameworks and inadequate follow-up evaluations to address household energy barriers.
Mapping Synergies and Trade-offs Between Energy and SDGs: A Case Study of Off-Grid Solar. [27]	Bisaga et al. (n.d.)	Explores the interactions between off-grid solar energy and SDGs, emphasizing cross-sectoral benefits and informing future policy and investment decisions.	Limited evidence on resilience-building and intra-household decision-making in relation to off-grid solar. Slow dissemination of research relative to market developments.
Discussion Paper Series on Demand for Off-Grid Solar Electricity: Experimental Evidence from Rwanda [28]	Grimm et al. (2016)	Analyzes willingness-to-pay (WTP) for off-grid solar technologies, emphasizing affordability and cost-benefit dynamics.	Does not explore the long-term impact of solar technology adoption on household welfare and fails to address biases in WTP due to irregular income patterns.
Key Technology Development Needs	Niyonteze et al.	Recommends renewable energy hybrid combinations	Insufficient guidelines for rural electrification

Title	**Authors**	**Contributions**	**Research Gaps**
for Off-Grid Areas in Rwanda. [29]	(2020)	for rural areas, using HOMER for cost analysis. Highlights renewable systems' potential in off-grid applications.	strategies and a lack of wind integration studies in Rwanda. Updated data collection methods needed for collaboration with stakeholders.
Assessing Opportunities and Challenges Facing Off-Grid Solar in Eastern Africa. [30]	Mugisha et al. (2021)	Compares rural electrification challenges and opportunities in Kenya, Ethiopia, and Rwanda, emphasizing funding mechanisms and policy implications.	Limited exploration of financial constraints and insufficient incentives for private investors in off-grid markets.
Design and Optimization of Off-Grid Hybrid Renewable Systems for Rural Rwanda. [31]	Bedadi & GebreMichael (2021)	Designs and optimizes a hybrid system combining solar PV and micro-hydropower using HOMER Pro. Highlights cost-competitiveness and environmental benefits.	The study also notes that while individual renewable energy sources have low efficiency and are weather-dependent, there is limited exploration of hybrid systems that could enhance efficiency and reliability in rural areas.
Feasibility Study of Hybrid Hydro-PV Power Plants in Remote Rural Areas. [32]	Dusenge et al. (2022)	Evaluates the technical feasibility of hybrid hydro-PV systems in Baziro village. Assesses load demands and provides recommendations for financial studies and hydrological simulation methodologies.	Lack of financial study to assess the viability of project investment and implementation, indicating a lack of economic analysis in the current research

2.5.4. Gaps in the above-discussed Research

In rural areas of Rwanda, significant gaps persist in the design and implementation of off-grid energy systems. A lack of localized data, particularly on energy needs and hydrology for hybrid systems, limits the ability to optimize solutions tailored to specific communities. Financial constraints also present a major barrier, with limited incentives for private investors and inadequate exploration of financing mechanisms for rural households. Furthermore, insufficient guidelines for rural electrification strategies and ineffective dissemination of frameworks, such as imihigo, hinder community engagement and participation in energy planning. Additionally, challenges such as resilience to seasonal variations, integration of diverse renewable sources like wind, and the scalability of hybrid systems remain underexplored. Addressing these gaps is essential to ensure reliable, sustainable, and cost-effective off-grid energy solutions for Rwanda’s rural population.

2.5.5. Research Contribution Recommendations for Gasenyi center

This thesis makes a significant contribution to addressing the gaps identified in previous research on off-grid energy systems in Rwanda. Unlike prior studies, which often lack localized data or focus primarily on specific renewable energy sources; This study evaluates the potential for implementing off-grid solar energy solutions tailored to the specific energy needs and consumption patterns of households in Gasenyi center, aiming to enhance access to reliable electricity in rural areas.

It investigates the feasibility of integrating energy storage systems, such as battery technology, to mitigate the intermittent nature of renewable energy sources and ensure a consistent power supply. Additionally, it explores the impact of community-based microgrid systems in promoting energy self-sufficiency, reducing transmission losses, and enhancing grid resilience, drawing insights from successful models implemented in similar rural settings.

This research closes that gap by: Compiling comprehensive community load profiles.

Assessing the viability of locally specific hybrid solar-battery systems.

- ✓ Offering practical suggestions for putting renewable energy solutions into practice in Rwanda's rural
- ✓ With an emphasis on improving access to reliable electricity in rural areas, we assess the feasibility of deploying off-grid solar energy solutions catered to the unique energy requirements and consumption patterns of homes in Gasenyi center.

- ✓ To solve the sporadic nature of renewable energy sources and provide a steady power supply for homes in Gasenyi center, look into the viability of incorporating energy storage solutions, such as battery technology.
- ✓ Examine how community-based microgrid systems in Gasenyi center can encourage energy self-sufficiency by using successful models that have been put into place in comparable rural areas.

CHAPTER 3. RESEARCH METHODOLOGY (DATA COLLECTION)

3.1. Introduction

The purpose of this research methodology is to outline the approach for designing a microgrid PV systems in Gasenyi center to promote energy self-sufficiency, Evaluating the potential for implementing off-grid solar energy solutions, Investigating the feasibility of integrating energy storage systems, such as battery technology, to address the intermittent nature of renewable energy sources and ensure a consistent.

3.2. Methodology used to design PV-Battery Microgrid System for Gasenyi center

In this feasibility study of a PV-Battery Microgrid System, a comprehensive methodology was employed to assess its technical and economic viability as presented in
Figure 3-1. Daily electricity consumption data for the target community was collected through direct surveys and utility records to accurately determine energy demand patterns. PVsyst 7.4 software was utilized to simulate the performance of the off-grid PV system, considering the community's load profile, local solar irradiation, and climatic conditions. The study involved detailed modeling of system components, including solar panels, battery storage, and inverters, to optimize the design for efficiency and reliability. Economic analysis was also conducted, evaluating installation costs, operational expenses, and payback periods, to ensure the proposed solution is both feasible and sustainable for the community.

The flowchart showing the sequence of planned activities to conduct this research is presented in the
Figure 3-1. This methodology outlines the steps for a feasibility study of a PV-Battery Microgrid System, starting with a literature review to set objectives. It includes data collection on site selection and daily load profiles, followed by technical analysis of the PV system's components and economic analysis of costs, energy consumption, and financial viability. The study concludes with simulation, results discussion, and recommendations for the system's feasibility

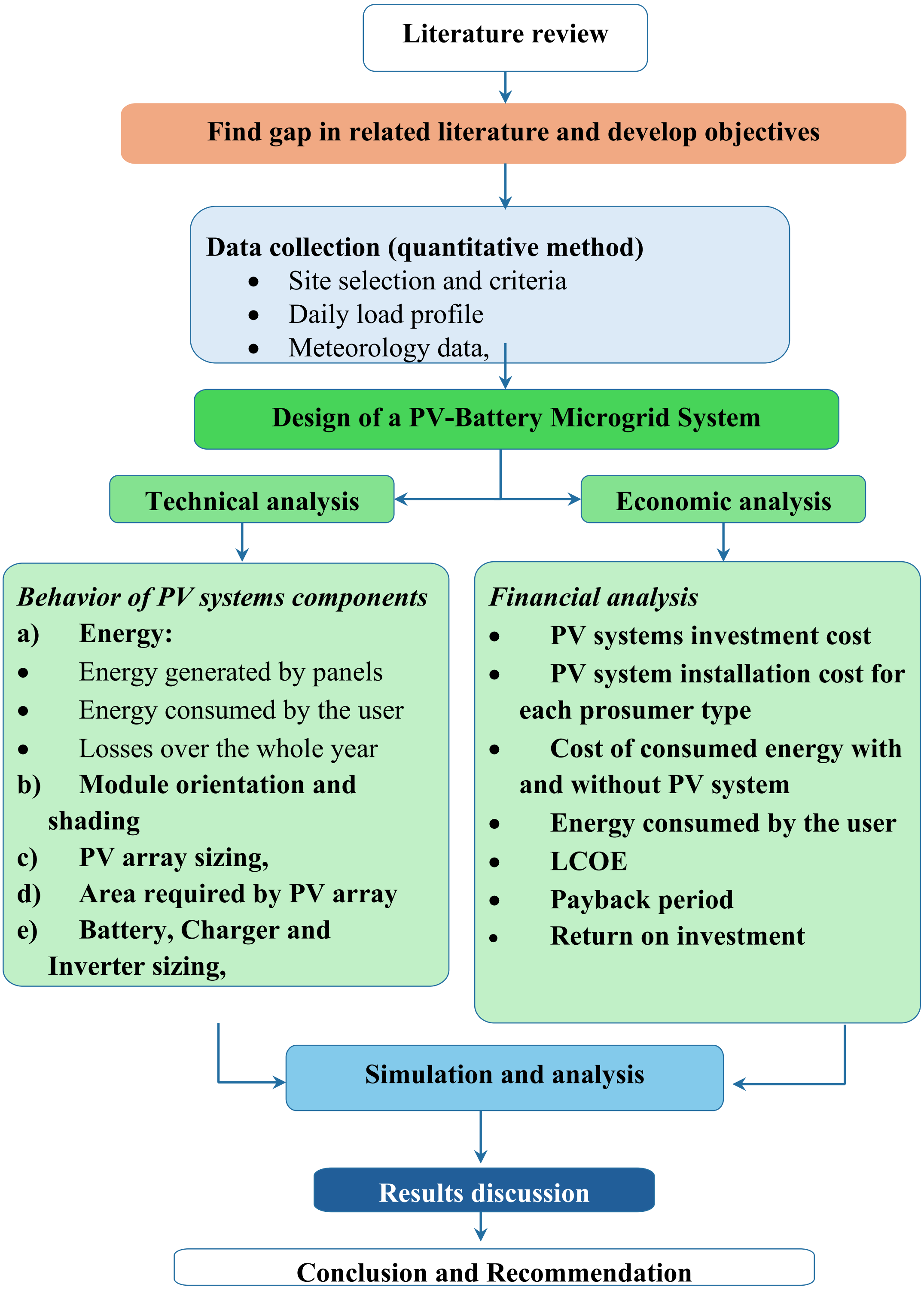


Figure 3-1: Methodology used to design PV-Battery Microgrid System for Gasenyi center

3.3. Data Collection

Data collection was a key part of this feasibility study, as it provided the essential information needed to design and evaluate the off-grid PV system. The primary focus of data collection was to gather daily electricity consumption data and other relevant parameters from the target community. This process was carried out through a combination of direct surveys, interviews, and utility records, ensuring that the data reflects actual energy usage patterns.

3.3.1. Daily Electricity Consumption of Gasenyi center Households

To estimate the community's energy demand, data on daily electricity consumption was collected from households, businesses, and community facilities.

The load profile for Gasenyi center households was categorized into three main types: **Tier 2, tier 3, and commercial house** as the National Electrification Plan in Rwanda [33] define energy consumers categories and put the descriptions provided in Figure 3-2 the current EARP subscribers' monthly usage by tier (as of 2013), along with a recommended alternate energy source for each tier.

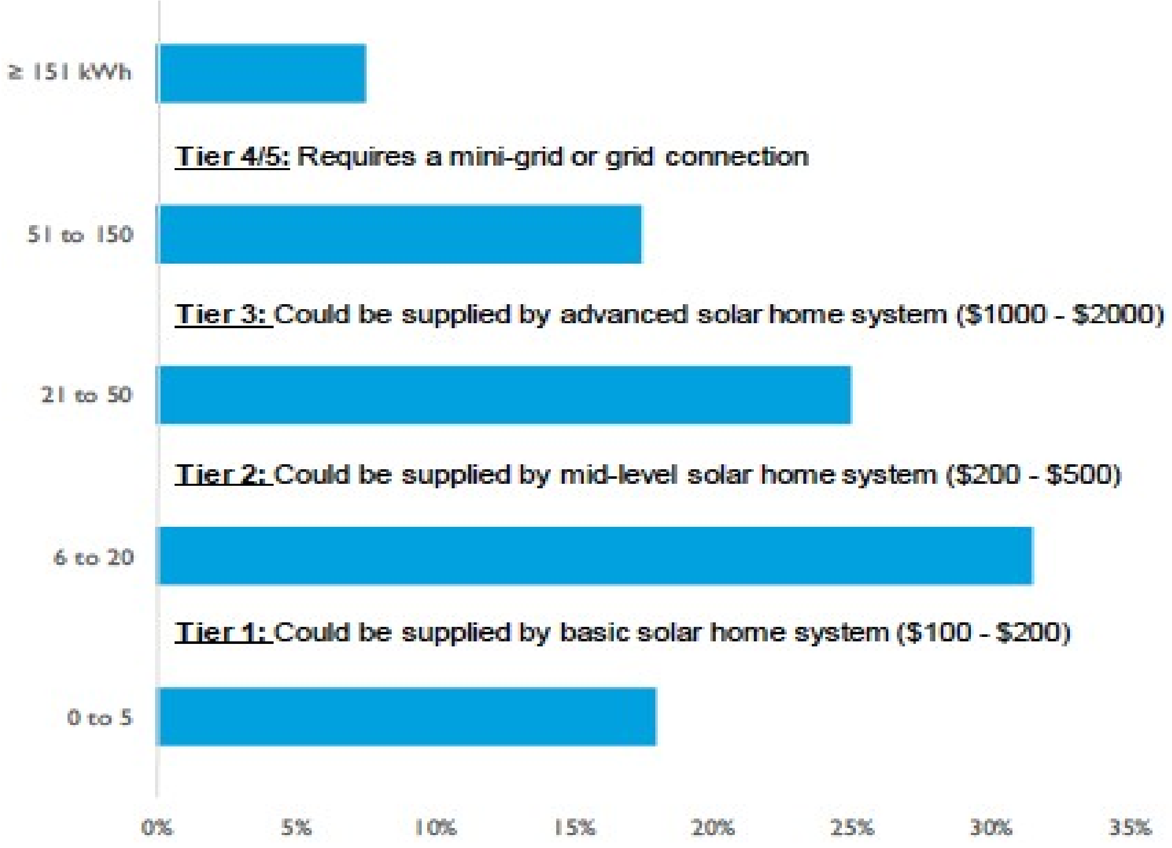


Figure 3-2: EARP_2013 Consumer Monthly Consumption Levels (kWh)

3.3.1.1. Load profile

Surveys were conducted to gather detailed information on the number and type of electrical appliances used, their operating hours, and peak demand times. This information was then aggregated to create a comprehensive load-profile that represents the community's energy requirements. Developing this load profile was essential for designing an efficient and reliable off-grid PV system tailored to meet the community's energy needs.

The load consumption profiles in these figures indicate varying hourly energy demands across different household tiers and commercial loads.

Tier 2 households (Figure 3-3 and Figure 3-4) show higher energy consumption concentrated in the evening hours (18:00–24:00), reflecting residential evening activities like lighting and cooking. Tier 3 households (Figure 3-5 and Figure 3-6), which likely have higher energy access and appliances, demonstrate peak demands in the early morning and evening, suggesting additional activities such as morning meal preparation. The total commercial load (Figure 3-7) is characterized by sharp peaks during typical working hours (6:00–18:00), indicative of business operations. The overall load profile (Figure 3-8) combines these trends, with significant peaks in the evening due to household consumption and smaller peaks during business hours from commercial activities. This profile highlights the need for an energy system capable of meeting evening and daytime peaks efficiently.

