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Research Article

Viability assessment of renewable energy potential for sustainable rural electrification in Bushenyi District, Uganda

Richard Kizza, *Val Hyginus Udoka Eze, Abubakar Abdulkarim, Kelechi John Ukagwu

Department of Electrical, Telecommunication and Computer Engineering, School of Engineering and Applied Sciences, Kampala International University, Western Campus, Kampala, Uganda
richard.kiiza@studwc.kiu.ac.ug , udoka.eze@kiu.ac.ug, aabdulkarim@kiu.ac.ug,ukagwu.john@kiu.ac.ug

**Corresponding Author: Val Hyginus Udoka Eze, ezehyginusudoka@gmail.com, udoka.eze@kiu.ac.ug, Kampala International University, Western Campus, Ishaka, Uganda (ORCID: 0000-0002-6764-1721)*

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Abstract

This research investigates the viability of solar and wind energy to sustainably address rural energy demands in the Bushenyi District, Uganda. As renewable energy adoption accelerates globally, rural settings present unique challenges and promising opportunities influenced by resource variability, infrastructure limitations, and distinct energy requirements. This research synthesizes assessments of local solar and wind potentials, employing climatic data to guide optimal system designs tailored to peak and average load demands. Mitigating intermittency through energy storage and hybrid system integration, along with modular, scalable configurations, emerges as crucial for enhancing cost-effectiveness, environmental sustainability, and operational reliability. Furthermore, the research examines the socioeconomic benefits of renewable energy access in rural communities, underscoring its capacity to drive economic development, improve access to public services, and strengthen energy resilience. Findings indicate that, with strategic planning and policy backing, renewable energy systems can become a reliable, sustainable solution for off-grid regions, advancing both local empowerment and Uganda's national energy goals.

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1.0 Introduction

Renewable energy originates from resources that naturally replenish, including solar, wind, hydropower, biomass, and geothermal energy. These sources offer a sustainable alternative to fossil fuels, which are not only finite but are also a major cause of environmental degradation and greenhouse gas emissions [1]. As the global energy demand continues to escalate, renewable energy has emerged as a critical solution to balance environmental sustainability with energy security. The recent, rapid adoption of renewable technologies is driven by notable advancements in photovoltaic efficiency, wind turbine design, and bioenergy systems, leading to declining costs and heightened feasibility. These technological improvements, coupled with an increased awareness of climate change, have made renewables more attractive to both private and public sectors. Governments and international organizations are supporting renewable energy transitions through subsidies, policy incentives, and strategic frameworks designed to mitigate carbon emissions and enhance energy security [2]. However, the widespread integration of renewables into energy systems poses significant challenges. The variability of solar and wind energy sources known as intermittency necessitates the development of robust energy storage solutions to ensure a consistent energy supply. Furthermore, the deployment of renewable energy technologies often involves substantial initial capital investment and requires navigating complex policy and regulatory landscapes. Despite these challenges, transitioning to renewable energy is essential for achieving long-term sustainable development goals, reducing the environmental footprint of energy generation, and promoting global resilience against climate change. The global shift toward renewable energy not only addresses pressing ecological concerns but also has the potential to drive economic growth, energy independence, and technological innovation, creating a foundation for a more resilient energy future.

2.0 Methodology

This research synthesizes literature from peer-reviewed journals, government reports, and case studies on renewable energy systems, with a focus on solar and wind energy potential assessments, load demand analysis, and hybrid renewable energy system (HRES) design in rural settings, particularly Bushenyi District, Uganda. The literature search was conducted using IEEE, Scopus, Web of Science, ResearchGate, and Google Scholar databases. Keywords included "renewable energy systems," "solar energy potential," "wind energy potential," "load demand analysis," "hybrid energy systems," and "rural energy solutions." A total of 94 articles were identified that met the inclusion criteria based on their relevance to the study objectives. This research systematically analyzes solar and wind resource assessments, load characteristics (peak, average, and variable loads), energy storage solutions, and hybrid configurations. Additionally, case studies and simulation results are incorporated to evaluate strategies that enhance the performance, scalability, and sustainability of renewable energy systems in off-grid rural regions. A critical analysis of the findings highlights practical considerations, potential challenges, and the effectiveness of hybrid configurations in meeting the unique energy needs of rural communities. Furthermore, a qualitative assessment of policy frameworks, economic factors, and technical challenges influencing renewable energy deployment in Uganda was conducted. These findings were synthesized and interpreted to offer insights into the feasibility, resilience, and long-term viability of implementing renewable energy solutions in Bushenyi District.

3. Energy Potentials and Load Characteristics of Renewable Energy

Renewable energy potentials represent the capacity of natural resources like solar, wind, hydro, geothermal, and biomass to generate energy, influenced by factors such as geographic location, climate, and resource availability. Solar potential depends on sunlight, while wind potential is determined by wind speed and consistency. Load characteristics describe how renewable energy systems meet demand, including peak, base, and variable loads. Since renewable sources often fluctuate (e.g., solar depends on daylight), understanding load characteristics is essential for optimizing energy storage, grid stability, and ensuring a reliable supply. Efficient use of these potentials is key to sustainable energy development.

3.1 Solar Energy Potential

Evaluating the solar energy potential in Bushenyi District involves analyzing key climatic factors like solar irradiance, temperature, and sunlight duration. Solar irradiance, or the amount of solar power received per unit area, is vital to understanding the energy that can be harnessed. Given Bushenyi's proximity to the equator, the district likely benefits from consistent levels of sunlight throughout the year, making it a favorable location for solar energy projects [3]. Another important factor is temperature; while high solar irradiance is advantageous, elevated temperatures can decrease the efficiency of photovoltaic (PV) systems, thus requiring considerations for cooling mechanisms or panel selection. Humidity, which is also prevalent in the region, can cause moisture accumulation on solar panels, potentially impacting long-term performance [4,5,6]. Additionally, understanding the duration of daily sunlight is necessary to predict the overall energy output from solar installations, as longer periods of sunshine equate to more energy generation, making solar energy a strong candidate for renewable energy solutions in the district, as shown in Figure 1.

Figure 1: Typical Image of a Solar Panel [3]

3.2 Wind Energy Potential

Wind energy potential in Bushenyi District can be assessed by examining the district's wind speeds, directions, and air stability. Wind speed is a fundamental factor for power generation, with most turbines needing speeds of 4-5 m/s or higher to operate effectively. The height at which wind speed is measured also plays a role; winds at higher altitudes tend to be stronger, suggesting the importance of selecting the right elevation for wind turbines [7]. Wind direction is another crucial factor, as it affects the positioning and orientation of turbines to maximize energy capture. An in-depth analysis of prevailing wind patterns is essential for optimizing turbine placement [8]. Furthermore, turbulence in wind flow can lead to inefficiencies and wear on turbine components; thus, understanding both the stability and consistency of wind patterns over time will help determine the feasibility of wind energy in Bushenyi. Stable, strong winds are ideal for continuous energy generation, assessing wind conditions critical in gauging the potential for wind power development. Figure 2 is the typical diagram of a wind turbine and its components well labelled.

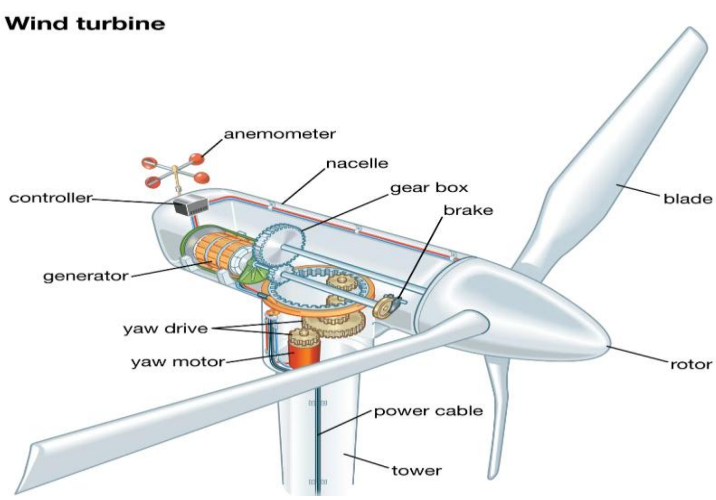

Figure 2: A Typical Image of Wind Turbine [8]

3.3 Load Characteristics Analysis of Renewable Energy

A comprehensive load characteristics analysis is essential for aligning renewable energy potential with its actual energy demands. This process involves examining the fluctuations in energy consumption both daily and seasonally, especially since agriculture is the dominant economic activity in the region. During peak agricultural periods, such as planting and harvesting seasons, energy demand tends to spike, requiring a robust power system capable of accommodating these variations. Furthermore, a critical assessment of the current grid infrastructure is necessary to evaluate its capacity to integrate renewable energy sources like solar and wind. If the grid is outdated or has limited capacity, additional measures such as energy storage systems or backup generators may be needed to maintain stability, particularly during periods of low solar irradiance or weak wind conditions [9] Understanding the district's specific energy consumption patterns, including how they vary over time, is vital for designing renewable energy systems that can efficiently meet both peak and base load demands [10]. This ensures a stable, reliable, and sustainable energy supply for the region. Additionally, a detailed climatic data analysis, combined with an evaluation of energy load characteristics, will provide a more accurate assessment of Bushenyi District's renewable energy potential. This holistic approach will guide the development of infrastructure capable of supporting renewable energy projects, ensuring they are feasible and tailored to the district's unique energy needs.

