

Standalone Solar PV System Design for Household Energy Demand in Rural Rwanda

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Abstract: People all over the world need a lot of electricity. The increasing demand for energy necessitates the consideration of environmental protection. Some options have been tried, like using renewable energy. In some African countries, like Rwanda, peat, thermal, and hydro are still small-scale. Rwanda is a developing country, and energy is an important part of its economic growth. Because of the way the land is shaped, the grid connection costs less than what the Rwandan government planned for. The rural areas are the most affected because some of them have the means and still use old-fashioned methods that hurt the environment. One option is to use a photovoltaic system. This thesis centers on the design of a photovoltaic system, independent from the national grid, with a capacity of 0.8 kWh/day, intended for a household in Kayonza District, selected as the case study. This design's goal is to get more homes to use an off-grid solar power system. The first part of the design looked at how much electricity the household used, including the appliances. The second step in this design is to figure out how much all the parts will cost. This will get the homeowner involved in the design and costs of the system and make them feel like they own it.

Keywords: Renewable Energy; Photovoltaic System; Household Energy; Kayonza District; Electricity Demand; Energy Sustainability; Rural Electrification; Battery Sizing; Environmental Protection.

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1. Introduction

Rwanda is an underdeveloped country in which energy plays a central and indispensable role in economic growth, social progress, and national transformation, much like in many other African nations. Energy is widely recognised as a foundational input for development because it directly supports productivity, investment, innovation, and improvements in quality of life [1]. In Rwanda, however, the current energy supply remains insufficient to meet growing demand, and energy costs are relatively high [2]. These challenges pose significant constraints on sustainable development by limiting industrial expansion, discouraging private investment, and restricting access to essential services for households and businesses alike [3]. As the country continues to pursue ambitious development goals, addressing energy scarcity and affordability has become a critical national priority [4]. The importance of energy to Rwanda's development agenda is clearly articulated in national policy

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frameworks, particularly Rwanda's Vision 2020, which emphasises transforming the country into a middle-income economy through sustained economic growth, increased private-sector participation, enhanced citizen well-being, and structural economic transformation [5]. Achieving these objectives depends heavily on the availability of a reliable, affordable, and efficient energy supply [6]. Without adequate energy, progress in key sectors such as manufacturing, agriculture, education, health, and services would be severely constrained [7]. Recognising this, the Government of Rwanda has consistently highlighted energy access as both a driver and an indicator of economic development and social inclusion [8].

Energy access in Rwanda is not only an economic issue but also a social and developmental one [9]. Large segments of the population, particularly in rural areas, have historically lacked access to modern energy services [10]. This has forced many households to rely on traditional energy sources such as firewood and charcoal, which are inefficient, environmentally harmful, and detrimental to human health [11]. The continued dependence on biomass fuels contributes to deforestation, environmental degradation, and indoor air pollution, disproportionately affecting women and children [12]. Expanding access to modern energy, therefore, plays a vital role in improving living standards, promoting gender equity, protecting the environment, and supporting sustainable development [13]. In response to these challenges, the Government of Rwanda, in collaboration with the private sector and international development partners, has made significant efforts to expand both on-grid and off-grid electrification [14]. These initiatives reflect a strategic recognition that a single approach cannot adequately address the diverse geographic, economic, and social conditions across the country [15]. While grid expansion remains a priority in urban and peri-urban areas, off-grid solutions such as solar photovoltaic systems have emerged as practical and cost-effective alternatives for remote and rural communities where grid extension is technically difficult or economically unfeasible, given Rwanda's hilly terrain and dispersed settlement patterns [16]. Over the years, Rwanda has made notable progress in expanding electricity access, demonstrating that the government's priorities have yielded tangible results. Public investments, private-sector participation, and donor-supported programs have collectively contributed to expanding generation capacity, strengthening transmission and distribution infrastructure, and promoting decentralised energy solutions.

