

Research Article

Standalone and Minigrid-Connected Solar Energy Systems for Rural Application in Rwanda: An In Situ Study

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In recent years, several factors such as environmental pollution, declining fossil fuel supplies, and product price volatility have led to most countries investing in renewable energy sources. In particular, the development of photovoltaic (PV) microgrids, which can be standalone, off-grid connected or grid-connected, is seen as one of the most viable solutions that could help developing countries such as Rwanda to minimize problems related to energy shortage. The country's current electrification rate is estimated to be 59.7%, and hydropower remains Rwanda's primary source of energy (with over 43.8% of its total energy supplies) despite advances in solar technology. In order to provide affordable electricity to low-income households, the government of Rwanda has pledged to achieve 48% of its overall electrification goals from off-grid solar systems by 2024. In this paper, we develop a cost-effective power generation model for a solar PV system to power households in rural areas in Rwanda at a reduced cost. A performance comparison between a single household and a microgrid PV system is conducted by developing efficient and low-cost off-grid PV systems. The battery model for these two systems is 1.6 kWh daily load with 0.30 kW peak load for a single household and 193.05 kWh/day with 20.64 kW peak load for an off-grid PV microgrid. The hybrid optimization model for electric renewable (HOMER) software is used to determine the system size and its life cycle cost including the levelized cost of energy (LCOE) and net present cost (NPC) for each of these power generation models. The analysis shows that the optimal system's NPC, LCOE, electricity production, and operating cost are estimated to 1,166,898.0 USD, 1.28 (USD/kWh), 221, and 715.0 (kWh per year, 37,965.91 (USD per year), respectively, for microgrid and 9284.4(USD), 1.23 (USD/kWh), and 2426.0 (kWh per year, 428.08 (USD per year), respectively, for a single household (standalone). The LCOE of a standalone PV system of an independent household was found to be cost-effective compared with a microgrid PV system that supplies electricity to a rural community in Rwanda.

1. Introduction

Small electricity systems that can run independently, known as off-grid microgrids, could play a pivotal role in the development of electricity systems based on decentralized renewable energy (RE) technologies. These networks are more cost-effective than stretching transmission lines to rural places [1, 2], thereby providing the possibility to produce sufficient electricity in countries where the national demand surpasses the regular production. In East Africa, for example, the energy deficiency is a significant impediment to social and economic growth. The capital expenses of wide grids can be incredibly expensive for developing countries leading to a shortage of roads and utilities [3–5]. To this end, community-based microgrids are considered the best option that would help rural areas in developing countries to reap the benefits of geospecific renewable energy sources.

The people who are not connected to nor served by the public or private power grid are referred to as “off-grid users.” According to the authors’ definition in Ref. [6], the term “off-grid” refers to a system and way of life that allows people to function without the assistance of remote infrastructure, including an electrical grid. It is a method of gaining access to electricity that is used in countries and areas where there is limited access to electricity due to a dispersed or remote population. It corresponds to living without relying on one or more public services, commonly referred to as electrical grids. Off-grid users are people who live off the grid, and those systems can be categorized as standalone power systems, minigrids, and microgrids, which should typically provide energy to a smaller community. In this research, the HOMER software (HOMER Pro, version 3.13.1) had been used to model, simulate, and optimize potential renewable energy sources, as well as solutions to ensure universal access to energy Rwandan for off-grid users. HOMER has a built-in optimizer through the proprietary derivative-free method that was adopted in Section 2. The simulation models took place in Rwanda’s Western province (Rutsiro, Rwanda, 1°56.3’S, 29°19.5’E). To optimize standalone solar systems, several site visits were conducted in the Rutsiro district of Rwanda’s Western province, precisely to the location of the typical sample residential house used in this section. The owner of the residential house listed his electric household items, along with their rated power and daily usage hours. For this study, a sample size of 121 residential houses was chosen.

2. Literature Review: A Comparative Analysis of Standalone and Minigrid-Connected Solar Energy in a Rural Area

With the mounting consequences of global warming, pollution, scarcity of fuel, and energy use, renewable energy sources (RES) is constantly getting more attention around the world. Therefore, the need for renewable energy to plan and build a grid-connected or standalone, microgrid, the minigrid system has risen and will continue to increase. When the price of conventional energy is compared to the price of renewable energy,

renewable energy is much less costly [7]. Given that many of Africa’s rural areas are plagued by an unsustainable energy system, building standalone, minigrid can solve energy problems for scattered people [8]. In developing nations like Rwanda, where power outages are common, implementing supportable energy development and clean energy needs extensive preparation, particularly given the financial impacts. As a result, the HOMER (hybrid optimization model of electric renewable) Pro software can design, prepare, and simulate the model in a variety of environments, including restrained and unrestrained systems, standalone, grid systems, and/or storage. The microgrid system design has advantages that lead to efficient source loading for microgrids and facilitate power systems operators. HOMER’s benefits lie in the features used in the design, planning, and simulation of the microgrid model discussed in [9, 10]. In contrast to African countries, developed countries like the United States, China, and Japan have increased their investment in renewable energy by billions of dollars. Researchers are attempting to produce more electricity from cost-effective resources that are not detrimentally impacting the environment [11].

HOMER was used to examining selected rural places in Nigeria based on the availability of wind and solar energies so that healthcare centers or clinics in isolated regions can provide quick delivery of medical services to the people who need them. It uses the best technical and economic design and sizing of hybrid electric power system components like wind, PV, battery, and inverter systems, where PV/wind/diesel/battery hybrid setup is best for rural health centers, while PV/diesel/battery hybrid systems are best for Port Harcourt considering the quality of renewable energy potential [12].

Tourist destinations in the South China Sea, Malaysia were at risk due to the widespread use of diesel generators and pollutants from diesel-based power plants. HOMER software was used for economic and technical analysis of the system. The best optimized standalone hybrid energy system consists of PV, wind, diesel generator, converter, and battery. The output has proved the diesel-only system has a higher net present cost, cost of energy, and CO₂ emission compared to the optimized hybrid renewable energy system [13].

The study on decentralized power stations in Sabah, Malaysia [14], with a diverse combination of photovoltaic (PV), diesel generators, system converters, and storage batteries. The impact of PV integration using HOMER was properly quantified by analyzing the practical behaviors of different PV penetration levels. The analysis based on technical, economic, and environmental constraints has resulted in satisfying the load demand with the minimum total net present cost (NPC) and the levelized cost of energy (LCOE). The sensitivity analysis and the impact of different PV penetration levels on the system performance and the generation of harmful emissions has been carried out. The findings reveal an increase in the use of renewable energy (RE) sources in energy generation, as well as a decrease in the reliance on standalone diesel generators.

The ability to supply power for rural health clinics (RHC) in six geopolitical regions of Nigeria has also been

TABLE 1: Summary of comparative analysis based on standalone, microgrid, on-grid, and off-grid results.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
1.	M.K Deshmukh, Athokpam Bharatbushan Singh [23]	2018	—	Standalone	Street lighting	Electrical	HOMER	The objective is to quantitatively estimate energy losses due to the standalone operation mode
2.	U Subramaniam et al. [24]	2020	—	On-grid and off-grid	Villages, islands, and hilly areas	Electrical	Hybrid PV battery with controller	The current method can work in various operating modes, and during transient and steady-state situations. With both off-grid and on-grid situations, the suggested power management controls were approved.
3.	C Marino et al. [25]	2020	Italy	Standalone photovoltaic	Residential user	Electrical	Comparative analysis of the costs of a standalone and a grid- networked PV system vs. grid distance	The study looked at the economics of an islanded PV project with two configurations that measure diminishing self-sufficiency.
4.	MH Mohamed Hariri et al. [26]	2020	—	Grid- connected	Villages, islands	Electrical	Grid synchronization and islanding detection methods	This review highlights the recent development of systems for generating grid-connected PV (GPV) involving many sub-components, like DC-DC converters, PV modules, maximum power point tracking (MPPT), and inverter technologies
5.	FA Alturki, EM Awwad [27]	2020	Saudi Arabia	Standalone	Remote community	Electrical	Hybrid photovoltaic (PV)/wind turbine (WT)/biomass/pump hydro/storage	The aim was sizing and price reduction of islanded hybrid WT/PV/biomass/pump-hydro storage-energy systems
6.	T Wu et al. [28]	2020	—	Grid- connected	Load serving	Electrical	Salp swarm algorithm (SSA).	This study provides a new approach to maximizing the scale of grid-connected renewable energy sources integrated with the salp swarm algorithm (SSA) pumped storage system. This method enables different energy sources to be explored and their combination to contact the base in the optimum configuration of the hybrid system
7.	BE Türkay, AYTelli renewable energy [29]	2011	Turkey	Standalone and grid- connected	Pilot area	Electrical	HOMER	The research explores the viability of using wind and solar energy. Using hydrogen as storage in combination with traditional grid-based electricity to fulfill the