3.4 Optimal Site Selection for Solar Panels and Wind Turbines Based on Energy Potential and Water Demand Distribution

This process involves analyzing the geographic and environmental factors that influence energy generation and considering water demand distribution, which can affect energy requirements. For solar panels, the primary factor in selecting optimal locations is solar irradiance**,** which is influenced by geographic latitude, altitude, and shading. Figure 3 shows the instruments used in measuring the optimal location of the solar station. Areas with high solar irradiance and low levels of obstruction, such as mountains or tall buildings, are ideal for solar panel installations. Temperature is also another important factor to be considered when sitting in a solar station as temperature affects the solar panel performance [11, 12]. In Bushenyi District, flat or slightly elevated areas that receive consistent sunlight throughout the year would be preferable for sitting solar stations. In areas with high water demand, such as irrigation fields or water treatment plants, solar energy can be used to power pumps and other water-related infrastructure.

Figure 3: Solar PV Optimal Locations Instruments [13]

Furthermore, wind speed and wind direction must be considered when identifying the best locations for the installation of wind turbines as illustrated in Figure 4. Wind turbines perform optimally in regions where the wind speed is consistently high and stable, typically in open, elevated areas such as hills or ridges [11, 12]. In Bushenyi, identifying such regions through wind mapping will help pinpoint ideal turbine sites. Additionally, selecting locations away from densely populated areas will minimize noise and visual impact, while positioning turbines near high-demand areas, such as industrial zones or agricultural regions, will reduce transmission costs. Wind energy could be particularly valuable in areas with fluctuating water demand, where turbines can provide supplemental energy for water pumping and distribution systems.

Figure 4: Wind Turbine Optimal Locations Instruments [14]

3.5. Analysis of Energy Demand Profiles in Rural Areas

Energy demand in rural areas is shaped by several interrelated factors, such as economic activities, lifestyle patterns, infrastructure availability, and access to modern energy sources [15]. Unlike urban centres, where energy consumption is largely driven by industrial and commercial sectors, rural energy demand is typically aligned with agricultural practices, household consumption, and limited access to the national power grid [16]. In many rural settings, agriculture dominates energy use, with demand peaking during critical periods like planting, harvesting, and post-harvest processing [17]. Energy is required for irrigation, water pumping, food refrigeration, and operating agricultural machinery. Irrigation, in particular, plays a crucial role in water-scarce regions, often necessitating substantial energy inputs for effective crop production [18]. These agricultural energy demands are heavily influenced by seasonal cycles, with spikes in energy consumption during planting and harvesting seasons, followed by a decline during off-peak agricultural periods [15].

Household energy consumption in rural areas tends to focus on basic needs such as lighting, cooking, heating, and powering small appliances [19]. However, due to the limited reach of grid electricity in these areas, many households continue to rely on traditional fuels such as firewood, charcoal, and kerosene [20]. This reliance on traditional energy sources not only hinders development but also exacerbates health and environmental concerns. Nevertheless, the introduction of decentralized renewable energy solutions, such as solar home systems or microgrids, has significantly improved living conditions in rural areas by providing clean and reliable energy [20]. Energy demand in rural communities is further influenced by social and community infrastructure. Institutions like schools, health centers, and local markets require reliable energy for lighting, water pumping, refrigeration of medicines, and powering educational tools [19]. As a result, access to modern energy in these areas is vital for enhancing the quality of life and fostering rural development [16]. Figure 5 is a typical rural village setting without grid-connected electricity [21].

Figure 5: Traditional Isolated Rural African Village Homestead [21]

Water supply systems also contribute significantly to rural energy demand. In regions with limited water availability, energy is essential for pumping, treating, and distributing water [17]. Solar-powered pumps and small wind turbines offer sustainable energy solutions that address these needs, reducing reliance on fossil fuels and minimizing operational costs [15]. One of the most persistent challenges in rural areas is the limited access to national grid electricity, resulting in a dependence on off-grid renewable energy systems such as solar home systems, mini-grids, and standalone systems [22]. These off-grid solutions are crucial for meeting rural energy needs, even though energy demand is generally lower than in urban settings [23]. Moreover, the intermittent nature of rural energy demand, particularly in agriculture-dependent regions, poses a challenge for energy providers due to fluctuations based on seasonal agricultural activities [24]. Affordability remains a significant barrier, as rural households often lack the financial resources to invest in modern energy systems, and the dispersed nature of rural populations makes grid expansion more difficult and costly [18].

Despite these obstacles, rural areas have strong potential for renewable energy integration. Solar, wind, and biomass energy offer flexible, scalable, and sustainable solutions that align with the specific energy needs of rural communities [22]. Solar-powered irrigation systems, for example, can help meet peak energy needs during dry seasons, while wind energy can be harnessed in regions with favorable wind patterns [18]. The deployment of these renewable off-grid systems is already improving rural electrification, enhancing quality of life, and supporting sustainable development [16]. In conclusion, understanding the unique energy demand profiles of rural areas is essential for designing effective and sustainable energy systems. These systems must address the specific needs of rural communities while ensuring long-term viability, affordability, and scalability to support their development [22].

3. 6 Electrical Loads

In designing renewable energy systems, it's important to differentiate between constant vs. variable loads and critical vs. non-critical loads [25]. This analysis will guide the designer in designing a suitable renewable energy system as detailed below:

1. Constant Load vs. Variable Loads

Constant Loads require a steady, continuous power supply. Examples include refrigeration units and industrial machinery that run consistently throughout the day. Renewable energy systems for constant loads focus on reliable, stable power generation, often reducing the need for large energy storage or backup systems since the demand is predictable. Whereas, Variable Loads, on the other hand, fluctuate depending on usage patterns or external factors. Examples include lighting systems and household appliances, which have intermittent power needs. These fluctuations can strain the energy system, especially during peak usage. To manage variable loads, renewable energy systems are often paired with storage solutions like batteries or hybrid systems to ensure a steady power supply during demand fluctuations [26].

2. Critical vs. Non-Critical Loads

Critical Loads are essential systems, such as medical equipment or emergency communications, that require uninterrupted power. Renewable energy systems for critical loads emphasize high reliability and redundancy, often combining renewable sources with backup systems (e.g., diesel generators) and enhanced storage capacity to prevent power disruptions whereas Non-Critical Loads, such as lighting or entertainment devices, are less essential and more flexible in energy management. These loads can be reduced or turned off during periods of peak demand or when renewable supply is low, allowing for more efficient system design and reducing the need for oversized or costly storage solutions. Furthermore, understanding these distinctions helps optimize renewable energy systems to meet both the predictable and fluctuating energy needs of various applications [27].

3.6.1 Electrical Load Profiles

A load profile is a graphical or data representation of the variation in electrical power consumption by a specific user, group of users, or region over a period of time, typically over a day, week, or year. It shows how energy demand fluctuates during different times of the day or across seasons, highlighting peak demand periods and periods of lower energy use. The two main load profiles are the daily and seasonal load profiles.

1. Daily Load Profiles

Renewable energy systems, particularly solar photovoltaic (PV) systems, generate energy primarily during daylight hours. Consequently, the energy production pattern does not always align with the demand patterns of a typical daily load profile. If a system's daily load profile indicates higher energy demand during times when generation is low (e.g., nighttime), implementing storage solutions becomes crucial. Batteries or other energy storage systems can store excess energy generated during peak sunlight hours for use during periods of high demand. Alternatively, load-shifting strategies can be employed to better align energy consumption with production. By adjusting energy usage patterns to coincide with peak generation times, such as running energy-intensive appliances during the day when solar generation is highest, the reliance on storage can be minimized [28]. This approach optimizes the use of generated energy and reduces the need for large-scale storage systems.

2. Seasonal Load Variations

Energy demand often fluctuates with the seasons, such as increased cooling needs in summer and heating needs in winter. Renewable energy systems must be designed to accommodate these seasonal variations to maintain efficiency and reliability. For instance, a solar PV system in a region experiencing cold winters might generate less energy due to reduced sunlight hours and lower solar intensity. To address these seasonal changes, it may be necessary to incorporate complementary energy sources. Wind power, for example, might be more effective during winter months when solar energy is less abundant. Designing the system to integrate multiple renewable sources or include additional storage capacity can help ensure that energy needs are met throughout the year [29]. Systems should be sized appropriately to handle seasonal spikes in demand while maintaining overall operational efficiency.

3.6.2 Load Demand Magnitude

Peak Load Demand represents the maximum level of electrical demand within a system at any given time. While designing renewable energy systems to meet peak demand is essential to prevent outages during high-demand periods, focusing exclusively on peak loads can lead to oversized, inefficient, and costly systems. To avoid this, demand response strategies such as reducing non-essential loads during peak times or utilizing smart grid technologies that adjust energy generation in real-time can help manage peak demand efficiently, minimizing the need for oversized systems while maintaining reliability. In contrast, Average Load Demand reflects typical daily energy consumption and provides a more accurate foundation for system design. Optimizing renewable energy systems to meet average demand ensures efficiency during regular conditions, with backup or storage solutions reserved for peak demand periods. This approach strikes a balance between cost-efficiency and reliability, ensuring that the system meets both everyday energy needs and occasional peak loads without unnecessary overcapacity, thus enhancing the system's sustainability and affordability [30].