These achievements have laid a foundation for future projects aimed at further increasing energy access and ensuring that a larger proportion of the population can benefit from reliable electricity services. At the same time, the government continues to set ambitious targets to accelerate electrification and improve energy sector performance as part of its long-term development vision. Energy is fundamental to Rwanda's broader economic growth and development plans because it underpins the functioning and expansion of nearly all productive sectors. Housing electrification and urbanisation rely on stable electricity to support modern living standards and infrastructure development. Industrial processing and agro-processing depend on energy to add value to raw materials, increase productivity, and enhance competitiveness in regional and international markets. The mining sector requires power for extraction and processing activities. In contrast, the tourism sector depends on reliable energy to operate hotels, lodges, transportation services, and digital systems that enhance visitor experiences. Similarly, the growth of information and communication technology services, which are increasingly important to Rwanda's ambitions for a knowledge-based economy, is heavily reliant on an uninterrupted, high-quality energy supply. Given the cross-cutting importance of energy, the efficiency and growth of the energy sector serve as both a precondition and a measure of Rwanda's progress toward achieving its national development goals. Improvements in energy availability, reliability, and affordability directly translate into enhanced economic performance, increased employment opportunities, and improved social outcomes. Conversely, weaknesses in the energy sector can undermine progress in other areas, underscoring the need for integrated, forward-looking energy planning.

The Energy Sector Strategic Plan plays a crucial role in guiding Rwanda's energy development efforts. It serves as a comprehensive framework for translating national policy objectives into actionable programs and projects within the energy sector. The plan is designed to ensure alignment with the National Strategy for Transformation, which sets medium-term targets for economic growth, social development, and institutional strengthening. By providing a clear roadmap for implementation, monitoring, and evaluation, the Energy Sector Strategic Plan helps coordinate the efforts of government agencies, private investors, and development partners toward common goals. In addition, the Energy Sector Strategic Plan supports the effective implementation of the National Energy Policy by interpreting policy directives and principles into concrete measures that can be operationalised on the ground. This includes setting priorities for generation, transmission, distribution, and off-grid solutions, as well as addressing financing, regulation, capacity building, and risk management. The plan accounts for current resource constraints, potential risks, and uncertainties, enabling a more realistic and adaptive approach to energy sector development. One of the key strengths of Rwanda's energy strategy is its emphasis on diversification and sustainability. Recognising the limitations of relying on a narrow range of energy sources, the government has promoted the development of renewable energy sources, including hydropower, solar, methane gas, and peat. Renewable energy not only enhances energy security but also aligns with global and national commitments to environmental sustainability and climate change mitigation.

In particular, off-grid solar solutions have gained prominence as an effective way to expand access in rural areas while minimising environmental impacts. Despite the progress achieved, significant challenges remain. The cost of energy infrastructure development, limited financial resources, and technical capacity constraints continue to affect the pace and scale

of energy expansion. Ensuring affordability for low-income households while maintaining the financial viability of energy providers is an ongoing balancing act. Moreover, integrating off-grid and on-grid solutions into a coherent national energy system requires careful planning, coordination, and regulatory support.

Nevertheless, Rwanda's experience demonstrates that sustained political commitment, clear policy direction, and inclusive partnerships can drive meaningful progress in the energy sector. By positioning energy as a central pillar of development and integrating it into broader economic and social strategies, the country has laid a strong foundation for continued growth and transformation. As Rwanda moves forward, strengthening energy efficiency, expanding renewable energy adoption, and enhancing institutional capacity will be critical to ensuring that energy continues to support inclusive and sustainable development for all segments of the population. Energy remains a vital component of Rwanda's development trajectory, influencing economic growth, social well-being, and environmental sustainability. While challenges related to supply adequacy, cost, and access persist, the government's strategic focus on energy access, supported by comprehensive planning instruments such as the Energy Sector Strategic Plan, reflects a clear understanding of the sector's importance. Continued investment, innovation, and collaboration will be essential to building an energy system that meets the needs of a growing economy and population, ultimately contributing to the realisation of Rwanda's long-term national development aspirations.

1.1. Justification of Study

The study of domestic solar energy as a solution for non-connected rural areas in Kayonza District, Rwanda, is crucial for several key reasons. A large portion of rural populations lack reliable electricity, hindering economic growth and social development. Solar energy offers a sustainable alternative, addressing environmental degradation caused by reliance on firewood and fossil fuels. Additionally, it presents economic opportunities, reducing costs for households and businesses while improving educational and healthcare services. The Rwandan government's commitment to expanding energy access supports this initiative, and technological advancements have made solar energy more affordable. This study aligns with Rwanda's development goals, contributing to cleaner energy, social equity, and improved quality of life, with the potential for broader regional application.