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
8.	D Mazzeo et al. [30]	2020	Koppen	Standalone and grid-connected	Office building district.	Electrical	Hybrid renewable system	<p>electricity needs of the pilot area</p> <p>The goal of this work is to bridge the absence of direct comparisons between the technoeconomic output of islanded and grid-networked investigations in the same operating environment, providing global technoeconomic mapping, and optimizing islanded and grid-networked PV-wind systems</p>
9.	A Chakir et al. [31]	2019	—	Grid-connected	Load serving	Electrical	MATLAB/Simulink	<p>The research focused on the grid-connected development system's management, connection with the grid, and storage hybrid renewable energy system's management</p> <p>The various cases were examined based on their location, design and year of development, as well as the power, the technology used, and performance that can help design a PV plant considering the achievements of the previously commissioned plant. The material of the PV module and panel tilt angle was found to be crucial for the design of a PV plant</p>
10.	R Srivastava et al. [32]	2020	—	Standalone and grid-connected	Load serving	Electrical	Review	<p>The study focused on a cost-benefit analysis of grid-affiliated rooftop PV systems for private use. There was the suggestion to increase the number of private PV incentives and cultivate a regional support system, considering solar differences among regions</p>
11.	AC Duman, Ö Güler [33]	2020	Turkey	Grid-connected	Load serving	Electrical	HOMER	<p>The purpose of the research was to provide a thorough analysis of the recent progress in the design of standalone PV systems. Multiobjective optimization (MOO) and multicriteria decision-making (MCDM)</p>
12.	HM Ridha et al. [34]	2020	—	Standalone photovoltaic	Remote areas	Electrical	Review	<p>The purpose of the research was to provide a thorough analysis of the recent progress in the design of standalone PV systems. Multiobjective optimization (MOO) and multicriteria decision-making (MCDM)</p>

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
13.	MJ Mayer et al. [35]	2019	Hungarian region	Grid-connected	Load serving	Electrical use	Mathematical model	methodologies, including the mathematical models used to measure the PV module power output and storage battery Grid-connected, ground-mounted technoeconomic optimization of genetic algorithm-based photovoltaic power plants on a comprehensive mathematical model. The target function is the internal rate of return and a genetic algorithm performs the optimization Dust is one major parameter affecting photovoltaic efficiency, yield, and profitability linked to the grid. The proposed model in the paper took account of the dust on the grid-affiliated photovoltaic output power innovatively
14.	HA Kazem et al. [36]	2020	Oman	Grid-connected	Load management	Electrical	X-ray diffraction (XRD) and X-ray fluorescence (XRF)	The research focused on technology, cost-benefit, and environmental analyses of grid-affiliated hybrid wind/PV/biomass systems, Marmara University, Goztepe campus. The performance of the hybrid electricity system was assessed using both the net present cost (NPC) and cost of energy (COE) and found to be cheaper
15.	E Aykut, ÜK Terzi [37]	2020	Marmara University, Turkey	Grid-connected hybrid	Load serving	Electrical	HOMER	This research specifies the optimum solar capacity for grid-affiliated households, photovoltaic (PV), and battery energy storage (BES) to minimize the net present cost of electric power networks The study sized an islanded and grid-affiliated solar PV electricity provision to a small neighborhood. The result reflects major cost savings through the incorporation of the PV module into the grid
16.	R Khezri et al. [38]	2020	Australia	Grid-connected	Households serving	Electrical		
17.	BK Das [39]	2020	Bangladesh	Standalone and grid-connected	Load serving	Electrical	HOMER	

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
18.	ALM Maher [40]	2019	Palestine	Grid-connected and standalone	Industrial zone	Electrical	Open distribution source simulator (OpenDSS)	<p>This study provided a layout for a grid-affiliated PV system and an islanded PV system. Factors influencing device design and size were also described and analyzed. The results showed a good improvement in the overall energy losses and voltage profile concerning load and capacity production</p> <p>It provided a precise Buck-Boost DC-DC converter design powered by the fuzzy logic controller (FLC). The research concentrated on suggesting a suitable solar PV panel model configuration and attachment</p>
19.	HA Attia, F delAma Gonzalo [41]	2018	United Arab Emirates	Standalone	Remote building	Electrical	Fuzzy logic control	<p>Thermal modeling of a typical Pakistani rural house was performed using BEOpt throughout this research to assess the hourly load profile. System studies indicated that such a system can primarily reinforce the lighting and loading of appliances in a rural household</p>
20.	A Iqbal, MT Iqbal [42]	2019	Pakistan	Standalone PV	Rural area	Electrical	HOMER Pro	<p>The study tracked how the maximum power point (MPP) transferred the maximum available power to the load. The control fed the AC load by a sinusoidal output current</p>
21.	Y Chaibi et al. [43]	2019	—	Standalone PV	Load serving	Electrical	Sliding mode MPPT/MATLAB Simulink	<p>The study proposed a viable solution to the problem of energy output in the private dwellings sector using unpredictable PV systems operating in islanded and grid-affiliated modes. The battery storage framework enables private dwellings to secure stable energy operations</p>
22.	MA Omar, MM Mahmoud [44]	2018	Palestine	Grid-connected and standalone	Residential sector	Electrical	Unconventional PV system/MATLAB software	<p>This paper briefly discusses the modeling, simulation, and performance evaluation of hybrid and conventional</p>
23.	PK Bonthagorla, S Mikkili [45]	2020	—	Grid-connected/standalone	Load serving	Electrical	MATLAB/Simulink	

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
24.	M Salimi et al. [46]	2021	—	Hybrid grid-connected	Load serving	Electrical	MATLAB/Simulink	array configurations during different PSCs in MATLAB/Simulink environment A fresh concept to active modeling and locked-loop control of hybrid grid-affiliated multi-input multioutput (MIMO) renewable energy systems was addressed
25.	M Dali et al. [47]	2010	—	Grid-connected and standalone modes	Load serving	Electrical	Standalone inverter	A hybrid system associated with the grid was described in the study. The experimental findings show that the system can operate parallel to or independent of the grid A multiobjective optimization design accounted for lossy load likelihood (LLP), energy cost (COE), price of battery life loss, and cost of service, substitution, and repair.
26.	MI Hlal et al. [48]	2019	Malaysia	Off-grid or standalone	Load management	Electrical	Non-dominated separating genetic algorithm (NSGA-II) method	The study is based on the evaluation of economic expenses of grid-affiliated and islanded photovoltaic systems using PVsyst This research proposes a hybrid system consisting of an array of photovoltaic (PV) and rechargeable batteries integrated into the distribution grid to share loads with the grid system
27.	KNB Akshai, R Senthil [49]	2020	—	Standalone	Household electricity	Electrical	Simulation software PVsyst	The research resolved the power grid stability and control problems. The PV grid system consists of an 8.0 kW PV array and battery energy storage unit connected to the power grid over AC or DC links This study mainly explores the design features of a solar photovoltaic device based on a grid connection. The analysis sheds light on various subjects like creating Sankey energy loss diagrams, efficiency
28.	S Odeh et al. [50]	2019	Palestinian	Standalone	Load serving	Electrical	PVsyst software	
29.	J Kumar et al. [51]	2020	—	PV grid-tied	Residential load serving	Electrical	System advisor model (SAM) software	
30.	J Kumar [52]	2020	—	Grid-connected	Island	Electrical	PVsyst software	

