DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

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Community Microgrid: Approach Towards Positive Energy community in Rwanda

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ABSTRACT

Reliable and affordable access to electricity remains a critical challenge in Rwanda, hindering socio-economic development mostly in rural areas. Despite efforts to expand the national grid, many communities still lack access to modern energy services, sustaining poverty cycles and limiting economic opportunities. This dissertation aims to develop a framework for designing, optimizing, and managing smart microgrids for isolated communities in Rwanda, addressing technical, economic, and socio-environmental aspects to enable widespread adoption and sustainable electricity access.

The methodology involves a combination of analytical modeling, simulation studies and case studies. Optimization techniques are adopted for microgrid sizing and resource allocation using software tools like HOMER Pro. Socio-economic and policy analyses are conducted through literature reviews and for Rwanda in general particularly in isolated communities.

The study presents case studies of Kadahokwa and Mashyoza villages, developing models for PV systems, wind turbines, and energy storage. Load profile estimation, resource assessment, and cost modeling are key components of system design. Results for both villages compare different scenarios involving combinations of PV, wind turbines, diesel generator batteries, and converters, providing detailed analyses of electrical production, consumption trends, and system costs.

Key findings indicate that smart microgrids significantly improve energy access and resilience in Rwanda. The study outlines the socio-economic and environmental benefits of renewable energy adoption and suggests control and management strategies for integrating microgrids with the national grid. The dissertation concludes that microgrids are a viable solution for enhancing energy access and resilience in Rwanda, with potential socio-economic and environmental benefits.

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I offer my sincere thanks.

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LIST OF SIMBOLS

T	Temperature
P	Atmospheric pressure
ρ	Density
δC	Temperature coefficient
α	Correction exponent
Ta	Ambient temperature

ACRONYMS

IRENA:	International Renewable Energy Agency
REG:	Rwanda Energy Group
RURA:	Rwanda Utilities Regulatory Authority
MINENFRA:	Ministry of Infrastructure
SSA:	Sub-Saharan Africa
LCOE:	Levelized Cost of Electricity
NPC:	Net Present Cost
SDGs:	Sustainable Development Goals
PV :	Photovoltaics
WT:	Wind Turbine
BESS:	Battery Energy Storage System
GDP:	Gross Domestic Product

1 INTRODUCTION

1.1 Problem definition

Rwanda is a country in Sub-Saharan Africa where oil is the main source of energy. As such, the constantly rising and highly volatile diesel prices used for electricity production severely undermine the business environment in a region[1]. This problem is particularly relevant in a region striving to transition from post-conflict recovery to relatively rapid economic growth. The unpredictable nature of these price fluctuations poses a significant challenge for the area's efforts to achieve sustainable economic development after emerging from a conflict situation[2] .

On top of challenges posed by price fluctuation, access to electricity also hinders economic development. Access to electricity avoids many households and around 588 million persons in SSA do not have access to electricity (IEA, 2017). In 2011, the United Nations launched a “Sustainable Energy for All” initiative. At the heart of this initiative is a call for universal access to affordable, reliable and modern energy services by 2030. The initiative also includes a target to double the rate of improvement in energy efficiency and increase substantially the share of renewable energy in the global energy mix. It must be noted that the vast majority of the people in SSA who lack access to electricity live in rural areas (World Bank, 2017). Therefore, in order to achieve universal access to modern energy services, rural electrification must be made a priority[3,4].

Reliable and affordable access to electricity remains a critical challenge in Rwanda, hindering socio-economic development in both rural and urban areas. Despite efforts to expand the national grid, many communities, mostly isolated communities, still lack access to modern energy services, sustaining poverty cycles and limiting economic opportunities[5].

Microgrids, localized energy systems that can operate independently or in conjunction with the main grid, have emerged as a promising solution for enhancing energy access and resilience [6]. However, the design, implementation, and management of microgrids in Rwanda face several challenges, including:

- Optimal sizing and resource integration: Determining the appropriate mix while minimizing costs and environmental impact is a complex task, particularly in urban areas with high energy density and diverse load profiles [7].
- Grid integration and stability: Integrating microgrids with the existing national grid poses technical challenges related to grid stability, power quality, protection

systems, and bidirectional power flow, requiring advanced control and management strategies tailored to both rural and urban contexts[8].

- Socio-economic and policy factors: Successful microgrid deployment requires addressing socio-economic factors, such as affordability, community engagement, and capacity building, as well as developing supportive policies and regulatory frameworks that consider the unique needs of rural and urban areas[9].
- Scalability and replicability: Developing scalable and replicable microgrid solutions that can be adapted to different rural and urban contexts, energy needs, and load profiles is crucial for widespread of renewable energy sources (solar, wind, hydro), energy storage systems, and conventional generators to meet specific energy demands[7].
- Smart grid technologies and data management: Leveraging smart grid technologies, such as advanced metering infrastructure, demand response, and data analytics, can enhance the efficiency, reliability, and sustainability of microgrids, but requires robust data management and communication systems, particularly in urban areas with high data volumes and complexity[6,10].
- Urban energy planning and integration: Integrating microgrids into urban energy planning and smart city initiatives requires a comprehensive understanding of urban energy systems, infrastructure interdependencies, and the role of microgrids in enabling sustainable and resilient urban communities.

Addressing these challenges through comprehensive research and development is essential to unlock the full potential of microgrids in providing reliable, affordable, and sustainable energy access to both rural and urban communities in Rwanda.

A Microgrid is defined as a small energy system or network at the distribution level that can operate in stand-alone or grid-connected configuration. The main elements of a Microgrid are energy sources, storage systems and loads [10]. The energy sources can be of any kind, i.e. renewable or no renewable; however, a strong trend currently promotes the use of renewable energy sources because of the positive environmental impact that can be thus achieved. Photovoltaic (PV) arrays, wind turbines, biomass, and hydroelectric and diesel generators are the most common energy sources in Microgrids reported in the literature [10]. The selection of other components (such as inverters, protection devices, controllers and all the necessary equipment to manage the Microgrid) depends on the type of energy source.

1.2 Aim

The aim of this project is to develop a comprehensive framework for the design, optimization, and management of smart microgrids for isolated communities in Rwanda, addressing the technical, economic, and socio-environmental aspects to enable widespread adoption and sustainable electricity access in Rwandan isolated areas by providing entry-level access to electricity, ensuring that even the most underserved communities can benefit from energy services.

1.3 Objectives

- Develop a model for sizing and resource allocation in microgrids, considering renewable energy sources, energy storage using convectional batteries, and demand profiles.
- To determine the economically viable microgrid plant size in the case study regions by considering various key factors
- Explore the integration of a mix sources focusing on renewable technologies, including solar, wind, and dispatchable generator, to optimize the energy mix for sustainability and reliability.
- Increasing the share of renewable energy sources in the energy mix, thereby supporting environmental sustainability and reducing carbon emissions.

1.4 Outline of Methodology

The research methodology will involve a combination of analytical modeling, simulation studies and case studies. Optimization techniques, such as metaheuristic algorithms, to be employed for microgrid sizing and resource allocation, using software tools like HOMER Pro [11]. Socio-economic and policy analyses are conducted through literature reviews. Smart grid technologies and data management strategies are explored through literature reviews and case studies[11].

1.5 Scope

The scope of this dissertation is to develop a comprehensive framework for the design, optimization, and management of smart microgrids for isolated communities in Rwanda by using the available renewable sources. The framework addresses the technical, economic, and socio-environmental aspects to enable widespread adoption and sustainable energy access in rural areas as it is in line with SDGs mainly affordable and clean energy (7)[12], and to take urgent action to combat climate change[12].

2 LITERATURE REVIEW

2.1 Rwanda background

Rwanda is a small, landlocked country in equatorial East Africa covering 26,338 km2, bordering the Democratic Republic of Congo (DRC), Burundi, Uganda, and Tanzania. Rwanda is divided into 5 administrative provinces, 30 districts and 416 sectors with Kigali city as the capital city. Rwanda is known as the “land of a thousand hills” as its terrain is characterized by steep slopes and green hills, upon which its predominantly rural population survive on subsistence agriculture[13,14]. The Fifth Rwanda Population and housing census held in August 2022 illustrated that Rwanda has a population of approximately 13,246,394 with an average of 501 inhabitants per square kilometer[15], with an annual population growth of 2.3%; where 27.9% of the total population lives in urban centers, and 72.1% lives in rural regions of the country with the migration rate of approximately 7% where the third of the population migrate to the capital city[15]. Rwanda’s GDP per capita was approximately $1000.22 in 2023[16].

After the 1994 genocide Rwanda aimed to transition from a humanitarian assistance phase to sustainable development. Key goals include achieving middle-income status by 2035 and high-income status by 2050[17,18]. After recognizing the vital role of energy access in catalyzing economic growth and human development, the Rwandan government prioritized increasing electricity access as a critical indicator and enabler for achieving its development goals[19]. Efforts were directed towards expanding the national grid, promoting off-grid solutions, and harnessing the country's abundant renewable energy resources, such as hydropower, solar, and biomass[20]. The government's commitment to increasing energy access was driven by the understanding that reliable and affordable electricity is essential for powering industries, supporting agricultural productivity, enabling access to modern healthcare and education services, and improving the overall quality of life for its citizen [21]. Initiatives were undertaken to attract private sector investment, develop institutional and technical capacity, and implement innovative financing mechanisms to accelerate the electrification process, particularly in rural and underserved areas. Moreover, energy policies and strategies were aligned with broader regional and global development frameworks, such as the United Nations Sustainable Development Goals (SDGs), emphasizing the importance of affordable and clean energy as a catalyst for sustainable development[18,22].

2.1.1 Rwandan Isolated community

Rwanda has a significant rural population, with 72.1% of the total population living in rural regions as from census 2022, in urban areas the main source of energy for lighting is electricity (81%); In rural areas, the main sources of energy for lighting are flashlight/phone flashlight (36% and electricity (33%) respectively[23]. Many of these rural communities are isolated, lacking access to reliable and affordable electricity, which hinders socio-economic development in terms of health, education, employment and finance, and female empowerment. Rwanda has prioritized rural electrification through off-grid solutions like solar home systems and mini-grids to reach isolated communities mostly focusing on rooftops solar panels. The Rural Electrification Strategy aimed for 48% of rural households to gain at least basic (Tier 1) energy access through off-grid solutions by 2024 but it was not successful[24]. with different case studies in the rural districts found that only approximately 8.5% of households had access to electricity in 2012, with the majority relying on kerosene lamps and firewood for lighting and cooking respectively[25]. Many studies recommended solar PV mini-grids and micro-grids as a viable solution for electrifying isolated villages in the districts[26,27,28].

2.2 Climate and Solar Irradiation

Rwanda has a consistent tropical climate with temperatures averaging around 21°C (70°F) during the day and dropping to around 16°C (61°F) at night due to the country's high altitude[29]. Rainfall patterns vary across regions, with the eastern and southeastern areas being more exposed to droughts, while the northern and western regions experience abundant rainfall that can lead to erosion, flooding, and landslides[30] .The long rainy season (February to May) and the long dry season (June to September) are considered the most distinct seasons, with the short rainy and short dry seasons being transitional periods between the two main seasons[31].

Rwanda receives abundant sunshine and favorable solar irradiation levels across most regions as shown in Figure 1, making it well-suited for harnessing solar energy. The country experiences global horizontal solar irradiation ranging from 4.8 kWh/m2/day to 5.8 kWh/m2/day, with an annual daily mean global solar radiation of around 5.2 kWh/m2/day[32,33]. This solar resource varies geographically, with the northern areas near the Musanze city receiving around 4 kWh/m2 of daily solar irradiation, while the southern and eastern provinces, particularly south of the capital Kigali, enjoy higher levels of up to 5.4 kWh/m2 per day. Despite seasonal fluctuations, Rwanda benefits from consistent solar energy potential, even during the rainy months. While average daily irradiation levels may drop to around 4.5 kWh/m2 during cloudy periods, the Eastern province, known for its high irradiance values, experiences sufficient daily sunshine throughout the year[34]. According to the Photovoltaic Geography Information System (PVGIS), the average daily global solar irradiation on a tilted surface in Rwanda is estimated to be 5.2 kWh per m2 per day. The long-term monthly average daily global irradiation ranges from 4.8 kWh/ (m2 day) in Burera district during May to 5.8 kWh/(m2 day) in Nyanza district during July [35]

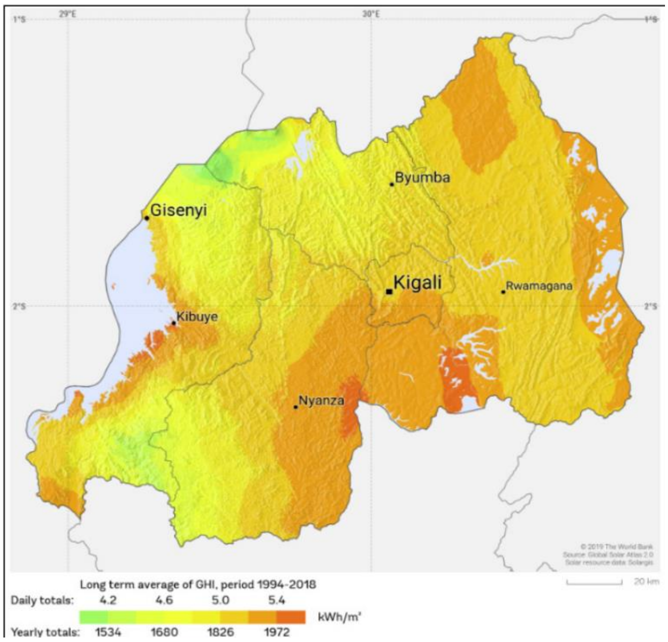

Figure 1: Global horizontal irradiation map for different districts of Rwanda[36]

2.3 Energy Sector

Rwanda faces an energy crisis due to lack of investment, growing population, and increasing urbanization. The country's electricity is heavily dependent on imported petroleum products and Hydro power that are mainly used in households, industries, transport and so forth. Furthermore, biomass like wood fuel, plays a vital role in cooking as it constitutes 85% of total energy consumption[19]. The electricity access rate was around 61% as of 2022, with 47.0 % using the national grid and 14% using off-grid power, primarily solar PV. Rwanda aimed to achieve universal electricity access by 2024[15].

The main sources of electricity generation are hydropower (51%), thermal plants (43%), and solar PV (5%). However, Rwanda has abundant renewable energy resources like solar, biomass, geothermal, and methane gas from Lake Kivu that remain largely untapped.

Figure 2 illustrates the trend of 4 sources of electricity from 1980s to 2019. Where the first electricity source was Hydropower followed by fossil fuels that finally led the trend. Solar and biomass are the current inverted sources, but they are at a low level of electricity production (below 0.1TWh/year). The trend shows great reduction of hydropower plants production in 2007 from the drought in the preceding years that led to the reduction of precipitation/rainfall and a steep decline in reservoir water levels at Rwanda's two largest hydropower stations.