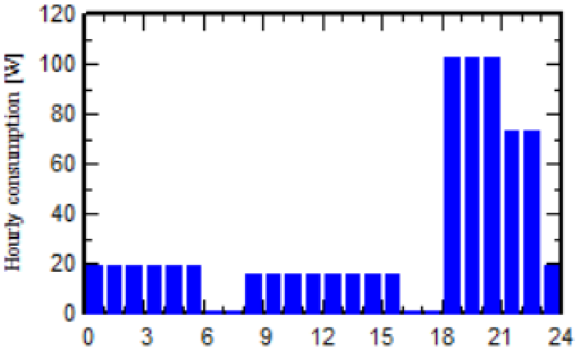


Figure 3-3: Tier 2 -single household

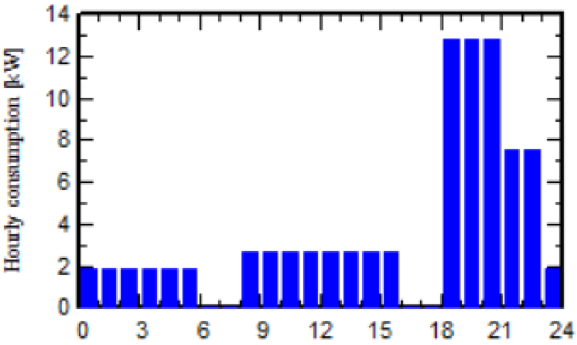


Figure 3-4: Tier 2 -All households

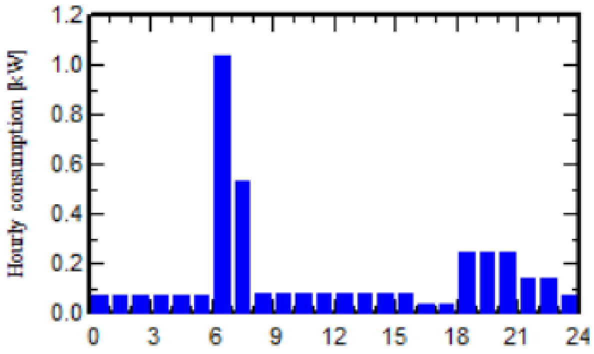


Figure 3-5:Tier 3 -single household

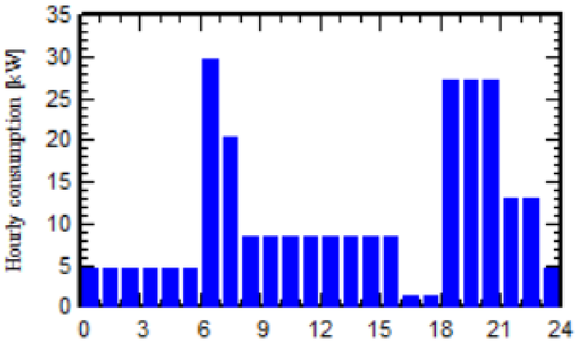


Figure 3-6: Tier 3 -All households

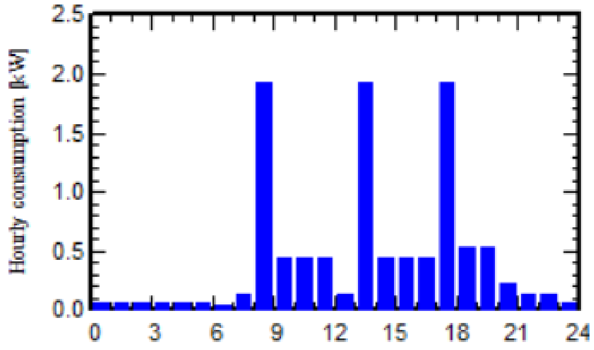


Figure 3-7: Total commercial load

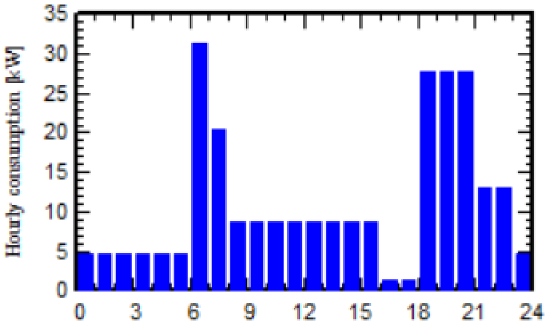


Figure 3-8: Load profile for all load

3.3.2. Site identification

Gasenyi center is located in Murya village, Murya cell, Nzahaha Sector, Rusizi District, Western Province, Rwanda, within the East African region. Gasenyi center is a rural commercial and residential center with lack of energy access, not connected to national grid and REG energy mapping categorized the area as off grid solution. The center is composed by 104 households in total with 3 commercial household.

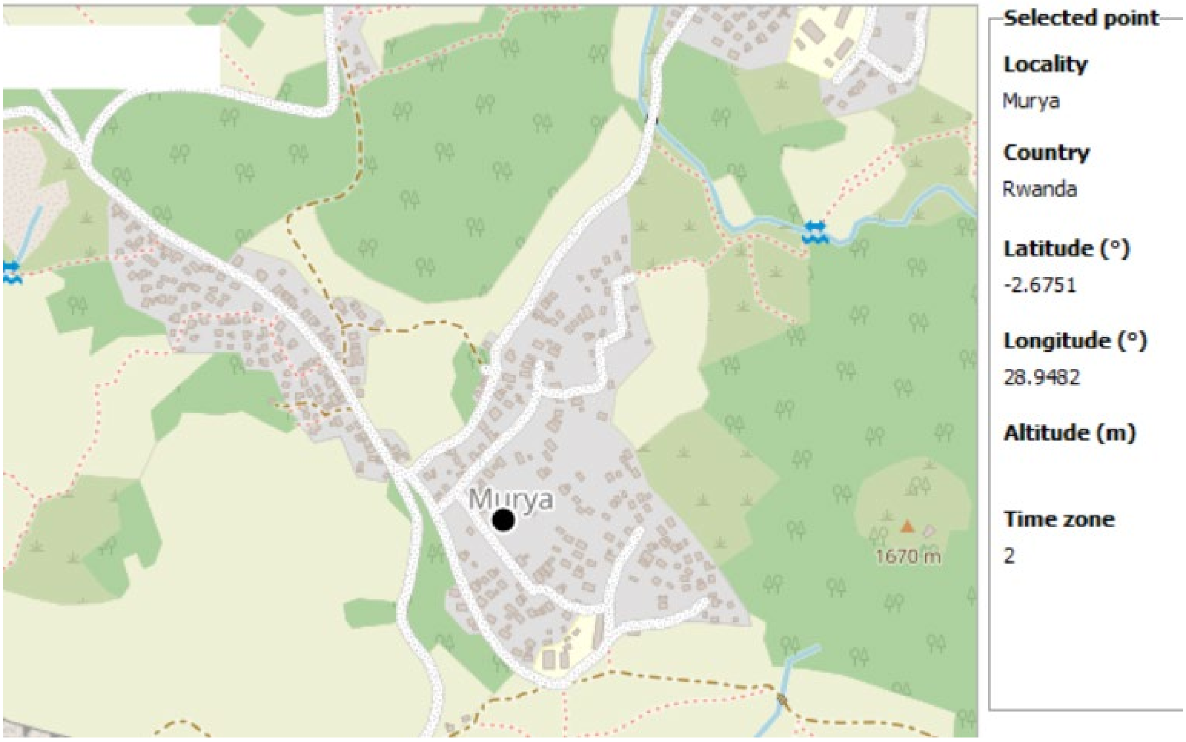
3.3.3. Geographical location, Topography, elevation and Climate

Gasenyi center geographical coordinates are approximately 2° 40' 29" South latitude and 28° 56' 54" East longitude, positioning it near the villages of Ngoma and Buganza. At an elevation of 1,548 meters (5,079 feet) above sea level see Figure 3-9, Murya is situated in a highland region characterized by rolling hills and valleys, typical of Rwanda's mountainous terrain. This location offers scenic landscapes and a temperate climate that supports agricultural and rural community activities.

The village experiences a climate influenced by its high altitude, which provides moderate temperatures throughout the year.

Being close to the equator ensures consistent sunlight hours, making the area highly suitable for solar energy generation.

The combination of its topography, elevation, and favorable solar potential makes Murya an ideal site for implementing renewable energy projects like off-grid photovoltaic (PV) systems. These geographical and climatic factors collectively contribute to the viability of sustainable energy solutions for the community.



Selected point

Locality
Murya

Country
Rwanda

Latitude (°)
-2.6751

Longitude (°)
28.9482

Altitude (m)

Time zone
2

Figure 3-9: Map of Murya village in Gasenyi center and its location

3.3.4. Meteorology data

Local climatic conditions, including solar irradiation, temperature, and weather patterns of Gasenyi center, were obtained from reliable meteorological databases and satellite sources. This data is crucial for simulating the performance of the PV system in PVsyst 7.4 and ensuring that the system design is optimized for the site's specific conditions.

The chart in Figure 3-10 illustrates the daily global horizontal irradiance (GlobHor) in kWh/m²/day and the ambient temperature (T_Amb) in degrees Celsius for Gasenyi center throughout a one-year period. The green bars represent the solar energy received per square meter per day, while the red line shows the corresponding daily average ambient temperature.

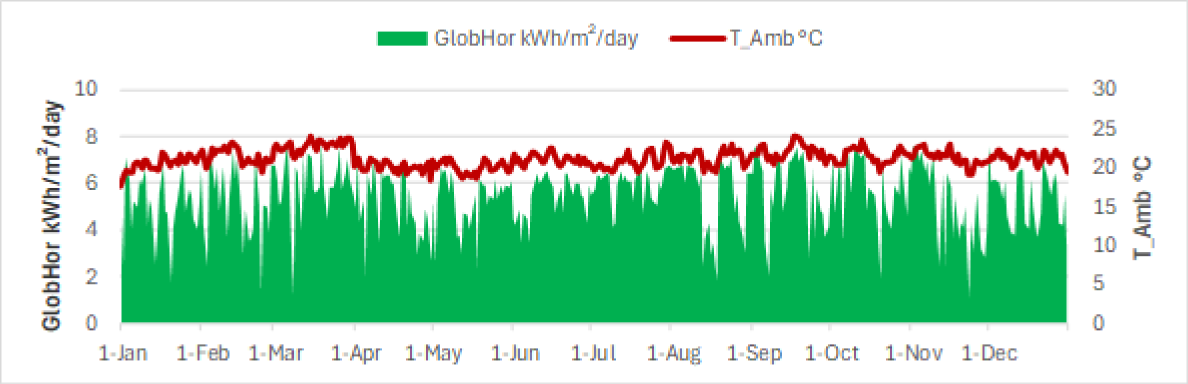


Figure 3-10: Daily meteorology data for Gasenyi center

The global horizontal irradiance remains relatively consistent, ranging between approximately 4 to 7 kWh/m²/day, indicating a high potential for solar energy generation. Similarly, the ambient temperature fluctuates mildly, mostly between 15°C and 25°C, reflecting a favorable climate for solar PV performance and minimal overheating issues. This combination of steady irradiance and moderate temperature underscores the suitability of the region for off-grid solar energy systems.

3.3.5. Solar Resource Data

This image provides a crucial step in the feasibility study of an off-grid photovoltaic (PV) system for Gasenyi center by presenting synthetic hourly meteorological data generated using PVSyst software. The data, sourced from the PVSIG TMY 5.2 database, includes monthly averages for global horizontal irradiation (in kWh/m²/day), diffuse irradiance, and ambient temperature. For Murya, the global irradiation averages 5.44 kWh/m²/day, with diffuse irradiation at 2.32 kWh/m²/day and an ambient temperature of 21.2°C. This information forms the foundation for assessing the solar energy potential in the area, enabling accurate simulations of PV system performance and provide insightful information on the system's viability and efficiency for meeting the energy demands of the community.

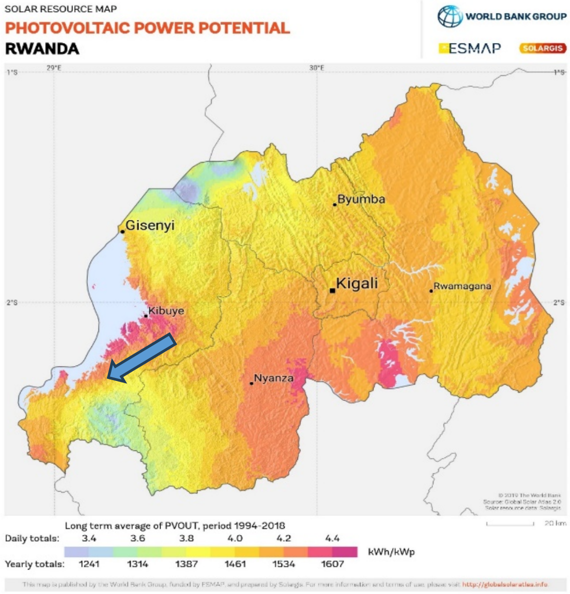
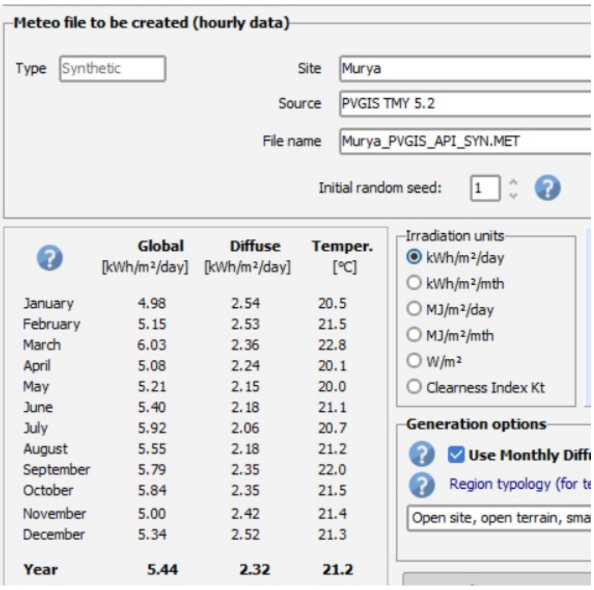


Figure 3-11: Direct Normal Radiation and Photovoltaic power potential in Rwanda



Meteo file to be created (hourly data)

Type: Synthetic

Site: Murya

Source: PVGIS TMY 5.2

File name: Murya_PVGIS_API_SYN.MET

Initial random seed: 1

	Global [kWh/m²/day]	Diffuse [kWh/m²/day]	Temper. [°C]
January	4.98	2.54	20.5
February	5.15	2.53	21.5
March	6.03	2.36	22.8
April	5.08	2.24	20.1
May	5.21	2.15	20.0
June	5.40	2.18	21.1
July	5.92	2.06	20.7
August	5.55	2.18	21.2
September	5.79	2.35	22.0
October	5.84	2.35	21.5
November	5.00	2.42	21.4
December	5.34	2.52	21.3
Year	**5.44**	**2.32**	**21.2**

Irradiation units
● kWh/m²/day
○ kWh/m²/mth
○ MJ/m²/day
○ MJ/m²/mth
○ W/m²
○ Clearness Index Kt

Generation options
☑ Use Monthly Diff
Region typology (for t
Open site, open terrain, sma

Figure 3-12: Solar Resource Data for Gasenyi center

3.4. Modeling of PV System

In this feasibility study, PVsyst 7.4 was used to simulate and model the off-grid PV system. The software provided a detailed technical and economic analysis, helping to assess how well the system would perform. It considered important factors such as energy generation, component sizing, and the financial aspects, all based on the data collected from daily load profiles and site conditions. By using PVSYST 7.4, we were able to evaluate whether the system could reliably and sustainably provide power to the target community.

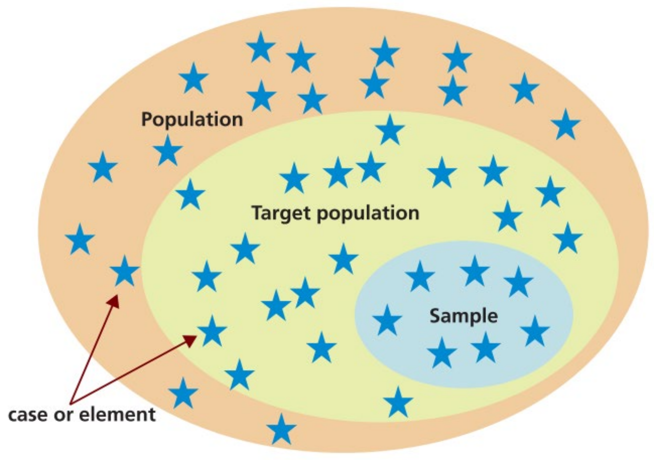
3.5. Sample sizing

In research methodology, sample size refers to the number of individuals or observations included in a study to represent a larger population. Determining the appropriate sample size is crucial for ensuring the study's results are reliable and generalizable to the broader population.

3.5.1. Key elements of sampling:

- **Population:** A complete set of elements (persons or objects) that possess some common characteristic defined by the sampling criteria established by the researcher. It is composed of two groups; target population and accessible population

- **Target Population:** is the entire group of people or objects to which the researcher wishes to generalize the study findings. It meets a set of criteria of interest to researcher



- **Sample:** A subset of the population that is selected for the study.
- **Sample Size:** The number of participants or observations included in the sample.

3.5.2. Some reasons why we choose a sample

- **Time and Cost Efficiency:** Collecting data from an entire population can be time-consuming, expensive, and sometimes even impossible.
- **Feasibility:** In some cases, collecting data from the entire population may be impractical or unfeasible.
- **Destructive Testing:** In certain research scenarios, taking measurements from the entire population could destroy it.

3.5.3. The major steps in sampling include

1. **Define the population**: The entire group of individuals, items, or events that the researcher is interested in studying. In my study the population is 104 households in Gasenyi center.
2. **Determine the sampling design:** Sampling design depends on the size of population.

Here are some strategies used in sampling design:

a) Use the entire population as sample
b) Using a sample size of a similar study
c) Rely on published tables
d) Using formulas for sample size
e) Using Software or web site

For my research, I preferred using formulas for sample sizing because it is much reliable according the population size of 104 households in Gasenyi center.