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
31.	ZB Duranay, H Guldemir [53]	2019	—	Standalone	Load management	Water pumping	MATLAB/Simulink	<p>proportion, and total photovoltaic plant capacity</p> <p>A water-pumping double-deck converter and inverter for a single-phase islanded PV system were investigated. The single-phase islanded PV system was modeled using insolation and temperature values as simulation data</p> <p>The study was a technoeconomic evaluation of grid-affiliated residential construction applications photovoltaic (PV) systems. The system met the residential electricity demand from April to October and the 1530.23 kWh excess electricity was supplied to the grid</p>
32.	Y Cui et al. [54]	2020	—	Grid-connected	Domestic building	Electricity	@risk software	<p>The research developed grid-connected PV system sensitivity and reliability models. For PV cell and DC-DC converters, analytical relationships of first-order sensitivity are formed and the developed models can be implemented to any PV system for better performance</p>
33.	N Gupta et al. [55]	2017	—	Grid-connected	Load serving	Electrical	Pareto analysis and logic gate representations	<p>For an islanded PV-battery energy storage (BES) hybrid device, a power management control strategy is suggested in the research. The evaluation shows that the power management design was successful and met many islanded PV-BES hybrid systems goals, without overcharging, no output excess power generation, and no power transfer to the dump load</p>
34.	MP Bonkile, V Ramadesigan [56]	2019	—	Standalone	Load management	Physics-based battery	Single-particle model (SPM)	<p>The research concept of this paper includes the mathematical simulation of the solar panels and a battery backup study of the standalone unit</p>
35.	SS Dheeban et al. [57]	2019	—	Standalone	Load management	Electrical	MATLAB Simulink	

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
36.	E Roumpakias, A Stamatelos [58]	2019	Greece	Grid-connected	Load serving	Electrical	Performance ratio (PR), yield factor (YF), reference yield (YR), capacity factor (CF), and an array to capture losses (LC)	The emphasis of the research was on the efficiency of a grid-affiliated PV system in Central Greece that was operational for six years. The study indicates a slight efficiency reduction over the years, which declined between 1 and 4 percent
37.	BR VS, GG Devadhas [59]	2019	—	Standalone	Load serving	Electrical	Sub-maximum power point tracking (S-MPPT)	This research recommends a single-phase linear PV default scheduler system. It initializes any device to zero in the shortest period
38.	N Manoj Kumar et al. [60]	2017	Malaysia	Grid connected	Load serving	Electrical	Photovoltaic geographical information systems (PVGIS) and Watts PV software	The primary target of the research was to build a sun-based PV plant at two diverse campuses. The specialized feasibility used the open rack or free stand mounting position crystalline innovation-based PV plant utilizing the PVGIS and PV Watts software. The specialized presentation acquired through PVGIS is very similar to the PV Watts results
39.	N Kumar et al. [61]	2019	—	Grid-connected	Load serving	Electrical	Fifth-order general integrator (FOGI)	In the study, an instinctive control procedure dependent on 'fifth-order general integrator (FOGI)' was proposed for framework-associated sun-powered photovoltaic (PV) energy conversion system (SECS)
40.	YZ Alharthi et al. [62]	2019	—	Grid-connected	Load serving	Electrical	HOMER	The study assessed a hybrid renewable energy system linked to the power grid with 15000.0 kW daily load demand and 2395.3 kW peak load. The net present cost (NPC), leveled energy cost (LCOE), and system environmental effects were examined
41.	E Kurt et al. [63]	2019	—	Grid-connected	Load serving	Electrical	PSCAD	The efficiency of a DC grid-affiliated PV device under insolation and temperature variations was investigated in the study. The DC-DC boost

TABLE 1: Continued.

S. no.	Authors & references	Year	Location	Adopted technologies	Load type	Consumption type	Method	Objectives
42.	H Rezk et al. [64]	2019	Egypt	Standalone	Irrigation	Electrical	HOMER	converter was constructed to increase the system's performance An optimal islanded irrigation solar PV battery system (BS) for Al Minya, Egypt, was used in the study paper. The energy costs obtained were lower than those previously reported due to the correct selection of PV size and shape, as well as the correct selection of the site

achieved by hybrid optimization model for electric renewable (HOMER). At the selected sites, the technoeconomic feasibility of using hybrid photovoltaic/wind/diesel with battery storage systems to match the load of a typical rural healthcare center was evaluated. The system is based on long-term daily meteorological data ranging between 18 and 39 years in this study. The findings of HOMER simulations show that the hybrid system is the best solution for all of the study's locations. Since the diesel-only system provides the highest COE and emits CO₂, the hybrid systems involving PV/diesel/battery are considered ideal for RHC at remote locations within Iseyin and Port-Harcourt, due to the quality of renewable energy potential [15].

Fossil fuels like oil and gas are still playing a role in energy generation though people are now considering an alternative that provides energy demand by reducing it via energy efficiency and environment-friendly use of that energy resources. Since transport consumes a lot of conventional energy and generates greenhouse gases, therefore, the proposed measure to alter this issue is to use electric transportation. The HOMER program was used in this study [16] to develop and optimize a wind-solar hybrid energy charging station that will be beneficial for supplying power from renewable resources effectively and sustainably, managing grid load, and establishing additional charging stations.

PV systems have used distributed microgrids as efficient local electricity sources in regulated environments for energy consumers and inexhaustible energy generation. The global deployment of PV microgrids has expanded while taking the benefit of daily unrestricted solar insolation. In Rwanda, the average daily solar irradiation is between 4.0 and 5.0 kWh/m²/day [17]. The highest solar radiation for the selected site is seen in July where the value is 5.87 kWh/m²/day. Energy storage has been proposed, with the backup used during peak demand, power shortages, blackouts, or some other power loss in grid-connected systems. Global studies show that the world's total implemented photovoltaic capacity has been steadily increasing [18]. Rwanda is educating private investors on how to implement solar energy projects and narrow the gap between electricity

demand and supply [19]. Sustainable power sources to replace fossil fuels have been prioritized throughout the world for both economic and environmental reasons. The authors in [20, 21], confirmed the feasibility of a stable standalone electricity generation system for off-grid users using HOMER to model, evaluate, and optimize sustainable power sources that replace traditional energy sources. Table 1 below summarizes the successfully implemented researches made on a standalone, microgrid, and grid-connected solar systems in different parts of the world and their results prove to be viable.

This study gives a complete comparison of the state-of-the-art deterministic methodology to build a minigrid, including the influence of operating strategies to provide recommendations on conceptual models and operating strategies to researchers, developers, and professionals in the field. The standalone like, home lighting system (HLS) requires no major maintenance, and consumers could use it without being subjected to any influences, whereas minigrids are administered by cooperative societies founded by local governments and beneficiaries. In order to provide minigrid services in underdeveloped countries, it is necessary to establish an appropriate business strategy. The comparison as explained in literature, and Table 1 below was mainly based on consumer characteristics, net present cost, and the cost of energy, where it will depend on the quantity of the consumer as well as the different components available to be used in each household. Therefore, the result of the method adopted in our research compared to the electricity tariff in Rwanda is much more viable.

HOMER is particularly well suited to assessing prospective electricity possibilities in rural areas, as well as investigating the technical and economical effectiveness of hybrids provided a village load and energy resource availability. Therefore, this means different areas with different solar resources will provide different output solar powers where a minigrid supply system is being proposed for rural electrification programs. When the obtained energy costs were compared to the existing, current costs of electricity in Rwanda, it was discovered that this was the most cost-effective option. Previously, the solar home system was a simple choice, which included the

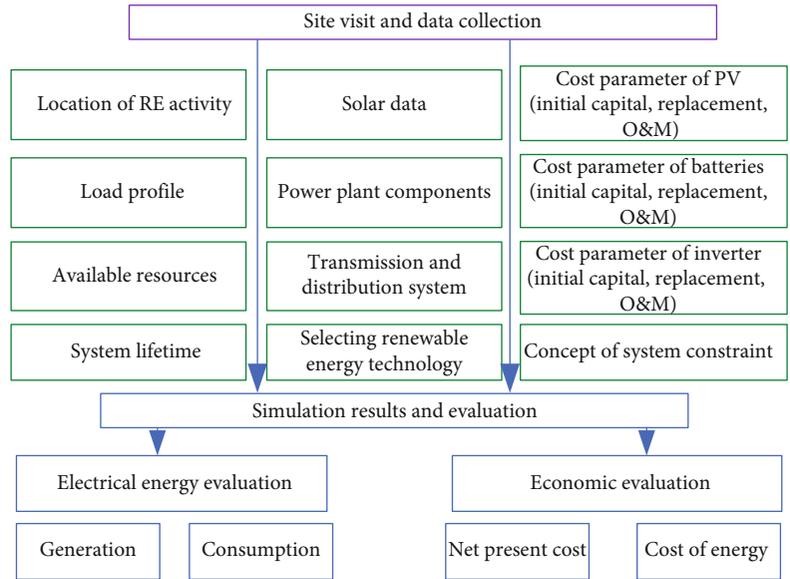


FIGURE 1: Illustration of the framework for analysis of the study. Abbreviations: RE: renewable energy; O&M: operation and maintenance.