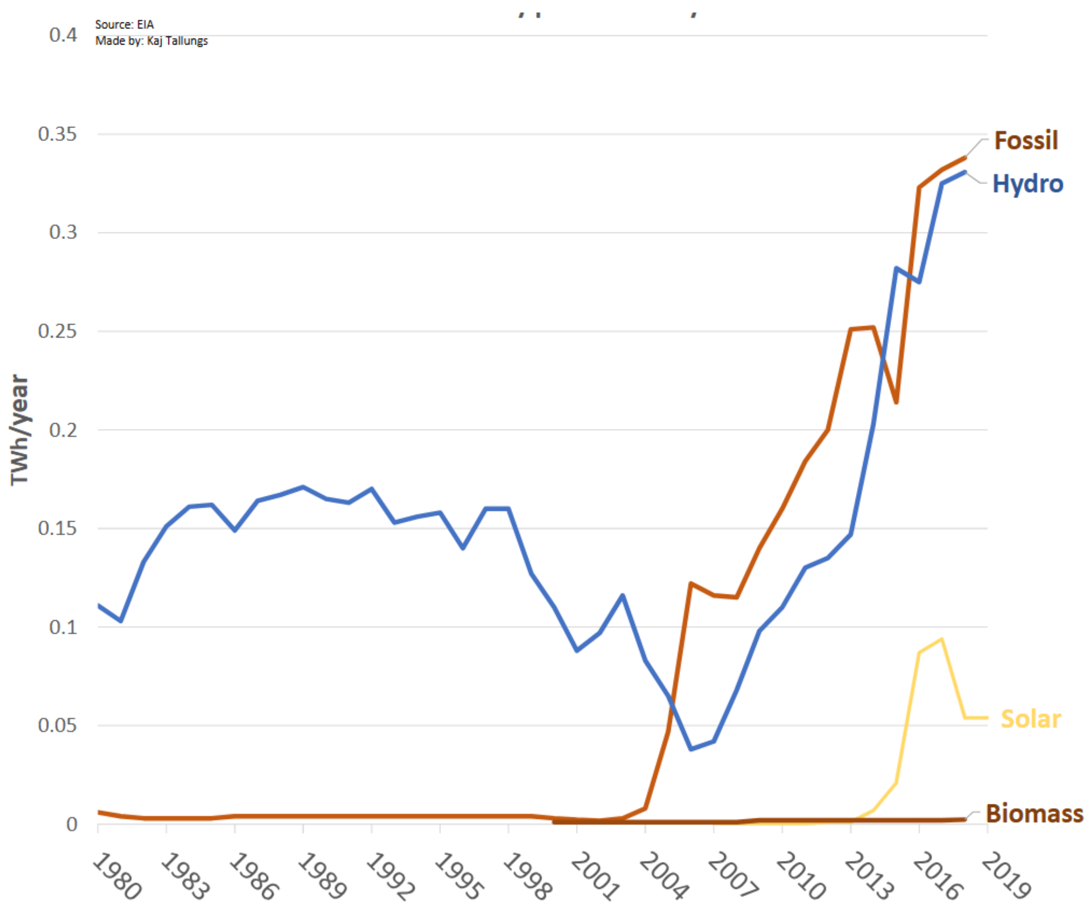

Figure 2: Rwanda electricity production by sources trend[36].

Currently, thermal units, especially diesel, contribute a big share to the installed capacity of the Rwandan system means that a significant portion of Rwanda's total installed electricity generation capacity comes from thermal power plants that run on diesel fuel. But because the cost of operating diesel generators is relatively high compared to other sources, they are mostly used during periods of high electricity demand (peak hours). Rwanda Energy Group (REG) prioritizes using hydroelectric power plants as much as possible since hydropower is a cheaper source of electricity compared to diesel generators. However, this source faces difficulties during the dry season when water levels are low, reducing the output from hydropower plants.

- Table 1 presents 6 available sources for electricity in Rwanda (2022), where Hydropower is the main source of electricity and solar is the least source. There is a big gap between installed capacity (311.1MW) and available capacity (213.4MW) where some improvements are needed to improve the plants' productivity, mainly for solar power as it is mostly available. Methane contributed a huge role in Rwanda's electricity production, the launch of KivuWatt Phase 1 as shown in Figure 3 and Figure 1 that involves the construction of an integrated methane gas extraction facility and a 26 MW (35,000 hp) methane gas-fired power plant in Kibuye, Rwanda. This $200 million project is being developed by KivuWatt Limited, in cooperation with Wärtsilä. The Phase 1 project activities primarily involved the construction and installation of a 750-ton floating barge integrating a gas extraction and treatment facility, a submerged floating pipeline to transport the extracted methane gas ashore, an onshore gas receiving facility, and the 26 MW power plant. The power plant consists of three 20-cylinder Wärtsilä 34SG gas-powered engines with a combined capacity of 25 MW. The extracted methane gas from Lake Kivu is processed and pumped ashore through the submerged pipeline to fuel the 25 MW power plant [37].

Figure 3: Kivu watt phase 1 [38].

Table 1: summarized Electricity generation [37].

Plant type	**Available plants**	**Installed capacity (MW)**	**Available capacity (MW)**
Hydro	30	107.3	58.0
Diesel	2	58.8	55.9
Peat	2	85	55.6
Methane	2	29.8	23.8
Solar	2	12.05	2
Imports	3	18.1	18.1
Total		**311.1**	**213.4**

2.4 Electricity consumption

Figure 4 illustrates both Power consumption (a) and available electricity and usage (b). The left side bar chart (a) shows the consumption by source and the pie chart consumption by sector. It clearly shows how biomass is massively produced in Rwanda; the main sources of biomass in Rwanda are firewood, commonly used in rural areas, charcoal mostly used in urban centers and biogas from both human and animals' residues and commonly used in high population zones like schools and prisons. Petroleum (oil and gas) come second with 13% of general consumption and it is mainly used in transport and in industries. Electricity is the least consumed source with only 2% and needed almost in all sectors of life in Rwanda.

The bar and pie chart on the right present the nominal capacity installed, where hydro power serves almost a half of the total electricity produced and consumed in Rwanda, followed by diesel and Methane as other two good sources of electricity. Peat from the swamps and some river basins and are extracted to generate electricity at an approximate rate of 7%. Solar electricity generation sector is still on a lower level. Rwanda doesn't depend on imported electricity the much as it only imports 1.6% of the total electricity used. Households and industries use 93% of the total electricity produced and 7% of the electricity is used in other activities.

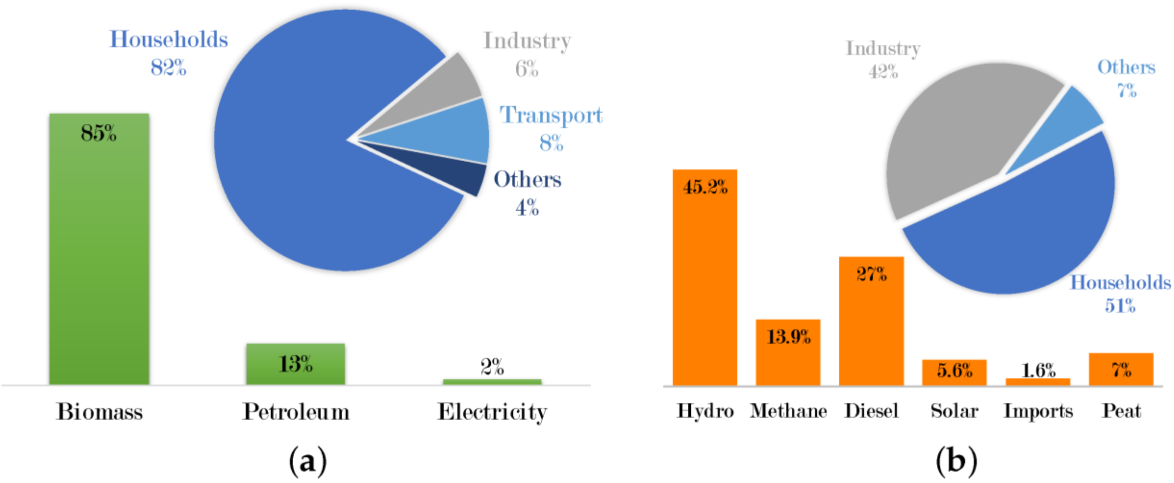

Figure 4 :Power and electricity. (a) Power consumption. (b) Available electricity sources and consumption [19].

2.5 Electricity evolution

In just 15 years, Rwanda has increased its electricity access to 75% from 6% in 2009. This took government ownership, leadership, and commitment, partnership with the private sector, funding from development partners, and dedicated structure and institutional strengthening[39].

During the formulation of the Economic Development and Poverty Reduction Strategy (EDPRS) II, the Rwandan government made a deliberate policy decision to diversify electricity sources beyond the traditionally dominant national grid, including off-grid connections. Consequently, households located outside the intended areas for national grid presence were advised to explore alternative, more cost-effective connections. Mini-grids and solar photovoltaic (PV) systems were recommended as options to reduce their electricity costs. Despite efforts to increase electricity access, statistics from June 2021 indicate that the access rate in Rwanda was 65%, with 47.2% using the national grid and 17.8% using off-grid power, primarily solar PV. The current targets aim was to provide universal electricity access by 2024, with complete business connectivity by 2022. To achieve this goal, the Rwanda Energy Group (REG) plans to add approximately 500,000 new electrifications annually, including around 200,000 on-grid and 300,000 off-grid connections. According to the findings, nine districts (30%) have an access rate below 65%. Only one district (3.3%) has an electricity rate above 90%, while three districts (10%) have a rate above 70%. The remaining districts (40%) have an access rate below 50%. The districts with the lowest energy availability rates are in rural areas, making it challenging to connect to the national grid due to the high cost of distributing grid electricity in sparsely populated, mountainous regions with high usage. Additionally, many rural residents have low incomes, making energy costs burdensome[40,41].

Figure 5 presents the econometric analysis and forecasting of annual growth rates that were conducted based on available data on residential consumption levels and electrical appliance usage in Rwanda. This analysis estimated an annual electricity demand growth rate of 9.8% for the period from 2016 to 2050. To account for uncertainties associated with demand projections, the growth rates were broken down into 5-year medium-term spans, revealing varying levels of growth. The lowest growth rate was 4.97% during the period from 1998 to 2003. Over the past 25 years, the overall average growth rate was 8.44%, which is consistent with the implementation of Rwanda's current strategic plan. For the period from 2017 to 2022, a demand growth rate of 8.65% was projected. For developing generation expansion scenarios and planning electricity supply expansion in Rwanda, an annual electricity demand growth rate of 10% was used as the central assumption. However, analyses were conducted by considering a range of annual demand growth rates between 5% and 10% from 2030 onwards to account for potential variations and uncertainties in future demand projections[42].

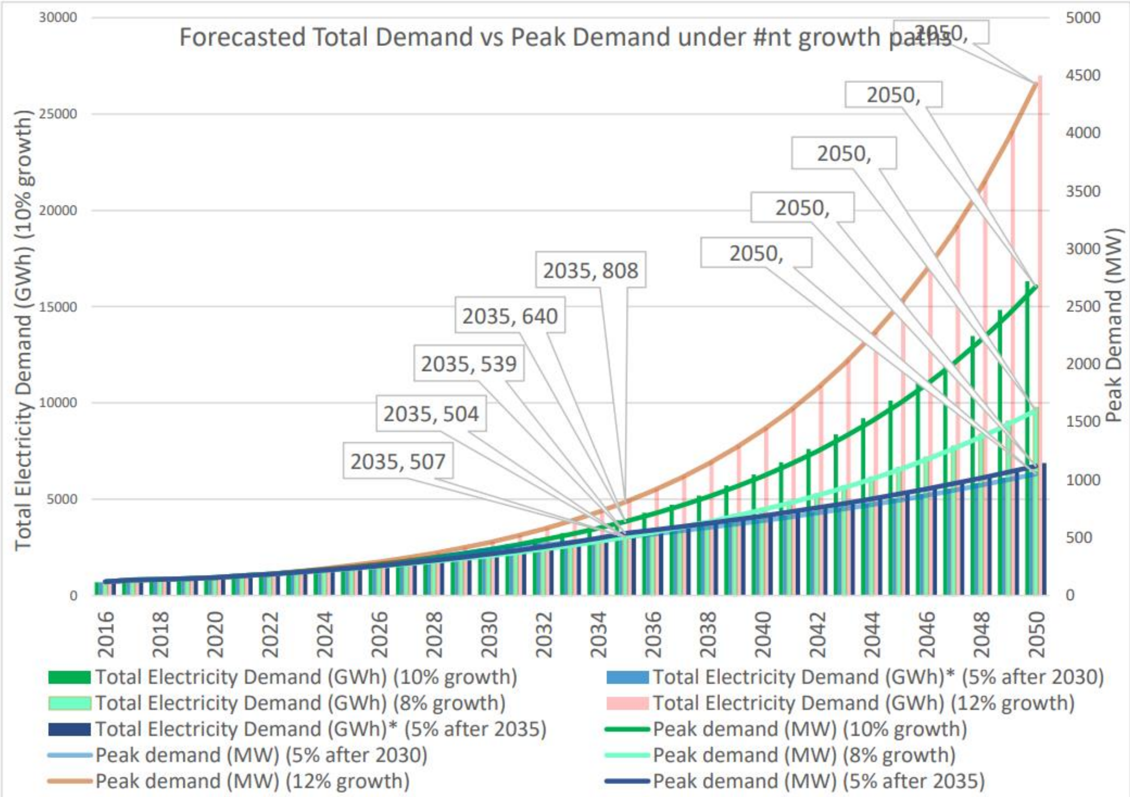

Figure 5: Rwandan forecasted Total Demand and Peak Demand[42].

2.6 Cost of electricity in Rwanda

Rwanda is on 18th place for countries with most expensive electricity worldwide with average electricity price of 26 cents USD per kWh[43].

Table 2: Rwanda electricity prices[44].

Rwanda	Electricity prices
Residential price	0.197
Business price	0.074
Measure	USD / kWh
Reference	September 2023

From Table 2, as of September 2023, the residential electricity price in Rwanda is RWF 257.290 per kWh or USD 0.197 per kWh. There is a tiered pricing structure for households based on monthly consumption levels[44] The business/commercial electricity price in Rwanda is RWF 96.000 per kWh or USD 0.074 per kWh. For non-residential buildings consuming 0-100 kWh per month, the rate is RWF 204 per kWh.

Compared to the global average electricity prices during the same period, Rwanda's residential rates are higher at USD 0.197 per kWh versus the worldwide household average of USD 0.156 per kWh. However, the business electricity price of USD 0.074 per kWh is lower than the global commercial average of USD 0.152 per kWh[44]. The electricity tariffs in Rwanda are regulated by the Rwanda Utilities Regulatory Authority (RURA). While the government recognizes the importance of increasing electricity access, the relatively high cost of electricity, especially for residential consumers and rural households with lower incomes, raises concerns about affordability for a significant portion of the population[44].

Table 3: Rwanda electricity price analytics compared globally and regionally[44].

Electricity price analytics	Values
Residential / World average price	139.18 %
Residential / Africa average	185.46 %
Business / World average price	52.65 %
Business / Africa average	76.33 %
Residential / Business price	268.01 %
Low / High income households	58.95 %
Small / Large businesses	117.90 %

Table 3 provides insights into electricity pricing in Rwanda compared to global and regional averages, as well as pricing disparities between different customer segments.

- Residential vs. Global and Regional Averages.

Residential electricity prices in Rwanda are 39.18% higher than the global average. Residential prices are 85.46% higher than the African regional average, indicating relatively high residential rates in Rwanda[43].

- Business vs. Global and Regional Averages

Business electricity prices in Rwanda are 47.35% lower than the global average. Compared to the African average, business prices are 23.67% lower in Rwanda[44].

- Residential vs. Business Pricing

Residential customers in Rwanda pay 168.01% more per kWh than business customers, highlighting a significant pricing disparity between these segments[43].

- Low vs. High Income Households

Low-income households consuming 25% of the average annual household electricity pay 41.05% less per kWh than high-income households consuming 300% of the average[44].

- Small vs. Large Businesses

Small businesses with an annual consumption of 30,000 kWh pay 17.9% more per kWh than large businesses consuming 7,500,000 kWh annually, indicating economies of scale in electricity pricing for larger businesses[44].

In summary, the residential electricity prices in Rwanda are substantially higher than global and regional averages, while business prices are lower. There is also a significant pricing gap between residential and business customers, with households paying significantly more per unit. Additionally, low-income households enjoy lower rates compared to high-income households, and small businesses face higher per-unit costs than larger enterprises[44].

2.7 Electricity demand in Rwandan isolated communities

Figure 6 shows the map of Rwanda by highlighting the 10 sectors that were not connected in 2019 with the aim of connecting them within one year (2020). There are no clear follow up if they have been connected successfully but from the 2022 census the districts where these sectors are located are still connected on a very low trend as illustrated in figure 7 which means maybe something has been done but a lot is to be done to achieve 100% electricity connections in Rwandan communities[45].