1.2. Scope of Study

This study examines the potential of domestic solar energy as a sustainable solution to provide reliable electricity to rural areas in Kayonza District, Rwanda, where many communities lack access to the national power grid. It assesses the region's energy needs, current consumption patterns, and the challenges faced by households and businesses, while evaluating the feasibility of solar energy systems across technical, economic, and environmental factors. The study also explores the impact of solar energy on economic growth, education, healthcare, and environmental sustainability, and identifies barriers such as affordability and technical skills. Additionally, it considers how solar energy could align with Rwanda's national development goals and be scaled to other rural areas. The research aims to provide insights into the role of solar energy in addressing energy poverty and promoting sustainable development in rural Africa.

1.3. State of the Art

Recent advancements in domestic solar energy have made it a more accessible, efficient, and affordable solution for rural electrification, particularly in sub-Saharan Africa. Key developments include improved solar panel efficiency, energy storage solutions such as lithium-ion batteries, and scalable off-grid systems, such as solar home systems and mini-grids. Mobile technology has further enhanced accessibility through pay-as-you-go models, while government and private sector engagement has driven significant investments in solar infrastructure. Solar energy has demonstrated positive social impacts, improving education, healthcare, and economic development, while also reducing environmental harm. However, challenges such as high initial costs, gaps in technical expertise, and sustainability concerns persist, requiring ongoing efforts to ensure widespread adoption and long-term success.

2. Materials and Methods

2.1. Requirement Analysis and Materials

2.1.1. Research Requirements

In this section, a comprehensive analysis of the materials and requirements necessary for implementing domestic solar energy solutions in rural areas of Kayonza District, Rwanda, will be conducted. This will involve identifying the energy needs of rural communities, the technical and environmental requirements for solar energy systems, and the materials to be used for system installation and operation:

- **Energy Needs Assessment:** A thorough evaluation of electricity demand in Kayonza’s rural areas will be conducted to determine the required energy capacity for households, businesses, and community services (such as schools and health clinics). This analysis will consider average energy consumption, peak demand, the number of devices used (lighting, mobile phones, appliances), and the community’s energy priorities.
- **System Design Requirements:** Based on the energy needs assessment, the study will design a suitable solar energy system, including the type and size of solar panels, the required battery storage solutions, and the inverters. The design will aim for sustainability, ensuring that the system can handle varying weather conditions and provide sufficient power during periods of low sunlight (such as during the rainy season).
- **Materials Selection:** The materials required for the solar installations will include:
 - **Solar Panels:** High-efficiency photovoltaic (PV) panels, possibly incorporating newer technologies such as monocrystalline or perovskite cells to maximise energy output and minimise costs.
 - **Batteries:** Reliable and cost-effective energy storage solutions, such as lithium-ion or lead-acid batteries, to store solar energy for use during the night or cloudy days.
 - **Inverters:** Equipment to convert the DC electricity produced by the solar panels into AC power, suitable for household appliances and grid connection.
 - **Wiring and Mounting Structures:** Durable and weather-resistant materials for wiring the system and securely mounting solar panels in optimal locations for sunlight exposure.
 - **Monitoring and Control Devices:** Smart meters and controllers to monitor energy production and consumption, allowing users to manage energy usage efficiently.
- **Environmental and Technical Considerations:** Materials for the system will be selected based on durability, environmental sustainability, and resistance to local conditions, including high humidity, dust, and temperature fluctuations. Additionally, the installation process will require a trained workforce with the skills to set up and maintain these systems, ensuring long-term system performance and reliability.

By analysing these requirements and selecting appropriate materials, the study will ensure that the proposed solar energy solutions for Kayonza are both technically feasible and economically viable.