3.6.3 Load Factor

Load factor is a measure of how consistent a system's electrical demand is over time and it is calculated as the ratio of the average load to the peak load, as shown in equation (1)

$$Load\ factor = \frac{Average\ load}{Peak\ load} \quad (1)$$

A high load factor indicates that the demand is relatively stable and consistent throughout the period of analysis. This results in more predictable and stable system performance. Systems with high load factors benefit from simpler designs, often requiring less energy storage and fewer backup solutions. This is because the consistent demand minimizes the risk of energy shortfalls and reduces the need for oversized equipment [31]. Conversely, a low load factor reflects significant fluctuations between peak and average demand. Such variability necessitates additional design considerations, including energy storage solutions or hybrid systems. Energy storage helps smooth out these fluctuations by storing excess energy during periods of lower demand and supplying it during peak times. Hybrid systems, which combine multiple energy sources (e.g., solar and diesel), provide flexibility and ensure reliable operation despite demand variability. Addressing a low load factor is crucial to prevent energy wastage and avoid overloading the system [32].

3.6.4 Power Quality and Reliability

Power quality and reliability are critical factors in the effective and efficient operation of renewable energy systems. Ensuring high power quality helps maintain system stability, reduce losses, and protect sensitive equipment. Two fundamental parameters that influence power quality are **power factor** and **voltage sensitivity**. A low power factor indicates inefficient utilization of electrical power, while high voltage sensitivity can lead to instability in load performance and increased system stress. These parameters directly affect the continuity and stability of power supply, particularly in systems with variable generation such as solar and wind. **Figure 6** illustrates the I-grid power system and the root mean square (RMS) voltage profile, providing insights into system voltage behavior under different load and generation conditions [33].

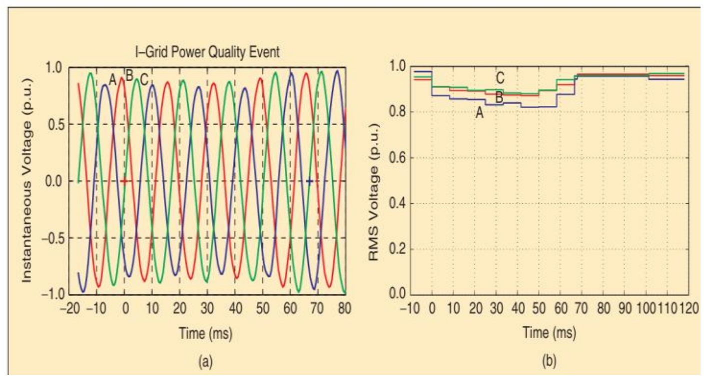

Figure 6: Diagram of the I-grid power system and the RMS Voltage of the Renewable Energy system

1. Power Factor is a measure of how efficiently electrical power is utilized within a system. A low power factor signals inefficiencies, leading to higher energy losses and greater demand for power generation. This can strain both conventional and renewable energy systems. To address this, power factor correction equipment, such as capacitors, can be integrated into the system design. These devices reduce energy losses by improving the power factor, enabling more efficient use of renewable energy sources, and optimizing overall system performance [33].

2. Voltage Sensitivity is particularly important for protecting sensitive electronic equipment, which can be affected by voltage fluctuations. In renewable energy systems, such as those powered by solar or wind, voltage fluctuations may occur more frequently due to the intermittent nature of energy generation. To mitigate these fluctuations, it is essential to incorporate voltage regulators or advanced inverters that stabilize voltage levels [33,34,35]. These components ensure that voltage remains within acceptable ranges, thereby protecting sensitive equipment and maintaining consistent power quality across the system.

3.6.5. Intermittency and Load Matching

Intermittency and Load Matching are critical challenges in renewable energy systems, as energy generation from sources like solar and wind depends on fluctuating environmental conditions. This variability makes it difficult to align energy supply with demand. To address these challenges, two primary strategies can be employed and Figure 7 illustrates the typical intermittency challenges and load matching in renewable energy.

1. Energy Storage Technologies: Systems like batteries and thermal storage capture excess energy generated during low-demand periods and release it when demand is higher. This helps balance supply and demand by ensuring that stored energy is available during periods of low generation, improving the overall efficiency and reliability of the system.

2. Hybrid Systems: By integrating multiple energy sources, such as solar, wind, and conventional power, hybrid systems increase reliability. These systems offset the variability of renewable sources with the consistent output of traditional energy, creating a more stable and dependable energy supply. These strategies are essential for managing the intermittency of renewable energy systems, ensuring a more consistent match between energy supply and demand, and enhancing system performance.

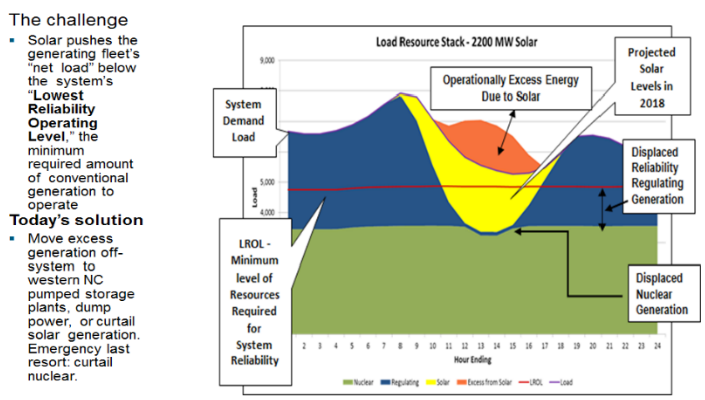

Figure 7: Intermittency Challenges

3.6.6 Grid-Tied vs. Off-Grid Systems

These refer to two distinct approaches in renewable energy system design, each offering different benefits and applications as discussed below:

1. Grid-tied systems are connected to the main electricity grid, allowing users to draw power from the grid when their renewable energy sources, such as solar or wind, cannot meet demand. These systems offer flexibility and reliability by enabling surplus energy to be sold back to the grid, improving cost efficiency while maintaining access to conventional power when needed. The connection and diagram of the on-grid system is shown in Figure 8

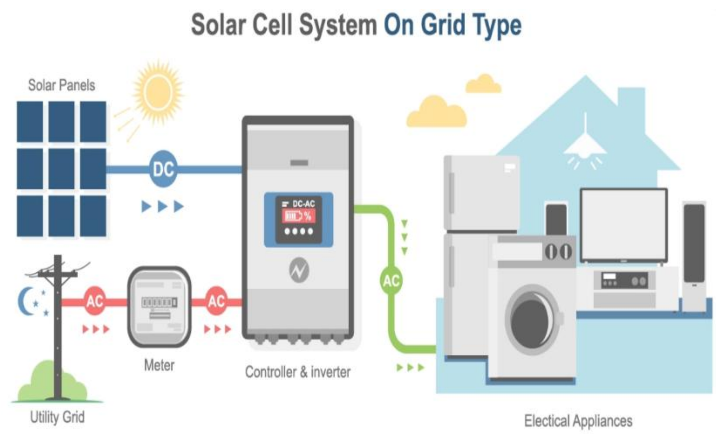

Figure 8: On-Grid Solar System

2. Off-grid systems operate independently from the grid, relying solely on renewable energy and storage solutions like batteries to provide power. These systems are ideal for remote locations with no grid access, offering complete energy autonomy. However, they require careful design to ensure consistent power availability, especially during periods of low energy generation. Figure 9 is the diagram of the on-grid solar system.

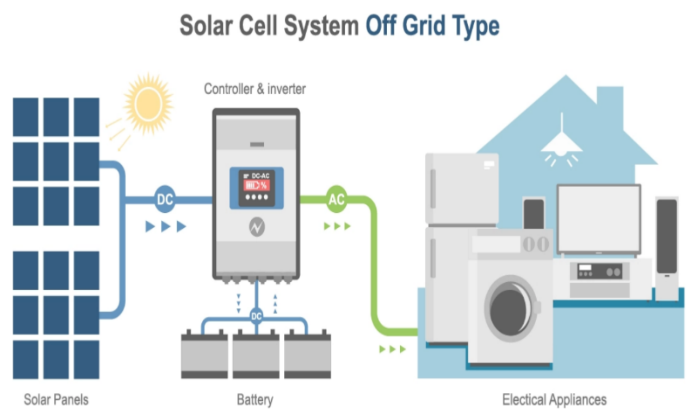

Figure 9: Off-Grid Solar System

3.7 Energy Demand and Load Characteristics in Uganda

Uganda's energy sector has historically relied on biomass, which still constitutes over 90% of total energy consumption, mostly in the form of firewood and charcoal used for cooking and heating. The remaining share is distributed between electricity, petroleum, and renewable energy sources such as solar and hydroelectricity. Despite efforts to increase electrification, especially in urban areas, rural areas remain underserved, with limited or no access to reliable electricity. This disparity is driven by challenges related to infrastructure development, high capital investment costs, and the technical difficulties of extending the national grid into remote regions. Off-grid solutions, particularly solar home systems, have emerged as an alternative but remain underutilized due to affordability and logistical challenges.

3.7.1 Energy Demand in Rural Uganda

Studies from the early 2000s show that energy demand in rural Uganda is primarily driven by domestic and agricultural activities. In households, the most common energy needs are cooking, lighting, and mobile phone charging. However, the high cost and limited availability of electricity make it difficult for rural populations to access modern energy solutions. As a result, most households rely heavily on biomass, such as firewood and charcoal, which are readily available and more affordable than grid electricity or off-grid alternatives like solar. Electricity use in rural areas remains minimal, largely restricted to basic lighting, primarily due to the high cost of appliances and the inconsistent supply of power. Even when electricity is available, the upfront costs of connecting to the grid are often prohibitively high for rural households. Combined with their low purchasing power these factors create significant barriers to electrification, limiting the adoption of modern energy technologies and perpetuating reliance on traditional energy sources. These studies highlight the critical need for affordable, accessible energy solutions to address the growing demand for electricity in rural Uganda, particularly in ways that can bridge the gap between economic constraints and energy access.