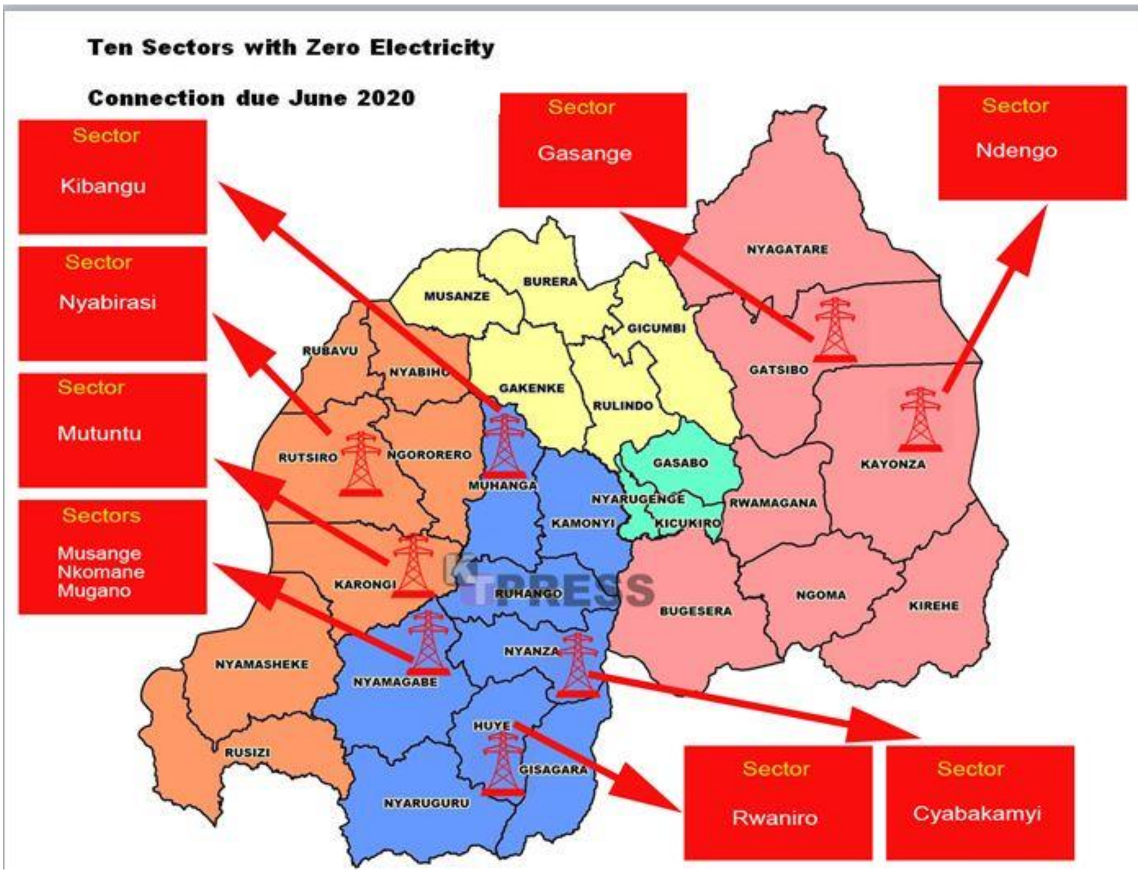

Figure 6: Sectors with zero electricity 2019[45].

From Figure 7, The table provides valuable insights into the energy sources used for lighting by households across different provinces and districts in Rwanda, including isolated communities. Here are some key points regarding the demand for various sources in isolated areas:

- Solar Power:

Solar power emerges as a significant energy source for lighting in isolated rural areas, with districts like Nyaruguru (33.6%), Nyamagabe (25.8%), Gakenke (23%), and Ngoma (22.1%) having high percentages of households relying on solar power.

This highlights the importance of solar energy in providing lighting solutions to isolated communities that may lack access to the national grid or other conventional sources[23].

- Firewood:

A substantial portion of households in isolated rural districts still depend on firewood for lighting, such as Ngororero (15.6%), Gakenke (6.9%), Burera (7.7%), and Nyamagabe (12.4%).

This reliance on traditional biomass sources like firewood is likely due to the lack of access to modern energy services in these isolated areas[23,46].

- Flashlights/Phone Flashlights:

The use of flashlights and phone flashlights as a source of lighting is prevalent in many isolated districts, with high percentages observed in Gicumbi (41.3%), Gakenke (39.2%), Ngororero (39%), and Rulindo (36%)[23].

This temporary and often inadequate lighting solution highlights the energy poverty and lack of access to reliable sources in these areas.

There is an indication that candles are also one of the traditional lighting sources still widely used in rural Rwanda [46].

- Electricity from the National Grid (REG):

Isolated districts generally have lower percentages of households connected to the national grid for electricity, such as Nyamagabe (20.7%), Ngororero (27.4%), Rulindo (30.2%), Gakenke (26.6%), and Gatsibo (27%).

This indicates the challenges in extending grid infrastructure to remote and isolated areas, leading to a higher reliance on off-grid solutions.

Nationally, 47% of households use electricity from the national grid (REG) for lighting.

The city of Kigali has the highest percentage of households (88%) using electricity from the national grid. Among provinces, the Western Province has the highest percentage (45.5%) of households using national grid electricity, while the Southern Province has the lowest (35%)[23].

Province/ District	Total	Electricity from REG	Private Hydro Mini grid	Solar power	Generator/ Betteries	Kerosene/ Paraffin/ Lantern lamp	Biogas	Candles	Firewoods	Flashlight/ phone flashlight	Other	Not Stated
Rwanda	**100.0**	**47.0**	**0.1**	**13.9**	**1.3**	**1.6**	**0.0**	**2.9**	**4.2**	**28.4**	**0.5**	**0**
City of Kigali	**100**	**88.0**	**0.1**	**1.6**	**0.2**	**0.4**	**0.0**	**3.9**	**0.2**	**5.5**	**0.1**	**0.0**
Nyarugenge	100	92.0	0.1	0.8	0.1	0.3	0.0	3.0	0.1	3.5	0.1	0.0
Gasabo	100	84.5	0.1	2.0	0.2	0.5	0.0	4.6	0.3	7.6	0.2	0.0
Kicukiro	100	91.5	0.0	1.4	0.1	0.4	0.0	3.1	0.1	3.2	0.1	0.0
Southern Province	**100**	**35.0**	**0.2**	**19.9**	**1.8**	**1.3**	**0.0**	**2.0**	**4.7**	**34.6**	**0.6**	**0.0**
Nyanza	100	35.2	0.1	16.3	2.2	1.3	0.0	1.1	2.5	40.6	0.6	
Gisagara	100	38.6	0.1	13.8	2.0	0.8	0.0	1.8	4.5	37.5	0.7	0.0
Nyaruguru	100	32.0	0.2	33.6	0.8	0.9	0.0	1.8	10.4	19.6	0.8	0.0
Huye	100	41.2	0.1	15.1	2.0	2.1	0.0	3.2	4.1	31.6	0.5	0.0
Nyamagabe	100	20.7	0.1	25.8	1.7	0.8	0.0	2.2	12.4	35.6	0.5	0.0
Ruhango	100	42.2	0.2	16.2	1.8	1.4	0.0	1.3	2.4	34.0	0.5	0.0
Muhanga	100	34.1	0.5	22.6	1.8	1.3	0.0	1.4	2.2	35.8	0.4	0.0
Kamonyi	100	34.3	0.4	19.3	1.8	1.6	0.0	3.0	0.9	38.2	0.5	0.0
Western Province	**100**	**45.5**	**0.1**	**11.1**	**1.0**	**2.1**	**0.0**	**3.2**	**9.8**	**26.7**	**0.6**	**0.0**
Karongi	100	30.6	0.1	19.7	1.9	1.3	0.0	1.9	7.1	36.6	0.8	0.0
Rutsiro	100	42.1	0.1	8.0	1.1	1.2	0.0	1.8	13.8	31.4	0.6	0.0
Rubavu	100	67.8	0.1	3.6	0.3	1.9	0.0	6.7	6.5	12.7	0.5	0.0
Nyabihu	100	37.3	0.1	9.7	0.5	2.0	0.0	3.0	14.9	32.0	0.5	0.0
Ngororero	100	27.4	0.1	13.0	1.3	1.7	0.0	1.3	15.6	39.0	0.6	0.0
Rusizi	100	58.2	0.1	8.9	1.1	3.2	0.0	3.2	5.4	19.1	0.7	0.0
Nyamasheke	100	44.0	0.3	17.3	0.9	3.2	0.0	2.8	7.8	23.0	0.7	0.0
Northern Province	**100**	**39.0**	**0.1**	**15.0**	**0.9**	**1.2**	**0.0**	**3.0**	**5.0**	**35.3**	**0.4**	**0.0**
Rulindo	100	30.2	0.1	24.3	0.9	1.1	0.0	4.0	2.9	36.0	0.4	0.0
Gakenke	100	26.6	0.1	23.0	1.3	1.4		1.2	6.9	39.2	0.4	0.0
Musanze	100	58.7	0.0	4.2	0.3	1.1	0.0	4.7	4.5	26.1	0.3	0.0
Burera	100	45.7	0.0	6.9	0.5	1.5	0.0	1.8	7.7	35.4	0.5	0.0
Gicumbi	100	30.0	0.1	19.0	1.5	0.9	0.0	2.9	3.7	41.3	0.5	0.0
Eastern Province	**100**	**40.3**	**0.2**	**17.1**	**1.9**	**2.4**	**0.0**	**3.1**	**1.4**	**33.2**	**0.5**	**0.0**
Rwamagana	100	53.0	0.2	14.5	1.0	1.3	0.0	4.6	0.8	24.2	0.5	0.0
Nyagatare	100	37.0	0.1	17.4	2.4	1.5	0.0	2.7	1.5	37.0	0.4	0.0
Gatsibo	100	27.0	0.4	21.4	2.8	1.5	0.0	3.2	1.3	41.8	0.6	0.0
Kayonza	100	39.6	0.2	18.1	1.7	3.7	0.0	2.7	1.4	32.1	0.4	0.0
Kirehe	100	40.6	0.3	16.2	1.6	3.8	0.0	2.4	1.4	33.3	0.4	
Ngoma	100	36.0	0.1	22.1	1.7	5.5	0.0	1.8	1.1	31.1	0.6	
Bugesera	100	49.8	0.3	10.7	1.7	0.9	0.0	3.8	2.0	30.5	0.4	0.0

Figure 7: Distribution of private households by main source of energy for lighting, Province and District

2.8 Available renewable electricity sources for microgrids in Rwanda

Determining the structure of Rwanda's energy system involves assessing the available resources that can be utilized for energy supply through extraction, imports, or other identified means. By focusing on renewable sources like solar, wind, hydro, green hydrogen, geothermal, and biomass are viable options for powering microgrids in Rwanda. Here's a detailed discussion on each source:

2.8.1 Solar Energy

Solar energy presents a promising source for powering microgrids in Rwanda. The country has abundant solar radiation, with an average daily solar irradiance ranging from 4.5 to 6 kWh/m2, making it an attractive option for harnessing solar power[47]. The Rwandan government has recognized the potential of solar energy and has taken steps to promote its integration into the country's energy mix, particularly for rural electrification and microgrid applications. One of the key advantages of solar energy for microgrids is its modularity and scalability[48]. Solar photovoltaic (PV) systems can be easily installed and expanded as energy demand grows, making them well-suited for remote and off-grid areas. This flexibility allows communities to start with small-scale solar PV systems and gradually increase their capacity as needed, minimizing upfront costs and ensuring a sustainable energy solution, Rwanda has already implemented several successful solar microgrid projects, demonstrating the feasibility and impact of this technology. For instance, the Jali project, one of the biggest distributed mini grids, utilizes solar PV as its primary energy source, powering over 1,000 homes, businesses, and community facilities[36]. This project has not only provided reliable and affordable electricity to off-grid communities but has also enabled productive uses of energy, such as powering small businesses and agricultural activities. The integration of solar energy into microgrids can be further enhanced by combining it with other renewable sources, such as hydropower or biomass, creating hybrid systems that can provide a more stable and reliable energy supply[49].

Moreover, the deployment of solar microgrids in Rwanda has the potential to contribute to several Sustainable Development Goals (SDGs), including SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action)[50]. By providing access to clean and affordable energy, solar microgrids can support economic development, create job opportunities, and reduce greenhouse gas emissions associated with traditional fossil fuel-based energy sources. However, the widespread adoption of solar microgrids in Rwanda also faces challenges. These include the initial capital costs of solar PV systems, the need for skilled technicians and maintenance personnel, and the potential for intermittent and energy storage requirements[35].

2.8.2 Wind Energy

While Rwanda has moderate wind energy potential, with average wind speeds ranging from 2.4 m/s to 6.5 m/s in meteorological stations of Kanombe, Gisenyi, Butare, Kamembe and Kaniga as shown from the figure [51], wind power can complement other renewable sources in a hybrid microgrid system. Wind turbines can generate electricity during periods when solar or hydro resources are limited, improving the overall reliability and stability of the microgrid[52] .The combination of wind and solar energy in a hybrid system can help mitigate the intermittency of individual sources, reducing the need for energy storage or backup generators. The research conducted analyzed that the existing wind resources in the country have the capability to serve as drivers for energy solutions and supply. It shows that the current wind resources could generate up to 66 megawatt-hours (MWh) of energy[51].

$$\text{Maximum share of wind power}=\frac{maximum\ wind\ power\ generated\ (MW)}{minimum\ load+power\ exchaange}\ [51] \quad (1)$$

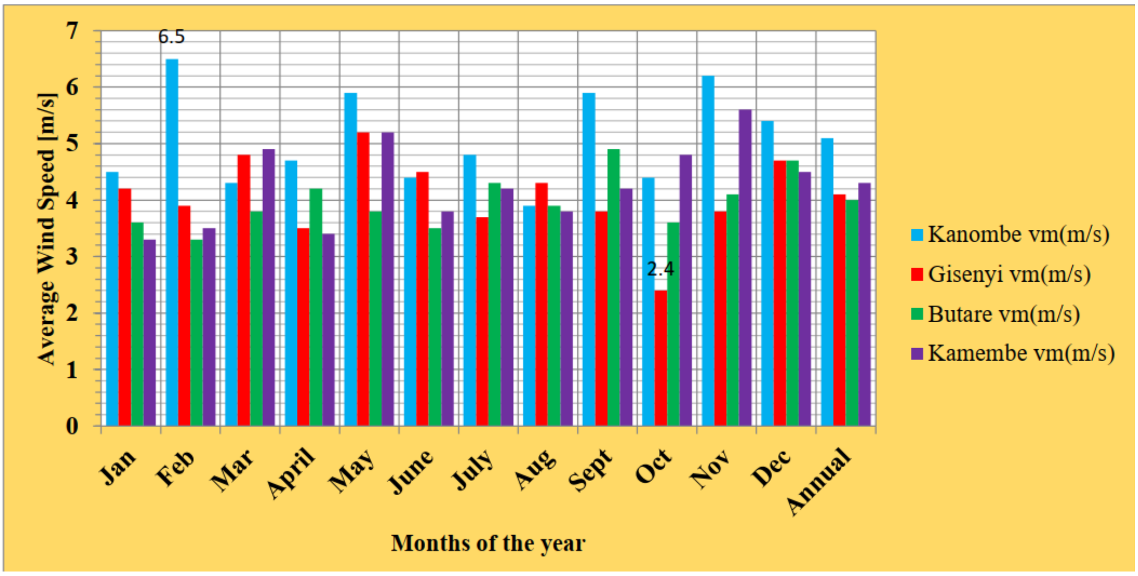

Figure 8: Monthly and annual mean wind speeds for the investigated Stations[51].

2.8.3 Hydropower

Rwanda has recognized the potential of small hydropower plants to contribute to its electrification goals, particularly in powering microgrids and providing energy access to remote and off-grid communities[52]. Hydropower is currently the main source of electricity generation in Rwanda, contributing around 48% of the total installed capacity of 210 MW as of the sources provided. A significant portion of this hydropower capacity comes from small hydropower plants (less than 10 MW). Rwanda had an installed small hydropower capacity of 47.5 MW from 28 operational facilities. Small hydropower plants can provide a reliable and renewable source of baseload power generation for microgrids, complementing other intermittent sources like solar photovoltaics. The combination of Rwanda's favorable topography and hydrology makes it well-suited for the development of small hydropower resources. A government study identified 333 potential sites for small hydropower development, with many sites having a capacity range of 50-1000 kW, which is suitable for powering microgrids[53]. However, the development of small hydropower for microgrids also faces challenges, such as the need for innovative business models, financing mechanisms, and technical capacity building.

2.8.4 Green Hydrogen

Green hydrogen refers to hydrogen produced through the electrolysis of water using renewable energy sources like solar, wind, or hydropower[54]. This hydrogen can then be used as a fuel for electricity generation or other applications, offering a clean and potentially sustainable energy solution[55]. However, the development and deployment of green hydrogen technologies are still in relatively early stages globally, and the sources do not indicate any significant initiatives or plans related to green hydrogen in Rwanda's microgrid or broader energy strategy[56].