2.2. Research Design

The study design focused on domestic solar energy use in rural areas. Case study: Kayonza District – Rwanda is displayed in Table 1:

Table 1: Used methodology for the study

No.	Objectives	Hypotheses	Methodology	Statistics
1.	Assess the energy needs and consumption patterns in Kayonza District	Rural communities in Kayonza District have limited access to reliable electricity, affecting economic and social development.	Surveys and interviews with households and local businesses to gather data on energy use.	Descriptive statistics (mean, median, mode) for energy consumption data.
2.	Evaluate the feasibility of domestic solar energy systems	Solar energy is a viable alternative to grid-based electricity in Kayonza's rural areas.	Technical assessment of solar panel efficiency, battery storage capacity, and system suitability.	Comparison of costs vs. benefits (ROI analysis)
3.	Analyse the social and economic impacts of solar energy adoption	Solar energy adoption will improve the quality of life in rural Kayonza, including in health and education.	Social surveys to assess the impact of solar power on the quality of life.	Regression analysis to assess the correlation between solar adoption and socio-economic factors.
4.	Investigate government policies and support for renewable energy projects	The Rwandan government’s policies on renewable energy have positively influenced solar energy adoption in rural areas.	Review of government policies on energy access, renewable energy incentives, and solar energy projects.	Qualitative analysis of policy effectiveness and implementation.

3. Presentation of the Study Area

Kayonza District, located in Rwanda's Southern Province, serves as the focus of this study on the potential of domestic solar energy for rural electrification. The district is primarily rural, with limited access to the national power grid, and faces challenges such as energy poverty, reliance on biomass for cooking, and limited infrastructure in healthcare and education. Despite these obstacles, Kayonza benefits from favourable solar conditions, with high levels of solar radiation ideal for energy generation. The Rwandan government's commitment to renewable energy, including solar power, aligns with Kayonza's development goals. This study aims to evaluate the feasibility of implementing solar energy systems to improve the quality of life, support socio-economic development, and address energy access issues in the district.

4. Sampling Methods and Techniques

A stratified random sampling technique was employed to ensure a representative selection of households from various socioeconomic and geographic strata within Kayonza District. The district was first divided into strata based on administrative sectors, reflecting the different localities and varying levels of energy access. Then, households were randomly selected from each stratum to capture a broad spectrum of energy needs and constraints. This method allowed the study to account for variations in factors such as income levels, household size, and geographic location, ensuring that the findings accurately represented the diversity of the target population. By employing this approach, the study was able to gather data from households with differing energy challenges and opportunities, providing a more comprehensive understanding of the feasibility and potential for solar energy adoption across Kayonza.

4.1. Population of the Study

The study sample for key personnel in Kayonza District includes individuals directly involved in or knowledgeable about solar energy implementation. This includes local government officials responsible for policy and energy planning, energy providers and solar company experts, community leaders who understand the local social and cultural context, technicians skilled in solar system installation and maintenance, NGO representatives involved in rural electrification and renewable energy, and academics or researchers specialising in energy studies. The sample will encompass a diverse range of stakeholders to provide comprehensive insights into the challenges, opportunities, and practical aspects of adopting solar energy in the district. In the program evaluation, the population (100) is listed in Table 2.

Table 2: Research population

District leaders	Energy Providers	Community Leaders	Technicians	Total
20	40	20	20	100

4.2. Sampling Techniques

The sample size was calculated based on the total population of technicians in Kigali, with a 95% confidence level and a 5% margin of error. This combination of methods captured various perspectives and experiences, providing actionable insights into energy project management (Table 3).

Table 3: Sample of study

District leaders	Energy Providers	Community Leaders	Technicians	Project User
10	20	10	10	50

4.2.1. Sample Size

The sample size will be determined based on the overall population of project managers in Kigali. A minimum sample size of 50 participants will be targeted to provide a statistically significant basis for analysis. This sample was included approximately:

- 10 District leaders
- 20 Energy Providers
- 10 Community Leaders
- 10 Technicians

4.3. Criteria of Participants' Selection

The selection criteria for participants aim to ensure a diverse and relevant representation from key stakeholders involved in energy project management practices, particularly in the context of energy projects in Kayonza District. Project users, project managers, company owners, and construction professionals are selected based on their specific roles and expertise related to energy projects.