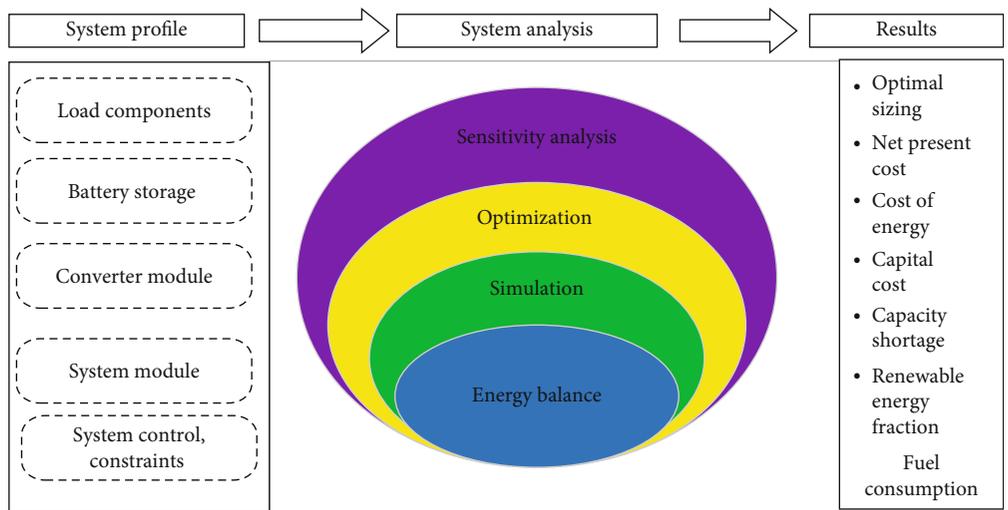


FIGURE 2: A detailed schematic representation of HOMER software.

implementation of PV panels, batteries, charge controllers, and inverter units for every residence and business structure in the village that used roof areas [22].

3. Methodology

HOMER software analyzed the data gathered from governmental energy organizations considering different photovoltaic systems uses in Rwanda’s rural settlements [65]. HOMER software created a variety of models that demonstrate how different natural sustainable energy sources combine to produce green power in this study. In addition, we started working with power plant owners and operators throughout the research to ensure the study’s reliability. According to these experts, relevant guidelines for the rural electrification planning process are lacking, posing risks,

causing market distortions, and necessitating research projects for new electric power plants.

The methodology of this study is depicted in Figure 1 below. All of the study requirements were conducted based on our team’s site visits and data collection. The data collected include electricity load demand profile, available resources, power plant production capacity, solar power plant components, and constraints. HOMER software performed the techno-economic analyses in this research. The purpose of these technical and economic analyses was to develop a practicable off-grid photovoltaic system that would suit Rwanda’s power sector at lower tariffs and maximum availability.

3.1. *HOMER Pro Software.* The HOMER Pro microgrid software is the world’s standard software for optimizing microgrids, from community power and islet utility services to grid-affiliated sites, and army assets [65]. Figure 2 presents

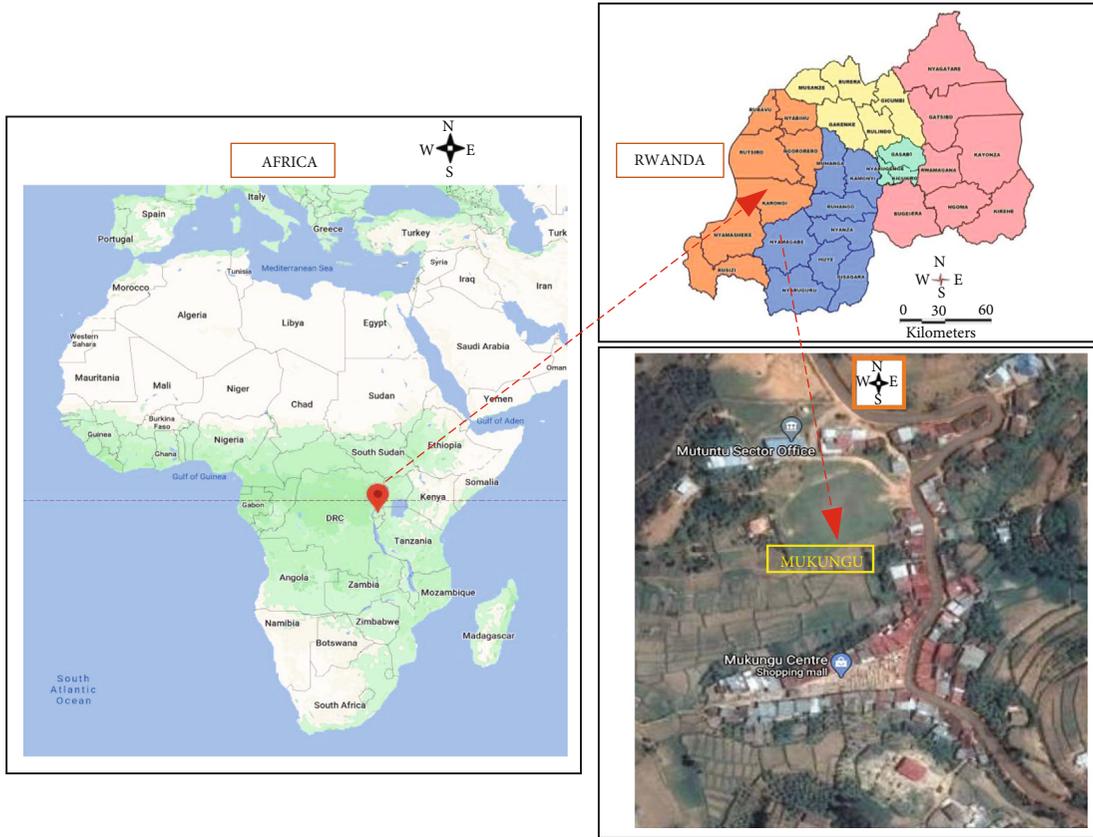


FIGURE 3: Location map of the selected study area (Mukungu village).

a schematic representation of the HOMER software. Imitation, optimization, and sensitivity analysis are the three primary functions of HOMER. It can strengthen power balance measurements, load profiling, location-specific tools, and system components are all factors taken into consideration by HOMER.

HOMER simulates feasible systems with device configurations in the simulation model. After each simulation, there is an optimization step. To achieve the best possible match, all imitated systems are categorized and refined according to specified parameters. Sensitivity analysis, on the other hand, is an optional function that allows HOMER users to model resource variables that are outside their control, like fuel prices and wind speeds. As a result, researchers can see how the ideal system changes because of these modifications [66]. The optimization ellipsoid encircles the simulation ellipsoid, showing that an imitation consists of several simulations. The sensitivity analysis ellipsoid, encircles the optimization ellipsoid, as in Figure 2.