2.8.5 Biomass

Biomass is a significant potential source for powering microgrids in Rwanda. The country has a high reliance on traditional biomass, primarily in the form of firewood and charcoal, which accounts for a staggering 83% of the total energy consumption[57]. This heavy dependence on unsustainable biomass usage has led to environmental degradation, deforestation, and health issues due to indoor air pollution. However, the potential of biomass as a renewable energy source for microgrids lies in the sustainable utilization of various biomass resources, including agricultural residues, forestry waste, and energy crops[58]. By transitioning from traditional biomass to modern bioenergy pathways, Rwanda can harness the benefits of biomass while mitigating environmental impacts and improving energy access[57]. The Rwandan government recognizes the importance of sustainable biomass management and has outlined strategies to promote more efficient production and use of biomass energy through the National Energy Policy and National Energy Strategy. This includes initiatives to productively manage forests and woodlots, promote efficient charcoal production, and explore alternative biomass sources such as biogas, pellets, and briquette[59]. Biomass-based microgrids can provide reliable and locally sourced energy solutions, particularly in off-grid areas where biomass resources are readily available where biomass can be burned directly in boilers or furnaces to produce steam, which can drive turbines for electricity generation.

2.8.6 Geothermal

Geothermal energy presents a promising potential source for powering microgrids in Rwanda. As the country situated along the Western Branch of the East African Rift Valley, a region known for its geothermal activity[60]. Preliminary studies and surface explorations have identified several prospective areas for geothermal development in Rwanda. The most significant geothermal potential lies in the Virunga Volcanic region, also known as the Volcanoes National Park, located in the northwest of the country[60]. This area hosts five major volcanic structures within Rwandan territory: Muhabura, Gahinga, Sabyinyo, Bisoke, and Karisimbi. Surface manifestations, such as hot springs and travertine deposits, indicate the presence of geothermal systems in this region [61]. Detailed geological, geochemical, and geophysical studies have been conducted in the Virunga region, particularly around the Karisimbi volcano[47]. Preliminary results from magneto telluric (MT) and transient electromagnetic (TEM) surveys suggest the existence of a medium to high-temperature geothermal system, with estimated reservoir temperatures between 150-210°C[62]. These findings indicate the potential for electricity generation from geothermal resources in this area. Another area of interest for geothermal development is the southern part of Lake Kivu Graben;d within the Eastern part of the Graben, a tectonic feature associated with the Rift Valley[60]. The Rwandan government recognizes the importance of geothermal energy as an indigenous and renewable source of power. In 2007, Rwanda signed a joint project with the German Federal Institute for Geosciences and Natural Resources (BGR) for geothermal resource assessment and capacity building. This collaboration aims to further explore and evaluate the country's geothermal potential, with plans for exploratory drilling in the identified prospective areas[62].

As a renewable and locally available resource, geothermal power can contribute to energy security, reduce dependence on imported fuels, and promote economic development. Additionally, the modular nature of geothermal power plants makes them suitable for integration into microgrids, providing a reliable and sustainable baseload power source for off-grid areas[61].

2.9 Existing study on Microgrids in Rwanda

This is the study of smartness and flexibility in the context of off-grid, community renewable microgrids for displaced contexts, specifically in refugee camps. It investigated whether advances in cyber-physical systems can enable overlays of architectures for flexible demand management, enhanced sustainability and longevity, and improved service delivery in microgrids. The study focused on a microgrid project providing energy to two nurseries and a playground in Kigeme refugee camp in Rwanda. It aimed to address the limited access to electricity faced by an estimated 89% of camp-based refugees globally. The paper proposed an easy-to-retrofit energy management system overlay that allows for various demand control plug-ins and user-driven demand optimization for the solar-battery community microgrid in the camp. The research questions addressed include:

To what extent cyber-physical design elements and control methods can be overlaid into existing smart microgrid structures to arrive at controllable community-led energy systems.

How deterministic and metaheuristic methods compare in achieving conflicting multi-objective priorities such as battery health, system efficiency, and user satisfaction.

How existing metaheuristic methods can be improved for better convergence in environments with large search spaces.

The study evaluates and compares different control methods, including a modified genetic algorithm (GA) employing search-space reduction techniques. The findings showed that microgrid control search spaces can be larger than resource-constrained computational units can solve using conventional metaheuristic methods. They highlighted the importance of microgrid developers and operators being aware of the challenges in defining high-complexity objective functions and considerations when selecting suitable control methods to meet different community requirements in refugee camp settings[63].

Another study on the feasibility and potential of microgrids for rural electrification in Rwanda and the broader Sub-Saharan Africa region.

The research discusses the low electrification rates in Sub-Saharan Africa, with only 24% of the population having access to electricity in 2013, and the challenges impeding rural electrification efforts, such as political instability, lack of financial resources, and dispersed rural settlements.

It highlights the potential of microgrids, particularly those with high renewable energy penetration, as a viable solution for rural electrification in Sub-Saharan Africa, given the region's abundant renewable energy resources and the advantages of microgrids, such as proximity to loads, improved efficiency, and flexibility.

With a case study focused on the rural village of Rwamiko in Rwanda, the simulations and compared different electrification solutions using the HOMER software.

The simulation results showed that a microgrid system comprising solar photovoltaic (PV) panels, batteries, and a micro-hydropower plant was a more cost-effective solution for electrifying Rwamiko compared to extending the central grid to the village[64].

2.10 Literature review summary and sources selection

The literature review provides the overview of the energy landscape in Rwanda, with a focus on the potential for microgrids to power isolated communities.

Here are the key points:

Rwanda is a small, landlocked country with a predominantly rural population (72.1%) and aims to achieve middle-income status by 2035 and high-income status by 2050. Increasing electricity access, particularly in rural areas, is a priority for driving economic growth and development.

Rwanda has abundant solar irradiation, with an average daily global solar irradiation of around 5.2 kWh/m2, making solar energy a promising source for powering microgrids. The country also has significant hydropower potential, with small hydropower plants (less than 10 MW) well-suited for microgrids in remote areas.

Biomass, particularly firewood and charcoal, is widely used for lighting and cooking in isolated rural areas, highlighting the need for alternative energy sources. As of 2022, only around 33% of rural households had access to electricity, primarily through solar home systems and mini grids.

Rwanda has made progress in increasing electricity access from 6% in 2009 to 75% in 2024, with a target of achieving universal access by 2024. However, challenges remain in terms of financing, technical capacity, and infrastructure development for off-grid solutions.

The review discusses the potential of various renewable energy sources, such as small hydropower, geothermal, wind, and biomass, for powering microgrids in isolated communities, and solar and wind sources was considered as two most suitable options based on their compatibility, energy potential, and feasibility to the selected area. It also highlights the need for innovative business models, financing mechanisms, and capacity building.

the reviews include studies on microgrid control methods, feasibility assessments, and the potential of microgrids for rural electrification in Rwanda emphasizing the challenges and opportunities in this area.

3 METHODOLOGY

This chapter will describe the case studies, the selected sources and energy storage, demand profiles and simulation process to achieve results.

3.1 Case study

- **Case study 1 (Kadahokwa):** Kadahokwa Village is located in Southern province,Huye district, Gishanvu sector, Ryakibogo cell (Longitude: 2.63S, Latitude 29.69E), and It involves approximately 65 households (averaging 5 people per household),two grocery shops, barber shop, and one school (Groupe Scholaire Vumbi). With total load demand 143kWh.

Figure 9: Kadahokwa village: Google Earth view

- **Case study 2(Mashyoza village):** Mashyoza village is in the Western province, Rubavu district, Kanama sector, Rusongati cell (Longitude: 1.74S, Latitude 29.37E). It involves approximately 60 households (averaging 5 people per household) , two small grocery shops and a barber shop. With the total daily demand of 85Kwh.

Figure 10: Mashyoza village: Google Earth view

3.2 PV model

Photovoltaic (PV) cells are semiconductors that convert light photons into electricity through the photovoltaic effect. This transformation of solar energy into electrical energy has various applications. PV systems offer several advantages, such as being environmentally friendly, reliable, having no moving parts, requiring minimal operating and maintenance costs, and being easy to install. However, PV systems also have drawbacks, including high capital costs and intermittent power output.

The power output of a PV system can be calculated using the equation[65]:

$$PPV(t)= \eta PV \cdot APV \cdot G(t) \quad (2)$$

The efficiency of the PV module is given by equation (3) based on the solar irradiation at time t:

$$\eta PV= \eta STC \cdot \eta MPPT[1- \alpha (TC-TSTC). \quad (3)$$

Where APV is the area of the PV module in m^2, G(t) is the hourly total solar irradiance in W/m^2, ηPV is the efficiency of the PV array, ηSTC is the reference efficiency of the PV cell at standard test conditions (STC), ηMPPT is the efficiency of the maximum power point tracker, TC is the temperature of the PV cell in °C, TSTC is the reference temperature of the PV cell at STC (25°C), α is the temperature coefficient of the PV cell, typically 0.4%/°C to 0.6%/°C for silicon cells[66]. The temperature coefficient α is provided by the PV cell manufacturer and can be obtained from the PV panel datasheet. The PV cell temperature TC depends on the ambient temperature and solar irradiance according to[66]:

$$TC = Ta + [(NOCT - 20)/800] * G(t) \qquad (4)$$

Where Ta is the ambient temperature and NOCT is the nominal operating cell temperature (45°C to 47°C)

3.3 Wind Turbine model.

Wind power density is a useful metric for quantifying the wind energy potential at a given location. It considers both the wind speed distribution and its dependence on wind speed and air density. The wind power density, dwp, can be calculated using the following equation[67]:

$$dwp = 0.5 * \rho * Cp * \Sigma(Vi^3 * ti) \qquad (5)$$

Where Vi is the mean wind speed for the x-th time interval, ti is the ratio of the number of hours in the x-th time interval to the total number of hours, Cp is the power coefficient provided by the wind turbine manufacturer, and ρ is the air density

The air density ρ can be estimated using the following equation[67]:

$$\rho = P / (287.05 * (273.15 + T)) \qquad (6)$$

Where: P is the atmospheric pressure in Pa, T is the air temperature in °C.

Using wind power density provides more accurate assessment of the wind energy potential compared to just considering the wind speed alone. It accounts for the non-linear relationship between wind speed and power, as well as the effect of air density variations. The wind power density can be used to compare the wind energy potential at different sites or to estimate the energy output of a wind turbine at a specific location. It is an important parameter in the design and evaluation of wind energy systems.

The air density ρ can be calculated using the ideal gas law[67]:

$$\rho = P / (R * T) \quad (7)$$

Where P is the atmospheric pressure in Pa, R is the specific gas constant for air (287.05 J/kg·K), T is the absolute ambient temperature in K, Wind turbines (WTs) only generate electricity when the wind speed is between the cut-in speed Vci and the cut-out speed Vco. Many assume the WT output is constant between the rated speed Vr and Vco. However, wind speed varies with height above ground. wind speed V at a given height H can be estimated from the wind speed Vref at a reference height Href using the following equation[67]:

$$V = Vref * (H/Href)^\wedge\alpha \quad (8)$$

Where α is the correction exponent that accounts for factors like surface roughness, wind speed, temperature, time of day and season.

3.4 Energy storage

To integrate wind turbines and photovoltaic (PV) systems, energy storage is crucial[68]. Battery energy storage systems (BESS) maximize the impact of the microgrid by decoupling energy production and consumption. Battery allows the microgrid to store excess renewable energy generated by the wind turbines and PVs, and then discharge that energy when needed to support critical loads or offset utility power during peak demand periods[68].

The battery capacity varies with temperature, which is accounted for using the temperature coefficient δC. The available battery capacity C'bat at a given temperature Tbat is calculated as[65]:

$$C'bat = Cbat * [1 + \delta C * (Tbat - 298.15)] \quad (9)$$

Where C'bat is the available battery capacity at temperature Tbat, Cbat is the original battery capacity, δC is the temperature coefficient provided by the manufacturer, 298.15K is the reference temperature[69]

3.5 System design

Component specifications are determined using input parameters of load profiles and renewable energy resources, following Rwandan electrical design standard methods. The output provides a system design including component specifications, grid architecture, controls, and associated costs to inform the business model.

3.5.1 Load profiles estimation.

The load characteristics, both current and projected, are crucial for informing microgrid power generation system design and financial modeling in Rwanda. The energy demand is calculated as the sum of the products of appliance power and hours of use and was calculated based on equation (10).

$$\boldsymbol{D = \sum_{i=0}^{n} hWi} \quad (10)$$

Where D is total demand in Wh, h is the duration of operation of different appliances and Wi is the wattage of the i-th appliance. By considering the daily lifestyle of the two villages by connecting households' basic demands for lighting, radio and phone charging. shops lighting, TV sets and phone charging and refrigeration are considered for shops, and for schools lighting and computer lab are considered as illustrated in

Table **4**,Table 5,Figure 11 and Figure 12

Table 4: Mashyoza Village total daily energy by customers

Customer segment	LED light	Fluorescent light	Fridge	TV	Radio	Phone Charge	Total daily demand
Barber shop	*			*		*	30kWh
Household	*				*	*	29.03kWh
Grocery shop		*	*	*		*	24.24kWh

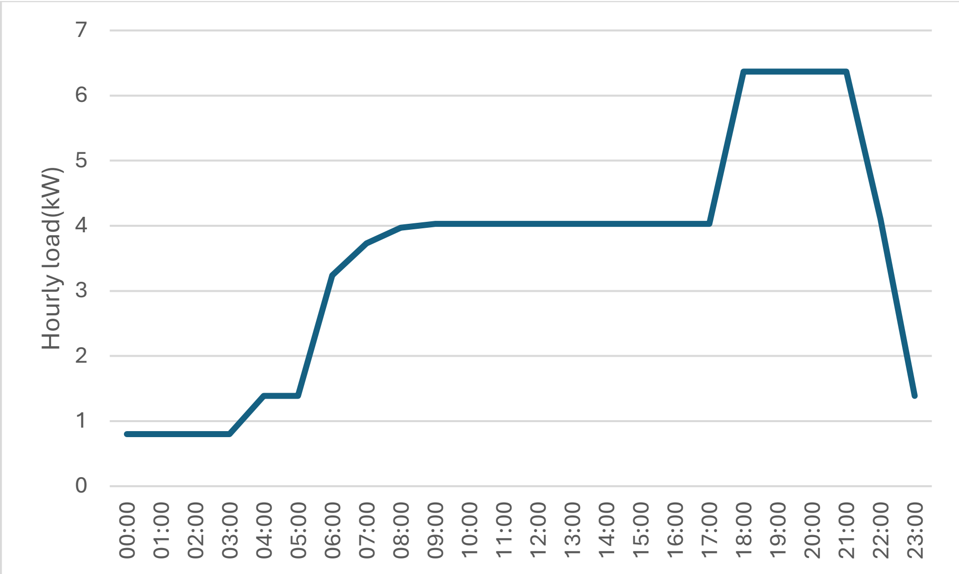

Figure 11: Mashyoza daily load profiles.

Table 5: Kadahokwa village total daily energy by customers

Customer segment	LED light	Fluorescent light	Radio	Computers and Printer	Phone Charge	TV	Refrigerator	Total daily demand
Barber shop	*				*	*		30kWh
Household	*		*		*			29.03kW
school		*		*				50.14kW
Grocery shop		*			*	*	*	25.7kWh

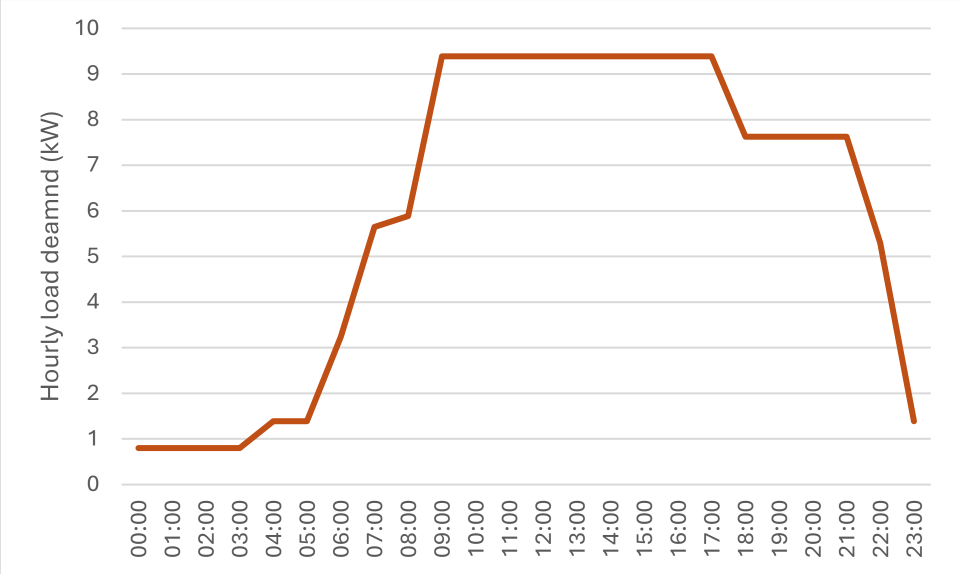

Figure 12:Mashyoza daily load profiles.