3.7.2 Load Characteristics in Rural Uganda

Energy consumption in rural Uganda exhibits distinct seasonal patterns, influenced primarily by agricultural cycles and domestic activities. For instance, during the harvesting season, there is a notable increase in energy demand as households require more energy for crop processing, food preservation, and irrigation. Conversely, in the off-season, when agricultural activities decline, energy demand tends to decrease. Despite these fluctuations, the limited access to electricity means that a significant portion of energy needs is met through non-electric sources such as firewood, charcoal, and kerosene. This reliance on traditional energy sources underscores the low penetration of electrification in rural areas and highlights the ongoing dependency on biomass and fossil fuels. The scarcity of modern energy services reinforces this dependency, particularly for households unable to afford or access reliable electricity solutions. Overall, these patterns illustrate the need for targeted efforts to enhance electrification and energy access, which could help stabilize energy availability throughout the year and reduce reliance on less sustainable energy sources.

3.8 Factors Influencing Energy Demand

Energy demand is shaped by a range of socioeconomic and environmental factors that collectively determine the type, quantity, and patterns of energy consumption. In Uganda, particularly in rural settings, understanding these factors is crucial for developing effective energy policies and strategies. Below is a logical discussion of the key factors influencing energy demand:

1. Population Growth and Demographics: One of the most significant drivers of energy demand is population growth. As the population increases, so does the number of households, leading to a proportional rise in energy consumption. Uganda has one of the fastest-growing populations in Africa, which exacerbates energy demand, particularly for basic needs such as cooking, lighting, and mobile phone charging. Demographics also play a role, with younger populations being more likely to adopt modern energy services, while older populations may continue to rely on traditional energy sources like firewood and charcoal. Rural households with more children may also have increased energy needs for heating, cooking, and sanitation.

2. Income Levels and Economic Development: Income levels are a critical factor in determining energy demand. In low-income rural areas, energy consumption is typically low because households can only afford basic energy services such as cooking and lighting. As income levels rise, households are more likely to invest in appliances that increase their energy needs, such as refrigerators, televisions, and electric cooking devices. Economic development is similarly tied to energy demand. As businesses grow, particularly in agriculture, manufacturing, and service sectors, they require more reliable and higher-quality energy to operate machinery, refrigeration, lighting, and other business-related equipment. Rural electrification, when combined with economic activities such as agriculture and small enterprises, leads to higher overall demand for energy.

3. Access to Energy Infrastructure: The availability and accessibility of energy infrastructure significantly influence energy demand. In areas with low electrification rates, demand remains suppressed because households and businesses rely on alternative, often less efficient, energy sources like biomass or kerosene. On the other hand, areas that have access to electricity either through grid extensions or off-grid solutions experience an increase in energy demand as households transition from traditional energy sources to modern electricity for daily needs. Limited connectivity to the national grid, particularly in rural areas, means that demand for renewable energy solutions such as solar home systems and mini-grids is higher in off-grid regions. The expansion of energy infrastructure in these areas could unlock latent demand for electricity and stimulate economic growth.

4. Technological Advancements: Technological advancements have a profound impact on energy demand. The introduction of energy-efficient appliances like LED lighting and DC-powered equipment in rural settings can lead to a more efficient use of electricity, reducing the overall demand while still improving living standards. Moreover, advancements in renewable energy technologies such as solar photovoltaics, battery storage systems, and solar-powered mini-grids have made clean energy more accessible and affordable. These technologies have particularly transformed energy access in off-grid areas, driving up demand as they become more affordable and reliable.

5. Government Policies and Subsidies: Government policies play a vital role in shaping energy demand. For instance, policies aimed at reducing connection fees, providing subsidies, and incentivizing the adoption of renewable energy technologies can make electricity more affordable for low-income households, boosting demand. Conversely, a lack of supportive policies or high taxes on solar systems can suppress demand by keeping costs high [36]. Programs such as the Rural Electrification Strategy and Plan (RESP) in Uganda, which aim to increase grid connectivity and promote off-grid solutions, have helped stimulate energy demand by making electricity more accessible to remote areas.

6. Energy Prices and Affordability: The cost of energy is a key factor influencing demand. In rural Uganda, where electricity tariffs can be relatively high compared to household incomes, the electricity demand may remain low as families are unable to afford regular electricity consumption. This forces many to continue relying on cheaper, traditional fuels such as firewood and charcoal. However, when affordable renewable energy solutions such as pay-as-you-go solar home systems are introduced, demand tends to rise because of the manageable costs.

7. Environmental Factors: Environmental conditions, such as climate, also affect energy demand. In Uganda, seasonal variations influence energy consumption patterns, particularly in rural areas. For example, during the rainy season, there may be higher energy demand for heating, while the harvesting season may see a spike in demand for energy used in crop processing, irrigation, and food preservation. The availability of natural resources, such as biomass, also impacts demand. When these resources become scarce due to deforestation or land degradation, rural households may be forced to seek alternative energy sources, increasing the demand for renewable energy

2.2 Renewable Energy Potentials in Rural Uganda

Uganda is rich in renewable energy resources, with solar photovoltaic and wind energy showing significant potential for sustainable energy development. Located along the equator, Uganda enjoys high solar radiation year-round, averaging between 4-6 kWh/m² per day. This makes solar PV an ideal solution for generating electricity in both urban and rural areas, especially in off-grid communities where extending the national grid is economically unfeasible. Solar energy has already been widely adopted nationwide, with solar home systems and mini-grids providing essential electricity to households, schools, health centers, and small businesses. These systems have been critical in expanding energy access, particularly in rural regions with limited grid connectivity. Furthermore, solar energy leads the way, Uganda also has potential for wind energy development, though it remains less explored than solar PV. Wind speeds in various parts of the country, particularly in regions like Karamoja and along the shores of Lake Victoria, average 4-6 m/s, making them suitable for small-scale wind turbines. Wind energy, although still in its early stages of exploration, offers a valuable opportunity to diversify Uganda's renewable energy portfolio. Research suggests that wind energy could serve as a complement to solar, especially in areas where favorable wind conditions exist. The development of both solar and wind resources holds great promise for advancing Uganda's renewable energy goals, enhancing energy security, and reducing reliance on non-renewable sources such as biomass and fossil fuels.

3.9 Challenges and Opportunities in Harnessing Solar Energy in Rural Areas: Evidence from Bushenyi District, Uganda

The deployment of solar energy systems in rural areas of Uganda, particularly in Bushenyi District, reveals a complex interplay of challenges and opportunities across the project lifecycle. A comprehensive understanding of these dynamics is critical for formulating context-specific interventions and policies that support sustainable rural electrification.

3.9.1 Initial Assessment and Planning: Constraints and Enablers

A key constraint in the initial assessment and planning phase is the lack of essential infrastructure. Many rural communities in Bushenyi are characterized by inadequate road networks and limited grid connectivity, complicating the logistics of transporting equipment and increasing the cost of system installation and maintenance. These infrastructural deficits not only constrain project timelines but also elevate capital expenditures (CapEx), thereby discouraging private-sector engagement [37]. Furthermore, the scarcity of granular solar resource data specific to Bushenyi impedes precise system sizing and yield forecasting. While Uganda exhibits a national average solar insolation of 5.0–5.5 kWh/m²/day, the absence of localized irradiance profiles compromises the accuracy of feasibility assessments and may result in suboptimal system performance [38]. Nonetheless, Bushenyi's favorable solar radiation levels present a substantial opportunity for decentralized energy systems. The district's solar resource potential, coupled with increasing interest from governmental and non-governmental stakeholders such as the Uganda Rural Electrification Agency (REA), GIZ, and Power Africa, has led to increased funding for energy audits and pre-feasibility studies. These developments underscore the potential for evidence-based planning frameworks tailored to rural contexts [37,38].

3.9.2 Development and Implementation: Barriers and Catalysts

During implementation, the high upfront capital requirements for PV systems remain a major deterrent for rural households and institutions. Most communities in Bushenyi lack access to structured financial instruments such as green microloans or pay-as-you-go models, which limits their ability to adopt solar technologies [39]. In addition, the limited availability of trained solar technicians within the district necessitates reliance on service providers from urban centers, increasing project costs and leading to delays in installation and commissioning. This capacity gap also raises concerns about the long-term reliability of installed systems [40]. On the positive side, international donor support and technological advancements are increasingly mitigating these barriers. Donor-funded programs now offer technical assistance, capacity building, and concessional financing to support rural electrification. Simultaneously, improvements in panel efficiency, inverter technology, and energy storage systems have reduced the levelized cost of electricity (LCOE), making solar systems more financially and technically viable for rural applications [39,40].