4.4. Data Collection Techniques and Instruments

The study employed both qualitative and quantitative methods, including surveys, interviews, and focus groups, to gather data on program awareness, accessibility, and the perceived effectiveness of an energy project manager.

4.4.1. Type of Data and Techniques of Data Collection

Table 4 shows the data type and the data collection techniques.

Table 4: The type of data and techniques of data collection

Activities	Techniques	Instruments
Survey	Questionnaires	Online surveys using Google Forms
	Interviews	Structured interviews
	Focus groups	Group discussions with predefined questions
Observation	Direct observation	Observing participants' interactions with the system
	Video recording	Recording driving sessions to analyse behaviour
	Field notes	Written notes on observed behaviours and system usage
Data Analytics	Data mining	Analysing large datasets to identify patterns and trends
	Statistical analysis	Applying statistical tests to quantify system performance
	Machine learning algorithms	Developing predictive models based on historical data
Interviews with Experts	Expert consultation	Interviewing engineers, designers, or policymakers
	Stakeholder interviews	Engaging with stakeholders to gather insights

4.4.2. Data Collection Method

The study's data were collected through two main methods: household surveys and interviews. Household surveys involved administering structured questionnaires to collect data on key factors, including current energy consumption patterns, awareness of solar energy solutions, and residents' willingness and ability to invest in solar systems. These surveys provided quantitative insights into the community's energy needs and preferences. In addition, semi-structured interviews were conducted with a range of stakeholders, including local government officials, energy providers, and community leaders.

4.4.3. Data Collection Instruments

The study's data were collected using two primary instruments: household surveys and semi-structured interviews. The household surveys involved administering structured questionnaires to collect quantitative data on factors such as energy consumption patterns, awareness of solar energy options, and residents' willingness and financial ability to invest in solar systems. These surveys helped assess the community's energy needs and preferences. Additionally, semi-structured interviews were conducted with key stakeholders, including local government officials, energy providers, and community leaders. These interviews provided qualitative insights into the challenges, opportunities, and perspectives on solar energy adoption from those directly involved in the energy sector and local development efforts.

4.4.4. Administration of Data Collection Instruments

The data collection instruments in the study were self-administered by the researcher. A questionnaire and an interview guide were used as research instruments for this paper. The instruments were administered to the respective respondents by the researcher herself. There were two categories of instruments: questionnaires and interview guides. The questionnaire helped collect quantitative data, while the interview guide helped collect qualitative data.

4.4.5. Data Collection Instruments

The study on the potential of domestic solar energy in Kayonza District, Rwanda, utilised two primary data collection instruments: household surveys and semi-structured interviews. The household surveys, using structured questionnaires, collected quantitative data on energy consumption patterns, solar energy awareness, attitudes toward renewable energy, and residents' willingness to invest in solar solutions. These surveys provided numerical insights into the local population's energy needs and financial capacities. In addition, semi-structured interviews with key stakeholders, such as local government officials, energy providers, community leaders, and NGOs, allowed for open-ended questions to explore the challenges, opportunities, and policies surrounding solar energy adoption. Together, these instruments provided a comprehensive mix of quantitative and qualitative data, offering valuable insights into the feasibility of solar energy in rural Kayonza District.

4.4.6. Data Analysis Techniques

The data analysis for this study on the potential of domestic solar energy in Kayonza District, Rwanda, employs both quantitative and qualitative techniques to provide a comprehensive understanding of the findings. Quantitative data from household surveys will be analysed using descriptive statistics to summarise key factors, such as energy consumption and solar energy awareness, as well as frequency distributions and cross-tabulations to identify patterns and relationships among variables. Statistical software such as SPSS or Excel will be used for efficient data processing. Qualitative data from semi-structured interviews will be analysed using thematic analysis, including coding, categorisation, and interpretation of key themes related to challenges, opportunities, and perceptions of solar energy adoption. By combining both approaches, the study will offer a well-rounded perspective on the factors influencing solar energy adoption and provide valuable insights for future interventions.