3.2. Data Collection. In this survey, data were collected from 121 households in four Rwandan provinces, excluding Kigali city, using a specially designed questionnaire. Residents in the area were asked a series of questions as part of this study. The data were then summarized and analyzed using the Statistical Package for the Social Sciences (SPSS version 23.0). Consequently, the total energy

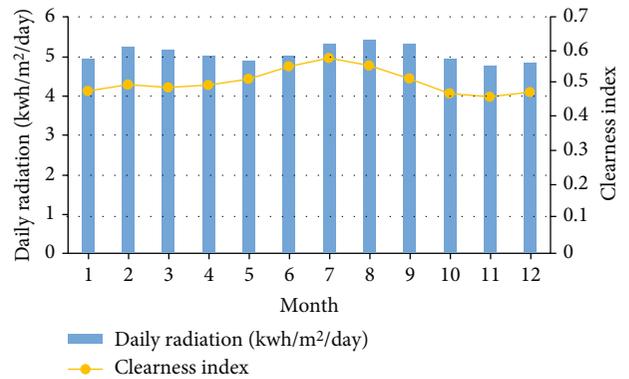


FIGURE 4: Solar energy profile at the preferred site.

consumption of people living in Rwanda’s off-grid areas was calculated, as well as the energy needs of each house. As a result, this investigation is aimed at approximating consumer requests, which is a prerequisite for designing a power plant.

Off-grid solar power deployment necessitates a year’s worth of solar irradiation. The National Aeronautics and Space Administration provided the input data for solar resources over a year in this case (NASA). Other data from the Rwanda Meteorology Agency was obtained and

TABLE 2: The projected everyday electricity demand for 121 houses in the village.

No.	Equipment in 121 households	No. in use	Power consumption (W)	Total power consumption (W)	Hours of use/day (Hrs/day)	Watt-hours/day
1	Lamps	891	10.0	8910.0	5.0	44550.0
2	Mobile phone	335	10.0	3350.0	8.0	26800.0
3	Ceiling fan	0	75.0	0.0	0.0	0.0
4	Radio	113	20.0	2260.0	5.0	11300.0
5	Television	49	120.0	5880.0	5.0	29400.0
6	Computer	4	100.0	400.0	5.0	2000.0
7	Refrigerator	5	500.0	2500.0	24.0	60000.0
8	Iron	19	1000.0	19000.0	1.0	19000.0
Daily total energy consumption in 121 households					193,050.0 Watt-hours/day = 193.05kWh/day	

Abbreviations: W: Watt; kWh: kilowatt-hour; Hrs: hours.

compared to NASA's data to ensure that the solar resource data obtained was correct. All these data were accurate, and they satisfy the requirement to be used in our study. Finally, the obtained data helped us to evaluate and verify the integration of solar power systems into Rwanda's power system.

3.3. Selected Site. Rwanda's government had approved a rural electrification strategy in the termination of 2016, in which the government, private industry, and relevant stakeholders collaborated to significantly boost rural electrification and establish lofty potential targets. Thus, in Rwanda's rural areas, pico/minihydropower, and minigrids from solar energy have been successfully implemented [67]. Mukungu village located in the Karongi District of Rwanda's Western province was chosen for this study, with GPS coordinates of S 02°13.9310' and E 29°24.590'. In addition, the details of the chosen village location are shown in Figure 3. This village has a picohydropower plant that provides energy to up to 400 households in the off-grid region, promoting economic development. Solar energy, fortunately, can also be used as an alternative energy source in this situation.

3.4. Solar Resource Availability Evaluation. HOMER utilizes four renewable energy sources: biomass, hydro, solar, and wind, as well as other fuels that the system's equipment requires [65, 66]. Rwanda has abundant renewable energy resources, and it is attempting to electrify Rwanda's off-grid villages. The Mukungu village solar resources were extracted from the surface meteorology and solar website of NASA. The solar energy profile at the preferred study site is depicted in Figure 4.

Generally, the PV array's power output is determined by the angle of incidence of the solar radiation on the earth. HOMER calculates the PV array output in Equation (1) below [65]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + \alpha_p (T_c - T_{c,STC})]. \quad (1)$$

The temperature power coefficient is zero if the temperature effects on the PV array are not modeled by HOMER software. Equation (1) becomes [65]

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right). \quad (2)$$

On the other hand, HOMER can define the monthly average clearness index K_T using the following [65]:

$$K_T = \frac{H_{ave}}{H_{o,ave}}, \quad (3)$$

where Y_{PV} is the PV array rated capacity (kW), f_{PV} is the PV discounting factor (%), \bar{G}_T is the PV array incident solar irradiation (kW/m²), $\bar{G}_{T,STC}$ is the emitted radiation under normal assessment conditions (1 kW/m²), α_p is the temperature power coefficient (%/°C), T_c is the PV cell temperature (°C), $T_{c,STC}$ is the PV cell temperature standard test conditions (at 25°C); H_{ave} is the normal monthly irradiation from the earth (kWh/m²/day); and $H_{o,ave}$ is the extraterrestrial horizontal insolation (kWh/m²/day).

3.5. Load Details of the Selected Site. All types of electrical appliances at home, as well as the time that the appliances are used by the residents, determine energy consumption [68]. The estimated load was determined in this study based on a survey directed at various communities across the country. Experienced judges tested a series of the developed questionnaires for validity and used them to gather energy consumption data from respondents. Representatives from 121 households completed the questionnaires about their household electrical devices and monthly power consumption pattern in the research. Table 1 shows the summary of results obtained through analysis of other studies and their input data. The daily energy demand of 121 homes, as well as their respective power ratings, are shown in Table 2.

The electricity demand in remote areas is lower than in cities, according to a comprehensive energy consumption

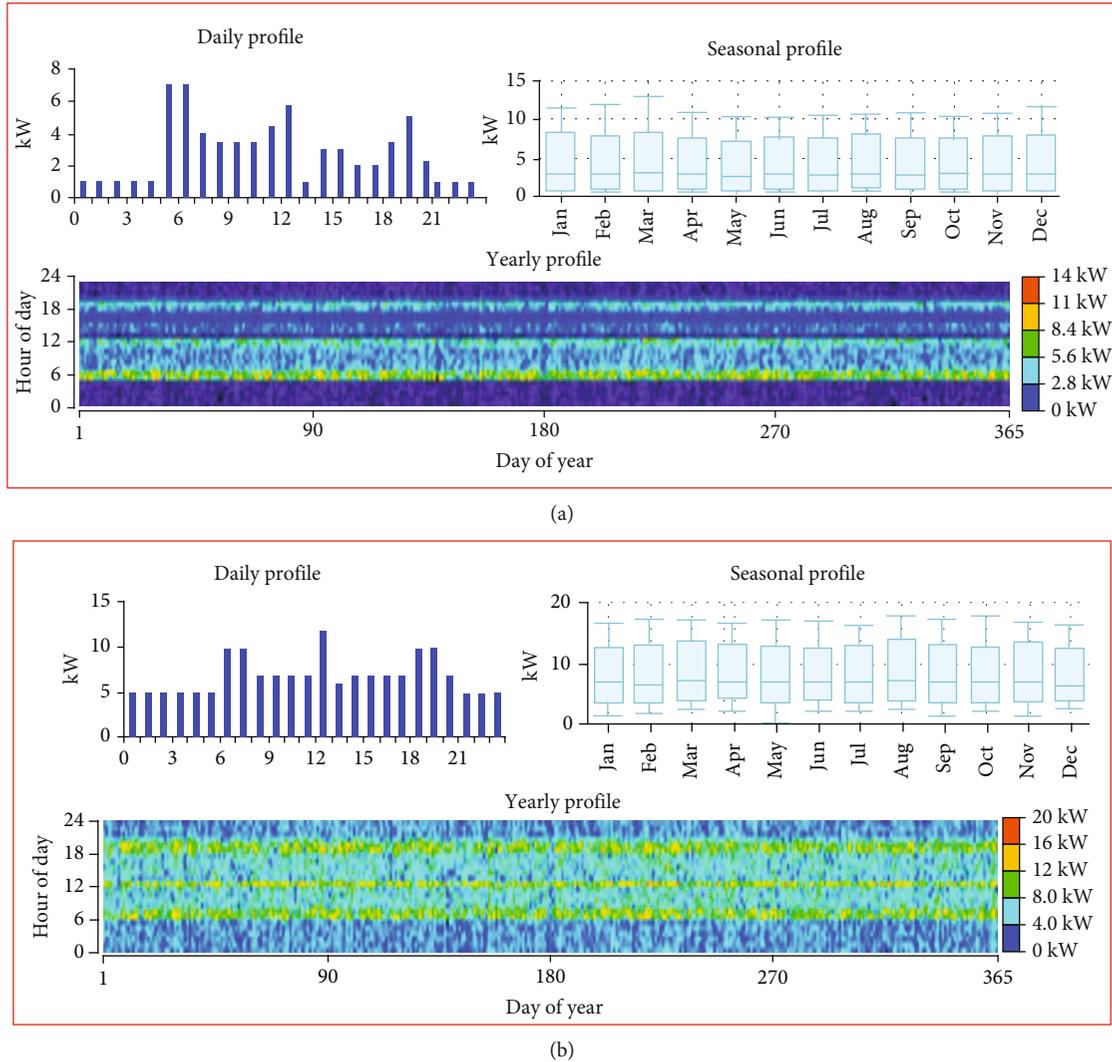


FIGURE 5: The daily, seasonal, and yearly load profiles: (a) electric load for the distinct off-grid household and (b) electric load for microgrids for a rural community in an off-grid area.