3.9.3 Operation and Maintenance: Sustainability Considerations

Post-installation, maintenance challenges persist due to limited access to spare parts and a lack of localized service centers. Regular system diagnostics and servicing are often neglected, leading to performance degradation over time. The limited technical workforce exacerbates this issue, undermining system reliability and user confidence [41]. Moreover, the integration of solar systems with the national grid or mini-grids in semi-urban growth centers such as Ishaka and Kizinda is constrained by regulatory uncertainty and underdeveloped grid infrastructure. This inhibits the full realization of solar energy's potential to enhance grid stability and energy diversification [42]. However, community-based approaches to system maintenance offer a promising alternative. Training local youths and technicians in routine system servicing fosters community ownership and builds local technical capacity. Additionally, the adoption of hybrid solar systems incorporating battery storage and/or diesel generators can mitigate the challenges of intermittency and improve supply reliability in critical applications, including rural health centers and schools [41,42].

3.9.4 Long-Term Sustainability: Policy and Institutional Dimensions

From a sustainability perspective, economic viability and policy coherence are major concerns. The absence of performance-based incentives, dynamic tariff systems, and long-term service contracts limits the financial resilience of rural energy systems. Furthermore, inconsistent policy implementation such as delays in operationalizing feed-in tariffs or rural electrification subsidies undermines investor confidence and project scalability [43]. Nevertheless, there are emerging opportunities to strengthen long-term sustainability. Uganda's Renewable Energy Policy (2007), coupled with recent revisions under the Electricity Connections Policy (2018–2027), provides a supportive institutional environment for renewable energy deployment. Tax exemptions on solar components, coupled with donor-backed capacity-building programs, further incentivize uptake [44]. Equally important is the promotion of local innovation ecosystems. In Bushenyi, grassroots initiatives and technical colleges are beginning to experiment with context-specific renewable energy solutions, such as solar agro-processing units and off-grid cold storage systems. Supporting such localized innovation can enhance technological relevance, cost-effectiveness, and community buy-in [43,44]. Furthermore, some of the executed renewable energy projects in Uganda are illustrated in Figure 10.

Finally, the case of Bushenyi District illustrates that while significant barriers exist in harnessing solar energy in rural Uganda, targeted investments in data infrastructure, capacity building, and policy reform can unlock the transformative potential of decentralized renewable energy. Integrating these interventions within a participatory development framework is essential for achieving sustainable and inclusive energy access in off-grid communities.

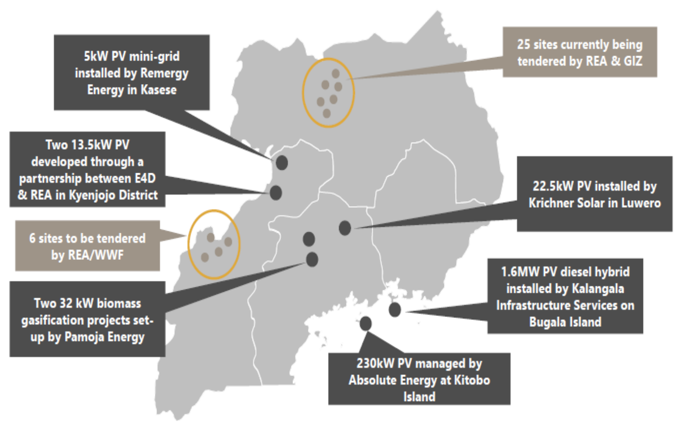

Figure 10: Renewable Energy Projects in Uganda

3.10 Hybrid Renewable Energy Systems (HRES)

HRES combines two or more renewable energy sources, such as solar, wind, biomass, or hydro, with energy storage or backup systems like batteries or diesel generators. These systems aim to address the intermittent nature of renewable energy by integrating complementary energy sources, ensuring a reliable and continuous power supply. HRES are increasingly important in both off-grid and grid-tied applications, particularly in remote areas where energy security is crucial. By optimizing the use of available resources, HRES enhances energy efficiency, reduces dependency on fossil fuels, and contributes to sustainable energy solutions [47].

3.10.1 Design Components of Hybrid Renewable Energy Systems (HRES)

Hybrid Renewable Energy System (HRES) components consist of diverse energy sources that can be simultaneously integrated to generate sustainable and substantial energy. These components can be categorized as either passive or reactive, each playing a distinct role in the efficient operation of the system, as detailed below:

1. Primary Renewable Energy Sources

The main renewable energy sources used in HRES include solar PV systems, wind turbines, biomass energy, and small-scale hydropower systems. Solar PV systems are widely used due to their simplicity and efficiency in converting sunlight into electricity. Solar panels are highly effective in regions with abundant sunlight and can be easily integrated into hybrid systems. Wind energy complements solar power, especially in areas where wind speeds are higher at night or during periods of reduced sunlight. Wind turbines harness wind energy and convert it into electricity, ensuring a more consistent energy supply [48]. Biomass energy is another significant renewable source in HRES, particularly in areas with ample organic materials like agricultural waste. Biomass can be stored and used when solar or wind energy is unavailable, providing reliable power. Similarly, small-scale hydropower systems can generate consistent electricity by harnessing the energy of flowing water. These renewable energy sources complement each other, enabling HRES to balance the variability and intermittency of individual renewable energy systems [47].

2. Energy Storage Systems and Backup Energy Systems

Energy storage systems (ESS) are crucial for balancing supply and demand in HRES. Batteries are the most common energy storage solution, with lithium-ion and lead-acid batteries being widely used due to their ability to store excess energy generated by renewable sources for later use. Batteries ensure that power is available even when renewable energy generation is low, such as during the night or cloudy days. Flywheels and supercapacitors are also employed in HRES to store energy in kinetic and electrostatic forms, respectively [49,50,51]. These storage solutions are capable of rapidly responding to fluctuations in energy demand and supply, stabilizing the system during short-term power outages or fluctuations [48]. Backup energy systems are included in HRES to ensure reliability, particularly in off-grid or isolated areas. Diesel or gas generators are commonly used as backup systems to provide power during periods when renewable sources and energy storage solutions cannot meet demand. These generators are typically used sparingly, only, when necessary, to reduce fuel consumption and emissions. The integration of backup systems is essential for ensuring continuous power supply, especially in regions where renewable energy sources are highly variable or insufficient for consistent power generation [52].

3. Charge Controller and Optimization

Charge controllers and optimization systems are renewable energy components that are vital for managing the interaction between different energy sources and energy storage devices. Inverters, for example, convert the DC power generated by solar panels and stored in batteries into AC power, which can be used in households or fed back into the grid. Controllers play a key role in determining which energy source or storage device should be used at any given time to maximize system efficiency. These controllers ensure that the system operates smoothly by regulating when to charge or discharge batteries or when to switch between renewable energy sources and backup systems [47]. One critical technology in solar PV systems is Maximum Power Point Tracking (MPPT), which optimizes the energy output by ensuring that solar panels operate at their most efficient voltage and current. MPPT ensures that the system extracts the maximum possible energy from the solar panels under varying conditions, such as changes in sunlight intensity or temperature [52]. Figure 11 is the solar MPPT meter.

Figure 11: Solar MPPT Meter [52]

4. Grid Connection

In grid-tied HRES, the hybrid system is connected to the national grid, enabling the system to feed excess energy back into the grid or draw power when renewable energy production is insufficient. Grid-tied systems offer increased flexibility and energy security, as they can rely on the grid for power during low renewable energy periods while reducing the overall energy demand from the grid during periods of high renewable energy generation. This arrangement is particularly beneficial in regions with strong regulatory frameworks that allow consumers to sell surplus energy to the grid [48].

3.10.2 Advantages of HRES

Hybrid Renewable Energy Systems provide several key advantages. One of the most significant is the improvement in reliability. By combining different energy sources, HRES can ensure continuous power availability even when one or more renewable sources are unavailable or generating less power. This is especially important in remote or off-grid areas where energy reliability is critical [52]. In addition, HRES increase overall system efficiency by optimizing energy production from multiple sources, reducing energy waste, and lowering reliance on fossil fuels. Another important advantage is the environmental benefit that HRES offer. By reducing dependency on fossil fuels, HRES contribute to lowering greenhouse gas emissions and promoting environmental sustainability. Furthermore, while the initial setup costs of hybrid systems may be high, they can result in significant long-term cost savings due to lower operational and maintenance costs, particularly in comparison to traditional fossil fuel-based systems [47,53].

3.10.3 Challenges of HRES

Despite their advantages, Hybrid Renewable Energy Systems also present several challenges. One of the main issues is the complexity involved in designing and controlling the system. Integrating multiple renewable energy sources and storage solutions requires sophisticated control systems to ensure optimized performance. The interaction between these components must be managed effectively to maintain balance and avoid energy wastage or inefficiencies [48]. Another challenge is the higher initial capital investment required for HRES, particularly when energy storage systems, such as batteries, are included. These systems can be expensive to install, making it difficult for some users, especially in developing regions, to adopt HRES. The intermittency of renewable energy sources also poses a challenge for HRES. While hybrid systems aim to mitigate the variability of sources like solar and wind, careful planning and resource assessment are required to ensure a reliable and continuous energy supply. Full reliability often depends on the availability of complementary resources, such as biomass or hydropower, or the inclusion of backup energy systems like diesel generators [53].