3.5.2 Solar and wind resources of the selected area

Solar and wind data for a 21-year period (2001-2022) obtained from the National Renewable Energy Laboratory and NASA's surface meteorology and solar energy database, serving as inputs for HOMER pro[70]. Wind characteristics and potential for Kadahokwa and Mashyoza villages as shown in Figure 13. indicates the higher maximum wind speeds at 10m height observed from January to December, with lower speeds from October to March. Kadahokwa village recorded a maximum wind speed of 6.09 m/s, while Mashyoza village reached 6.21 m/s. For solar data, monthly average daily solar irradiance (kWh/m2/day) and clearness index are presented in Figure 14. The annual average solar irradiance is estimated at 5.02 kWh/m2/day in Kadahokwa and 4.95 kWh/m2/day in Mashyoza. July was identified as the month with the highest solar potential in both locations.

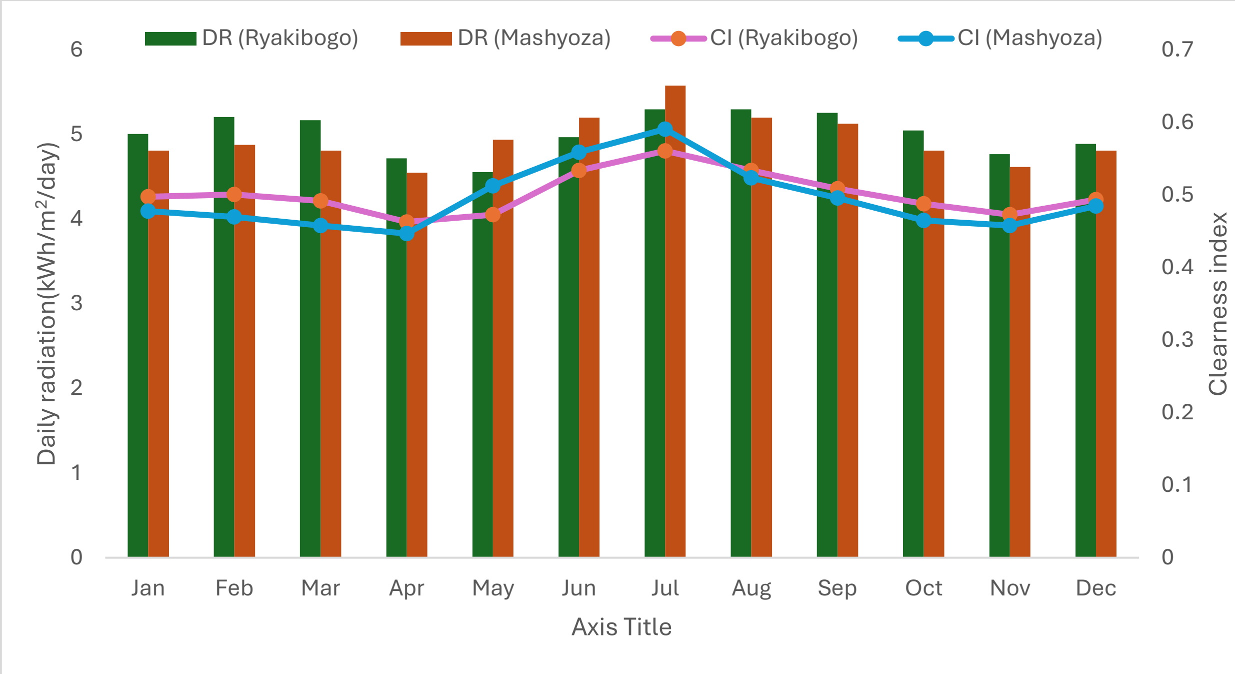

Figure 13: Average daily radiation and clearness index for Kadahokwa and Mashyoza villages.

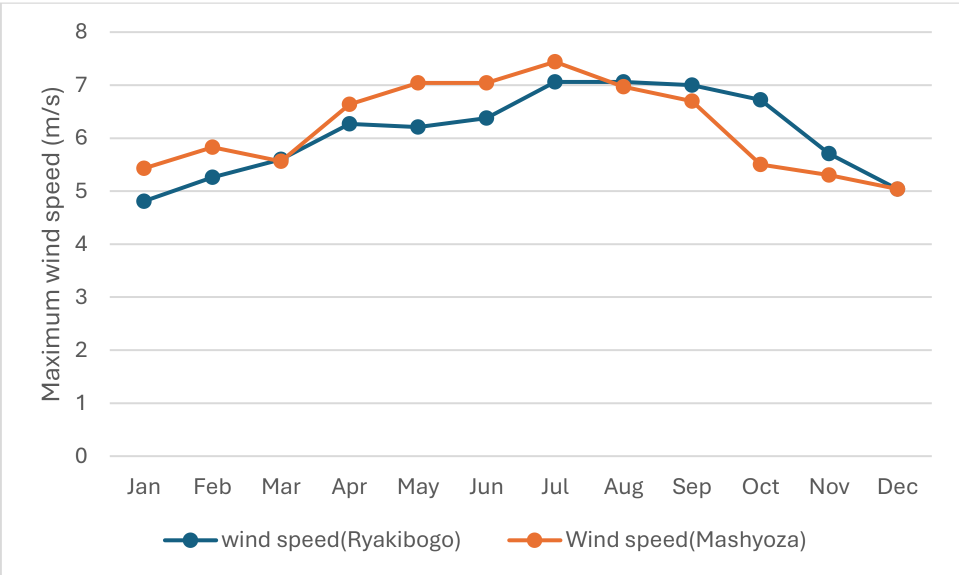

Figure 14: Maximum wind speed for both Kadahokwa and Mashyoza villages.

3.6 System design in given location.

Table 6 presents the financial breakdown for the components of the suggested microgrid system, including photovoltaic (PV) arrays, wind turbines, diesel generators, converters, and batteries. For each component, there is initial capital cost, replacement cost, and annual operation and maintenance cost. The costs are given in US dollars, with some expressed per kilowatt (kW) of capacity and others per unit. PV arrays have the highest capital cost at $1950/kW, while wind turbines are slightly less expensive at $1570/kW. Diesel generators have the lowest capital cost among the main power sources at $1340/kW and has hourly operational cost. Converters and batteries are priced per unit, with batteries being more expensive. The price information is crucial for planning and budgeting for the system and allowing the inputs for Homer Pro.

Table 6: Components per unit cost for both villages

System components	capital cost ($)	Replacement cost ($)	Operation and maintenance cost ($)
PV array	1950/kW	950/kW	15/year
Wind turbine 10kW	35000/unit	35000/unit	500/year
Wind turbine 3kW	5000/unit	5000/unit	100/year
Diesel generator	1340/kW	1000/kW	0.25/hr
Converter	320/unit	320/unit	10/year
Battery	380/unit	380/unit	10/year

The sensitivity analysis parameters for the microgrid system simulation are presented in

Table 7. It includes five key variables: inflation rate, discount rate, battery minimum state of charge, wind turbine hub height, and fuel price. For each variable, three different values are provided, representing low, medium, and high scenarios. The inflation rate ranges from 1.1% to 5%, while the discount rate varies from 4% to 8%. The battery minimum state of charge, which affects the system's energy storage capacity, is set at 10%, 20%, and 40%. Wind turbine hub height, a big factor in wind energy generation, is considered at 10m, 17m, and 40m. Lastly, fuel prices, likely for a backup diesel generator, range from $1.19/L to $1.5/L. These parameters allow for a comprehensive analysis of how different economic and technical factors might impact the overall performance and cost-effectiveness of the renewable energy system under various scenarios.

Table 7: Variables used for sensitivity analysis.

Inflation rate (%)	Discount rate (%)	Battery minimum state of charge (%)	wind turbine hub height(m)	Fuel price($/L)
1.1	4	10	10	1.19
2	5	20	17	1.25
5	8	40	30	1.5

3.7 Cost modelling

Renewable energy projects may not always be feasible, as incorrect sizing can compromise the microgrid's effectiveness. Therefore, comprehensive design and analysis are crucial. To efficiently utilize renewable energy in a microgrid, financial viability must be assessed based on various factors, including the Levelized Cost of Energy (LCOE), replacement costs, operation and maintenance expenses, net present cost (NPC), capital costs, and other relevant considerations. The NPC represents the difference between the project's total cost and the revenue generated by the system over its lifetime. The NPC can be calculated using the equation (11).

$$CNP = \frac{Ctot}{CRF}, \qquad (11)$$

Where CRF is the capital recovery factor, determined by equation (12)

$$CRF = \frac{i(1+i)^N}{(1+i)^{N-1}} \qquad (12)$$

The equation, i represents the real discount rate, and N is the project's lifespan in years. The real discount rate is calculated as:

$$i = \frac{inom-di}{1+di} \qquad (13)$$

Where i-nom is the nominal discount rate and di is the inflation rate. The LCOE represents the cost of electrical energy generated by a microgrid system. It is defined as the ratio of annual costs to the electric load served. For electrical energy only, the LCOE is calculated using equation (14)

$$LCOE = \frac{Ctot}{Eserved} \qquad (14)$$

Where Ctot is the total annualized cost and Eserved is the total electric load served. The total energy served can be determined by:

$$Eserved = Es.ACpr + Es.DCpr + Es.DEF + ES.grid \qquad (15)$$

In this equation, Es.ACpr represents the AC primary load served, Es.DCpr is the DC primary load served, Es.DEF is the deferrable load served, and ES.grid is the energy sold to the grid.

4 RESULTS AND DISCUSSIONS

This section presents results from various simulations done in Homer Pro. Where many microgrid designs were evaluated, several designs were considered to identify the one with the minimum NPC and initial capital. Out of the total simulations, few microgrid designs were considered feasible, while other cases were eliminated due to constraints mostly the system with diesel generator were not considered. For each feasible microgrid design, an hourly time-series simulation is conducted over a 25-year planning period for both case studies by considering the Rwandan inflation rate (5%) and the discount rate (1.1%)[71]. The results are presented in tables and figures by considering the techno-economic assessment, technical and environmental results of the optimal system and energy system.
For both villages 2 case scenarios are presented in detail while others are discussed in summary based on the cost of the system and Levelized cost of electricity.

4.1 Kadahokwa village results.

The diagram in Figure 15 illustrates a hybrid energy system in Kadahokwa village that integrates a 10-kW wind turbine (XL10), solar panels (CS6X-325P), a generator (Gen), a Fronius inverter/charger (SMA, Germany), and a lithium ion battery to meet an electrical load that consumes 80 kWh per day with a peak demand of 9.51 kW. The wind turbine and generator provide power directly to the AC side of the system, while the solar panels generate DC power that can either charge the battery or be converted to AC by the inverter. The battery stores excess energy and supplies it when needed, ensuring a continuous power supply. The inverter plays a big role in managing energy flow, converting DC to AC, and ensuring efficient battery charging, while the generator serves as a backup to maintain reliability in periods of low renewable energy generation.

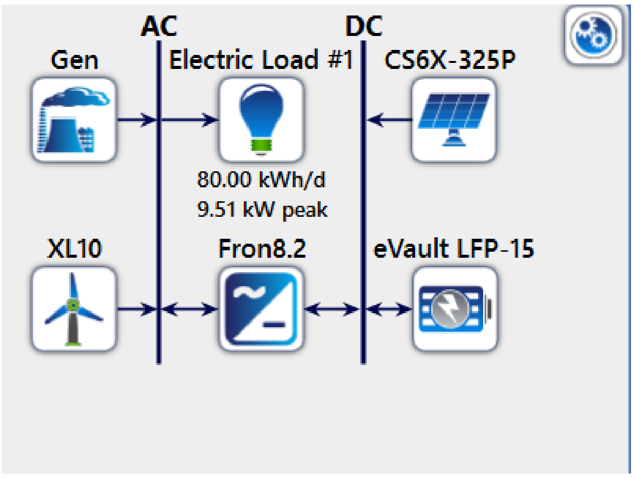

Figure 15: Kadahokwa microgrid schematic overview.

4.1.1 Scenario 1: PV, battery and converter

Table 8 presents a solar photovoltaic (PV) system with integrated battery storage. The system has a PV capacity of 22 kW, consisting of 68 individual PV panels (325 W each). The array produces approximately 33,700 kWh of electricity per year. a battery storage capacity of 40 kWh, comprised of 4 separate batteries. The storage allows for energy to be used in cloudy days or during peak demand periods. The system also has two converters with a total capacity of 8.5 kW. The total annual load (electricity consumption) for the system is 28,603 kWh/year. There is excess electricity generation of 11.5% of the total production. This excess could potentially be fed to the grid or act as buffer energy for the increase of load demand.

The initial capital cost for the system is $35,525. The Net Present Cost (NPC), which represents the present value of all the costs over the project lifetime, is $55,730, and the Levelized Cost of Energy (LCOE), which is the average cost per kWh of useful electrical energy produced by the system, is $0.122/kWh.

Table 8: scenario 1 results output

Component	Specification
PV Capacity	22 kW (68 PVs)
PV Production	33,700 kWh/year
Battery Capacity	40 kWh (4 batteries)
Converter Capacity	8.5 kW (2 converters)
Excess electricity	3,871 kWh/year (11.5%)
Total Load	28,603kWh/year
Initial capital	$35,525
NPC	$55,730

The bar chart in Figure 16 present monthly electric production in a year period, measured in megawatt-hours (MWh). The monthly production changes slightly, generally ranging between approximately 2.5 MWh and 3.0 MWh. The highest production occurs in July, peaking just above 3.0 MWh, while the lowest production is observed in April, slightly below 2.5 MWh. This consistency suggests a stable energy generation system from photovoltaic array. The chart indicates that the system can maintain steady production throughout the year, ensuring a reliable supply of electricity.

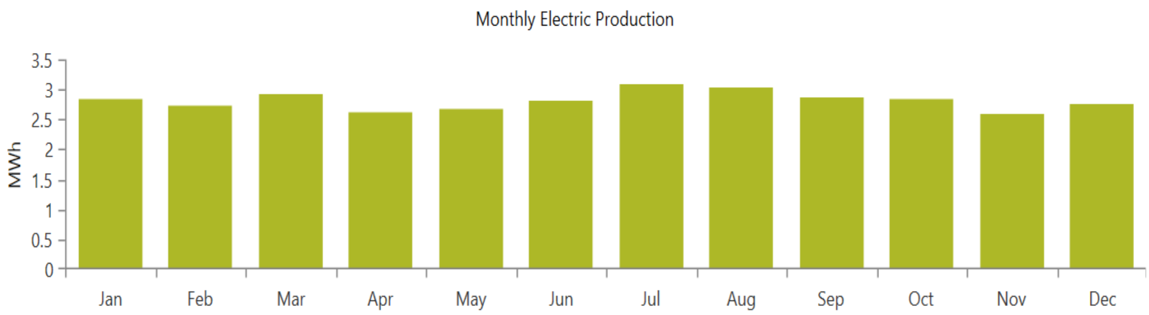

Figure 16: Monthly electrical production.

Figure 17 presents a detailed hourly breakdown of the system in January sample week showing AC primary load (electricity demand), PV output, and the state of charge of the battery. Throughout there is a clear daily electricity demand and solar power generation.