3. **Determine the appropriate sample size:** in this step, the researcher determine the sample size. In my research I selected using formulas for sample sizing. There are number of proven formulas to be used in sampling design which are the following:

a) Cochran Formula
b) Taro Yamane formula
c) Steven Thompson formula
d) Kergcie & Morgan formula
e) Richer Geiger formula
f) Robert Mason formula

Taro Yamane formula is mostly used for calculating sample size with finite population. It is the best formula to be used in **Design and Simulation of a PV-Battery Micro Grid System for Gasenyi center of Murya village** because it has a finite population of 104 households

$$n = \frac{N}{1 + N(e^2)}$$

Where: **n** is the sample size.
N is population size.
e is level of precision.

The level of precision varies from 80% or 0.2 to 95% or 0.05 according to the size of entire population. for my research, the level of precision is 85% or 0.15.

3.5.4. Execute the sampling process

$$n = \frac{N}{1 + N(e^2)}$$

N = 104

e = 0.2

$$n = \frac{N}{1 + N(e^2)} \quad n = \frac{104}{1 + 104(0.15^2)}$$

n=31 households

Data collection process is conducted for 31 household analyzed and the results are generalized on 104 household as total population for my study.

CHAPTER 4. SYSTEM DESIGN AND MODELING

4.1. Introduction

This chapter presents the detailed design and analysis of an off-grid photovoltaic (PV) system for Gasenyi center, located in Rusizi District, Rwanda. The study focuses on meeting the daily household energy demand of **265 kWh/day**, using a system sized based on daily solar irradiation specific to the region. Gasenyi center experiences consistent solar radiation throughout the year, making it an ideal location for implementing a PV system designed to operate under constant energy demand conditions. The chapter outlines the technical specifications of the system, including the PV array, inverter, battery storage, and overall system efficiency. Performance analysis is conducted to evaluate the reliability and effectiveness of the PV system in providing uninterrupted electricity to the community.

Additionally, the chapter delves into the economic aspects of the designed system, assessing its cost-effectiveness, financial feasibility, and economic viability. This involves analyzing the capital investment, operational and maintenance costs, and expected lifespan of the system, alongside potential savings compared to traditional energy sources such as diesel generators. The study aims to demonstrate how renewable energy solutions can address the energy access challenges faced by rural communities like Gasenyi center, offering sustainable, reliable, and affordable power solutions. Through this comprehensive analysis, the chapter provides valuable insights into the potential for scaling similar systems across other rural areas in Rwanda and beyond.

4.2. Assess Load demand

As presented in chapter 3.3.1.1- Figure 3-8 and in Figure 4-1, the user's power demand over 24 hours, with a total daily energy need of 264.7 kWh. The demand peaks twice: in the morning (6–8 hours) and evening (18–20 hours) at nearly 30,000 W, likely due to high energy activities during these periods. There are significant dips, especially around midday (12–15 hours) and late at night (3–5 hours), indicating periods of minimal activity.

A baseline load of about 5,000 W persists throughout the day, suggesting continuous essential operations. These fluctuations suggest opportunities for load balancing and energy optimization by distributing demand more evenly across the day to reduce peak loads and improve efficiency.

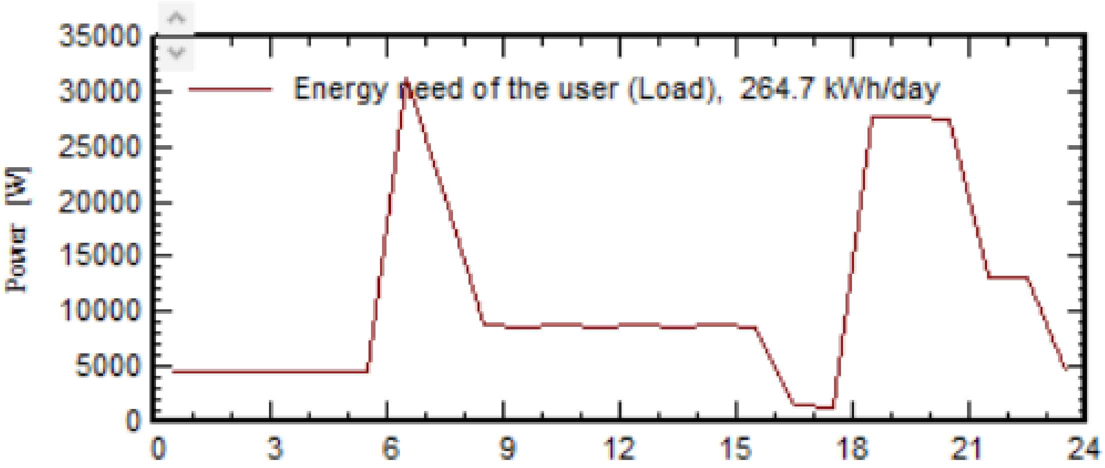
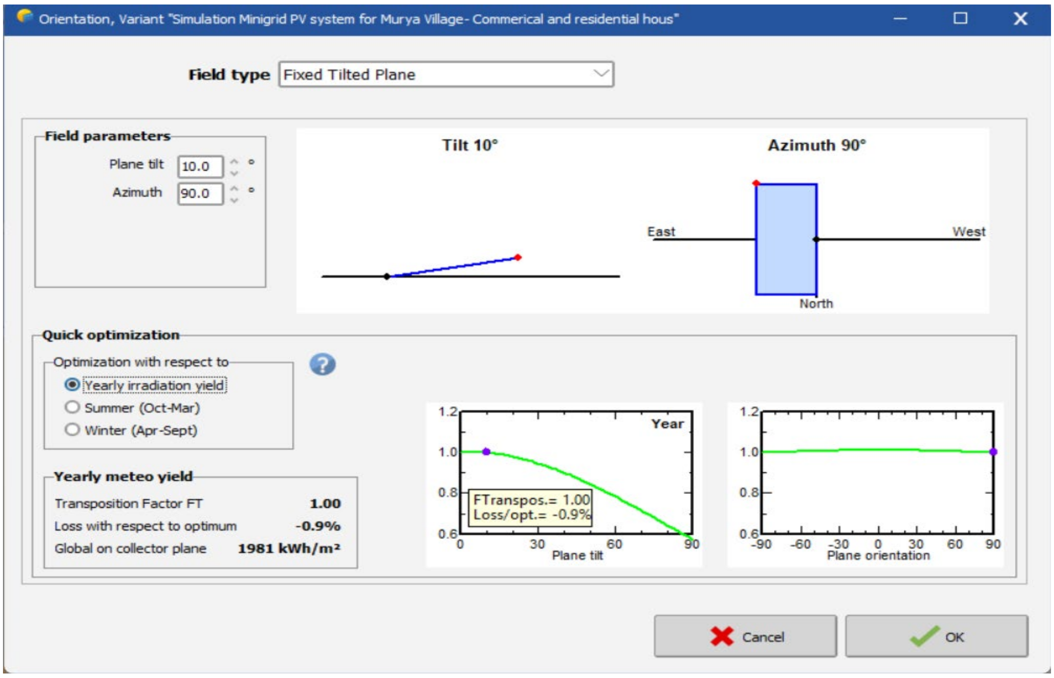


Figure 4-1: Load demand profile

4.3. PV system modeling

4.3.1. PV Module Orientation

The simulation report for the Gasenyi center mini-grid PV system indicates that the photovoltaic (PV) modules are installed in a fixed-plane orientation with a tilt angle of 10° and an azimuth angle of 90° as presented n Figure 4-2. This configuration was chosen to optimize solar energy capture based on Gasenyi center's geographical location and meteorological conditions. The azimuth angle of 90° means the panels are facing east, which may be intended to match local energy consumption patterns, particularly if morning energy demand is significant.


Orientation, Variant "Simulation Minigrid PV system for Murya Village- Commerical and residential hous"

Field type Fixed Tilted Plane

Field parameters

Plane tilt 10.0 °

Azimuth 90.0 °

Quick optimization

Optimization with respect to

- ● Yearly irradiation yield
- ○ Summer (Oct-Mar)
- ○ Winter (Apr-Sept)

Yearly meteo yield

Transposition Factor FT	1.00
Loss with respect to optimum	-0.9%
Global on collector plane	1981 kWh/m²

Figure 4-2: Module Orientation

4.3.2. Perspective View of Mounted Solar Panels

The perspective view of the mounted solar panels Figure 4-3 shows that they are installed on a single array shed structure, ensuring uniform exposure to sunlight while minimizing shading effects. The system utilizes four sheds, each designed to maintain optimal spacing between rows, reducing potential shading losses. The ground coverage ratio (GCR) is approximately 68.8%, indicating an efficient use of space while preventing excessive self-shading between panels. The figure 4-4 shows the plot for mounting solar panels. The plot is located near the center, facing to west and at the top of hill with no shading trees. Those factors make the area most suitable for mounting panels with no environment destruction.

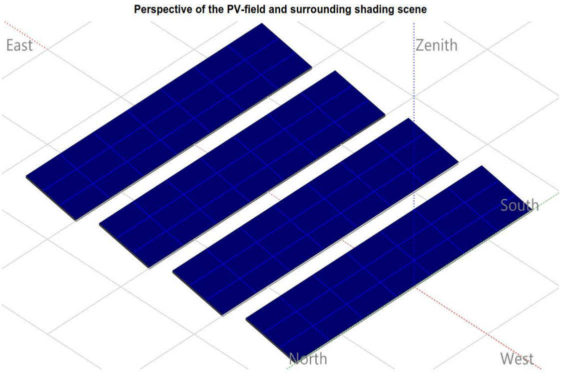


Figure 4-3: Perspective view of the mounted solar panels

Figure 4-4: Site Terrain Overview

4.3.3. Impact of West-Facing Slope on PV Panel Orientation

The decision to orient the solar panels westward in Gasenyi center is influenced by the natural slope of the land see Figure 4-4, which faces west. This topographical feature plays a critical role in determining the optimal tilt and orientation of the PV modules.

4.3.4. Reasons for Utilizing the West-Facing Slope

1. Reduced Installation Costs – Mounting the solar panels along the natural slope minimizes the need for extensive ground leveling or support structures, reducing civil works and installation costs.
2. Maximized Solar Exposure – A west-facing slope naturally aligns the PV panels toward the afternoon sun, enhancing energy generation during peak demand hours in the late afternoon and early evening.
3. Improved Drainage and Stability – Installing panels on a westward slope helps with water runoff during rainy seasons, preventing soil erosion and reducing the risk of water pooling under the panel structures.
4. Structural Integrity and Wind Resistance – The natural incline provides additional mechanical stability, reducing the need for additional support reinforcements that would otherwise be required on a flat or eastward-facing terrain.
5. Integration with Local Energy Demand Patterns – Since household energy usage in Gasenyi center is higher in the evening, the westward panel orientation ensures more solar energy is available during these critical hours, optimizing battery storage charging and utilization.

4.3.5. Iso-shadings analysis

Additionally, near shading analysis has been conducted using an iso-shading diagram on Figure 4-5, confirming that electrical effects of shading are managed within the design constraints. The layout ensures that shading losses remain minimal, enhancing overall system efficiency.

The westward-facing PV module orientation in the Gasenyi center microgrid is primarily dictated by the site's natural topography, which features a westward slope. Aligning solar panels with the terrain minimizes structural modifications, reducing installation complexity and costs while maintaining system stability. Although North-facing orientations typically maximize solar capture in the Southern hemisphere, the westward tilt benefits late-afternoon energy demand, which aligns with peak household consumption patterns.

The shading analysis reveals moderate losses, but the overall system efficiency, reflected in the 81.66% performance ratio, remains high and help achieve the projected annual solar energy generation of 74,010 kWh**.** This design choice exemplifies a practical balance between terrain constraints, energy yield optimization, and economic feasibility, ensuring reliable electricity access for the village.

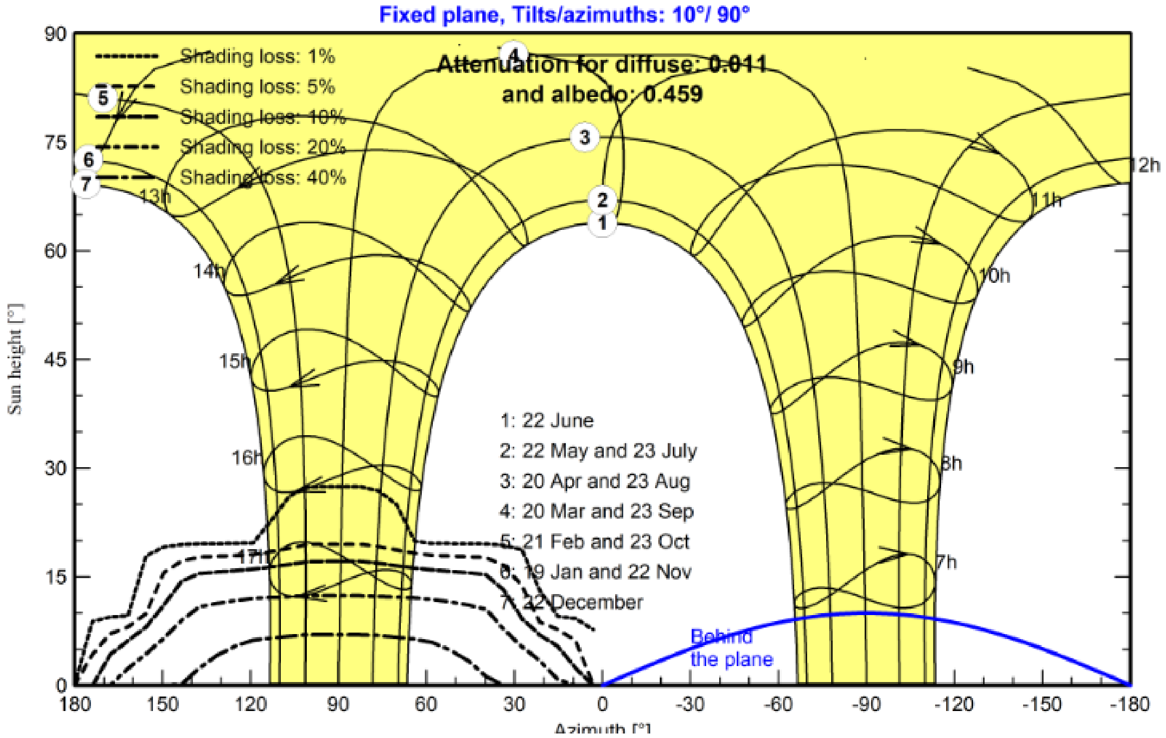


Figure 4-5: Iso-shadings diagram

4.3.6. Modelled Solar PV-Battery Storage System

As shown in Table 4-1, the PV system comprises JA Solar JAM72-S30-550-MR modules, with 80 units arranged in 10 strings of 8 modules, providing a nominal capacity of 44.0 kWp at STC. Under real conditions (50°C), output reduces to 40.4 kWp due to temperature-related losses. The system operates at an MPP voltage of 303V and an MPP current of 133A, ensuring efficient energy harvesting. Energy storage is managed by a BYD Battery Box Premium LVS 20.0, a Lithium Iron Phosphate (LFP) system with 12 parallel units, storing 255.6 kWh at 51V nominal voltage and 6240 Ah capacity. The battery management system (BMS) maintains SOC & DOD thresholds at 0.90/0.75 for charging and 0.20/0.45 for discharging, optimizing longevity and efficiency. A Victron Smart Solar MPPT RS 450/200 controller, with four MPPT units, regulates power conversion, with a temperature coefficient of -5.0 mV/°C per cell. The system's converter achieves up to 96.0% efficiency, ensuring minimal losses and reliable performance for sustainable energy applications.

Table 4-1: PV Array

PV module Manufacturer	JA Solar	**Battery** Manufacturer BYD
Model	JAM72-S30-550-MR	Model Battery Box Premium LVS 20.0
(Custom parameters		Technology Lithium-ion, LFP
Unit Nom. Power	550 Wp	Nb. of units 12 in parallel
Number of PV modules	80 units	Discharging min. SOC 20.0 %
Nominal (STC)	44.0 kWp	Stored energy 255.6 kWh
Modules **At operating cond. (50°C)** Pmpp	10 Strings x 8 In series 40.4 kWp	**Battery Pack Characteristics** Voltage 51 V Nominal Capacity 6240 Ah (C10)
U mpp	303 V	Temperature External ambient temperature
I mpp	133 A	
Controller Manufacturer		**Battery Management control** Threshold commands as SOC calculation
Model	SmartSolar MPPT RS 450/200	Charging SOC = 0.90 / 0.75
Nb. units	4 units	Discharging SOC = 0.20 / 0.45
Technology	MPPT converter	
Temp coeff.	-5.0 mV/°C/Elem.	
Converter Maxi and EURO efficiencies	96.0 / 95.0 %	

4.3.7. Seasonal Performance Analysis of a Photovoltaic System and Energy Reliability Considerations

The Figure 4-6 illustrates the daily array energy output of a photovoltaic (PV) system throughout the year, showing seasonal variations influenced by solar radiation, weather conditions, and system inefficiencies. Peak energy production occurs between March and October, averaging 180–220 kWh/day, while lower outputs of 120 kWh/day are observed in February, November, and December due to cloud cover and reduced sunlight hours.