3.10.4 Design of optimized HRES

Several HRES demonstrate their effectiveness in optimizing energy generation and supply. Solar-wind hybrid systems, for instance, are popular in areas where solar and wind resources complement each other. These systems generate solar energy during the day and wind energy at night, ensuring more consistent energy production. Similarly, solar-biomass hybrid systems are often used in rural areas with abundant biomass resources. In these systems, solar energy is harnessed during the day, while biomass is used at night or during periods of low sunlight, providing a continuous energy supply [48,53]. In summary, Hybrid Renewable Energy Systems represent a significant advancement in the transition toward sustainable energy solutions. By integrating various renewable sources with energy storage and backup systems, HRES can provide reliable, efficient, and environmentally friendly alternatives to traditional energy systems [54,55]. However, their success depends on careful system design, the availability of local resources, and cost-effective integration strategies. Addressing the challenges of HRES, including design complexity and high initial costs, is essential for broader adoption and implementation [47]. The general equation for hybrid systems is shown in equation (2) and the diagrammatic illustration is shown in Figure 12.

$$P_{total} = P_{renewable\ energy\ sources} + P_{batery} + P_{grid} \quad (2)$$

1. Where:
2. P_{total} = Total power supplied to the load,
3. $P_{renewable\ energy\ source}$ = Power generated by any other renewable sources (solar, wind, biomass etc)
4. $P_{battery}$ = power supplied by the battery storage, and
5. P_{grid} = power drawn from the grid.

Figure 12: A hybrid PV system [56]

3.10.5 Principles of Designing Cost-Effective Hybrid Energy Systems

Designing cost-effective hybrid energy systems (HES) requires balancing technical, environmental, and economic considerations. These systems integrate multiple energy sources, typically renewable (solar, wind) and conventional (diesel, grid power), to optimize energy reliability and cost efficiency. The major principles to consider when designing cost-effective HES are:

1 Resource Availability and Demand Analysis

The first principle in designing hybrid energy systems is understanding local resource availability and demand profiles. Solar and wind energy resources vary by location and season, which means an accurate assessment of resource availability is critical for determining the optimal mix of energy sources. Detailed resource analysis ensures the system design can meet energy demands without oversizing or undersizing the components, which can lead to inefficiencies. For this, tools like MATLAB and Hybrid Optimization of Multiple Energy Resources (HOMER) software are often used. HOMER simulates energy production and consumption to match the optimal combination of energy sources, based on real-time resource data, reducing the risk of underperformance. Therefore, Resource assessment plays a crucial role in the design of hybrid systems to avoid oversizing or undersizing components [57]. Figure 13 is a diagram showing the typical design of a solar-wind hybridized system using HOMER.

Figure 13: Typical Diagram of solar-wind design using HOMER [57]

2. Optimization of Energy Storage

Energy storage is fundamental to hybrid energy systems due to the intermittent nature of renewable resources like solar and wind. Energy storage systems, primarily battery-based, allow for the storage of excess energy during periods of high renewable output and supply it when renewable generation is low. Proper sizing and selection of storage components, such as lithium-ion batteries, are critical to minimizing costs while ensuring system reliability [58]. Energy storage technologies also extend the life and functionality of hybrid systems, especially in off-grid scenarios, by providing backup power when renewables are insufficient. Batteries, when optimized, reduce the need for diesel generators, thus lowering operational costs and fuel consumption. Hence, the integration of batteries or other storage technologies increases the flexibility of hybrid systems, especially in off-grid and micro-grid configurations [59,60]. Figure 14 is a diagram of the HREs optimized with ESS.

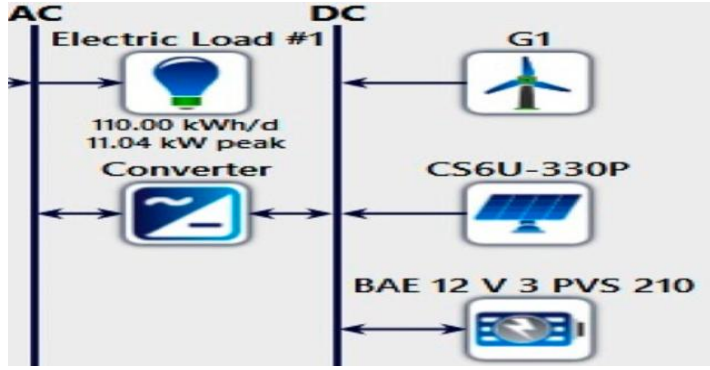

Figure 14: HRES with EES backup [59].

3. System Configuration and Component Sizing Design

The configuration of the system and the appropriate sizing of components such as solar panels, wind turbines, inverters, and battery banks is essential for cost-effectiveness. Oversizing leads to unnecessary capital expenditures, while under-sizing can cause system failures or reduced performance during peak demand periods. Software tools and algorithms like HOMER are employed to simulate and determine the most efficient system configurations based on cost, performance, and reliability criteria. The objective is to minimize costs without compromising energy reliability. In hybrid energy systems, the correct balance between renewable generation and backup power (diesel or grid) must be achieved for optimal system performance. Therefore, proper sizing of hybrid system components is key to maximizing efficiency and minimizing both capital and operating costs [49,61]. The system configuration of solar PV using Kirchhoff's law is depicted as shown in Figure 15. Equations (3)- (8) are the system optimization, configuration and optimization of solar PV using Kirchhoff's law.

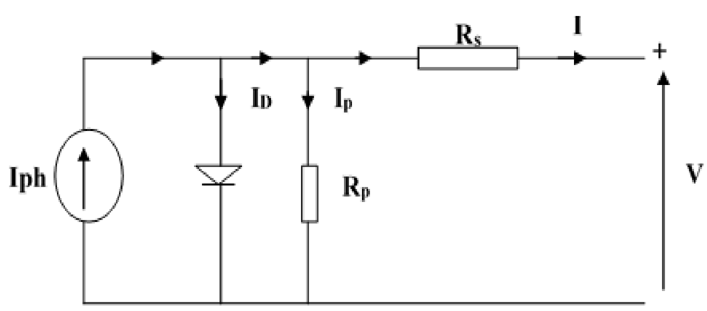

Figure 15: The Equivalent Circuit of a PV cell [62,63]

Applying and analysing Kirchhoff's law to the nodes of the circuit of Figure 15 gives Equation (3)

$$I = I_{ph} - I_D - I_p \quad (3)$$

Where: I is Output Current; I_{ph} is Photo generated Current; I_D is Diode Current and I_p is dark current. When Kirchhoff's law is applied in nodes of Figure 15, equations (4) - (9) were obtained.

$$I_{ph} = I_{sc}[1 + k_i(T - T_{ref})]\frac{G}{G_{ref}} \quad (4)$$

$$At\ STC; \quad I_{ph} = I_{sc} \quad (5)$$

$$I_D = I_o\left(\exp\left(\frac{q(V + IR_s)}{\alpha nkT}\right) - 1\right) \quad (6)$$

$$I_o = I_{rs}\left[\frac{T}{T_{ref}}\right]^3 \exp\left[\left(\frac{qE_{gap}}{\alpha k}\right)\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (7)$$

$$\text{At STC;} \quad I_o = I_{rs} \quad (8)$$

$$I_p = \frac{V_D}{R_p} = \frac{V + IR_s}{R_p} \quad (9)$$

Where: q is Electron charge (1.602 x 110^{-19}C); k is Boltzmann's constant (1.3865 x 10^{-23}J/K); T is cell Temperature in Kelvin; α is Diode ideality (0≤α≤2); n is number of PV cells in series; I_o is Diode/module saturation current; R_s is Resistance in series; I_p is dark current; I_{rs} is the reverse saturation current; E_{gap} is the Energy bandgap of the semiconductor material (E_{gap} for silicon polycrystalline =1.1ev). ki is the cell short circuit current temperature coefficient of Isc.

The PV characteristic equation was obtained by Substituting equations (6) and (9) in equation (3) to yield equation (10)

$$I = I_{ph} - I_o\left(\exp\left(\frac{q(V + IR_s)}{\alpha nkT}\right) - 1\right) - \frac{V + IR_s}{R_p} \quad (10)$$

4. Economic and Financial Viability

For hybrid energy systems to be viable, their financial feasibility must be evaluated throughout their lifespan. This includes capital investment, operational costs, and maintenance. Common financial metrics used are Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE). LCOE is particularly useful for comparing the costs of different energy generation technologies over their operational life, ensuring that designers select the most cost-effective solution. Economic viability is crucial, especially in remote or off-grid applications, where upfront capital costs may be high but operational savings from reduced fuel use and maintenance can offset the initial expenditure over time. Hence, LCOE provides an accurate basis for comparing different hybrid energy configurations, enabling designers to select the most cost-effective solution [64]. The system techno-economic Net present cost (NPC), Capital Recovery Factor (CRF), and Internal Return Rate (IRR) optimization are calculated using equations (11) - (13)

$$C_{NPC} = \sum_{t=0}^{N}\frac{C_t}{(1 + r)^t} \quad (11)$$

$$CRF = \frac{r(1 + r)^N}{(1 + r)^N - 1} \quad (12)$$

$$0 = \sum_{t=0}^{N}\frac{C_t}{(1 + IRR)^t} \quad (13)$$

Where; $C_t = Net\ cost\ flow\ in\ year\ t,$ r = discount rate or interest rate per period, N = total number of years.

The Total Annualized Cost (TAC) and the Cost of Energy will be calculated using equations (14) and (15).

$$TAC = C_o * \text{CRF} + \text{O} + \text{M} \quad (14)$$

$$COE = \frac{TAC}{E_{Annual}} \quad (15)$$

Where: C_o = Initial capital cost, CRF = Capital Recovery Factor, O = Annual operation cost, M = Annual maintenance costs, E_{Annual} = Annual energy production (kWh).