The AC primary load fluctuates throughout the day, with peaks typically occurring in the morning and evening hours, reflecting common household electricity usage patterns. The PV output starts at zero during nighttime hours, and increases as the sun rises, peaking during midday, and then decreasing to zero as the sun sets. The highest PV output is 17.18 kW. The state of charge of the battery system fluctuates in response to the balance between electricity demand and solar generation. It generally decreases during nighttime hours when there's no solar production and increases during daytime hours when solar production exceeds demand. The battery's state of charge ranges from a low of 36.26% to a high of 74.34%.

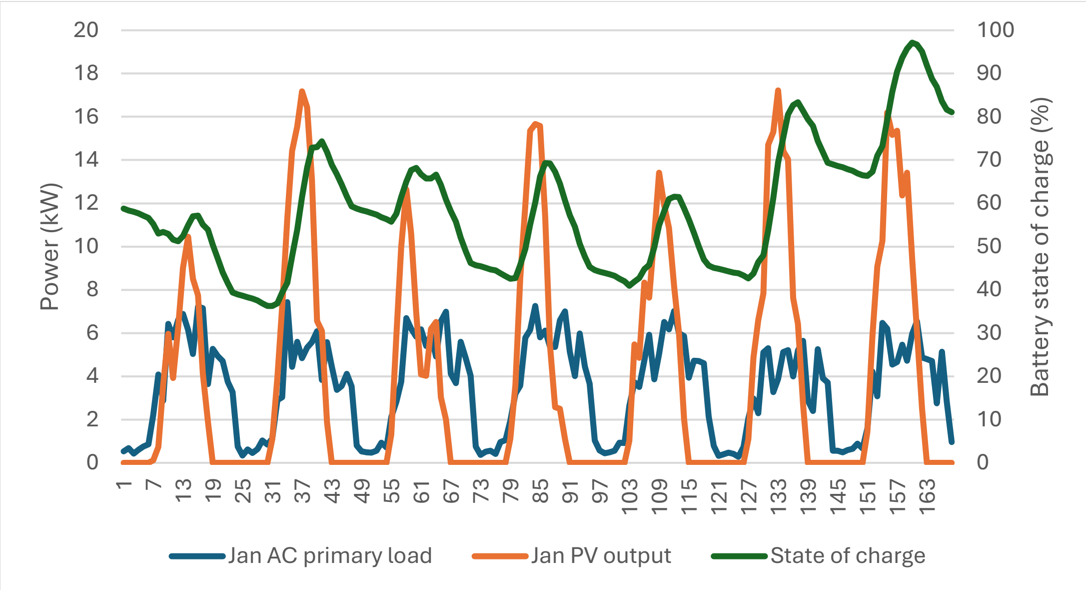

Figure 17: January sample week production vs consumption.

The results presented in Figure 18 shows July sample week hourly performance. It details the AC primary load, PV output, and the state of charge of the battery. The AC primary load increases and decreases as the day goes by. The PV output shows a clear daily pattern, increases as the sun rises, peaking during midday, and then decreasing back to zero during the night. The highest PV output recorded is 16.93 kW, indicating a particularly sunny midday period. The state of charge of the battery system starts high at 84.91% and fluctuates based on the balance between electricity demand and solar generation. During the daytime, when solar generation is high, the battery charges reach a peak state of charge of 98.78%. However, during nighttime or periods of high demand

and low solar generation, the battery discharges to meet the load. And some nights the state of charge steadily decreases to a low of 5%, indicating a period of sustained high demand and/or insufficient solar generation. The data also highlights periods of excess solar generation allowing the battery to charge significantly to balance supply and demand for the intermittent of solar power.

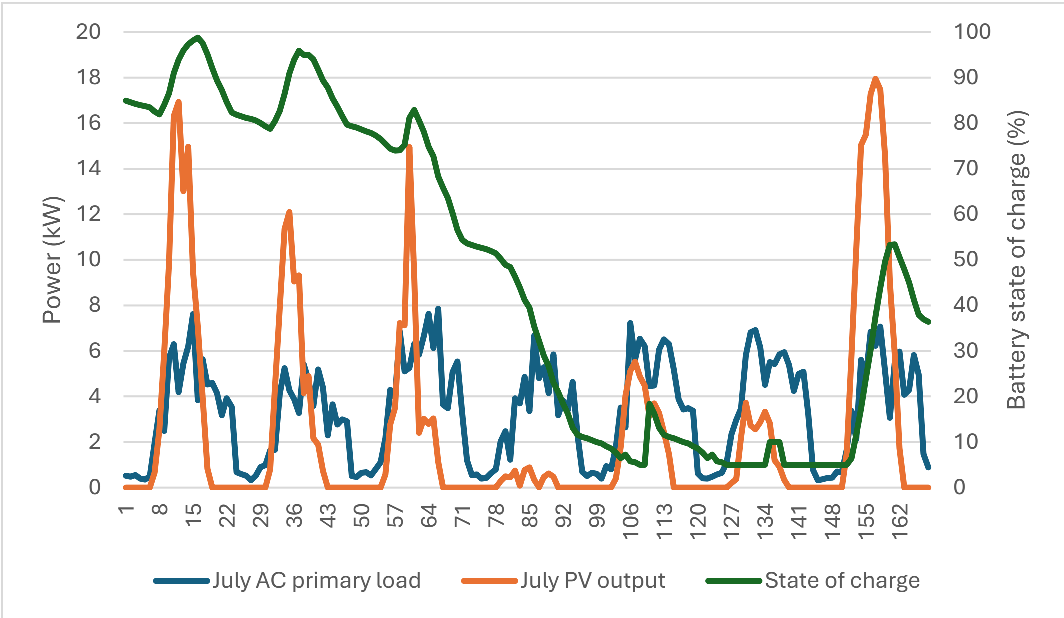

Figure 18: July sample week energy production vs consumption.

Table 9 and Figure 19 a financial breakdown of a considered renewable energy system combining PV panels, converters, and batteries. The capital cost, which represents the initial investment required to purchase and install the system, is dominated by the PV panels at $27,380. The converters and batteries also contributed significantly, costing $3,150 and $4,250 respectively. An additional $750 is allocated to other miscellaneous costs, bringing the total initial capital cost to $35,530. Operational and Maintenance (O&M) costs, which cover the ongoing expenses required to keep the system running efficiently, which is $8,540 over the system's lifetime. Replacement costs, which include the expenses associated with replacing components that have reached the end of their useful life, total $13,105. The Net Present Cost (NPC), represents the total cost of the system over its entire lifecycle, including capital, O&M, and replacement costs, is

$57,175. This figure provides a comprehensive measure of the long-term financial commitment required for the system, considering all expenses.

Table 9: scenario 1 system cost

components	Photovoltaic	Wind turbine	Converter	Battery	Other cost ($)	System ($)
Capital cost ($)	27,380	0	3150	4250	750	35,530
O&M cost ($)	0	0	3640	4900	0	8,540
Replacement ($)	6,950	0	1970	2,620	1,565	13,105
Total (NPC)						57,175

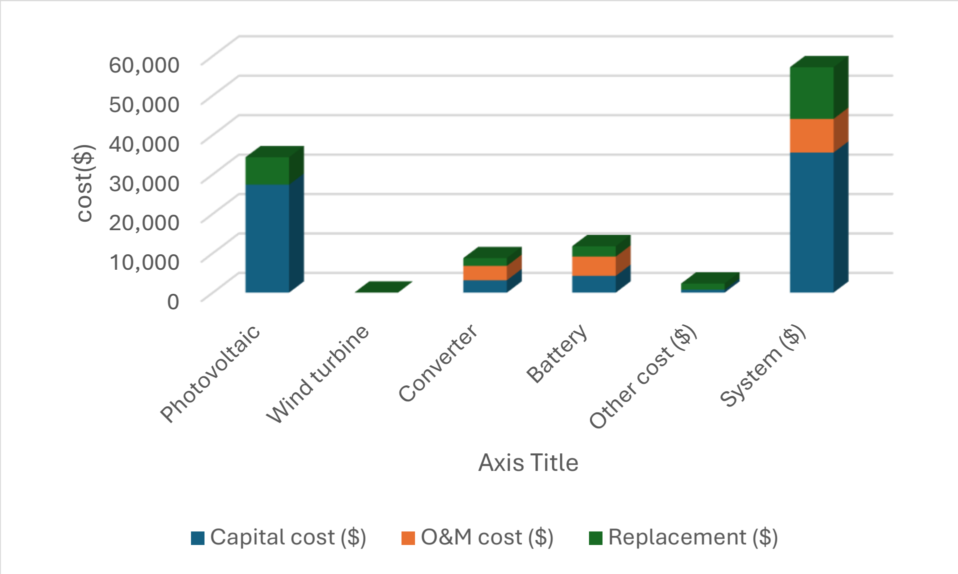

Figure 19: System cost for scenario 1.

Table 10 provides a detailed sensitivity analysis of various financial and operational parameters affecting a microgrid system. The Net Present Cost (NPC), Levelized Cost of Energy (LCOE), initial capital, and annual operation and maintenance (O&M) costs are evaluated under different conditions.

- Inflation Rate

The inflation rate affects the financial metrics of the system: the considered inflation rate 1.1% has The NPC is $55,730, with an LCOE of $0.122/kWh, the initial capital cost is $35,525, and the annual O&M cost is $1,275. For a 2% inflation rate, the NPC increases to $57,890, while the LCOE decreases to $0.115/kWh. The initial capital cost remains the same, but the annual O&M cost slightly increases to $1,280. 5% inflation rate shows the rise of NPC to $67,275, and the LCOE drops to $0.094/kWh. The initial capital cost is unchanged, and the annual O&M cost is $1,270.

- Discount Rate

The discount rate also affects the system's cost-effectiveness for 4% discount rate, the NPC is $58,080, with an LCOE of $0.114/kWh, The initial capital cost is $35,525, and the annual O&M cost is $1,276. The considered case of 5% discount rate, the NPC is $55,730, and the LCOE is $0.122/kWh. The initial capital cost is $35,525, and the annual O&M cost is $1,275. When the discount rate increased to 8% the NPC decreases to $50,295, but the LCOE increases to $0.148/kWh. The initial capital cost is slightly lower at $35,090, and the annual O&M cost is $1,285.

- Wind Turbine Hub Height

The hub height of the wind turbine does not affect the financial metrics in this scenario, as the system does not include wind turbines:
10m, 17m, 30m (considered): For all heights, the NPC is $55,725, the LCOE is $0.122/kWh, the initial capital cost is $35,525, and the annual O&M cost is $1,275.

- Battery Minimum State of Charge

The minimum state of charge for the battery affects the system's costs: 10% (considered) has the NPC of $55,730, with an LCOE of $0.122/kWh; The initial capital cost is $35,525, and the annual O&M cost is $1,275. When the minimum state of charge is 20% the NPC increases to $58,575, and the LCOE rises to $0.129/kWh, the initial capital cost is $35,935, and the annual O&M cost is $1,427. At 40% state of charge the NPC further increases to $62,475, with an LCOE of $0.138/kWh. The initial capital cost rises to $38,704, and the annual O&M cost is $1,500.

The data indicates that both inflation and discount rates impact the NPC and LCOE, with higher inflation increasing NPC but lowering LCOE, and higher discount rates reducing NPC but increasing LCOE. The battery's minimum state of charge influences costs, with higher minimum charges leading to increased NPC, LCOE, and initial capital costs. Overall, these parameters are important for assessing the long-term financial viability and cost-effectiveness of the renewable energy system.

Table 10: sensitivity analysis for the optimized system

Parameters	NPC ($)	LCOE ($)	Initial capital ($)	O&M($/yr)
Inflation rate (%)				
1.1(considered)	55,730	0.122	35,525	1275
2	57,890	0.115	35,525	1280
5	67,275	0.094	35,525	1270
Discount Rate				
4	58,080	0.114	35,525	1276
5(considered)	55,730	0.122	35,525	1275
8	50,295	0.148	35,090	1285
WT hub height(m)				
10	55,725	0.122	35,525	1275
17	55,725	0.122	35,525	1275
30(considered)	55,730	0.122	35,525	1275
Battery minimum state of charge (%)				
10(considered)	55,730	0.122	35,525	1275
20	58,575	0.129	35,935	1427
40	62,475	0.138	38,704	1500

4.1.2 Scenario 2: solar PV, wind turbine, storage and converters

The hybrid renewable energy system sample week presented in Table 11, combines solar PV panels and wind turbines with battery storage. The system is designed to meet a total annual load of 28,666 kWh/year while achieving a 100% renewable fraction. The solar component consists of 34 PV panels with a total capacity of 11 kW, producing 16,752 kWh/year. The wind energy component has a single wind turbine with a capacity of 10 kW, generating 31,537 kWh/year. Energy storage is provided by 3 batteries with a total capacity of 30 kWh, allowing excess energy to be stored for use during periods of low renewable generation. The system includes 2 converters with a total capacity of 7.50 kW, for converting DC power from the PV panels and batteries to AC power for household use. The system generates a significant amount of excess electricity, 19,135 kWh/year of the total production that can be used for additional load demand. From a financial point of view, the initial capital cost for this hybrid system is $49,420. The Net Present Cost (NPC), which represents the present value of all costs over the project lifetime, is $65,705.

The LCOE, which is the average cost per kWh of useful electrical energy produced by the system, is $0.144/kWh.

Table 11: scenario 2 system overview

Component	Specification
PV Capacity	11 kW (34PVs)
PV production	16,752 kWh/year
WT capacity	10 kW (1WT)
WT production	31,537 kWh/year
Battery nominal Capacity	30 kWh (3 Batteries)
Converter Capacity	7.50 kW (2 converters)
Total Load	28,666 kWh/year
Excess Electricity	19,135 kWh/year (39%)
Renewable Fraction	100%
Capital cost	$49,420
NPC	$65,705
LCOE	$0.144/kWh

Figure 20 represents the bar chart of the monthly electric production across a year, representing both solar and wind energy sources contributions.

Throughout the year, the PV production remains relatively consistent, suggesting a stable energy source, contributing between 1.5 to 2.5 MWh each month. The wind turbine dominates the system production reaching close to 3.0 MWh.

The system's total monthly energy production is higher in the summer months, with total outputs reaching up to 5 MWh in July, reflecting the combined contribution of a stable energy source and a seasonal source, ensuring a balanced and reliable electricity supply throughout the year.

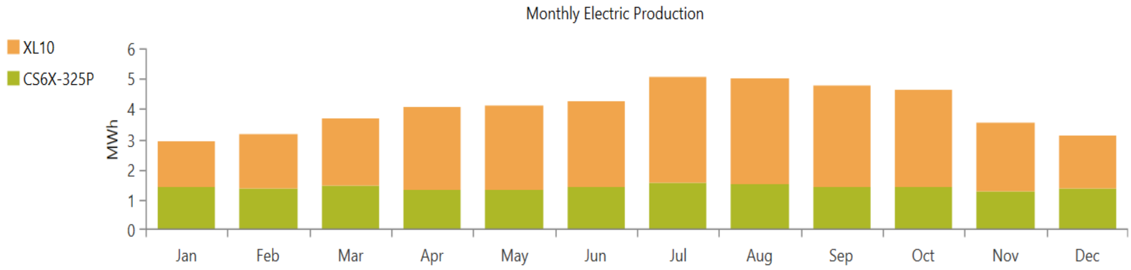

Figure 20: Scenario 2 system monthly electricity production.

The Hybrid renewable energy system's performance for January sample week is presented in Figure 21. The system combines solar photovoltaic panels and wind turbines with battery storage to meet the AC primary load. The primary loads range between 0.34 kW to peaks of 7.43 kW. The highest PV output is 8.54 kW, and wind turbine is 8.47 kW. The battery varies significantly throughout the period, reaching a low of 21.94% and highly charged at 96.65%. The battery discharges during periods of high demand and low renewable generation, and charges when renewable output exceeds demand.