Despite these fluctuations, the system maintains an annual efficiency of 81.66%, with a solar fraction (SF) of 73.09%, see Figure 4-7. However, energy shortages occur 28% of the time, emphasizing the need for optimized battery storage or demand-side management to enhance reliability and mitigate seasonal inconsistencies.

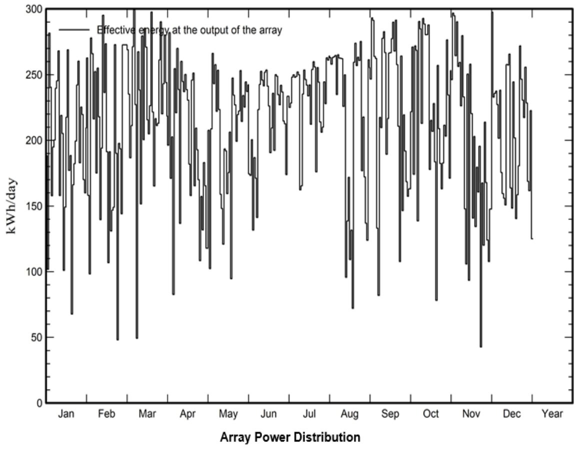


Figure 4-6: Daily Array Output Energy

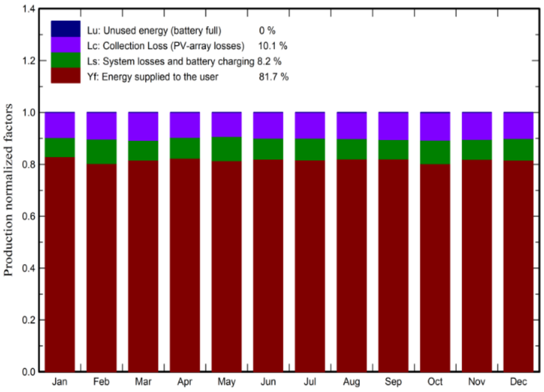


Figure 4-7: Normalized Production and Loss Factors

4.4. PV system sizing

The method used to evaluate the required PV system size considers daily solar irradiation and panel efficiency. It calculates the necessary power output to meet the daily load demand while accounting for the available solar energy resources at the site. Since the system is off-grid, the battery bank, charge controller, and inverter were also appropriately sized to ensure reliable energy storage and distribution.

4.4.1. PV array sizing

***1. Total Daily Load Demand*:**

We already have the total **daily energy consumption** E_{load} as shown in Figure 4-1

$E_{\text{load}} = 264.7\,\text{kWh/day(from the first image you provided).}$

***2. Solar Irradiation*:**

As presented in chapter 3.3.5 on the Figure 3-12 Gasenyi center has the global irradiation averages **5.44 kWh/m²/day**, with diffuse irradiation at 2.32 kWh/m²/day and an ambient temperature of 21.2°C.

3. Panel Efficiency:

As detailed in datasheet for JA solar 550W module, solar panels have an efficiency of 21**%**, ($\eta_{\text{panel}} = 0.21$) see Appendix 2. PV module datasheet.

4. System Efficiency:

Assume the overall system efficiency (η_{system}) to be 75% by considering losses like temperature, wiring, inverter, and battery efficiency.

5. Calculate the Required Nominal PV Power:

Now we can use the formula (4-1) to calculate the required nominal PV power, P_{PV}, in kWp [35],[36]:

$$P_{\text{PV}} = \frac{E_{\text{load}}}{G_{\text{daily}} * \eta_{\text{system}} * \text{system losses}} \tag{4-1}$$

Substituting the values:

- $E_{\text{load}} = 264.7\,\text{kWh/day}$
- $G_{\text{daily}} = 5.44\,\text{kWh/m}^2\text{/day}$
- η_{system} and system losses $= 0.75$

$$P_{\text{PV}} = \frac{264.7}{5.44 \times 0.75} = \frac{264.7}{4.08} \approx 64.877\,\text{kWp} \tag{4-2}$$

The required nominal **PV power** is approximately **65 kWp**.

4.4.2. Battery Storage Sizing

Batteries play a vital role in ensuring uninterrupted power supply, particularly during nighttime and cloudy periods: The equation (4-3) was used to size the battery bank.

$$E_{\text{battery, req}} = \frac{E_{\text{load}} \times \text{Autonomy Days}}{\text{DoD} \times \eta_{\text{battery}}} \tag{4-3}$$

Using:

- One-day autonomy
- 80% DoD
- 95% battery efficiency

$$E_{\text{battery, req}} = \frac{265}{0.8 \times 0.95} = 348.69 \text{ kWh}$$

However, PVSyst optimized the storage capacity to **255.6 kWh** based on practical constraints.

The simulation report in Table 4-2 outlines the performance of the battery system. The total battery capacity of 255.6 kWh ensures reliable backup during night or cloudy periods. With a depth of discharge (DoD) of 80%, the battery lifespan is extended, and it is expected to last for 10.6 years before replacement. However, charge/discharge losses of 3.9% indicate some conversion inefficiencies in the system, slightly reducing overall performance.

Table 4-2: Battery System Performance

Metric	Value	Interpretation
Total Battery Capacity	255.6 kWh	Ensures backup during night/cloudy hours
Depth of Discharge (DoD)	80%	Extends battery lifespan
Battery Lifetime	10.6 years	Expected before replacement
Charge/Discharge Losses	3.9%	Conversion inefficiencies

4.4.3. Charge Controller Sizing

The charge controller is sized based on equation (4-4) the PV array current:

$$\text{Controller Size (A)} = \frac{\text{PV Size (W)}}{\text{System Voltage (V)}} \times \text{Safety Factor} \tag{4-4}$$

Safety factor: 1.25 (to account for overcurrent conditions). Assuming a 48V system:

$$\text{Controller Size} = \frac{65{,}000}{48} \times 1.25 \approx 1{,}692 \ \approx 1{,}700 \text{ A}$$

This might require multiple controllers connected in parallel.

4.4.4. Inverter Sizing

Many inverters are equipped with multiple MPPT (Maximum Power Point Tracking) inputs, where each MPPT input can be connected to a separate sub-array. These inputs do not increase the inverter's rated power; rather, they enhance the system's ability to track the maximum power output from the PV array. To ensure that the off-grid inverter can accommodate the maximum power demand from the loads, a safety factor of 1.25 was applied.

This factor accounts for potential increases in load current caused by the addition of new equipment, allowing the system to handle slight expansions beyond the initially planned capacity. The equation (4-5) was used to size the capacity of inverter [37], [38], [39].

$$Inverter\ capacity = P_{pv} * 1.25 \qquad 4\text{-}5$$

Inverter capacity =65*1.25=81 kW

4.5. The discrepancy between the calculated values and the simulation results

The discrepancy between the calculated values and the simulation results in a PV system can arise due to several factors, including system losses, efficiency variations, and environmental conditions. In theoretical calculations, ideal assumptions are often made, such as perfect MPPT tracking, no losses in wiring, and constant solar irradiance. However, in a simulation, software like PVsyst incorporates real-world losses such as temperature effects on modules, inverter efficiency, shading losses, and DC/AC conversion losses. These factors result in a lower simulated power output compared to theoretical estimates, making the simulation more reflective of real-world performance.

Another key reason for discrepancies is the dynamic behavior of solar components under varying conditions. For example, in manual calculations, PV module performance is often estimated using standard test conditions (STC: 1000 W/m², 25°C, AM1.5), but actual conditions fluctuate throughout the day. The simulation software applies hourly or minute-based irradiance data, panel degradation, and even grid constraints (if applicable), which alter energy yields. Additionally, battery charging efficiency, inverter clipping, and MPPT voltage tracking mismatches can all contribute to differences. Understanding these simulation adjustments helps in refining system designs for better real-world efficiency and performance.

The simulation results indicate that the inverter system is composed of four Victron SmartSolar MPPT RS 450/200 controllers, each rated at 11,500 W (11.5 kW). The total controller power is 46.0 kW, which is different from your calculated inverter capacity of 65 kW.

4.6. Design process and validation

The study focuses on meeting the daily household energy demand of **265 kWh/day.** However, PVSyst software is used to design and optimize the energy needs based on its internal algorithms and input load demand. PVSyst optimized the storage capacity to **255.6 kWh** based on practical constraints.

PVSyst software is used to design different mode including Grid connected PV system, Standalone PV system and hybrid system. In my research I used a standalone PV system and it is selected to be used in software.

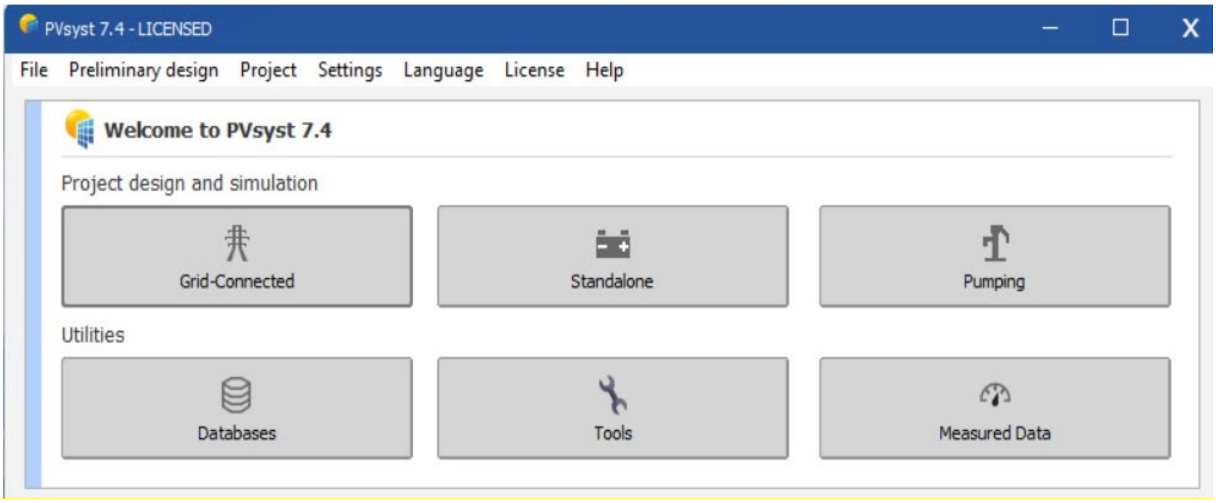
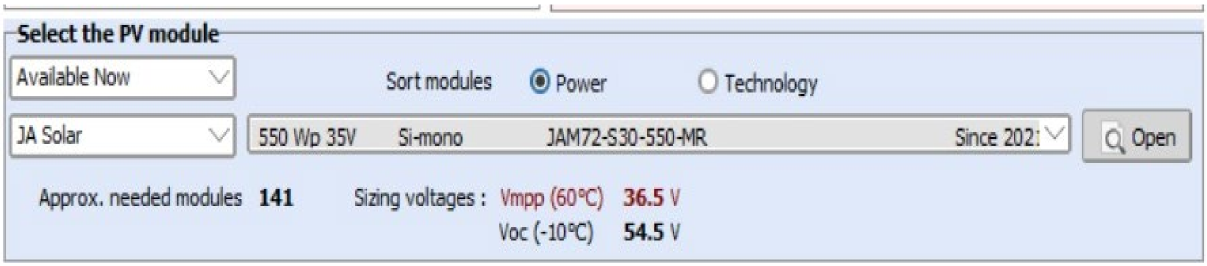


Figure 4-8: PVSyst project design view

4.6.1. PV module selection and sizing

PVSyst software is equipped with all modules on local and international market. They are from different manufacturer with different materials, size and efficient. The selection of appropriate module to be used depends on different factors including size of the project, climate condition, cost, efficient, maintenance cost and lifespan of the module. As seen on figure 4-9, the JA Solar JAM72-S30-550-MR PV module is selected in PVSyst to be used in the project.



Select the PV module

Available Now

Sort modules ● Power ○ Technology

JA Solar

550 Wp 35V Si-mono JAM72-S30-550-MR Since 202:

Approx. needed modules **141**

Sizing voltages : Vmpp (60°C) **36.5** V

Voc (-10°C) **54.5** V

Figure 4-9: PV module selection

As seen on figure 4-9, the JA Solar JAM72-S30-550-MR PV module's advantages include higher power output due to its half-cell and 11BB PERC technology, which also reduces shading and hot spots. It offers a lower Levelized Cost of Energy (LCOE), features enhanced mechanical loading tolerance, a superior warranty with slow annual degradation, and improved performance in high temperatures.

The above qualities of JA solar panels enhanced the selection of this type of PV module to be used in my design.

After PV selection, next step is PV array design (sizing). In this process; desired information such as area irradiance, energy demand per day, peak demand and peak hours, days of autonomy, PV type ambient temperature, type of system (standalone) are recorded in software. After analyzing them; PVSyst gives optimized design of PV module needed in the project.

PV Array design

Number of modules and strings

should be:

Mod. in series 8 ☐ between 3 and 8

Nb. strings 10 ☑ between 6 and 10

Overload loss **0.0%**

Pnom ratio **0.96**

Nb. modules **80** **Area** **207** m^2

Operating conditions:

Vmpp (60°C) 292 V

Vmpp (20°C) 337 V

Voc (-10°C) 436 V

Plane irradiance **1000** **W/m^2**

Impp (60°C) 133 A

Isc (60°C) 142 A

Isc (at STC) 141 A

Max. operating power (at max. irrad and 50°C) **40.4** kW

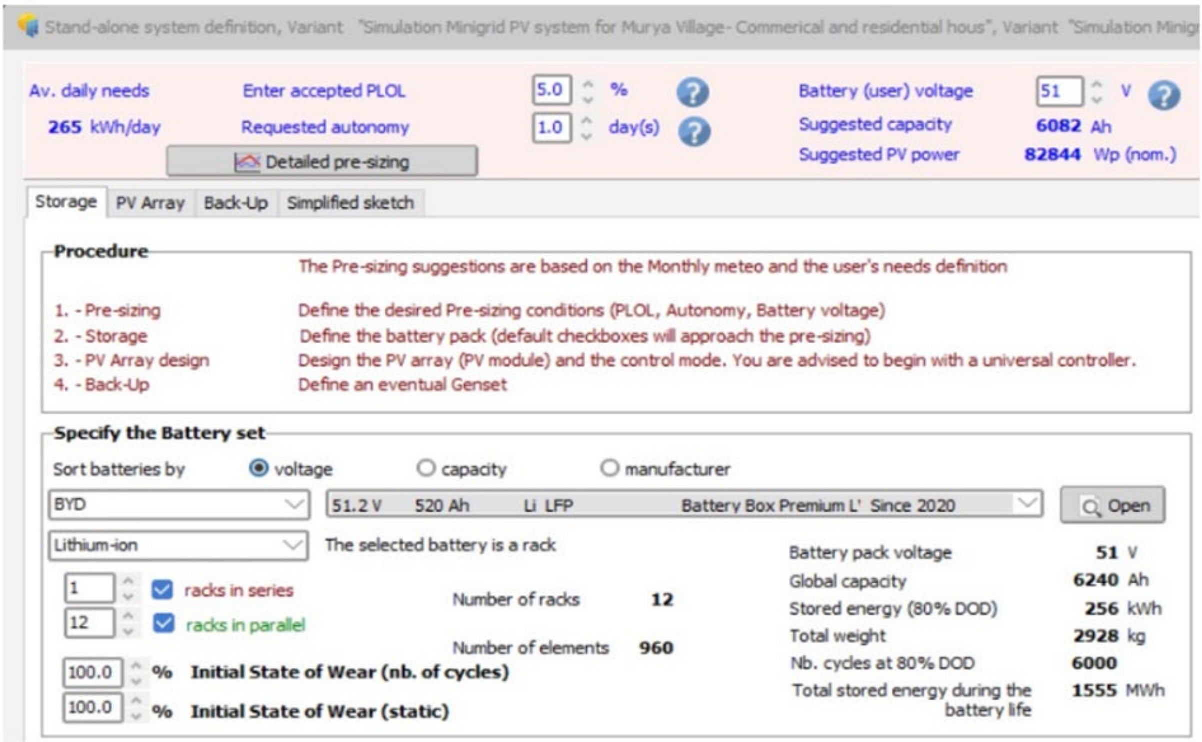
Array nom. Power (STC) **44.0** kWp

Figure 4-10: PV array design output

PVSyst optimized PV array design output shows that 80 modules are needed with 10 strings and 8 modules in series. Total area of modules is 207 m^2. More details on PV array design are found on figure 4-10 above.

4.6.2. Battery selection and sizing

After receiving validated data of PV module, PVSyst allows next step which is battery selection and sizing. As for PV array sizing, the process of battery sizing starts with battery selection based on technical and economic constraint.