survey conducted in Rwanda. Household appliances that use electricity include radios, light bulbs, mobile phones, ceiling fans, electric irons, refrigerators, and laptops. Within each hour of the year, we must measure the sum of primary load in kilowatts using HOMER, either by importing hourly data from a file or by permitting HOMER to create hourly data from typical everyday load profiles. Consequently, HOMER generates typical load results depending on the consumer's features of everyday load [65]. The photovoltaic systems were designed, and their performance was evaluated in this study, taking into account the following suppositions:

- (i) 193.05 kWh per day is the primary load, and 20.64 kW peak load was assumed for an outside-grid PV microgrid for the rural society (121 households)
- (ii) The prime load of 1.6 kWh per day and 0.30 kW peak load were assumed for a remote grid solar PV microgrid system in the rural community

- (iii) The project's lifespan was decided based on the component warranty, which was estimated to be around 25 years. The load profile used in this survey during imitation is shown in Figure 5

3.6. System Design Components. We used various components in this research depending on the photovoltaic systems we needed to simulate. Photovoltaic solar was the resource in the HOMER analysis. In addition, electricity is stored and converted using batteries and a converter. The efficiency and cost of each of the system's components have a significant impact on the design outcomes. Data from Rwandan generating companies and private sector companies' mini-grid remote grids, as well as existing literature, were used to develop the study's technical and cost parameters. Tables 2 and 3 show the performance and cost of each component for an islanded PV system for a single home and an outside-grid PV microgrid for a remote neighborhood, respectively.

TABLE 3: System elements and their costs for an islanded PV of an individual home.

No.	Component	Rated capacity	Capital cost (USD)	Replacement cost (USD)	O&M cost/year (USD)	Lifetime (years)
1	Converter (system converter)	1.0 kW	3000.00	2500.00	800.00	15
2	Batteries (generic 1.0 kWh lead acid)	1.0 kWh each	300.00	2,00.00	40.00	10
3	PV (generic flat plate)	1.0 kW	1500.00	1100.00	40.00	25

3.7. Design and Modeling of Selected PV Systems in Rwanda.

Rwanda has a large number of untapped renewable energy source sites. Electricity is generated using hydro, solar, methane, peat, geothermal, wind, and waste energy. According to Rwanda's Environmental Management Agency (REMA) Outlook report from 2007, there are approximately 1200 MW of untapped power generation resources in Rwanda [67]. Unfortunately, so many of these resources remain unexplored. Rwanda's gross electricity generation was just 224.6 MW in 2019 [67].

HOMER is a sophisticated numerical modeling framework that offers much more details than traditional statistical modelers. It can perform imitation and responsiveness analysis with modest data [69]. Better designs are produced for likely inputs using net present cost (NPC), which is cost-effective. In addition, it generates power balance equations for every one of the 8760 hours annually, to simulate network operations. Consequently, it helps to determine viable configurations and approximate the installation cost and implementation of the power system over the project's life [69–71].

HOMER computes the average annualized cost for every item utilizing diversified costs and penalties for device pollutants. This value is also used to calculate the overall net present cost and the levelized energy cost (LCOE or COE) [65]. In HOMER software, the NPC can be evaluated using [65, 66]

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}, \quad (4)$$

where i is the yearly actual interest rate and N is the duration (years). Also, Equation (5) assesses the levelized energy cost [65, 66]:

$$\text{COE} = \frac{C_{\text{ann,tot}}}{E_{\text{prim}} + E_{\text{def}} + E_{\text{grid,sales}}} \quad (5)$$

where $C_{\text{ann,tot}}$ is the overall annualized cost, E_{prim} and E_{def} are the yearly overall basic and postponed load, respectively, and $E_{\text{grid,sales}}$ is the yearly power grid sales.

3.7.1. Standalone Solar Photovoltaic for a Single Residential House. First and foremost, those who are unable to connect to and be assisted by the publicly or privately owned utility grids are known as “off-grid users” [6].

As a result, standalone PV, minigrids, and microgrids can be used to provide electricity to such users. As previously stated, this part used HOMER Pro software to design,

imitate, and process available inexhaustible power generation technologies to ensure everyone in Rwanda has access to sustainable energy. Importantly, several site visits to a delegate of selected residential houses in Rutsiro district, Western province, Rwanda, were made to design standalone solar photovoltaic systems, efficiently. Moreover, the electrical devices, power rating, and hours of use variables were used during the studies.

The sketch of the islanded remote grid photovoltaic system for an individual household is shown in Figure 6(a). The distinct islanded solar home system, comprises the PV panel, batteries storage, converter, DC, and AC buses, and electric load. As shown in Figure 6, the total load profile was 1.6 kWh/day and 0.30 kW daily peak load. The estimated daily energy consumption for 121 residential houses in the village was 193.05 kWh/day, as demonstrated in Table 2 above. So, the daily energy load average for one residential house in an off-grid area can be easily estimated to be 1.6 kWh/day per residential house.

Previous researchers and experts in renewable energy and minigrids or microgrids have provided insights on what hybrid systems are, why we need them, their uses, and applications for sustainable energy development. According to the previous surveys and the outcome of this study, standalone systems for one single household and a community are the first-choice decision to be made while they may not be cost-effective.

3.7.2. Off-Grid PV Microgrid System for Rural Community.

The microgrid is important to intelligent power systems for increasing the distribution system's energy supply reliability and resilience. A microgrid is an interconnected collection of distributed energy and demand entities that function in either grid-connected or island mode within the network. Microgrids comprise small cell phone towers (as well as nanogrids), large commercial, industrial, and military facilities with generation capacities ranging from kilowatts to megawatts [72–75].

During our study, Figure 6(b) is the representation of the off-grid solar photovoltaic microgrid system for rural areas. The average daily load for that rural area was 193.05 kWh per day and a daily 20.64 kW peak (for 121 households). In addition, the photovoltaic system provides DC, while the converter transforms DC to AC and vice versa, which is supplied to the battery storage facility. Undeniably, research on various configurations or architectures of microgrid systems is gaining more attention to achieve the goals of carbon emission reduction.

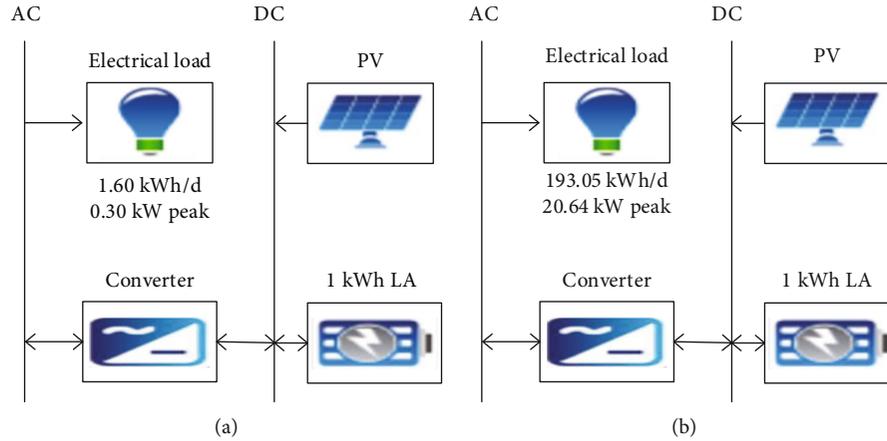


FIGURE 6: Various types of photovoltaic solar systems: (a) the standalone photovoltaic for a single residential household and (b) the PV microgrid system for the rural community in the off-grid area.