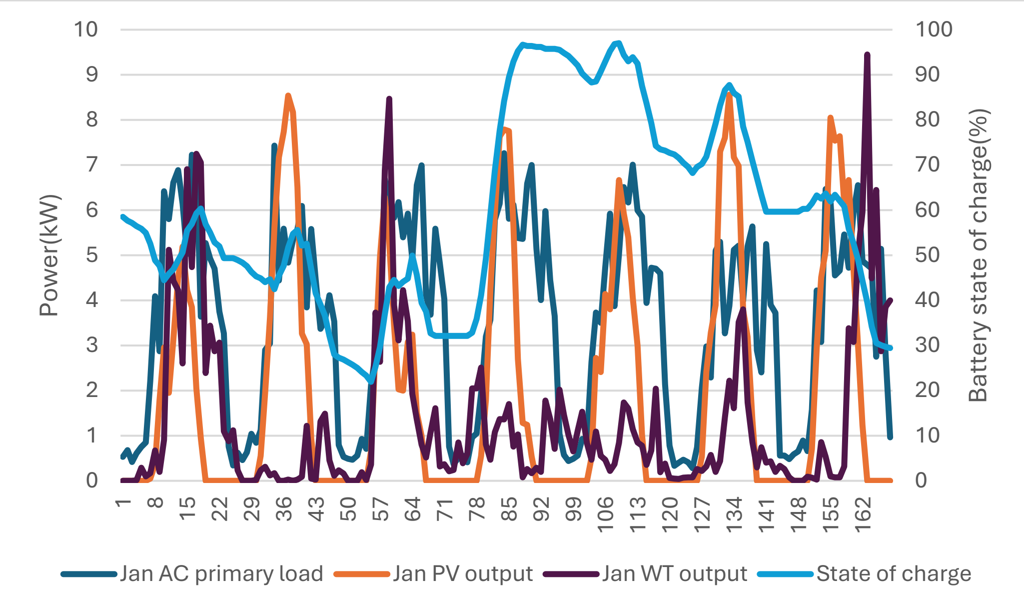

Figure 21: Scenario 2 sample January sample week.

Figure 22 illustrates the system performance in July sample week combining PV panels, wind turbines, battery storage, and AC primary load. The highest PV output recorded is

7.94 kW, and wind turbines peak is 12.53 kW. The battery's state of charge fluctuates in response to the balance between electricity demand and renewable generation. It starts at 94.16% and remains at high levels for much of the period, often reaching 99% or higher. This indicates that the combined solar and wind generation frequently exceeds demand during this summer period, allowing the battery to maintain a high charge state. the battery discharges sometimes drop below 50% charge. The figure shows the system's resilience, as it can handle peak loads.

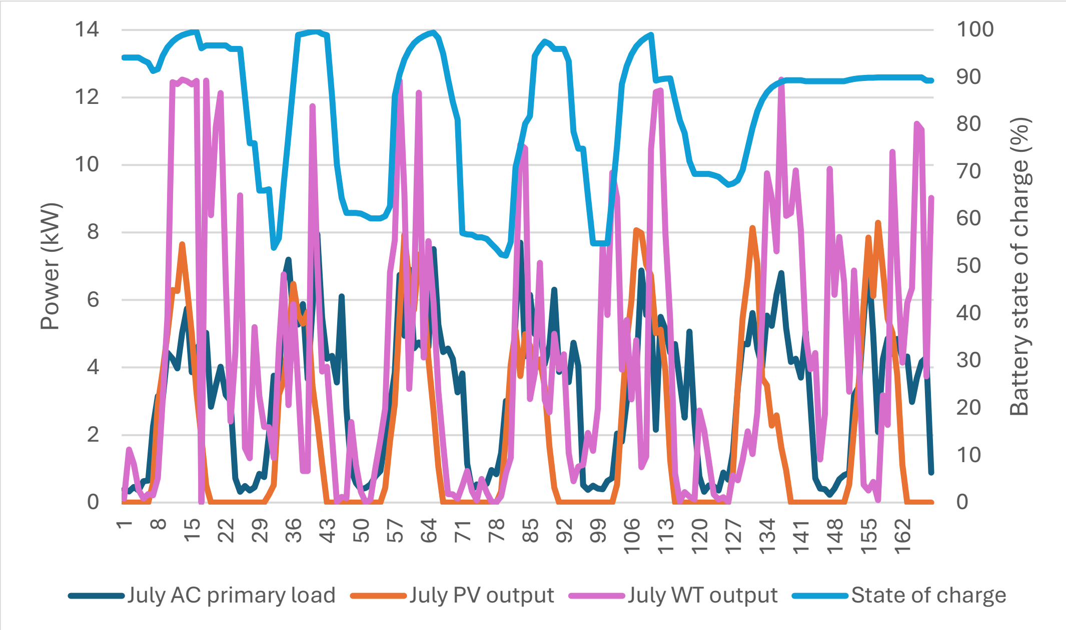

Figure 22: January and July sample weeks consumption vs production.

4.2 Mashyoza village microgrid Results

The diagram in Figure 23 illustrates a schematic view from Homer Pro of a hybrid microgrid system for Mashyoza village integrating both renewable and conventional energy sources. It combines a conventional generator, a small wind turbine (3KW) as the system is small, solar panels (CS6X-325P) and, a (SMA, Germany) converter managing the power flow between AC and DC components. The system serves an electric load with a daily consumption of 50.50 kWh and a peak demand of 6.54 kW. The configuration maximizes renewable energy utilization through simulating the best compatible system.

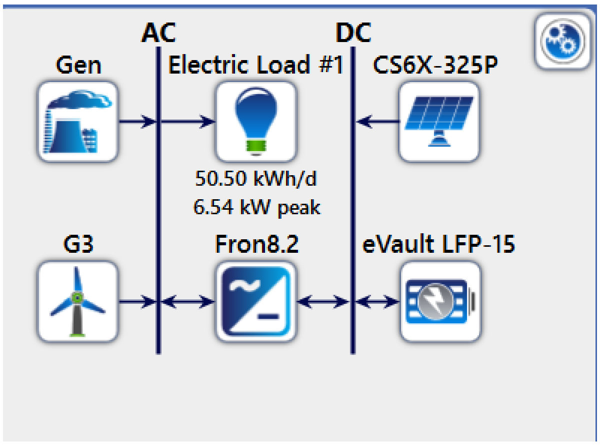

Figure 23: Mashyoza village schematic overview.

Scenario 1: PV, wind turbine, storage and converter.

Table 12 outlines the specifications and performance metrics of a microgrid system composed of photovoltaic solar panels, a wind turbine, batteries, and converters.

The system is designed to meet a total annual load of 18,042 kWh/year while achieving a 100% renewable fraction. The solar component consists of 33 PV panels with a total capacity of 10.6 kW, producing 16,145 kWh/year. The wind energy component comprises a single wind turbine with a capacity of 3 kW, generating 7,308 kWh/year. Energy storage is provided by 3 batteries with a total capacity of 30 kWh, allowing excess energy to be stored for use during periods of low renewable generation. The system includes one converter with a total capacity of 5.5 kW, which is crucial for converting DC power from the PV panels and batteries to AC power. The system generates excess electricity of 20.8% of the total production.

The Net Present Cost (NPC), which represents the present value of all costs over the project lifetime, is $33,045. The Levelized Cost of Energy (LCOE), which is the average cost per kWh of useful electrical energy produced by the system, is $0.109/kWh. The initial capital cost for this hybrid system is $22,560. This hybrid system demonstrates an efficient approach to renewable energy generation, leveraging both solar and wind resources to ensure a consistent power supply.

Table 12: Scenario 1 system overview

Component	Specification
PV Capacity	10.6 kW (33PVs)
PV production	16,145 kWh/year
WT capacity	3kW (1WT)
WT production	7,308kWh/year
Battery nominal Capacity	30 kWh (2 Batteries)
Converter Capacity	5.5 kW (1 converter)
Total Load	18,042kWh/year
Excess Electricity	4,880 kWh/year (20.8%)
Renewable Fraction	100%
NPC	$33,045
LCOE	$0.109/kWh
Initial capital	$22,560

Figure 24 presents the monthly electric production of the system combining PV panels and wind turbine production over the year. The photovoltaic panels produce higher energy ranging between 1 MWh to 2MWh with wind turbine produces less electricity. Between May and September, the electricity production for both sources increases significantly.

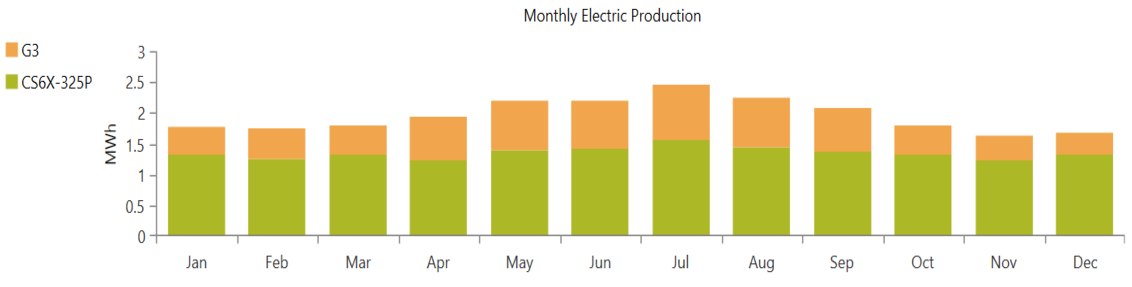

Figure 24: Scenario 1 monthly electricity production.

Figure 25 provides a detailed hourly results of load demand, wind turbine output, and photovoltaic (PV) output for a microgrid system during January sample week.
The highest PV output is 8.13 kW, there are still significant periods of solar generation. Wind turbine output is more ranges from 0 to 3 kW. Wind generation often complements solar production, providing power during nighttime hours and/or periods of low solar output. The battery's state of charge response to the balance between electricity demand and generation. It starts at a high level of 99.38% and generally maintains a good charge state throughout the period, rarely drops below 60%. This indicates that the combined solar and wind generation, along with battery storage, is effectively meeting the demand.

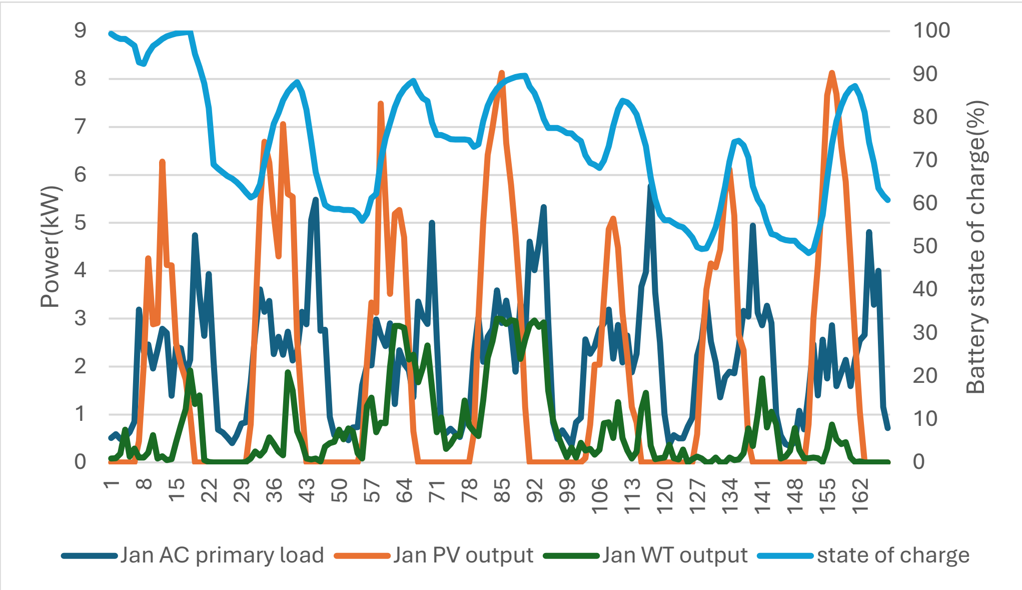

Figure 25: Scenario 1 January sample week energy production vs consumption.

This dataset provides hourly performance of load demand, wind turbine output, and photovoltaic output for a microgrid system during July sample week as presented in Figure 26. The electricity demand, ranging from low values of 0.34 kW to peaks of 5.46 kW. The peak PV output is 7.89 kW and the wind turbine output ranges from 0 to 3 kW. The storage maintains a good charge state throughout the period, often reaching above 85% during peak generation hours and drops below 60% in some cases through balancing the electricity demand when the demand is high, or the generation is low.

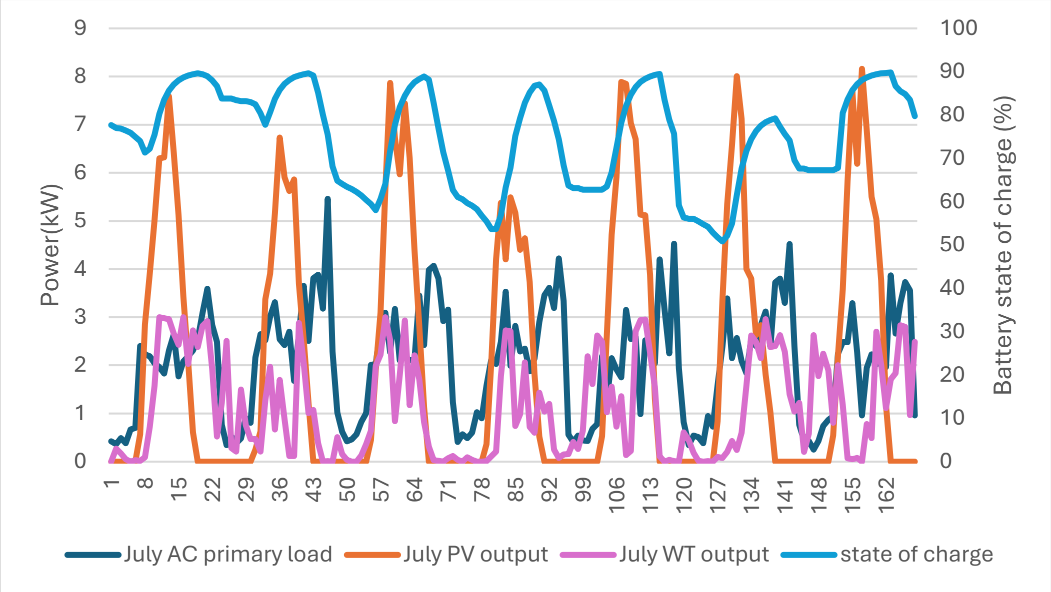

Figure 26: July sample week production vs consumption.

This financial breakdown presented in Table 13 and Figure 27 provides a comprehensive view of the costs of the system that combines PV panels, wind turbines, converters, and batteries. The capital cost, representing the initial investment of $22,555. The largest part of the system is consumed by photovoltaic system covering $13,230, followed by the wind turbine at $5,000, the converter and battery systems require $1,894 and $1,930 respectively. Operation and Maintenance costs, cover ongoing expenses over the system's lifetime, amount to $5,820. Replacement costs cover $4,670 of the system. The total Net Present Cost of the system is $33,045.

Table 13: optimized system cost overview

components	Photovoltaic	Wind turbine	Converter	Battery	Other cost ($)	System ($)
Capital cost ($)	13,230	5000	1894	1930	500	22,555
O&M cost ($)	0	1407	2185	2230	0	5820
Replacement ($)	1680	320	790	790	1090	4670
Total (NPC)						33,045

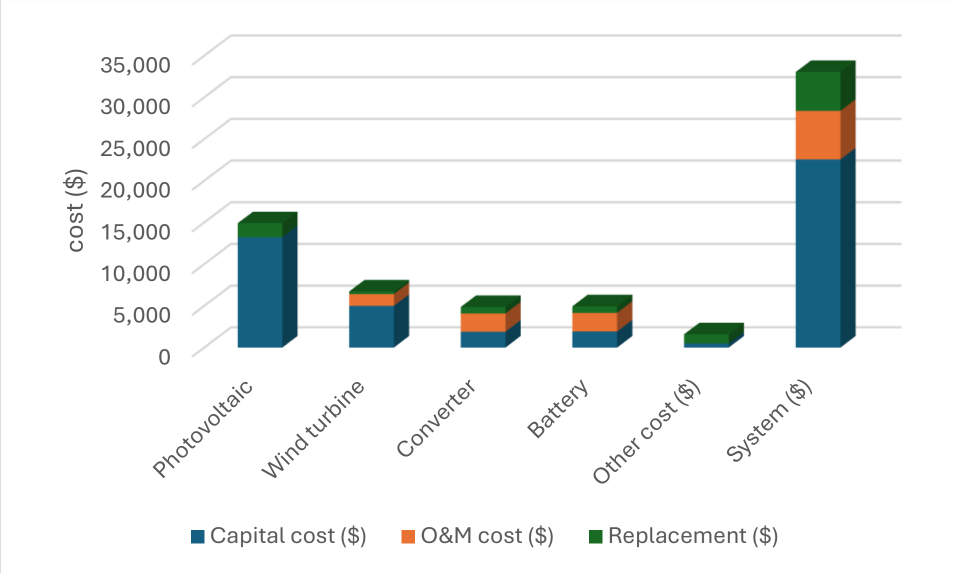

Figure 27: Optimized cost overview.