5. Integration with Conventional Systems

Hybrid systems often include conventional energy sources like diesel generators or grid power to provide backup energy during periods of low renewable output (e.g., cloudy days or no wind). This integration ensures continuous energy supply and operational flexibility. Control systems manage the integration, determining when to switch between renewable and conventional energy based on availability, demand, and costs. Hybrid systems with conventional backup can reduce reliance on fossil fuels, cutting operational costs and emissions. This balance helps achieve both energy reliability and cost efficiency in regions where renewables alone cannot meet energy demand year-round. Hybrid systems with diesel integration can reduce fuel consumption significantly, especially in remote areas, leading to overall cost savings [65].

6. Environmental Impact and Sustainability

One of the key advantages of hybrid systems is their reduced environmental impact compared to purely conventional energy systems. By incorporating renewables, hybrid systems help decrease greenhouse gas emissions. However, the environmental sustainability of these systems also depends on the management of components like batteries and generators. Energy storage systems, in particular, require responsible recycling or disposal at the end of their lifecycle. Designers should ensure that environmental impact assessments are carried out and that renewable sources are maximized, reducing dependence on fossil fuels while promoting sustainable energy generation. Hybrid energy systems offer a sustainable solution by reducing reliance on fossil fuels and minimizing environmental impacts [66].

7. Modular and Scalable Design

Hybrid energy systems should be designed to be modular and scalable. This allows for flexibility in system upgrades as demand increases or additional resources become available. In off-grid and rural applications, energy demand can grow over time, so the system must be able to scale without major redesign. A modular system design also simplifies maintenance, as individual components can be replaced or upgraded without disrupting the overall system. This adaptability is especially valuable in developing regions where infrastructure may be limited, and energy needs evolve as communities grow. Modular and scalable hybrid systems are essential in rural electrification projects, where the energy demand typically increases over time [67].

8. Control Systems and Monitoring

Hybrid systems require advanced control and monitoring systems to manage energy flows between different sources, including renewables, storage, and conventional power. These systems use real-time data to optimize energy use, ensuring that the lowest-cost and most sustainable energy sources are prioritized. Automation in control systems reduces the need for human intervention, thus minimizing operational costs. The ability to remotely monitor and control hybrid systems also improves system reliability and allows for early detection of any potential issues, increasing system lifespan. Advanced control systems are necessary to optimize the operation of hybrid systems, especially in real-time energy management [68]. In summary, designing cost-effective hybrid energy systems requires careful optimization of energy sources, storage, and conventional backup systems to ensure reliable and sustainable energy delivery. Proper resource assessment, component sizing, financial analysis, and environmental sustainability are essential for achieving an optimal balance. Advanced tools and monitoring systems play a critical role in enhancing the performance and scalability of hybrid energy systems while minimizing costs and environmental impacts.

3.11 Comparative Evaluation of Hybrid Energy Systems and Conventional Energy Systems in Rural Areas

The transition from conventional fossil-fuel-based energy systems to hybrid renewable energy systems has gained momentum globally, particularly in rural and off-grid regions. In the context of Bushenyi District, Uganda, a predominantly agrarian area with limited grid coverage and frequent power supply interruptions, understanding the relative performance, costs, and sustainability implications of these systems is critical for informing decentralized electrification strategies. This section critically compares hybrid energy systems, typically integrating solar PV, wind, and auxiliary diesel or biomass generators with conventional energy systems based solely on fossil fuel combustion (primarily diesel), across four core dimensions: efficiency, environmental impact, cost-effectiveness, and scalability.

3.11.1 Efficiency and Reliability

Conventional energy systems in Uganda, particularly diesel generators, are widely deployed in off-grid institutions and enterprises due to their immediate availability and relatively low setup complexity. However, these systems exhibit low thermodynamic efficiency, often operating in the range of 25–35% due to conversion and transmission losses. In Bushenyi District, where fuel logistics and maintenance are challenging due to poor rural infrastructure, generator downtimes and inefficiencies are exacerbated [69]. Conversely, hybrid energy systems offer improved overall system efficiency by leveraging the intermittent but abundant solar resource (Bushenyi receives ~5.2 kWh/m²/day) and moderate wind speeds in elevated areas such as Kakanju and Kyabugimbi. When integrated with energy storage systems and smart load management, these systems ensure greater reliability and load-matching capabilities. Empirical studies in East Africa have shown that solar-diesel hybrid systems can reduce diesel consumption by 50–70%, extending generator lifespan and lowering system outages [70]. Pilot installations in nearby rural districts, such as the hybrid mini-grid in Kyenjojo District, demonstrate that reliability indices (e.g., SAIDI/SAIFI) of hybrid systems surpass those of standalone diesel systems, particularly during dry seasons when solar irradiation is high. Given the similar climatic and infrastructural context, Bushenyi stands to benefit from such hybrid configurations for health centers, schools, and agricultural cooperatives [69,70,71].

3.11.2 Environmental Impact

Fossil fuel-based systems are major contributors to local air pollution and global greenhouse gas (GHG) emissions. In rural Uganda, diesel generators emit not only CO_2 and NO_x but also particulate matter ($PM_{2.5}$), posing significant health risks in enclosed or poorly ventilated spaces. The cumulative emissions from small diesel generators across Bushenyi's rural institutions exacerbate both public health and environmental degradation [71]. Hybrid systems, integrating solar PV and wind turbines, drastically reduce emissions during operation. Life-cycle analyses indicate that GHG emissions from solar PV systems are 90–95% lower than from equivalent diesel systems over a 20-year operational period [72]. In Bushenyi, adopting hybrid systems could substantially contribute to Uganda's commitments under the Nationally Determined Contributions (NDCs) and the Vision 2040 strategy for sustainable development [723. Additionally, the adoption of biomass components in hybrid systems, such as biogas from agricultural waste (readily available in Bushenyi's banana plantations and cattle farms), offers an opportunity for closed-loop carbon-neutral systems, enhancing environmental sustainability [74].

3.11.3 Cost-Effectiveness

From a financial standpoint, conventional diesel generators appear attractive due to their low initial capital cost. However, in Bushenyi, fuel supply logistics, involving long-distance transport and poor rural roads, raise operational costs significantly. Current diesel prices (~UGX 5,000 per liter) and periodic maintenance make the Levelized Cost of Electricity (LCOE) from diesel systems among the highest, exceeding USD 0.60/kWh in remote sub-counties such as Nyabubare and Kyamuhunga [75]. Hybrid systems have higher upfront capital investment, particularly due to the cost of PV modules, wind turbines, inverters, and battery banks. However, they benefit from minimal recurrent fuel costs and declining prices of solar components. A techno-economic feasibility study using HOMER Pro software (based on Bushenyi's solar and wind resource data) demonstrated that a solar-wind-diesel hybrid system had a 45% lower lifecycle cost compared to a diesel-only system over a 20-year horizon [76]. Microfinance programs, such as those promoted by Uganda Energy Credit Capitalisation Company (UECCC), further enhance the financial viability of hybrid systems through credit guarantees and subsidies, making them economically suitable for rural households and cooperatives in Bushenyi.

3.11.4 Scalability and Flexibility

Conventional energy systems are inflexible and centralized, limiting their utility in sparsely populated rural areas. Extending the national grid to remote villages in Bushenyi (e.g., Rwengoma or Kitwe) is economically infeasible due to low load density and rugged terrain. In contrast, hybrid systems enable modular and decentralized electrification, where capacity can be scaled up incrementally based on demand growth [77]. A notable example is the Isingiro solar-wind hybrid mini-grid project, which successfully demonstrated phased expansion from 10 kW to 50 kW within three years, an approach that could be replicated in Bushenyi. Furthermore, hybrid systems are adaptable to sector-specific needs, such as powering cold chains for milk storage, solar irrigation pumps, and ICT centers for educational institutions. The flexibility of hybrid systems also aligns with Uganda's Energy for Rural Transformation (ERT-III) agenda and the Electricity Connections Policy (2018–2027), which promotes off-grid solutions for last-mile electrification [78].

In summation, hybrid energy systems provide a strategically superior alternative to conventional fossil-fuel systems in Bushenyi District. They offer enhanced energy efficiency, reduced environmental footprint, improved long-term cost-effectiveness, and scalable deployment models suitable for the district's topography and socio-economic realities. As Uganda intensifies efforts to close its rural electrification gap, integrating hybrid solar-wind systems tailored to local resource availability and community needs can significantly advance the goals of energy access, climate resilience, and inclusive rural development in Bushenyi and beyond.

3.12 Hybrid Solar-Wind-Powered Water Pumping Systems

Hybrid solar-wind-powered water pumping systems are emerging as a sustainable and resilient solution to address water scarcity and energy deficits, particularly in off-grid rural communities. By combining the complementary characteristics of solar and wind energy, these systems provide a more reliable and continuous energy supply than standalone solar or wind technologies. They reduce reliance on fossil fuels, minimize operational costs, and support year-round water access essential for domestic use, agriculture, and livestock [78,79]

In a pioneering simulation-based study, Smith et al. (2018) [80] investigated the optimization of hybrid solar-wind water pumping systems in off-grid areas. The research addressed the limitations of intermittent energy supply in standalone renewable systems by designing an optimized configuration based on real solar radiation and wind speed data from several rural sites in Mexico. Using an optimization algorithm, the study determined the ideal sizing of photovoltaic (PV) panels, wind turbines, and battery storage. Results showed that the hybrid system increased energy output by 20–30% compared to standalone configurations and consistently pumped water even during periods of low sunlight or wind. Battery storage played a critical role in enhancing system reliability. The authors concluded that optimized hybrid systems are particularly suitable for regions with fluctuating renewable energy availability.