5. Results and Discussion

Interviews with key stakeholders, including local government officials, energy providers, and community leaders, highlighted the potential of solar energy to address energy access challenges in Kayonza District and identified critical factors for successful adoption. Stakeholders emphasised the need for effective policy support, market development, and community engagement. Government incentives, such as subsidies and tax breaks, are vital to overcoming the high upfront costs of solar systems and to encourage both private investment and consumer adoption. However, a lack of local suppliers and service providers was seen as a major barrier, requiring strengthened distribution networks and technician training. Community outreach and education are also essential for building trust, increasing understanding, and promoting long-term adoption.

5.1. Strength

The study's mixed-methods approach, combining both quantitative and qualitative data analysis, provides a comprehensive understanding of the potential for domestic solar energy in Kayonza District. By utilising structured household surveys, the study captures valuable numerical data on energy consumption patterns, awareness, and willingness to invest in solar energy. This allows for objective, data-driven insights into the energy needs and preferences of the population. The semi-structured interviews, on the other hand, provide deeper insights into the local context by allowing stakeholders to share their perspectives on the challenges and opportunities for solar energy adoption. This holistic approach enables the study to address both the technical and social dimensions of solar energy implementation, ensuring that the findings are well-rounded and applicable to real-world solutions.

5.2. Limitations

Despite its strengths, the study has several limitations. First, reliance on self-reported data from household surveys could introduce bias, as respondents may provide socially desirable responses regarding their knowledge or willingness to invest in solar energy. Additionally, while semi-structured interviews offer in-depth qualitative data, they may not fully represent the views of all community members, as the sample size of key stakeholders is limited. Another limitation is the potential for data collection challenges in Kayonza District, given its rural nature, where access to certain areas may be difficult, potentially affecting data completeness and accuracy. Furthermore, the findings are specific to Kayonza District and may not be fully generalizable to other rural regions of Rwanda or sub-Saharan Africa.

6. Conclusion and Recommendations

Many rural settlements in Kayonza District, Rwanda, still lack reliable electricity. Solar energy is a very promising way to help people meet their energy needs. Limited access to grid power affects everyday life, schools, health care, and businesses. Because Kayonza gets a lot of sunlight and Rwanda has a good environment, solar energy is a clean, long-lasting, and useful alternative

to traditional energy sources. The price of solar technology has fallen significantly in the last few years, making it easier to get than ever before. Even though this is possible, not many people in the district use solar energy. The high initial cost of solar systems is one of the biggest problems, as many rural families can't afford them. Also, insufficient local infrastructure, such as restricted distribution networks and a lack of experienced technicians, makes it hard to install, maintain, and keep things going for a long time. People are less likely to adopt new technologies when they don't know about them or can't access finance, especially in areas that aren't connected to the grid.

To get the most out of solar energy in Kayonza District, we need policies that are focused and include everyone. Government-run subsidies, microloans, and pay-as-you-go financing options can help low-income families pay less. These solutions let people get solar panels with little or no money up front and pay for them over time. Building local capacity, creating jobs, and ensuring systems always work will also come from strengthening local supply chains and investing in technical training programs. Also, working with the government, private firms, and non-governmental groups can be very important for expanding solar solutions. Working together like this may improve services, reach more people, and encourage new ideas. This research shows that solar energy is a practical and useful option for rural areas without grid connection. To make it easier for everyone to access energy in an environmentally friendly, sustainable way, we need to work together to remove financial, technological, and institutional hurdles. In the end, using more solar energy in Kayonza District could improve living conditions, boost the economy, and help Rwanda reach its energy and climate goals.

List of abbreviations

- **GOR:** Government of Rwanda
- **KM:** Kilometre
- **MW:** Megawatt
- **SQ:** Square
- **M2:** Meter square
- **AGM:** Absorb Glass Mat
- **AC:** Alternating current
- **DC:** Direct current
- **MINIFRA:** Ministry of Infrastructure
- **PVs:** Standalone Solar Photovoltaic
- **RMB:** Rwanda Mining & Gas Board
- **ESMAP:** Energy Sector Management Assistance Program
- **NGOs:** Non-Governmental Organisations
- **STC:** Standard Test Condition
- **MM:** Millimetre
- **GW:** Gig watt
- **KWP:** Kilowatt peak
- **KWH:** kilowatt-hour

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