This result set presented in Table 14 illustrates a comprehensive analysis of how various parameters affect the economic and operational aspects of a microgrid system. The key metrics evaluated are Net Present Cost, Levelized Cost of Energy, Initial Capital, and annual Operation and Maintenance costs. The inflation rate significantly impacts the system's economics. At the considered rate of 1.1%, the NPC is $31,430, with an LCOE of $0.109/kWh, initial capital of $22,560, and annual O&M costs of $560. Increasing the inflation rate to 2% slightly increases the NPC to $32,383 and reduces LCOE to $0.102/kWh, while a 5% inflation rate increases the NPC to $38,594 but reduces the LCOE to $0.085/kWh, demonstrating the relationship between inflation and long-term costs.

The discount rate also plays a crucial role; The considered rate of 5% has an NPC of $31,430 and LCOE of $0.109/kWh. A lower discount rate of 4% increases the NPC to $32,464, while a higher rate of 8% reduces it to $29,045 but increases the LCOE to $0.136/kWh, illustrating how discount rates affect the present value of future costs.

Wind turbine hub height impacts system efficiency and costs. The considered height of 17m results in an NPC of $31,430. Decreasing the height to 10m increases the NPC to

$32,920, while increasing it to 30m reduces the NPC to $29,645, with corresponding changes in LCOE, demonstrating the potential benefits of taller wind turbines.

The battery's minimum state of charge significantly affects system costs. The considered 10% minimum has an NPC of $31,430 and LCOE of $0.109/kWh. Increasing this to 20% reduces the NPC to $30,920 and slightly decreases the LCOE to $0.108/kWh, while a 40% minimum significantly increases the NPC to $36,734 and the LCOE to $0.129/kWh, along with higher initial capital and O&M costs. This indicates that higher minimum battery charge levels, while potentially beneficial for battery longevity, can come at a significant economic cost.

Table 14: sensitivity analysis of the optimized system

Parameters	NPC ($)	LCOE ($)	Initial capital ($)	O&M($/yr)
Inflation rate (%)				
1.1(considered)	31,430	0.109	22,560	560
2	32,383	0.102	22,555	560
5	38,594	0.085	23,045	622
Discount Rate				
4	32,464	0.102	22,555	560
5(considered)	31,430	0.109	22,560	560
8	29,045	0.136	22,565	550
WT hub height(m)				
10	32920	0.136	23,140	5820
17(considered)	31,430	0.109	22,560	560
30	29,645	0.104	21027	545
Battery minimum state of charge (%)				
10(considered)	31,430	0.109	22,560	560
20	30,920	0.108	21,50	600
40	36,7340	0.129	24,640	765

4.2.1 Scenario 2: PV, storage and converter

Table 15 presents an overview of a standalone solar microgrid system's specifications and performance metrics to meet a total annual load of 17,980 kWh/year. The system includes 43 PV panels with a total capacity of 14.3 kW, producing 21,746 kWh/year. This production exceeds the total load, resulting in 2,960 kWh/year of excess electricity (13.6%). The system also includes two batteries combining 30 kWh, providing energy storage to ensure a stable power supply during periods of low solar generation; one converter with a capacity of 5.50 kW, to convert the DC power generated by the PV panels and stored in the batteries into AC power for household use. The system's LCOE is $0.115/kWh, with the net present cost of $33,920. The initial capital cost for setting up this system is $23,900. The system's monthly production for a year period is presented in Figure 28 varying between 1.5 MWh and 2MWh.

Table 15: scenario 2 system overview

Component	Specification
PV Capacity	14.3 kW (43 PVs)
PV Production	21,746 kWh/year
Battery nominal Capacity	30 kWh (2 batteries)
Converter Capacity	5.50 kW (1 converter)
Excess electricity	2,960kWhr/year (13.6%)
Total Load	17,980kWh/year
LCOE	$0.115/kWh
NPC	$33,920
Capital cost	$ 23,90

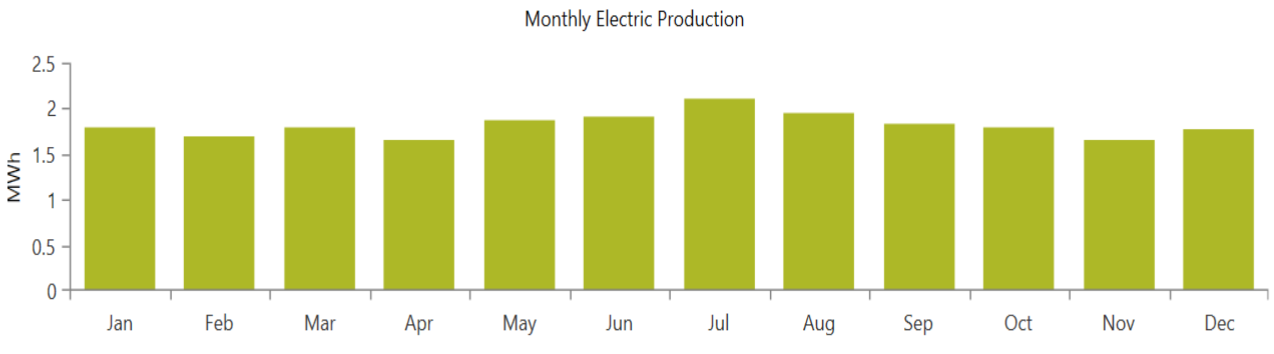

Figure 28: Monthly electricity production.

Figure 29 provides a comparison of photovoltaic output, load demand and battery state of charge for a microgrid system during January. The highest PV output was found to be 10.95 kW. The battery's state of charge fluctuates in response to the balance between electricity demand and PV generation ranging between 99.47% and 45% showing how the battery serves the demand when it higher than the electricity generation and got charged when the PV production is high.

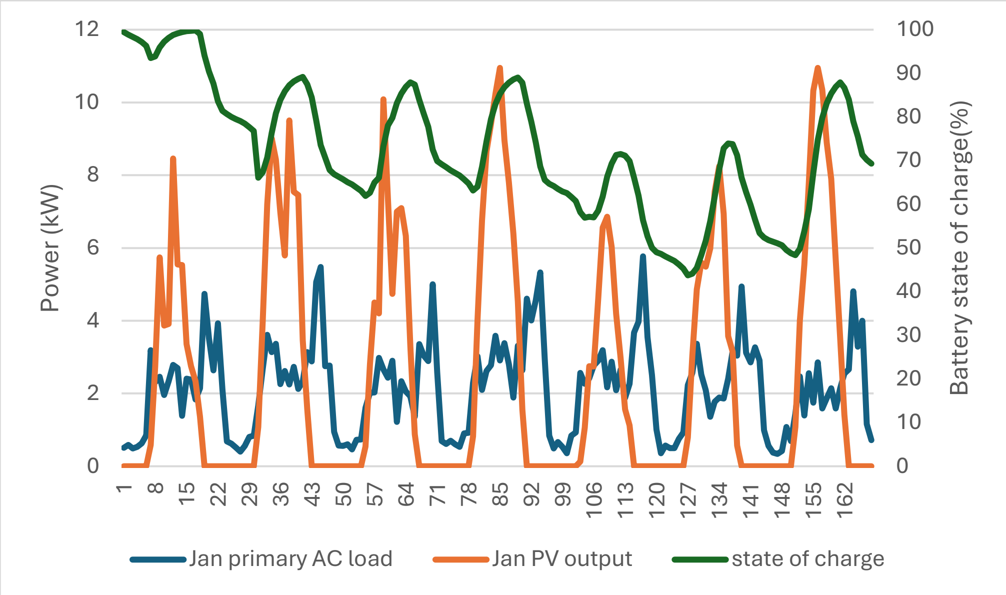

Figure 29: Scenario 2 January sample week production vs consumption.

A detailed hourly breakdown of a PV system's sample week in July is presented in Figure 30. The primary AC load ranges between 0.25 kW and 5.5 kW, with the highest PV output of10.79 kW. The battery's state of charge fluctuates in response to the balance between electricity demand and PV generation ranging between 60 and 99% operating mostly during the night as there is no PV production and recharge during the day when the PV output exceeds demand. The system appears well-sized for the demand and battery charging.

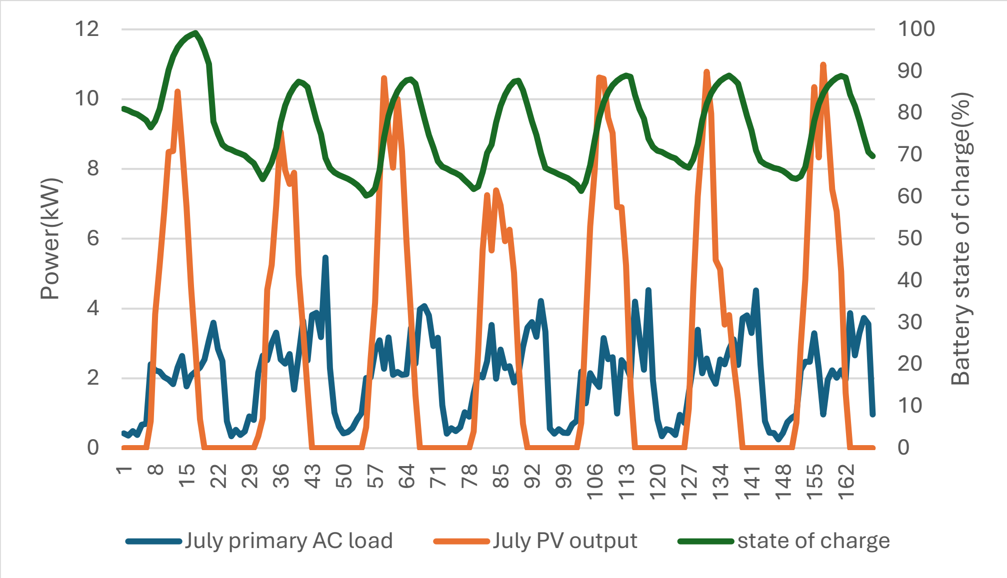

Figure 30: Scenario 2 July sample week production vs consumption.

4.3 System installation operation

The implementation or construction of any energy generation system requires further consideration for proper operation. The control room serves as the central hub for managing the electricity generation, battery storage, and distribution system. From the generation hub, electricity is distributed to poles using aluminum conductors steel reinforced cables, which offer a good balance of strength, conductivity, and cost-effectiveness. These cables connect to transformers on poles to step down voltage for residential use. House wiring then distributes electricity to individual homes, typically using copper wires due to their good conductivity. The connection includes the light bulbs and AC plug sockets for buildings. A critical component of this system is the implementation of smart meters at each connection point. Smart meters provide real-time data on electricity consumption, enabling more efficient grid management, accurate billing, and the ability for consumers to monitor and optimize their energy usage. They also facilitate the identification of outages or irregularities in the distribution system more quickly. The integration of smart metering is essential for creating a responsive, efficient, and future-proof electricity distribution network that can accommodate the growing of consumer demands [72].

4.4 Willingness and ability to pay.

The living income for a typical rural Rwandan family in 2023 is estimated at $268 per month[73][74] which provides a baseline for assessing willingness and ability to pay for electricity services. Rwanda's electricity tariff structure is arranged, with residential customers paying $0.068 /kWh for the first 15 kWh, $0.16/kWh for 15-50 kWh, and $0.19/kWh for consumption above 50 kWh. Non-residential customers pay $0.17/kWh for 0-100 kWh and $0.17/kWh for consumption above 100 kWh. The costs do not include the VAT and other regulatory fees which will change the cost significantly as shown from the Rwandan tariff study[75] as presented in Table 16. From the study one rural household in Rwanda consumes electricity which is not greater than 15KWh per month and spend approximately $1.01 per month and an additional $0.2 on dry cell batteries and phone charging, this total of $1.21 as presented in Table 17. However, the absence of data on willingness to pay for lighting and phone charging services indicates a need for further research.

Table 16: Monthly villages household electricity tariff

Description	kWh	USD
monthly energy spends per household	15	1.01
average monthly spend on dry cell batteries and monthly phone charging costs per household	3	0.2
What would you be willing to pay per month for lighting and phone charging in your house?	not found	not found

Table 17:Customer categories for residential and nonresidential in Rwanda

Categories	Consumption(kWh)	cost ($/kWh VAT& regulation fees excluded
Residential	0-15	0.068
	15-50	0.16
	>509	0.19
non residential	0-100	0.17
	>100	0.17

4.5 Note and assumptions for the results.

- For both case studies, the two best cases were discussed in details and the considered case was deeply discussed with sensitive analysis.

- The emissions are 0% (carbon dioxide, carbon monoxide, unburned hydrocarbon, particulate matter, sulfur dioxide, and nitrogen oxides) as renewable sources are the best and affordable combination for both villages.
- Homer Pro selects the best combinations that can meet the demands. That's why diesel generator was not considered in two best cases as it produces CO2 and has higher cost (LCOE, NPC, and capital cost) compared to other components.
- The selected battery seemed to be bigger for somedays as it is almost fully charged for the whole day, however in other days because of insufficient sunlight and/or wind the battery serves to balance the demand and supply and sometimes it discharges up to 5%.
- The load growth sensitivity is important for microgrid projects but because both villages' systems produce excess electricity that covers in terms of load demand growth.
- Distance and Material Costs: due to big distance between homes, the more materials are needed for installation. This includes longer lengths of wiring, piping, or other necessary infrastructure, which directly increases material costs

5 CONCLUSION

This project aimed to develop a comprehensive framework for designing, optimizing, and managing smart microgrids for isolated communities in Rwanda. The study has been accomplished through various analyses, simulations, and case studies. The conclusions drawn from this research are as follows:

- The case studies of Kadahokwa and Mashyoza villages demonstrated the feasibility and potential benefits of implementing microgrids in isolated Rwandan communities. Both villages showed significant results in energy access and cost-efficiency through the integration of renewable energy sources and energy storage systems.
- The optimization of microgrid configurations using HOMER Pro software presented that a combination of solar PV, wind turbines, and battery storage can provide reliable and cost-effective electricity supply in both rural and urban settings. The optimal system designs varied between the two villages.

- Economic analysis indicated that microgrids can offer substantial cost savings compared to traditional grid extension or diesel-based systems. The levelized cost of electricity (LCOE) for the optimized microgrid systems was found to be competitive with current electricity tariffs in Rwanda.

- For Kadahokwa village a 22kW PV array generating 33,700 kWh per year to cover the village's load demand for 65 houses, 2 shops, a school and a barber shop. The net present cost of the system is $55,730 and $0,122/kWh as the LCOE. For Mashyoza village a system combining 3kW wind turbine and 10.6 kW PV array generating 25,350 kWh for 60 households and 2 shops and a barber shop with the net present cost and LCOE of $33,045 and $0.109 respectively.

The integration of renewable energy sources in microgrids demonstrated significant environmental benefits, including reduced greenhouse gas emissions and decreased reliance on imported fossil fuels. This aligns with Rwanda's national goals for sustainable development and climate change mitigation.

Socio-economic analysis presented potential positive impacts of microgrid implementation, including improved access to education, healthcare, and economic opportunities in isolated communities. However, further research is needed to quantify these benefits more precisely.

While the project focused on two specific case studies, the developed framework and methodologies can be adapted and applied to other isolated communities in Rwanda, providing an approach to enhancing energy access across the country.

Due to time and resource constraints, long-term performance data and detailed economic impact assessments could not be obtained. Future studies should focus on gathering this data to validate the projected benefits and refine the microgrid design and management strategies.

Finally, the successful implementation of community microgrids in Rwanda will require supportive policies, regulatory frameworks, and capacity building initiatives. Further research and collaboration with policymakers and stakeholders are recommended to address these aspects and facilitate widespread adoption of microgrid solutions.

This study concludes that smart microgrids represent a viable and sustainable approach to addressing energy access challenges in Rwanda, with potential for significant positive impacts on isolated communities and the broader national energy landscape.

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