Stand-alone system definition, Variant "Simulation Minigrid PV system for Murya Village- Commerical and residential hous", Variant "Simulation Minig

Av. daily needs 265 kWh/day

Enter accepted PLOL 5.0 %

Requested autonomy 1.0 day(s)

Battery (user) voltage 51 V

Suggested capacity 6082 Ah

Suggested PV power 82844 Wp (nom.)

Procedure

The Pre-sizing suggestions are based on the Monthly meteo and the user's needs definition

1. - Pre-sizing	Define the desired Pre-sizing conditions (PLOL, Autonomy, Battery voltage)
2. - Storage	Define the battery pack (default checkboxes will approach the pre-sizing)
3. - PV Array design	Design the PV array (PV module) and the control mode. You are advised to begin with a universal controller.
4. - Back-Up	Define an eventual Genset

Specify the Battery set

Sort batteries by ● voltage ○ capacity ○ manufacturer

BYD

51.2 V 520 Ah Li LFP Battery Box Premium L' Since 2020

Lithium-ion

The selected battery is a rack

1 ☑ racks in series

12 ☑ racks in parallel

Number of racks 12

Number of elements 960

100.0 % **Initial State of Wear (nb. of cycles)**

100.0 % **Initial State of Wear (static)**

Battery pack voltage	51 V
Global capacity	6240 Ah
Stored energy (80% DOD)	256 kWh
Total weight	2928 kg
Nb. cycles at 80% DOD	6000
Total stored energy during the battery life	1555 MWh

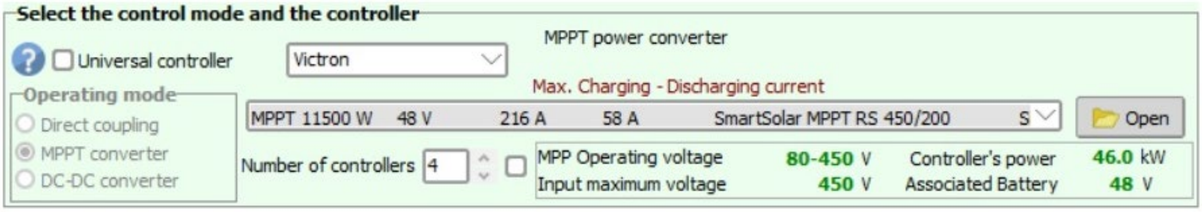
Figure 4-11: Battery selection and sizing

Li LFP 520Ah 51.2V battery is chosen to be used in my research project. The term lithium iron phosphate battery (LFP) refers to a particular kind of lithium-ion battery that uses the special cathode chemistry of lithium iron phosphate ($LiFePO_4$). Because of its chemistry, which excludes nickel and cobalt, LFP batteries are safer, more stable, and have a longer lifespan than some other lithium-ion technologies. This makes them a great option for stationary energy storage, electric vehicles, and other applications that demand dependability and durability. LFP batteries are a great option for energy storage and EVs because of their high thermal stability, extended cycle life, and affordability from a variety of materials. By avoiding cobalt and providing a smaller carbon footprint, they also aid the environment. They require little maintenance and function well in a range of temperatures.

After PVSyst software analysis, 12 batteries in parallel are optimized number of Li LFP 520Ah 51.2V to be used for storage system considering 1 day of autonomy. More details on battery storage system are found on figure 4-11.

4.6.3. Charge controller selection and design

Charge controllers are essential components in PV system design. They monitor the state of batteries; they stop charging when batteries are fully charged and start charging when the level meet low set value of charging.


Select the control mode and the controller

☐ Universal controller

Victron

Operating mode

○ Direct coupling

● MPPT converter

○ DC-DC converter

MPPT power converter

Max. Charging - Discharging current

MPPT 11500 W 48 V 216 A 58 A SmartSolar MPPT RS 450/200 S

Number of controllers 4 ☐

MPP Operating voltage 80-450 V

Input maximum voltage 450 V

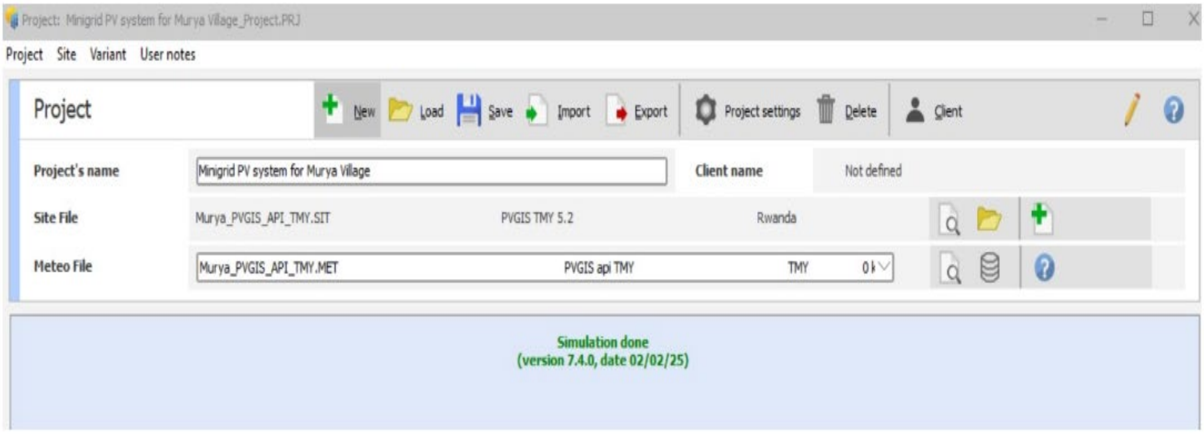
Controller's power 46.0 kW

Associated Battery 48 V

Figure 4-12: Charge controller selection and sizing

Victron 216A 48V charge controller are used with MPPT converter control mode. PVSyst software optimizes 4 charge controllers to be used in my design. More details are found on figure 4-12

After design and optimization with algorithms of PVSyst software, the final project with various output is saved figure 4-13. The output data are available to be implemented in selected area or any other area with same geographical and climate characteristics. Summary of the project design and simulation is found on figure 4-14.


Project: Minigrid PV system for Murya Village_Project.PRJ

Project's name: Minigrid PV system for Murya Village

Client name: Not defined

Site File: Murya_PVGIS_API_TMY.SIT PVGIS TMY 5.2 Rwanda

Meteo File: Murya_PVGIS_API_TMY.MET PVGIS api TMY TMY 0

Simulation done
(version 7.4.0, date 02/02/25)

Figure 4-13: Simulation confirmation view

User's needs	Household		Aver. power	11.0 kW
	Night ratio	50.0%	Daily energy	265 kWh
Battery pack	12 in parallel, 51 V		Capacity	6240 Ah
	Autonomy	1.0 day	Stored energy	256 kWh
PV Array	10 str. of 8 modules		Nom. Power	44.0 kWp
	PV/PLoad	4.0	Av. daily energy	149 kWh
Controller	MPPT converter		Nom. Power	46.0 kW
	PV/PConv	0.96	Thresholds	acc. to SOC

Figure 4-14: Project summary

4.7. Optimization Technics and model used.

Optimization in the context of the PV-Battery microgrid system is the process of designing the system's components (PV array, batteries, inverters) to achieve the best possible performance while minimizing costs and ensuring a reliable power supply. The main goal is to find the most cost-effective and technically feasible system configuration. PVSyst itself is an optimization tool, it can provide different output on same data. For optimization technic, optimum mode is selected in PVSyst software. for given inputs, software gives output of single optimum value considering technical, environmental and economic constraint.

The model used to conduct the simulation, sizing, and analysis of the system was the specialized software tool: **PVsyst 7.4 (Photovoltaic System Software):** This software was the primary **modeling tool** used to simulate the system performance and determine its optimal configuration.

It takes inputs like local meteorological data (solar resource availability), the load profile (energy demand), and component specifications (PV modules, battery, inverter) to calculate the annual energy yield and various loss factors. It ensures an optimal system configuration (e.g., array size, battery capacity) by running internal algorithms and incorporating real-world factors like temperature effects, shading losses, and inverter efficiency, which are typically ignored in manual, theoretical calculations. The financial assessment relied on established economic models such as **Net Present Value (NPV)** and **Levelized Cost of Energy (LCOE)** to validate the financial viability of the optimized system design.

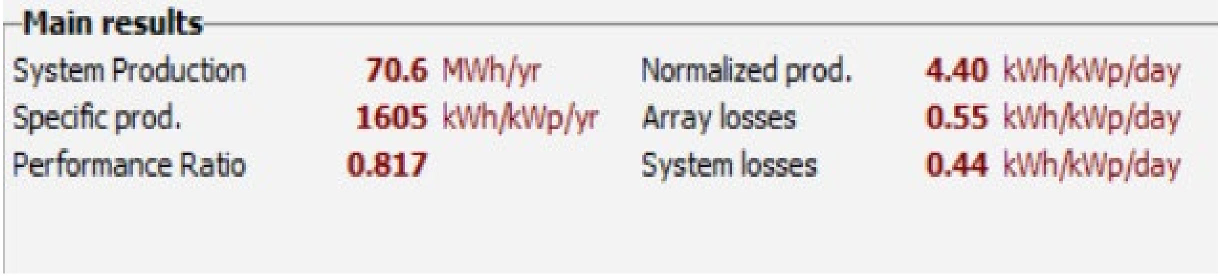
CHAPTER 5. RESULTS AND DISCUSSION

This chapter provides a comprehensive analysis of the simulation results obtained from the designed off-grid photovoltaic (PV) system for Gasenyi center. The discussion revolves around key performance indicators, energy utilization patterns, system losses, and financial viability, ensuring an in-depth evaluation of the system's technical and economic feasibility. By comparing these results against the initial design expectations and objectives, the chapter critically assesses the system's ability to meet the daily energy demand of 265 kWh for household consumers in Gasenyi center, located in Rusizi District, Rwanda.

5.1. Technical Performance Analysis

The system produces a total of 74,010 kWh of available solar energy annually, out of which 70,610 kWh is converted into useful energy. The performance ratio (PR) of the system is 81.66%, indicating a high efficiency in converting available solar energy into usable power. The solar fraction (SF) is 73.09%, meaning that 73.09% of the total energy demand is met by solar power. The system generates a minimal amount of excess (unused) energy, just 14 kWh per year, demonstrating an efficient and well-optimized system with very little wastage.

Table 5-1: Man result



Main results

System Production	70.6	MWh/yr	Normalized prod.	4.40	kWh/kWp/day
Specific prod.	1605	kWh/kWp/yr	Array losses	0.55	kWh/kWp/day
Performance Ratio	0.817		System losses	0.44	kWh/kWp/day

5.1.1. Technical results

The ***Table 5-2*** highlights the relationship between the Energy Supplied to the User (E_User), The technical performance analysis from the ***Table 5-2*** reveals that the system's annual available solar energy (E_Avail) is 74,010 kWh, with a total energy supplied to the user (E_User) of 70,610 kWh. The system maintains a consistent solar fraction (SolFrac) of 73.1%, indicating that 73.1% of the energy demand is met by solar energy. The total unused energy (E_Unused) is 13.968 kWh, with minimal missing energy (E_Miss) of 25,997 kWh.

The solar fraction reaches its highest value in July at 80.4%, showcasing the system's optimal performance during peak sunlight months.

The system ensures a reliable energy supply, with some variation in energy availability and demand, indicating that it efficiently manages the load throughout the year.

Table 5-2: Detailed Simulation result

	GlobHor kWh/m^2	GlobEff kWh/m^2	E_Avail kW	EUnused kW	E_Miss kW	E_User kW	E_Load kW	SolFrac
January	154.4	149.9	5786	0.000	2614	5591	8205	0.681
February	144.2	137.6	5272	0.000	2441	4970	7411	0.671
March	186.9	179.1	6832	0.000	1647	6558	8205	0.799
April	152.3	146.5	5665	0.371	2517	5423	7940	0.683
May	161.6	158.0	6129	0.000	2434	5771	8205	0.703
June	162.1	159.1	6161	0.000	2063	5877	7940	0.740
July	183.6	179.6	6950	0.000	1605	6600	8205	0.804
August	171.9	166.6	6418	5.618	2065	6140	8205	0.748
September	173.8	168.6	6461	0.000	1732	6208	7940	0.782
October	180.9	174.4	6656	7.812	1919	6286	8205	0.766
November	150.0	144.1	5528	0.000	2614	5326	7940	0.671
December	165.4	159.4	6150	0.167	2344	5861	8205	0.714
Year	1987.1	1922.8	74010	13.968	25997	70610	96607	0.731

Legends

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

5.1.2. Analysis of Solar Energy Generation, Storage, and Consumption Patterns

The data in *Figure 5-1* shows that The system generates a total of 74,010 kWh of solar energy annually, with the majority of this energy used to charge batteries (58,951 kWh). The batteries discharge 55,698 kWh to meet the load, supplying 70,612 kWh over the year. While solar energy generally covers battery charging, there is a consistent shortfall in meeting the total energy demand, particularly in months with lower solar availability like February. This indicates that the system relies on battery storage to bridge the gap but may require additional solar capacity or improved storage to fully meet the load year-round.

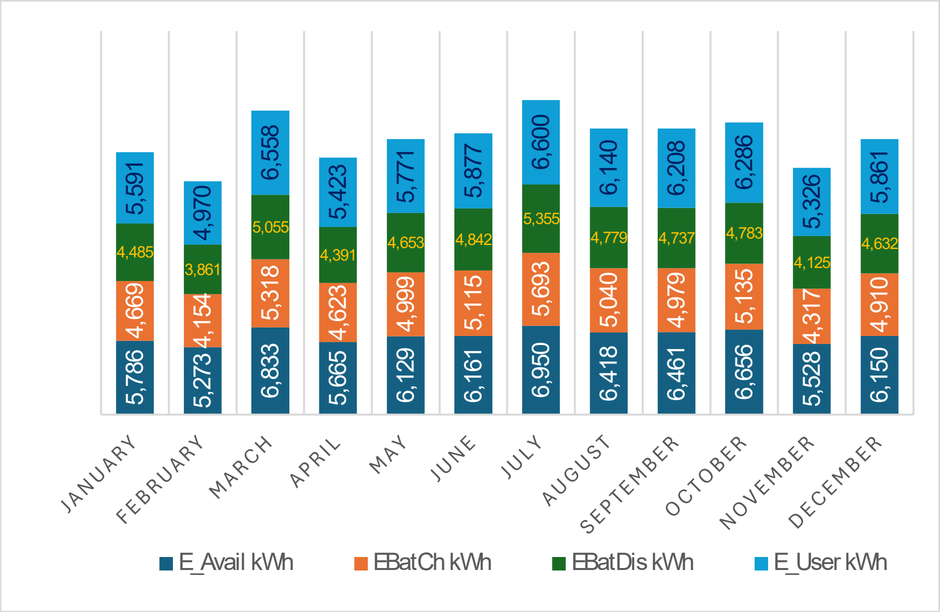


Figure 5-1: Energy generation, storage and consumption

E_Avail: Available solar energy

EBatCh: Battery charging energy

EBatDis: Battery discharging energy

E_User: Energy supplied to the load

E_Load: Energy need of the user (load)

5.1.3. Normalized production analysis

The Figure 5-2 provided data outlines the simulation of the MiniGrid PV system for Gasenyi center, covering both commercial and residential housing, reveals key performance metrics across the year. The energy supplied to the user (Yf) ranges from 4.03 kWh/kWp/day in February to 4.84 kWh/kWp/day in July, with an average of 4.40 kWh/kWp/day for the year. The performance ratio (PR) remains relatively consistent throughout the year, averaging 0.817, with slight monthly variations. Unused energy (Lur) is essentially zero across all months, indicating minimal excess energy during battery charging. System losses (Ls) fluctuate between 0.36 kWh/kWp/day in January and 0.52 kWh/kWp/day in October, with an average of 0.44 kWh/kWp/day for the year, reflecting typical energy losses in PV systems due to inefficiencies and conversion losses. The data highlights stable system performance with manageable energy losses, ensuring a consistent supply to both residential and commercial users.