TABLE 4: Comparative simulation analysis for the proposed PV systems (we did not consider the sensitivity variables).

Resource	System architectures	Electricity production (kWh per year) (portion)	Total NPC (USD)	Cost summaries	
				LCOE (USD/ kWh)	Operating cost (USD per year)
Solar	Standalone (1 household)	2426.0	9284.4	1.23	428.08
Solar	Microgrid (community)	221,715.0	1,166,898.0	1.28	37,965.91

4. Simulation and Optimization Results Using Homer Pro Software

HOMER’s micropower optimization model was used to process the modeling and simulation results. For each responsiveness case it solves, HOMER imitates each system in the search space and rates all practicable systems in order of decreasing net present cost. HOMER optimizes small power systems by simulating a variety of device options under different restrictions and stimuli. These systems are compared using optimization tables. The optimization table contains information about each system’s architecture, such as the number of batteries, converter size, and PV capacity. It also includes information on costs like the levelized energy cost (LCOE), net present cost (NPC), running costs, preliminary capital, and clean energy proportion. Also, two solar energy systems were designed in this research using a large number of hourly parameters in the HOMER software simulation. The simulations and analyses took into account a variety of solar radiation values. Without taking into account the sensitivity variables, Table 4 illustrates the imitation and processing of two dissimilar remote grid solar PV for the selected survey site.

The simulation in this study considered different photovoltaic systems. As illustrated in Table 5 above, the minimum levelized cost of energy (LCOE) found from the simulation results was USD 1.23 per kWh for a standalone photovoltaic for an individual household. This standalone system generates 2426 kWh total yearly production and

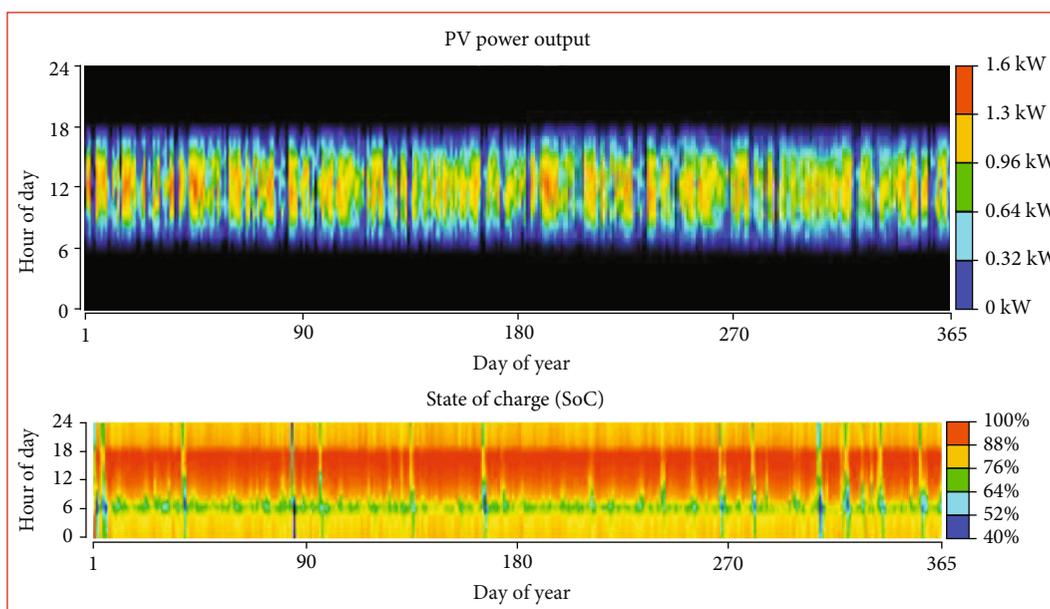
comprises 1.64 kW PV, 3 strings of batteries, and 0.262 kW of a system converter. The total operating cost and NPC for such photovoltaic systems are USD 428.08 and USD 9284.41 per year, respectively.

In contrast, the off-grid PV microgrid system for rural communities has shown a high LCOE compared to the standalone PV for an individual household. It generates 221,715.0 kWh total yearly production and comprises 150.0 kW PV, 443 strings of batteries, and 20.8 kW of system converter. For this photovoltaic system, the total NPC, LCOE, and operating costs were also USD 1,166,898.00, USD 1.28 per kWh, and USD 37,965.91 per year, respectively. In addition, PV output power and batteries’ charge state (SOC) of the simulated photovoltaic systems are graphically illustrated in Figure 7 below, where (a) is an islanded solar PV system for a dwelling house and (b) is a PV microgrid system for a remote neighborhood in the off-grid area.

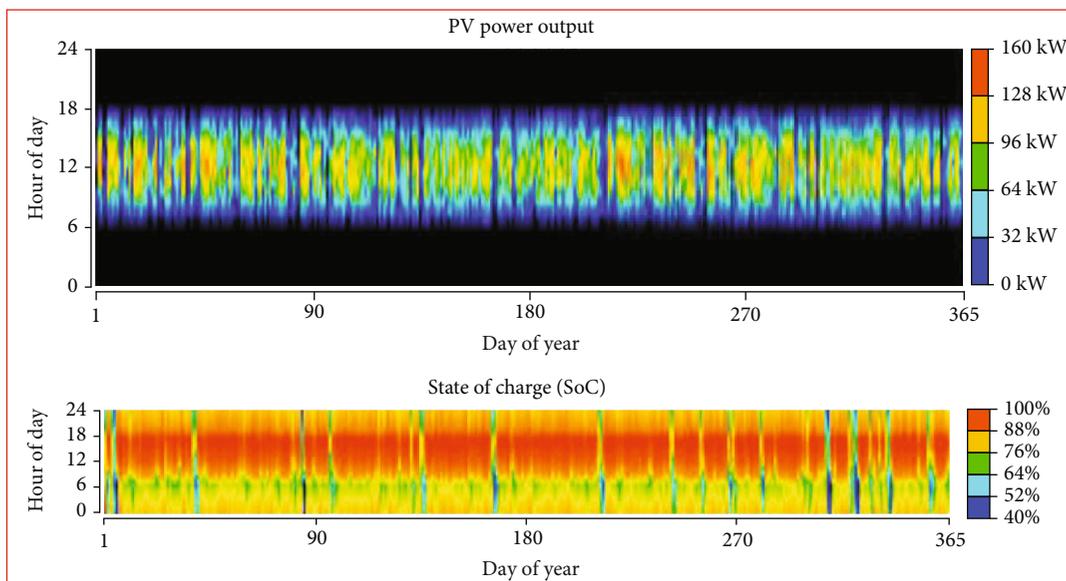
Because access to electricity is a key driver of development and welfare, Rwanda’s government has set a goal of providing electricity to 100 percent of all the population by 2024. Rwanda has future prosperity of renewable resources, including wind, solar, geothermal, hydro, and methane gas, all of which should be explored before making any decisions. This will undoubtedly encourage development projects, bringing the total capacity of electricity generation to 556.0 MW by 2024. Unquestionably, the findings of this study show that for off-grid users, small solar standalone systems for individual households are preferable because they can start providing energy more rapidly at a low price.

TABLE 5: Structure items and their expense for off-grid PV microgrid systems for the rural community.

No.	Component	Rated capacity	Capital cost (USD)	Replacement cost (USD)	O&M cost/year (USD)	Lifetime (years)
1	Converter (system converter)	10.0 kW	21,164.00	16,000.00	8000.00	15
2	Batteries (generic 1 kWh lead acid)	1.0 kWh each	1702.00	1000.00	60.00	10
3	PV (generic flat plate)	10.0 kW	18,500.00	15,000.00	20.00	25



(a)



(b)

FIGURE 7: PV power output and SOC of the simulated solar photovoltaic systems: (a) the standalone photovoltaic for a single residential house and (b) the off-grid solar photovoltaic microgrid system for the rural community.