Building on this foundation, a simulation-based study in rural India [78] further assessed the performance of a hybrid PV-wind system designed to power water pumps under varying climatic conditions. Real-time data on solar irradiance and wind speeds were used to evaluate annual water demand satisfaction. The system met up to 95% of annual pumping requirements, significantly reducing dependence on diesel generators during adverse weather. The research demonstrated the system's robustness and suitability for agricultural water demands, especially during dry seasons and critical planting periods.

In Sub-Saharan Africa, a techno-economic feasibility study conducted by [79] evaluated hybrid solar-wind water pumping systems for agricultural applications in a rural Kenyan farming community. Using HOMER software and local meteorological data, the system was modeled and compared with conventional diesel pumps. Findings indicated that the hybrid system was markedly more cost-effective, achieving a payback period of approximately seven years. It consistently supplied adequate water during peak irrigation seasons and provided significant long-term environmental and economic benefits.

In Pakistan, another field-based investigation [81] explored the deployment of a hybrid solar-wind-powered system to supply clean drinking water in rural areas. The system comprised PV panels, a small wind turbine, and a submersible pump. Over a six-month monitoring period, it reliably delivered water to the community with minimal interruptions, even during low-resource periods. Energy costs were reduced by 80% compared to the previously used diesel pump, emphasizing the system's sustainability and cost-effectiveness.

Further performance analysis was conducted in rural Egypt, where [82] simulated a hybrid solar-wind-powered irrigation system using MATLAB/Simulink. Real-time solar and wind data were input into the model to evaluate the system's efficiency under diverse environmental conditions. The results indicated that solar energy predominated during summer while wind energy was more effective in winter. The hybrid configuration was 85% more efficient than either standalone source in meeting irrigation demands. The study confirmed that proper system sizing and integration of both renewable sources could ensure a reliable, year-round irrigation solution.

3.12.1 Relevance to Bushenyi District, Uganda

Bushenyi District in Western Uganda presents a compelling case for the deployment of hybrid solar-wind-powered water pumping systems. As a predominantly agricultural region, it experiences seasonal rainfall and prolonged dry spells that strain water availability for irrigation, livestock, and domestic use. Many sub-counties, such as Kyeizooba, Nyabubare, and Bumbaire, remain off-grid and lack access to efficient water infrastructure. The district benefits from moderate to high solar insolation (averaging 4.5–5.5 kWh/m²/day) and consistent wind flows across its elevated terrains, particularly in Kyamuhunga and Kakanju. These climatic characteristics make it well-suited for hybrid renewable energy systems. Given the high cost and difficulty of transporting diesel fuel to remote areas, a transition to locally available, renewable energy can significantly cut operational costs and improve the reliability of water access. Integrating hybrid solar-wind pumping systems into Bushenyi's farming operations would enable year-round irrigation for key crops such as matooke (plantains), coffee, and tea, thus improving productivity and food security. Moreover, the systems align with Uganda's national energy policy, which promotes decentralized renewable energy technologies to foster rural development, enhance climate resilience, and improve living standards.

In summary, Global and regional evidence confirms that hybrid solar-wind-powered water pumping systems are technically viable, economically sustainable, and environmentally friendly for rural water access. These systems overcome the intermittency limitations of single-source renewables and offer reliable performance across seasons. For Bushenyi District, adopting such systems can transform agricultural practices, ensure water security, and contribute to broader sustainable development goals, particularly if supported through targeted investment, technical capacity-building, and community involvement.

Table 1: Summary of the Related Works

Contributions	Research Gaps	References
The hybrid tree generated 4709 kWh/year with the tracking system, significantly more than the 3763 kWh/year produced by fixed-tilt panels, highlighting the increased efficiency of combining solar and wind power with dynamic tracking.	Lack of long-term performance data and economic implications of scaling up.	[83]
The system was found to be adaptable to different hydrological conditions, offering reliable energy access for rural areas. Their implementation leads to economic growth by powering small industries and essential services, while also providing clean, renewable energy	site selection, and environmental impacts. Technical expertise and long-term maintenance pose hurdles, necessitating capacity building and robust operational frameworks for successful micro-hydro projects.	[84]
Zimbabwe's energy consumption is projected to increase to 2368.19 MW by 2030, with the hybrid PV-Wind system in Victoria Falls achieving the highest renewable energy fraction of 74.03% and the greatest reduction in carbon emissions, though energy storage systems increased costs without significant efficiency gain.	Further research is required to evaluate the cost-effectiveness of energy storage systems in hybrid configurations and to identify optimal locations across Zimbabwe for maximizing renewable energy output and grid stability	[85]
The 900W WT combined with the 640 W PV array achieved the highest pump efficiency at 55%, followed by the 480 W PV array at 51%, and the 320 W PV array at 47%. Interference, likely due to voltage mismatch, occurred between the WT and PV arrays, with the least interference seen in the WT/320 W PV array; overall, the hybrid system pumped 28% more water than individual systems	The use of controller with a buck/boost converter to improve the hybrid system's performance was not explored in depth, pointing to a need for further research on optimizing control strategies for these systems	[86]
The paper also performed cost optimization to provide guidelines for small-scale wind-solar hybrid system manufacturers, ensuring the system was economically viable.	It didn't consider or explore broader applications and scalability of such systems in diverse farming settings	[87]
The analysis indicates that system selection is largely influenced by cost, the variability of wind and solar resources, and system size.	There is a need for further research into optimizing hybrid system designs for small-scale irrigation, including better quantification of water and energy requirements.	[88]
The hybrid wind/PV system for water pumping in Baghdad, with performance varying based on critical parameters such as well depth and solar/wind conditions was demonstrated. The system's productivity was assessed under different scenarios to understand its effectiveness in the given context.	It didn't refine the model and test the system under a broader range of conditions and locations.	[89]

This study confirmed the optimization method's effectiveness, demonstrating that the hybrid system performs well under local conditions and supports the use of renewable energy for water pumping	The robustness of the model in diverse climates to evaluate the long-term operational and economic aspects of the hybrid system was lacking	[90]
The system demonstrated that wind power can meet 7.6% of the heat pump's yearly power demand for a 198 m² residential building in Beijing, and it can reduce carbon dioxide emissions by 31.3% compared to conventional systems.	Further research is needed to enhance the exergy efficiency of the solar thermal subsystem and to explore additional improvements in system design and integration for better performance and environmental impact	[91]
The PVWPS was found to be more cost-effective and environmentally friendly compared to diesel generators. The cost of electricity (COE) for PVWPS is US$ 0.4743/kWh, while for diesel generators it is US$ 0.6092/kWh, with PVWPS also producing zero carbon emissions	Further research is needed to explore the long-term maintenance and operational aspects of PVWPS and to investigate the integration of such systems with existing infrastructure in rural areas	[92]

Table 1 is the summary of the hybrid renewable energy systems, especially for water pumping and agricultural applications, which offer significant advantages in terms of energy efficiency, cost savings, and environmental sustainability. However, several challenges remain, including the need for comprehensive long-term performance data, cost optimization for scalability, the development of more efficient control strategies, and a thorough analysis of socio-economic impacts. This research seeks to address these challenges by designing a hybrid solar-wind-powered water pumping system specifically for the Bushenyi District, Uganda. The proposed system will be tailored to the region's load requirements, incorporating precise system sizing, an advanced control mechanism, and optimal site selection to ensure efficient and reliable operation. Through this approach, the system aims to maximize performance while minimizing costs and environmental impact.

4.0 Findings

Bushenyi District's renewable energy potential, particularly in solar, is promising due to its consistent equatorial sunlight, though high temperatures can impact photovoltaic efficiency, making heat-tolerant panels and cooling solutions essential [93]. Wind energy, while more variable, offers a valuable complement in hybrid systems, particularly in areas with sufficient wind speeds. Designing renewable systems for rural demand requires aligning generation capacity closely with local load profiles; thorough assessments of peak and average loads are crucial for proper system sizing and reliability. Hybrid systems integrating solar, wind, and biomass energy sources not only optimize generation but also mitigate intermittency, with modular design enabling scalability to meet growing energy demands. The integration of battery storage within hybrid configurations significantly enhances system reliability, allowing solar and wind hybrids to provide balanced energy output day and night vital in rural settings where uninterrupted electricity access remains challenging. Despite barriers such as limited infrastructure and high initial costs, recent advancements in hybrid technology and supportive government policies present opportunities to overcome these challenges. Targeted policies can stimulate investment, drive technological innovation, and ultimately broaden the reach of renewable energy solutions in underserved areas, paving the way for sustainable, resilient energy access in rural communities.

5.0 Conclusion

This research concludes that renewable energy systems, specifically hybrid solutions, hold substantial promise for meeting the energy demands of rural areas like Bushenyi District, Uganda. By aligning resource availability with rural load profiles and incorporating scalable, hybrid designs, renewable energy can effectively replace traditional energy sources. Optimized component sizing and advanced control systems are essential to enhance reliability and cost-efficiency, making renewable energy a practical and sustainable solution for energy access in off-grid areas. The findings support that renewable energy, with appropriate planning and support, is a feasible pathway to achieving sustainable rural electrification and improving the quality of life in remote communities

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Conflict of interest
All the authors declared no conflict of interest.

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