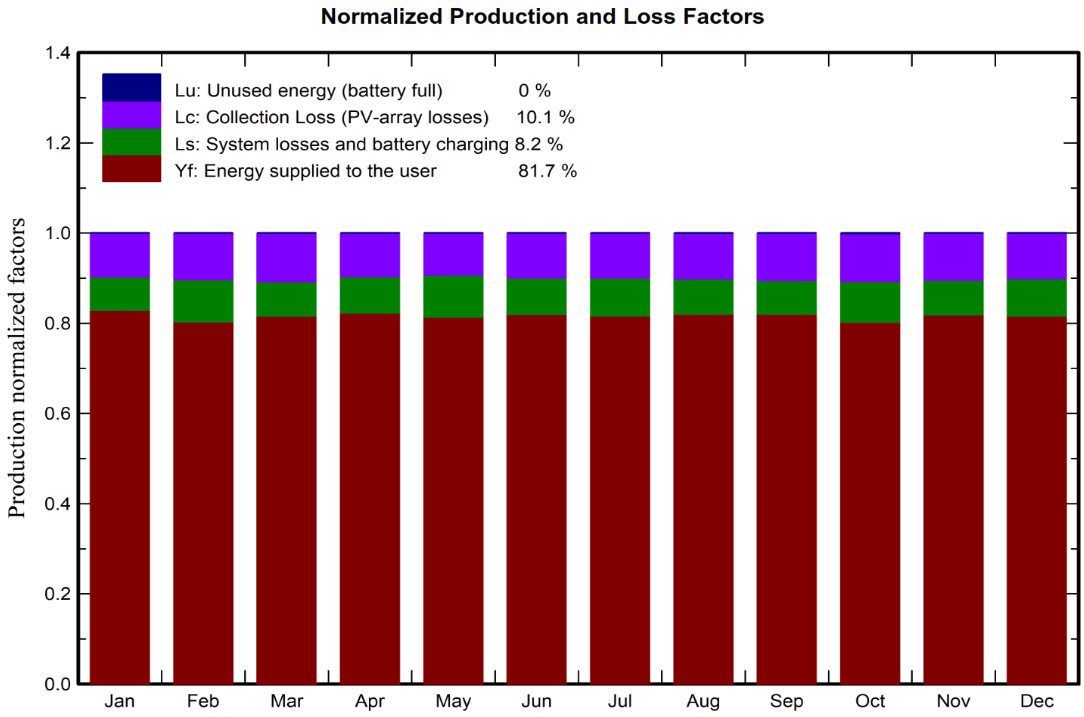


Figure 5-2: Normalized production analysis

5.1.4. System production and economic evaluation

The system's solar production results in in ***Table 5-3*** and Table 5-4 show 70,610 kWh/year of useful energy and 74,010 kWh/year of available solar energy, with an excess of 14 kWh/year remaining unused. The performance ratio (PR) is 81.66%, and the solar fraction (SF) is 73.09%, indicating effective use of available sunlight. However, 25,997 kWh/year is considered missing energy, with a loss of load time fraction of 28.0%. The battery aging has a State of Wear (SOW) of 96.7% with a static SOW of 90.6%, and the battery lifetime is estimated at 10.6 years. The cost of stored energy is 1.12 ctUSD/kWh. Economically, the total investment is $43,400, with annual running costs of $9,422.64 and an energy cost of $0.13 USD/kWh. The Levelized Cost of Energy (LCOE) is calculated based on these factors.

Table 5-3: System production

Useful energy from solar	70610 kWh/year	Perf. Ratio PR	81.66 %
Available solar energy	74010 kWh/year	Solar Fraction SF	73.09 %
Excess (unused)	14 kWh/year		
Loss of Load		**Battery aging (State of Wear)**	
Time Fraction	28.0 %	Cycles SOW	96.7 %
Missing Energy	25997 kWh/year	Static SOW	90.6 %
		Battery lifetime	10.6 years
		Cost of stored energy	1.12 USD/kWh

Table 5-4:Economic evaluation

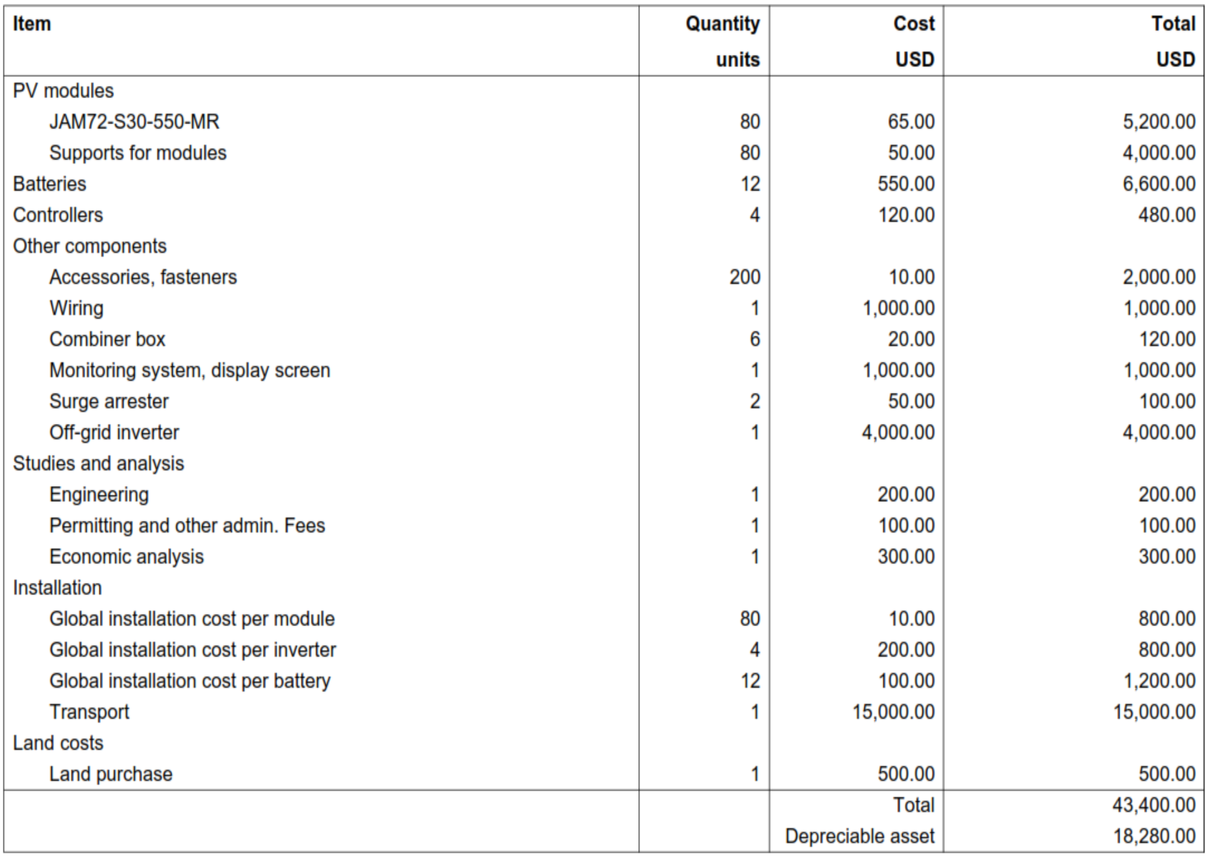
Investment		**Yearly cost**		**LCOE**	
Global	43,400.00	Annuities	0.00 USD/yr	Energy cost	0.13USD/kWh
Specific: USD/Wp	0.99	Run. Costs	9,422.64 USD/yr		

5.2. Financial analysis

5.2.1. Investment cost analysis

As shown in ***Table 5-5***, The financial analysis for the PV system demonstrates a detailed and structured cost breakdown, with major investments in core components such as PV modules, batteries, controllers, and associated mounting and wiring accessories. The table itemizes quantities and unit costs, ending in a depreciable asset value of USD 43,400, while additional economic factors contribute an extra USD 18,280. This comprehensive cost allocation, including installation, transport, land purchase, and administrative fees—illustrates a well-planned investment strategy designed to ensure system reliability and long-term viability, thereby providing a clear financial roadmap for the deployment of the off-grid solar solution.

Table 5-5: Cost of the system



Item	**Quantity units**	**Cost USD**	**Total USD**
PV modules			
JAM72-S30-550-MR	80	65.00	5,200.00
Supports for modules	80	50.00	4,000.00
Batteries	12	550.00	6,600.00
Controllers	4	120.00	480.00
Other components			
Accessories, fasteners	200	10.00	2,000.00
Wiring	1	1,000.00	1,000.00
Combiner box	6	20.00	120.00
Monitoring system, display screen	1	1,000.00	1,000.00
Surge arrester	2	50.00	100.00
Off-grid inverter	1	4,000.00	4,000.00
Studies and analysis			
Engineering	1	200.00	200.00
Permitting and other admin. Fees	1	100.00	100.00
Economic analysis	1	300.00	300.00
Installation			
Global installation cost per module	80	10.00	800.00
Global installation cost per inverter	4	200.00	800.00
Global installation cost per battery	12	100.00	1,200.00
Transport	1	15,000.00	15,000.00
Land costs			
Land purchase	1	500.00	500.00
		Total	43,400.00
		Depreciable asset	18,280.00

5.2.2. Annual operational costs analysis

The annual operational costs (OPEX) for the PV system total USD 9,422.64, covering essential services to keep everything running smoothly. This includes salaries for the maintenance team (USD 4,000), repair costs (USD 1,000), cleaning (USD 800), and setting aside money for future battery replacement (USD 622.64) as detailed in ***Table 5-6***.

On top of that, the system is insured for USD 1,000, with another USD 2,000 for insurance on the facilities. These costs reflect the ongoing investment needed to ensure the system operates efficiently and is protected over time.

system.

Table 5-6: Operating cost

Item	**Total USD/year**
Maintenance	
Salaries	4,000.00
Repairs	1,000.00
Cleaning	800.00
Provision for battery replacement	622.64
Security fund	1,000.00
Insurance	
Facilities insurance	2,000.00
Total (OPEX)	**9,422.64**

5.2.3. Long-term financial planning and sustainability

The positive impact of the depreciation table reflects long-term financial planning and sustainability. With assets like PV modules, batteries, and controllers depreciating over 30 years, the system ensures stable costs and efficient energy production. This approach supports reliable performance, reduces energy costs, and promotes renewable energy use, benefiting both financially and environmentally over the lifespan of the system.

Table 5-7: Depreciable asset

Asset	Depreciation method	Depreciation period (years)	Salvage value (USD)	Depreciable (USD)
PV modules JAM72-S30-550-MR	Straight-line	30	0.00	5,200.00
Supports for modules	Straight-line	30	0.00	4,000.00
Batteries	Straight-line	30	0.00	6,600.00
Controllers	Straight-line	30	0.00	480.00
Accessories, fasteners	Straight-line	20	0.00	2,000.00
		Total	**0.00**	**18,280.00**

5.2.4. Cumulative cash flow analysis

From the cumulative cash flow in ***Figure 5-3***, it's clear that while the initial investment of USD 43,400 leads to a loss in the first few years, the system starts to show profitability as early as the fourth year. By year 10, the system has already covered its costs and continues to generate increasing profits year after year. After 30 years, the system's cumulative profit reaches USD 309,407, with an impressive return on investment of 812.9%. This demonstrates that while the system requires patience for the initial recovery, it provides significant long-term financial benefits.

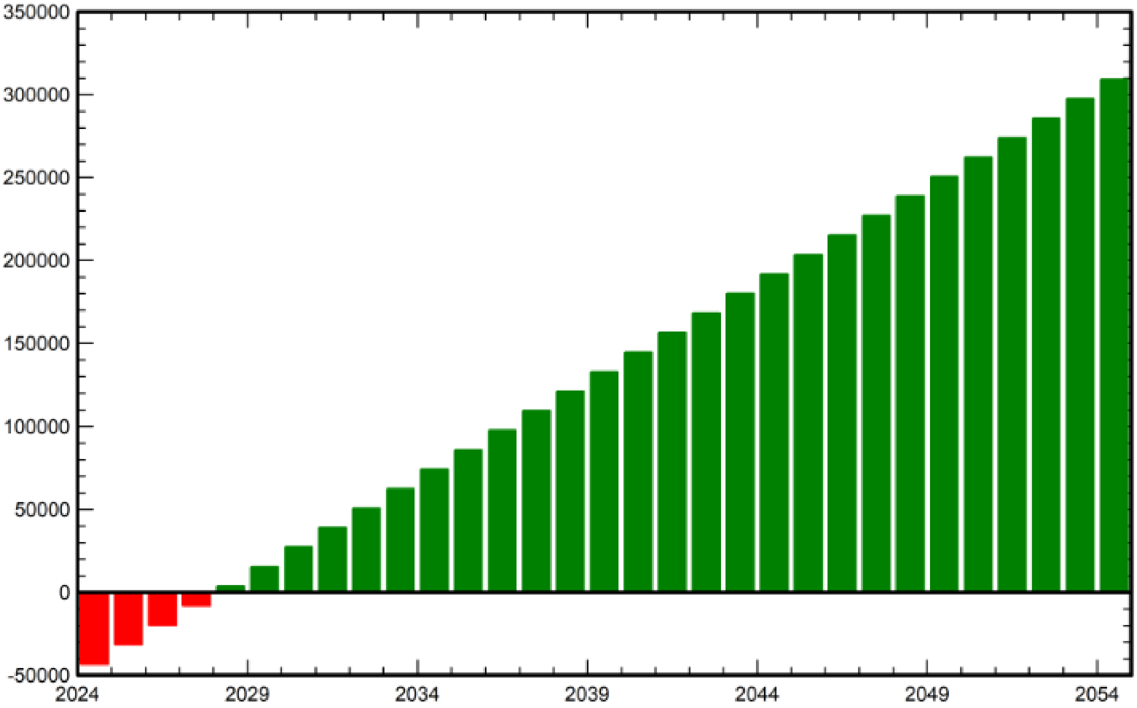


Figure 5-3: Cumulative cashflow USD

5.2.5. System summary

The project is financed through own funds of USD 43,400, with a total cost of installation of USD 43,400 and annual operating costs of USD 9,422.64. The system generates 70.6 MWh/year of solar energy, with no excess energy. The cost of used energy is USD 0.154 per kWh. With a feed-in tariff of USD 0.30 per kWh for electricity sales, the system achieves a payback period of 3.7 years, a net present value (NPV) of USD 309,407.42, an internal rate of return (IRR) of 27.08%, and a return on investment (ROI) of 712.9%, demonstrating strong financial performance with rapid payback and high long-term returns.

Table 5-8: System summary

Item	**Value**
Total Installation Cost	43,400.00 USD
Operating Costs	9,422.64 USD/year
Excess Energy	0.0 MWh/year
Used Solar Energy	70.6 MWh/year
LCOE	0.154 USD/kWh
Feed-in Tariff	0.30 USD/kWh
Payback Period	3.7 years
Net Present Value (NPV)	309,407.42 USD
Internal Rate of Return (IRR)	27.08%
Return on Investment (ROI)	712.9%

5.3. Environmental analysis

The environmental analysis of the PV system design and installation in Murya village of Rusizi District reveals significant positive environmental impacts related to reducing reliance on fossil fuels and biomass, alongside minor, manageable negative impacts primarily associated with land use and component disposal. The analysis is based on the design specifications of the PV-Battery Microgrid System for Murya Village Gasenyi center and general environmental studies of solar PV in Rwanda and the Rusizi District.

5.3.1. Positive Environmental Impacts (Avoided Emissions and Sustainability)

The PV system's primary environmental benefit is its displacement of conventional, polluting energy sources, directly contributing to Rwanda's national climate goals of achieving a climate-resilient and carbon-neutral economy by 2050.

Table 5-9: Positive Environmental Impacts

Impact Category	**Description & Local Context**
Reduction in Greenhouse Gases (GHG)	The operation of the PV microgrid generates zero direct greenhouse gas emissions or air pollutants. By replacing non-renewable energy sources, the project contributes to Rwanda's national target of reducing GHG emissions, with solar adoption actions expected to contribute to an 8.5% reduction in total GHG emissions by 2030.
Displacement of Fossil Fuels	The system avoids the use of diesel generators (often employed as an alternative in off-grid areas) and traditional lighting like kerosene lamps. The use of these fossil fuels is detrimental to the biophysical environment and exacerbates climate change.
Preservation of Natural Resources	In Rusizi District, a significant portion of the population relies on environmentally unfriendly traditional energy sources like charcoal and firewood. By providing clean electricity for lighting and appliances, the PV system helps reduce the demand for woody biomass, thereby mitigating pressures that lead to deforestation, soil erosion, and land degradation.
Promotion of Sustainable Development	The project is explicitly designed as an economical and environmentally friendly substitute for grid extension and is deemed an environmentally sustainable solution for rural electrification.

Apart of above contribution, the project will not lead to any environmental destruction like cutting forest, causing soil erosion, ecosystem destruction, noise pollution and so on.

5.3.2. Potential Negative Environmental Impacts and Mitigation

While operating a PV system is clean, the life-cycle of the components (manufacturing, installation, and end-of-life) poses environmental challenges that require mitigation strategies.