5. Discussion

The electricity prices is constantly increasing due to the world's fast growing population that needs access to sustainable electricity to sustain modern life expectancy. In Sub-Saharan Africa (SSA), for example, people living without access energy remain a determining factor that contributes to persistent poverty [5]. In this area, urban communities are still served by inefficient and unstable networks, while rural areas still lack access to electricity, except for power given to fairly wealthy households by small/private generators. Using fossil fuels to produce energy has long been regarded as unappealing due to the release of hothouse gases into the environment that raises the overall carbon trail. The latter encompasses disastrous consequences including increased global warming as well as its related consequences [76, 77].

In the current era of accelerated development and globalization, countries all over the world are looking at the low-cost PV systems to replace their existing power generation mix to ensure the reliability, affordability, and sustainability of potential power systems [78]. In fact, most governments have made renewable energy production a top priority, not only to minimize their overall carbon emissions and achieve international climate targets but also to gain wider socioeconomic benefits. And as per the International Energy Agency, 1.3 billion people everywhere in the world cannot have access to reliable electricity, particularly in the countryside of the developing world where the expansion of the utility grid is exceptionally difficult [79]. With distributed and independent control solutions, the microgrid model has confirmed to be one of the most realistic solutions that could be used to distribute inexhaustible energy sources (DRES) and can mitigate the perceived complications of deployment with increased stability with natural catastrophes, physical/cyberattacks, and cascading power black-outs [80].

To date, conventional energy resources cannot provide enough energy to meet the demand and are generally not environmentally friendly. Solving this problem of the energy gap, solar energy can yield an adequate solution [81]. However, due to every site requirement, they provide unpredictable power generation. Renewable energy presents a challenge of power quality, reliability, power system stability, and reactive power compensation. The intermittent nature of renewable energy like the solar, wind is less predictable and time-variant. The influence of dust on PV panels in the UAE was researched, and it was discovered that after 5 weeks of outside exposure, there was a 10% drop in power production [82]. Due to its stochastic and random character, renewable energy systems pose substantial issues to traditional grids, such as frequency variation, voltage fluctuation, and harmonics.

The low efficiency and unreliability of PV systems [83] are the most serious challenges. This article's techno-economic model simulates minigrid, microgrid performance utilizing meteorological data, demand profiles, technology capabilities, and pricing data to identify the ideal component sizing of hybrid minigrids for rural electrification. The findings show how system sizing is influenced by location,

renewable resource availability, technological cost, and performance which cause output power unstable. HOMER assesses different designs using the levelized cost of electricity (LCOE), but it cannot assess different financial models [84].

Rural areas' big issue is lacking consumer demand density and generally consists of low-income groups; therefore, project rate of return on investment is difficult to achieve as planned. High costs, low energy efficiency, and a lack of suitable rules and information are among issues that PV systems confront [85]. Unlike consumers in developed countries who can afford the high upfront costs of installing solar panels on their roofs to produce electricity, the number of Africans in stricken need of solar power cannot accommodate such an investment, despite the fact that solar power has a positive economic and environmental case. The global solar market is controlled by industrialized countries such as China, Europe, and the United States, making it difficult for industry knowledge and skills to spread to local businesses. The state's taxes and regulations have made solar-powered town electrification prohibitively expensive [86]. Because system functioning necessitates real-time measurements of solar irradiation and ambient temperature data, the data collected is limited due to flaws in the measuring equipment [14]. Because minigrid payback times can easily exceed several years, providing a regulatory environment that includes valid agreements or subsidies is necessary to limit risks for investors [87]. Long-term financing for minigrid projects is frequently difficult to come through due to inflation is either high or uncertain [88].

Challenges regarding policies are as follows: The necessity of policy support for off-grid electricity is critical where mostly there is no long-term electrification strategy [89]. Licensing challenges are as follows: Retail or generation licensing procedures that are complicated, costly, and time-consuming deter investors and businesses from starting minigrid initiatives [90]. Tariff setting challenges are as follows: Tariff design conflict is exacerbated by the fact that, in comparison to cheaper grid-based electricity, off-grid system developers must charge significantly higher tariffs to meet investment and operating costs [91]. The challenges are shown in Table 6.

The construction of a distributed power generation plant with a transmission and distribution systems for the generated power is typically the most cost-effective solution in isolated areas where grid expansion are considered expensive. Solar energy is an especially appealing renewable choice for most of the African countries because it is decentralized, abundant, and cost-effective as technology progresses. It is also resistant to supply and price swings while it remains equally qualified for funding from mutual and multinational organizations aiming to increase the renewable energy outputs in these countries. This is accomplished by inexhaustible energy sources available as well as the introduction of microgrids/standalone systems as ideal solutions to rural electrification problems in developing nations. In particular, microgrids, standalone remote-grid systems are suitable for off-grid lighting because they minimize device costs by combining streetlight storage and using pole-mounted solar PV

TABLE 6: Challenges of off-grid electrification in a nutshell.

Policies	Tariff	Licensing setting	Financial	Technical	Social
No energy access plan identifies off-grid areas	Minigrids economic feasibility is under doubt	Licenses are expensive	Minor projects are ignored by financing programs	When dimensioning, there is no consideration for future need	There are no community-based educational initiatives
There is no long-term electrification plan in place	Tariffs are too high for rural populations to sustain	Licensing is a time-consuming and complicated process	Programs for short-term funding	Technical standards are inadequate	There are not enough examples of productive use scenarios
Regulations that are only in effect for a short period of time and are subject to change	There is no suitable payment method	There is no differentiation made between project sizes	Fiscal incentives are not available	Components that are mismatched with the environment	
External stakeholders are not involved in the collaboration because it is done in isolation	Tariff criteria are strict, and there is no distinction between comprehensive financial		The rate of return on investment is predicted to be below	There is no monitoring mechanism in place, and there are no responsible, certified employees	There was no community input throughout the planning stage
In minigrid initiatives, there is no clear description of stakeholder duties			Initial investment costs are high	There are not enough restrictions in place to assure dependable operation and maintenance	There is not enough technical expertise to hire local workers

for both charging batteries and distributed generation. These technologies ensure a critical position in meeting the global energy demands, and they are more than capable of providing power in a more effective, safe, secure, and updated manner.

The use of standalone solar PV systems can provide significant energy and environmental benefits over grid-connected solar PV systems. In communities with traditional energy and the greatest solar capacity, standalone solar PV systems present the strongest air pollution control benefits. In fact, the solar rooftop provides environmental benefits by replacing traditional (conventional) grid electricity. The standalone and microgrid systems simulated in this paper have provided best results; however, due to financial instability of most of the Sub-Saharan countries, a standalone PV system proves to be more viable to those scattered households.

6. Conclusion

Limited access to energy slows down the development and makes it harder for governments and people to establish growth targets. In this study, we designed and simulated off-grid PV power systems to provide electricity to a Rwandan remote county using HOMER software. Simulation results revealed that an islanded PV system for a dwelling home is the ideal off-grid power generation system for use in rural areas. The system is particularly cost-effective compared with a microgrid PV system that supplies electricity to a rural community in Rwanda. Results indicate that the total NPC, LCOE, and operating costs of a standalone energy system are estimated to USD 9284.40, USD 1.23 per kWh, and

USD 428.08 per year, respectively. This is also evidenced by our results in Table 5.

Consistent with the aforementioned, not only could standalone PV power systems be the ideal solution to the electrification of rural areas in Rwanda but also these systems could help the government and environmental agencies in the efforts to minimize weather-related problems and stir up the development of green energy systems as the country strives to provide reliable and sustainable energy to all its citizens. It is also believed that the proposed standalone solar PV system would equally contribute to the development of future renewable energy generation systems in other countries with similar environmental, climate, weather, and meteorological conditions around the world. In particular, neighboring countries such as Burundi, Democratic Republic of Congo (DRC), Tanzania, and Uganda, and all other countries in the region are estimated to be good candidates for such a system.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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