Table 5-10: Potential Negative Environmental Impacts and Mitigation

Impact Category	Description & Project Specifics	Mitigation / Management
Land Use / Habitat	The project is a small-scale microgrid, but it still requires a physical footprint. The design requires a total PV module area of 207 m². Larger, utility-scale solar projects in Rwanda have previously raised concerns about land degradation and habitat loss.	Due to the small-scale project, impacts are low. built-up areas is small and minimize new vegetation and forestry and botany loss. Rwanda's strategy emphasizes grouped rural settlements to decongest agriculture and environmentally sensitive zones, which PV microgrids should align with.
Component Disposal (E-waste)	The most significant potential adverse impact for solar projects in Rwanda is the disposal of obsolete batteries and solar panels at the end of their lifespan (typically 10-25 years). If improperly disposed of, batteries and panels can leach toxic heavy metals into the soil and water.	The design specifically chose Lithium Iron Phosphate (LFP) batteries, which are noted to be safer, more stable, and have a longer lifespan than some other lithium-ion technologies, and avoid nickel and cobalt. Rwanda has mandatory Environmental Impact Assessment (EIA) for solar facilities to plan for proper disposal and mitigation.
Construction Phase Impacts	Minor, temporary impacts such as vegetation loss, noise, dust, and visual intrusion may occur during the construction and installation of the PV array and distribution lines.	These adverse impacts are considered moderate to low for mini-grids. Proper site management and adherence to an Environmental and Social Management Plan (ESMP) are required to contain and restore the site after construction.

The PV microgrid system in Murya village Gasenyi center is environmentally advantageous, aligning with the national policy of achieving a low-carbon energy supply. The core of the analysis is that the system's benefits primarily the avoidance of local air pollution and forest degradation through displacing firewood/kerosene far outweigh its localized, manageable impacts related to land occupation and component recycling.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

This research successfully designed and simulated a standalone PV-battery microgrid system to supply reliable and sustainable electricity to Gasenyi center, a remote village lacking access to the national grid. The study employed a comprehensive methodology, incorporating real community load profiles, meteorological and solar resource data, and system modeling using PVsyst 7.4 software.

The final system configuration consists of a 44 kWp PV array paired with a 255.6 kWh lithium-ion battery. It delivers an annual usable energy output of approximately 70,610 kWh, covering 73.09% of the community's energy needs. The system achieved a strong performance ratio of 81.66%, indicating high technical efficiency despite natural system losses. Additionally, the economic assessment confirmed the system's viability, with a total investment of \$43,400, operational costs of \$9,422.64/year, an LCOE of \$0.13/kWh, and favorable financial indicators: a payback period of 3.7 years, NPV of \$309,407.42, IRR of 27.08%, and ROI of 712.9%.

However, the analysis also revealed a loss of load fraction (LOLF) of 28.0%, meaning about 25,997 kWh/year of demand remains unmet. This highlights the need for system enhancements—such as increased PV or battery capacity or hybrid integration with complementary energy sources—to improve reliability and ensure full coverage of energy needs.

Overall, the study demonstrates that PV-battery microgrids are a technically feasible, economically viable, and environmentally sustainable solution for rural electrification in Rwanda. It contributes practical insights for policymakers, developers, and institutions aiming to scale similar systems in other underserved regions, in alignment with Rwanda's national electrification and green energy goals.

6.2. Recommendations for Future Research

While this study provides a robust framework for implementing off-grid renewable energy solutions, further research is needed to optimize system efficiency, reduce costs, and enhance scalability. The following areas are recommended for future investigation:

6.2.1. Energy Storage Optimization

- Explore alternative battery technologies such as advanced lithium-ion batteries and solid-state energy storage to improve efficiency and longevity.
- Assess the feasibility of second-life electric vehicle (EV) batteries as a cost-effective storage solution for rural electrification.

6.2.2. Hybrid Renewable Energy Systems

- Investigate solar-wind hybrid systems to enhance energy reliability and mitigate seasonal variations in solar radiation.
- Evaluate the integration of micro-hydro and biomass power to complement solar energy generation in rural settings.

6.2.3. Policy and Financial Incentives

- Conduct a comparative analysis of government subsidies and micro-financing models to improve the affordability of off-grid systems for low-income households.

6.2.4. Demand-Side Management and Load Optimization

- Develop smart load management algorithms to optimize electricity distribution based on real-time demand patterns.
- Implement community-driven energy consumption strategies to reduce peak demand and enhance system efficiency.

6.2.5. Scalability and Replicability Studies

- Perform case studies on the deployment of comparable off-grid systems in Sub-Saharan Africa and Rwanda's other rural regions.

- Assess the comparative benefits of off-grid vs. grid-extension solutions in different geographic and economic contexts.

REFERENCES

[1] J. Uwibambe, “Design of Photovoltaic System for Rural Electrification in Rwanda,” *University of Agder*, vol. 6, no. 07, pp. 1–94, 2017.

[2] “REG”, Accessed: Aug. 17, 2024. [Online]. Available: www.reg.rw

[3] “Powering Rwanda: Expanding Energy Access Amid Rural and Refugee Disparities - Sun Connect News.” Accessed: Jan. 16, 2025. [Online]. Available: https://sun-connect.org/powering-rwanda-expanding-energy-access-amid-rural-and-refugee-disparities/

[4] “RWANDA ELECTRICITY ACCESS DEVELOPMENT PLAN (2018-2024),” no. June 2022, 2024.

[5] “IRENA_Policies_Regulations_minigrids_2016”.

[6] A. Ghafoor and A. Munir, “Design and economics analysis of a PV-Battery Microgrid System for household electrification,” 2015. doi: 10.1016/j.rser.2014.10.012.

[7] “IRENA_Power_Generation_Costs_2019”.

[8] “IRENA_Net_billing_2019”.

[9] World_Bank, “Third-Rwanda-Energy-Sector-Development-Policy-Financing-Project,” 2019.

[10] C. Nsengimana, L. Kai, C. Yuhao, and L. Li, “Standalone photovoltaic and battery microgrid design for rural areas,” *Energy Exploration and Exploitation*, vol. 40, no. 6, 2022, doi: 10.1177/01445987221102196.

[11] S. Pokhrel, “Electricity statistics report as the first quarter of the year 2024,” 2024.

[12] REG, “https://www.reg.rw/what-we-do/generation/.” [Online]. Available: https://www.reg.rw/what-we-do/generation/

[13] REG, “Projects to increase electricity generation capacity and access by 2024.” Accessed: Nov. 30, 2024. [Online]. Available: https://www.reg.rw/media-center/news-details/news/projects-to-increase-electricity-generation-capacity-and-access-by-2024/

[14] “Global Solar Atlas.” Accessed: Nov. 30, 2024. [Online]. Available: https://globalsolaratlas.info/download/rwanda

[15] epd_rwanda, “Mini grid and C&I – EPD Website.” Accessed: Nov. 30, 2024. [Online]. Available: https://epdrwanda.com/energy-sector/mini-grid/

[16] P. Moriarty and D. Honnery, “Global renewable energy resources and use in 2050,” in *Managing Global Warming: An Interface of Technology and Human Issues*, 2018. doi: 10.1016/B978-0-12-814104-5.00006-5.

[17] A. Demirbaş, “Global renewable energy resources,” *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, vol. 28, no. 8, 2006, doi: 10.1080/00908310600718742.

[18] C. Li, “Comparative performance analysis of grid-connected PV power systems with different PV technologies in the hot summer and cold winter zone,” *International Journal of Photoenergy*, vol. 2018, 2018, doi: 10.1155/2018/8307563.

[19] A. J. Veldhuis and A. H. M. E. Reinders, “Reviewing the potential and cost-effectiveness of off-grid PV systems in Indonesia on a provincial level,” 2015. doi: 10.1016/j.rser.2015.07.126.

[20] D. Cho and J. Valenzuela, “Optimization of residential off-grid PV-battery systems,” *Solar Energy*, vol. 208, 2020, doi: 10.1016/j.solener.2020.08.023.

[21] B. Shakya, A. Bruce, and I. MacGill, “Survey based characterisation of energy services for improved design and operation of standalone microgrids,” *Renewable and Sustainable Energy Reviews*, vol. 101, 2019, doi: 10.1016/j.rser.2018.11.016.

[22] B. Soudan and A. Darya, “Autonomous smart switching control for off-grid hybrid PV/battery/diesel power system,” *Energy*, vol. 211, 2020, doi: 10.1016/j.energy.2020.118567.

[23] P. E. Campana, L. Wästhage, W. Nookuea, Y. Tan, and J. Yan, “Optimization and assessment of floating and floating-tracking PV systems integrated in on- and off-grid hybrid energy systems,” *Solar Energy*, vol. 177, pp. 782–795, Jan. 2019, doi: 10.1016/J.SOLENER.2018.11.045.

[24] Rwanda Energy Group, “Electricity Tariffs,” 2020. [Online]. Available: https://www.reg.rw/customer-service/tariffs/

[25] C. Nsengimana, X. T. Han, and L. L. Li, “Comparative Analysis of Reliable, Feasible, and Low-Cost Photovoltaic Microgrid for a Residential Load in Rwanda,” *International Journal of Photoenergy*, vol. 2020, 2020, doi: 10.1155/2020/8855477.

[26] I. Bisaga, P. Parikh, Y. Mulugetta, and Y. Hailu, “The potential of performance targets (imihigo) as drivers of energy planning and extending access to off-grid energy in rural Rwanda,” Jan. 01, 2019, *John Wiley and Sons Ltd*. doi: 10.1002/wene.310.

[27] I. Bisaga, P. Parikh, J. Tomei, and L. S. To, “Mapping Synergies and Trade-offs Between Energy and the Sustainable Development Goals: A Case Study of Off-Grid Solar Energy in Rwanda.”

[28] M. Grimm, L. Lenz, J. Peters, and M. Sievert, “Discussion PaPer series Demand for Off-Grid Solar Electricity: Experimental Evidence from Rwanda,” 2016. [Online]. Available: www.iza.org

[29] J. D. D. Niyonteze, F. Zou, G. Norense Osarumwense Asemota, S. Bimenyimana, and G. Shyirambere, “Key technology development needs and applicability analysis of renewable energy hybrid technologies in off-grid areas for the Rwanda power sector,” *Heliyon*, vol. 6, no. 1, Jan. 2020, doi: 10.1016/j.heliyon.2020.e03300.

[30] J. Mugisha, M. A. Ratemo, B. C. Bunani Keza, and H. Kahveci, “Assessing the opportunities and challenges facing the development of off-grid solar systems in Eastern Africa: The cases of Kenya, Ethiopia, and Rwanda,” *Energy Policy*, vol. 150, Mar. 2021, doi: 10.1016/j.enpol.2020.112131.

[31] L. A. Bedadi and M. G. GebreMichael, “Design and optimization of off-grid hybrid renewable power plant with storage system for rural area in Rwanda,” *IET Renewable Power Generation*, vol. 15, no. 15, pp. 3715–3731, Nov. 2021, doi: 10.1049/rpg2.12267.

[32] P. Dusenge, J. d’Amour Niyonsaba, J. De Dieu Samvura, J. Bikorimana, T. Rwahama, and E. Mudaheranwa, “Feasibility study of hybrid Hydro-PV power plant possible deployment in remote rural area,” in *2022 IEEE PES/IAS PowerAfrica*, Aug. 2022, pp. 1–5. doi: 10.1109/PowerAfrica53997.2022.9905275.

[33] Rwanda Energy Group, “Design of the National Electrification Plan in Rwanda,” *Government of Rwanda*, p. 73, 2019.

[34] J. d’Amour NİYONSABA, F. MUKUNDUFİTE, J. M. V. BİKORİMANA, and A. KYARUZİ LUGATONA, “Grid-connected photovoltaics prosumers to support smart city development in Rwanda: A case study for Ayabaraya Village,” *Journal of Energy Systems*, vol. 7, no. 1, pp. 18–29, Mar. 2023, doi: 10.30521/jes.1086675.

[35] T. Khatib, I. A. Ibrahim, and A. Mohamed, “A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system,” *Energy Convers Manag*, vol. 120, pp. 430–448, Jul. 2016, doi: 10.1016/J.ENCONMAN.2016.05.011.

[36] NIYONSABA Jean d’Amour, “TECHNICAL FEASIBILITY STUDY OF ON-GRID PV SYSTEM OF PROSUMERS IN RWANDA,” 2021. Accessed: Oct. 09, 2024. [Online]. Available: http://dr.ur.ac.rw/handle/123456789/1774

[37] I. M, I. U.H, and A. H., “Design Of An Off Grid Photovoltaic System: A Case Study Of Government Technical College, Wudil, Kano State,” *International Journal of Scientific & Technology Research*, vol. 2, no. 12, pp. 175–181, 2013.

[38] S. Jogunuri, R. Kumar, and D. Kumar, “Sizing an off-grid photovoltaic system (A case study),” *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing, ICECDS 2017*, pp. 2618–2622, 2018, doi: 10.1109/ICECDS.2017.8389927.

[39] A. Bensaha, F. Benkouider, and A. Cheknane, “Design and Size Optimization of the PV Modules for Stand-Alone Photovoltaic Systems,” 2020, pp. 167–172. doi: 10.1007/978-981-15-5444-5_21.

APPENDICES

Appendix 1. Daily load evaluation

Table 7-6-1: Daily load evaluation for tier 2 in Gasenyi center.

No.	Equipment	No. in use	Power (W)	Total Power	Hours/day	Duration of use
1	Lamps	6	9	54	5	18h00 to 22h00
2	lamps	2	9	18	12	18h00 to 06h00
3	Cellphones	2	5	10	4	17h00 to 21h00
4	Radio	1	10	10	10	10h00 to 20h00
5	TV	0	120	0	0	
6	DVD Player	0	30	0	0	
7	Computer	0	100	0	0	
8	Refrigerator	0	500	0	0	
9	Iron	0	1000	0	0	
10	Kettle	0	1000	0	0	
Total						
No. of houses	105					
Total for Poor families						

Table 7-6-2: Daily load evaluation for a tier 3 in Gasenyi center.

No.	Equipment	No. in use	Power (W)	Total Power	Hours/day	Duration of use
1	Lamps	8	9	72	5	18h00 to 22h00
2	lamps	4	9	36	12	18h00 to 06h00
3	Cell-Phones	3	5	10	5	17h00 to 22h00
4	Radio	1	10	10	12	08h00 to 20h00
5	TV	1	120	120	8	13h00 to 21h00
6	DVD Player	1	30	30	8	13h00 to 21h00
7	Computer	1	100	100	6	08h00 to 14h00
8	Refrigerator	0	500	0	0	
9	Shaving Machine	0	100	0	0	

10	Iron	1	1000	1000	1	06h00 to 07h00
11	kettle	1	1000	1000	1	18h00 to 19h00
Total						
No. of houses	38					
Total for medium families						

Table 7-6-3: Daily load evaluation for a commercial single house in Gasenyi center.

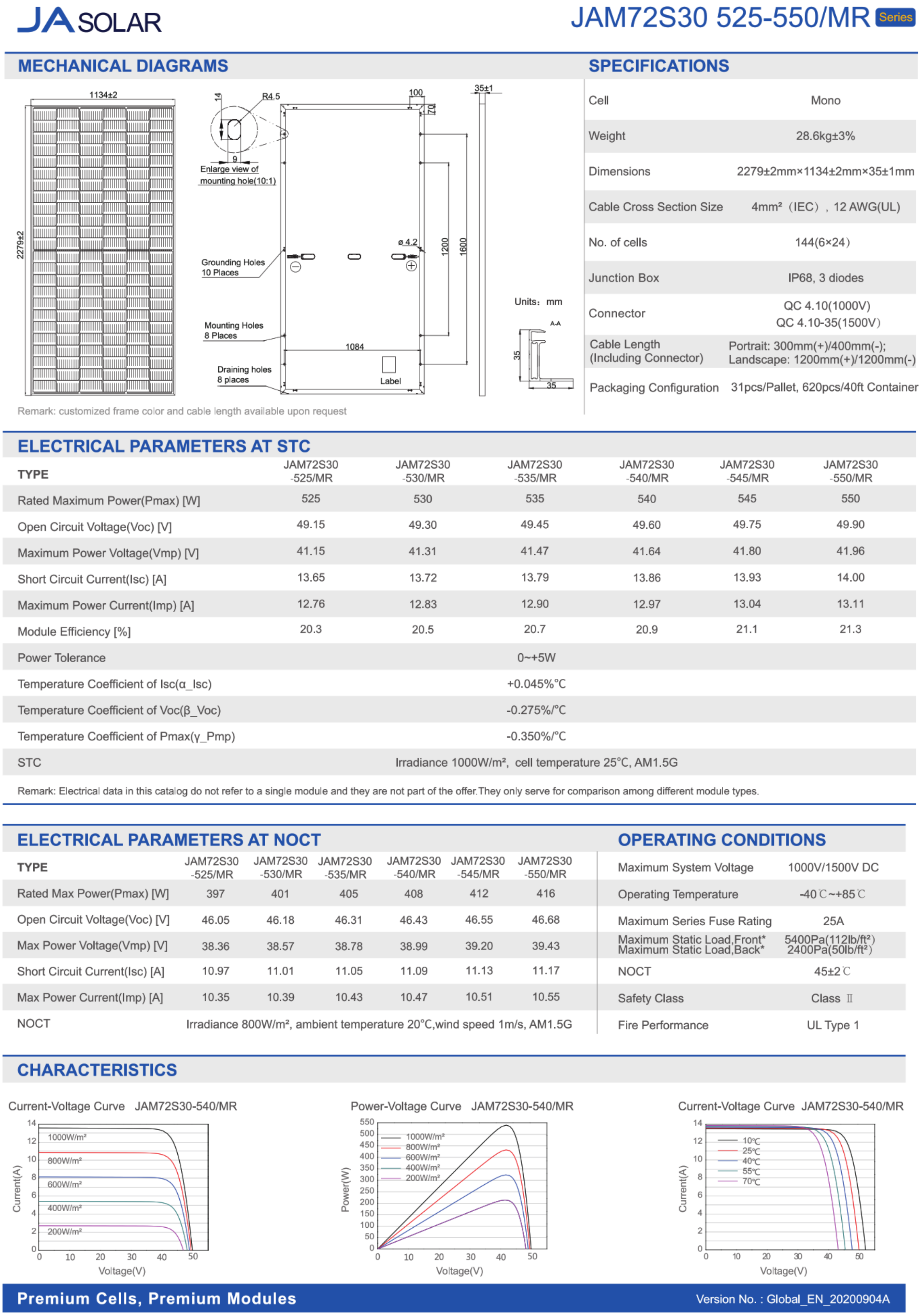
No.	**Equipment**	**No. in use**	**Power (W)**	**Total Power**	**Hours /day**	**Duration of use**
1	Lamps	8	9	72	5	18h00 to 22h00
2	lamps	4	9	36	12	18h00 to 6h00
2	Cell-Phones	3	5	10	4	08h to 12h00
3	Radio	1	10	10	12	08h00 to 20h00
4	TV	1	120	120	12	08h00 to 20h00
5	DVD Player	1	30	30	12	08h00 to 20h00
6	Computer	1	100	100	12	08h00 to 20h00
7	Refrigerator	1	500	500	7	10h00 to 17h00
8	Shaving Machine	3	100	100	12	08h00 to 20h00
9	Iron	0	1000	0	0	
10	Kettle	1	1000	1000	4	08h00 to 10h00 18h00 to 20h00
Total						
No. of houses	3					
Total for commercial families						

Table 7-6-4: Daily total load for Gasenyi center total

No.	**Equipment**	**Total No**	**Power**	**Total**	**Hours/**	**Duration of use**

		of use	**(W)**	**Power**	**day**	
1	Indoor Lamps	22	9	**198**	5	18h00 to 22h00
2	Outdoor lamps	10	9	**90**	12	18h00 to 6h00
3	Cellphones	8	5	**40**	4	08h to 12h00
4	Radio	3	10	**30**	12	08h00 to 20h00
5	TV	2	120	**240**	12	08h00 to 20h00
6	DVD Player	2	30	**60**	12	08h00 to 20h00
7	Computer	2	100	**200**	12	08h00 to 20h00
8	Refrigerator	1	500	**500**	7	10h00 to 17h00
9	Shaving Machine	3	100	**300**	12	08h00 to 20h00
10	Iron	1	1000	**1000**	0	
11	Kettle	2	1000	**2000**	4	08h00 to 10h00

Appendix 2. PV module datasheet



JA SOLAR

JAM72S30 525-550/MR Series

MECHANICAL DIAGRAMS

Remark: customized frame color and cable length available upon request

SPECIFICATIONS

Cell	Mono
Weight	28.6kg±3%
Dimensions	2279±2mm×1134±2mm×35±1mm
Cable Cross Section Size	4mm²（IEC）, 12 AWG(UL)
No. of cells	144(6×24)
Junction Box	IP68, 3 diodes
Connector	QC 4.10(1000V) QC 4.10-35(1500V)
Cable Length (Including Connector)	Portrait: 300mm(+)/400mm(-); Landscape: 1200mm(+)/1200mm(-)
Packaging Configuration	31pcs/Pallet, 620pcs/40ft Container

ELECTRICAL PARAMETERS AT STC

TYPE	JAM72S30 -525/MR	JAM72S30 -530/MR	JAM72S30 -535/MR	JAM72S30 -540/MR	JAM72S30 -545/MR	JAM72S30 -550/MR
Rated Maximum Power(Pmax) [W]	525	530	535	540	545	550
Open Circuit Voltage(Voc) [V]	49.15	49.30	49.45	49.60	49.75	49.90
Maximum Power Voltage(Vmp) [V]	41.15	41.31	41.47	41.64	41.80	41.96
Short Circuit Current(Isc) [A]	13.65	13.72	13.79	13.86	13.93	14.00
Maximum Power Current(Imp) [A]	12.76	12.83	12.90	12.97	13.04	13.11
Module Efficiency [%]	20.3	20.5	20.7	20.9	21.1	21.3
Power Tolerance	0~+5W					
Temperature Coefficient of Isc(α_Isc)	+0.045%℃					
Temperature Coefficient of Voc(β_Voc)	-0.275%/℃					
Temperature Coefficient of Pmax(γ_Pmp)	-0.350%/℃					
STC	Irradiance 1000W/m², cell temperature 25℃, AM1.5G					

Remark: Electrical data in this catalog do not refer to a single module and they are not part of the offer. They only serve for comparison among different module types.

ELECTRICAL PARAMETERS AT NOCT

TYPE	JAM72S30 -525/MR	JAM72S30 -530/MR	JAM72S30 -535/MR	JAM72S30 -540/MR	JAM72S30 -545/MR	JAM72S30 -550/MR
Rated Max Power(Pmax) [W]	397	401	405	408	412	416
Open Circuit Voltage(Voc) [V]	46.05	46.18	46.31	46.43	46.55	46.68
Max Power Voltage(Vmp) [V]	38.36	38.57	38.78	38.99	39.20	39.43
Short Circuit Current(Isc) [A]	10.97	11.01	11.05	11.09	11.13	11.17
Max Power Current(Imp) [A]	10.35	10.39	10.43	10.47	10.51	10.55
NOCT	Irradiance 800W/m², ambient temperature 20℃,wind speed 1m/s, AM1.5G					

OPERATING CONDITIONS

Maximum System Voltage	1000V/1500V DC
Operating Temperature	-40℃~+85℃
Maximum Series Fuse Rating	25A
Maximum Static Load,Front* Maximum Static Load,Back*	5400Pa(112lb/ft²) 2400Pa(50lb/ft²)
NOCT	45±2℃
Safety Class	Class Ⅱ
Fire Performance	UL Type 1

CHARACTERISTICS

Current-Voltage Curve JAM72S30-540/MR

Power-Voltage Curve JAM72S30-540/MR

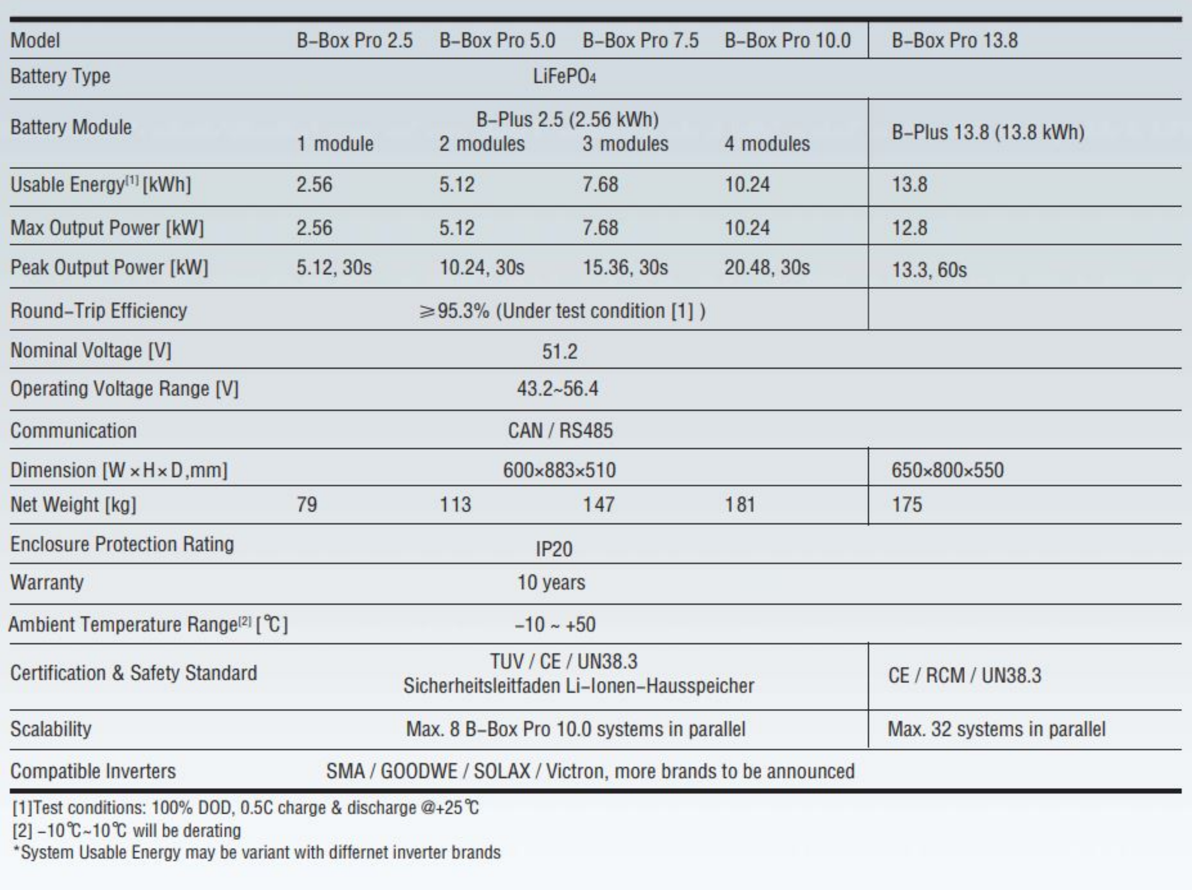
Current-Voltage Curve JAM72S30-540/MR

Premium Cells, Premium Modules

Version No. : Global_EN_20200904A

Appendix 3. Inverter, Charger and battery datasheet

Table 6-5: Battery datasheet



Model	B-Box Pro 2.5	B-Box Pro 5.0	B-Box Pro 7.5	B-Box Pro 10.0	B-Box Pro 13.8
Battery Type	$LiFePO_4$				
Battery Module	B-Plus 2.5 (2.56 kWh) 1 module	2 modules	3 modules	4 modules	B-Plus 13.8 (13.8 kWh)
Usable Energy[1] [kWh]	2.56	5.12	7.68	10.24	13.8
Max Output Power [kW]	2.56	5.12	7.68	10.24	12.8
Peak Output Power [kW]	5.12, 30s	10.24, 30s	15.36, 30s	20.48, 30s	13.3, 60s
Round-Trip Efficiency	⩾95.3% (Under test condition [1])				
Nominal Voltage [V]	51.2				
Operating Voltage Range [V]	43.2~56.4				
Communication	CAN / RS485				
Dimension [W×H×D,mm]	600×883×510				650×800×550
Net Weight [kg]	79	113	147	181	175
Enclosure Protection Rating	IP20				
Warranty	10 years				
Ambient Temperature Range[2] [℃]	-10 ~ +50				
Certification & Safety Standard	TUV / CE / UN38.3 Sicherheitsleitfaden Li-Ionen-Hausspeicher				CE / RCM / UN38.3
Scalability	Max. 8 B-Box Pro 10.0 systems in parallel				Max. 32 systems in parallel
Compatible Inverters	SMA / GOODWE / SOLAX / Victron, more brands to be announced				

[1]Test conditions: 100% DOD, 0.5C charge & discharge @+25℃
[2] -10℃~10℃ will be derating
*System Usable Energy may be variant with differnet inverter brands

Appendix 4. the questionnaires used for data collection

I am currently conducting research on: "**Design and Simulation of a PV-Battery Microgrid System for MURYA village Gasenyi center**". Thank you for taking the time to participate in this questionnaire. Your responses will remain confidential and will only be used for the purpose of this study. You are not obligated to provide your name, and you may choose to skip certain questions or withdraw from the survey at any time. The questionnaire consists of five sections, and I kindly ask that you respond to all questions in each section by either checking the appropriate box or providing a brief explanation in the space provided.

SECTION A: Household Demographics (please check all that apply and respond by ticking [√]

1. What is the size of household?

a) 1-2 rooms ☐

b) 3-5 rooms ☐

c) above 5 rooms☐

2. What is the number of household members?

a) 1-3 members ☐

b) 4-6 members ☐

c) 7 and above ☐

3. What is your highest level of academic qualification for Head of household?

a) Primary ☐

b) Secondary ☐

c) University ☐

d) Other specify: ……………………………………………………………………………….

4. What is the occupation of Head of household?

a) Agriculture ☐

b) Civil servant ☐

c) Merchant ☐

d) Business ☐

e) Other specify: …………………………………………………………………………..

5. What are the energy based assets in the house aside of light?

a) Telephone ☐
b) Radio ☐
c) Television ☐
d) Refrigerator ☐
e) Kettle ☐
f) Iron ☐
g) Electric cooker ☐
h) Water heater ☐

6. What are the energy based assets willing to have at home when you have energy access?

a) Telephone ☐
b) Radio ☐
c) Television ☐
d) Refrigerator ☐
e) Kettle ☐
f) Iron ☐
g) Electric cooker ☐
h) Water heater ☐

SECTION B: Household energy access (please check all that apply and respond by ticking [√]

1. What is the Main Source of Lighting?

a) Grid electricity, ☐

b) Solar home system ☐

c) Kerosene lamp ☐

d) Candles ☐

2. What is the source of electricity do you prefer to have?

a. Grid ☐
b. Solar microgrid ☐
c. Solar home system ☐
d. Other microgrid ☐

3. How much are you willing to pay on electricity per month in Rwandan franc?

a. 500-1000 ☐
b. 1000-3000 ☐
c. 3000-5000 ☐
d. Above 5000 ☐

4. To what extent do you think energy access affects the lifestyle in your household and village? Use a scale of 1-5, tick (√) in appropriate columns named to express your opinion where 5 = Very great extent, 4 = Great extent, 3 = Moderate extent, 2 = Minimal extent, 1 = Not at all

S/N	**ITEMS**	**1**	**2**	**3**	**4**	**5**
1	Do you think that energy access contribute to the development of the village, region or country					
2	Do you experience challenges in everyday life due to lack of connectivity					
3	Do you think that new jobs will be created in your					

	village after being connected to electricity?					
4	Are you willing to pay for electricity bill once your connected to on grid of off grid network?					
5	Access to electricity will improved your children's ability to study at night?"					
6	Do you think that using electricity for cooking is more convenient than using charcoal or wood?"					

SECTION C: GOVERNMENT POLICIE AND TARGETS ON ENERGY ACCESS AND INFRASTRUCTURE PROTECTION

1. In your opinion do you think that Rwanda energy access policy of 100% connectivity trough different source of energy is achievable.
   (a) Yes [ ] (b) No [ ]

2. To what extent do you think energy access policy is helping shareholders and private companies to invest in energy production business? Use a scale of 1-5, tick (√) in appropriate columns named to express your opinion where 5 = Very great extent, 4 = Great extent, 3 = Moderate extent, 2 = Minimal extent, 1 = Not at all

S/N	**ITEMS**	**1**	**2**	**3**	**4**	**5**
1	Shareholders are happy with government policies and are willing to invest in energy production projects					
2	Shareholders are happy with the energy access policies but investment for energy production project is very high.					
3	Energy production projects are not profitable					
4	Energy production projects have low revenues, high maintenance cost, not reliable and long return of investment					
5	Energy production businesses are not open to private companies					

3. what are the strategies to be in place to accelerate 100 % household connectivity in your district?

a) …………………………………………………………………………………………

b) …………………………………………………………………………………………

c) …………………………………………………………………………………………

d) …………………………………………………………………………………………

4. To what extent do you think peoples should protect energy production and distribution infrastructures. Use a scale of 1-5, tick (√) in appropriate columns named to express your opinion where 5 = Very great extent, 4 = Great extent, 3 = Moderate extent, 2 = Minimal extent, 1 = Not at all

S/N	**ITEMS**	**1**	**2**	**3**	**4**	**5**
1	All people and household members are responsible to protect energy access facilities and reports any damage					
2	Only civil servants are responsible to protect energy access facilities and reports any damage					
3	Energy production companies are one and only peoples to take care of energy access facilities					
4	Cooperation in protecting energy access is the only solution to get reliable energy access					
5	Cooperation in protecting energy access facilities will improve availability of energy access and reduces black out					

THANK YOU FOR YOUR TIME AND COOPERATION