Hindawi
International Transactions on Electrical Energy Systems
Volume 2022, Article ID 6349229, 14 pages
https://doi.org/10.1155/2022/6349229

Research Article

# Techno-Economic Feasibility Analysis of a Solar Photovoltaic Hybrid System for Rural Electrification in Sierra Leone for Zero Carbon Emission

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Received 6 March 2022; Revised 3 May 2022; Accepted 16 May 2022; Published 31 August 2022

Academic Editor: Qiuye Sun



Remote area electrification is a crucial need in sub-Saharan Africa's drive to attain universal electrification. In Sierra Leone, with a rural population of over 5 million, the electrification rate accounts for less than 10% of the total inhabitants. This paper presents a comparative techno-economic analysis carried out to determine the most feasible of four individual options for off-grid mini-grid power generation system utilizing sources that include: Solar Photo Voltaic (SPV), Diesel Generator (DG), and Battery Storage (BS) system, to provide electricity for a rural and remote village located in the northwestern part of Sierra Leone (longitude 9.1°W and latitude 12.6°N), with an average daily solar irradiance between 4.6 and 6 kWh/m$^2$/day. An assessment of the total electrical load estimated an expected daily consumption of 178 kWh. Simulation, optimization, and sensitivity analyses of each one of the individual power generation systems were carried out using HOMER software. Economic parameters such as Cost of Capital (CC), Net Present Cost (NPC), Levelized Cost of Electricity (LCOE)), technical parameters (energy production characteristics), and greenhouse gases emissions were compared and analyzed. Key findings from the simulation result indicate that systems consisting of DG only ($29,750) and SPV/BS ($110,131) obtained the least and highest CC, respectively. Similarly, in a respective manner, the highest and least NPC were obtained for systems with DG only ($496,336) and PV/DG/BS ($152,491) over a 25-year project lifetime. Furthermore, the least LCOE was obtained for the system comprising PV/DG/BS ($0.336/kWh). With an expected annual generation of (75,121 kWh), PV/DG/BS was obtained to be the most optimal solution. The sensitivity analysis observed that a reduction in the discount rate consequently reduces the LCOE of such a system. Furthermore, the model accounts for a 90% renewable energy fraction, with a significant reduction in the amount of annual GHG emissions, when compared with a generation system using diesel generator only.

## 1. Introduction

The sustainable energy development aims to create access to reliable and sustainable electricity supply for all by 2030. The continent of Africa is reported with an approximate population of 1.2 billion people, with 60% of this total population residing in rural area, whereas rural electrification accounts for approximately 45% of this total (The Alliance for Rural Electrification (ARE), 2020). Extending electricity access to many rural and remote communities of Africa is still a major challenge. A few literatures [1–3] have cited some of the associated technical and economic challenges that serve as a major hindrance to electricity grid extension to rural and remote locations.

Sierra Leone has a total national population of 8 million people, with 65% of this total residing in rural communities. The country however is faced with a challenge of creating access to sustainable electricity supply to meet the needs of about 80% of its population who presently live without access to on-grid electricity supply. In 2021, national electricity access rate was reported by [4] as 23%; meanwhile, rural electrification accounted for less than 10% of the inhabitants.

Electricity in rural areas is accessed mainly through the use of stand-alone diesel or gasoline generation units, rooftop solar-home systems, or solar pico-lanterns. Other sources of domestic energy supply include the use of kerosene lamps and nonrechargeable alkaline battery torchlights for lighting, as well as biomass wood for cooking and heating—which often results in health threats to mostly women and children who usually carry out domestic or commercial cooking activities.

Sierra Leone possesses exploitable potentials of renewable energy resources, namely, biomass, hydro, and solar energy resources. Solar energy potential is predominant, with an annual average direct normal irradiation ranging between 4.6 and 6 kWh/m$^2$/day . To date, there has been no comprehensive survey on the use of solar energy technologies in Sierra Leone. However, SPV systems in the form of mini-grids, stand-alone systems, and solar pico-lanterns are known to be widely used in generating and supplying power for use in households, hospitals, schools, and other important social facilities including communal water supply and farm irrigation systems.

Rural electrification remains a major challenge in Sierra Leone, where these communities mostly account for low-income inhabitants. Furthermore, the relatively high cost of extending the centralized national electricity grids has made the use of stand-alone off-grid power generation systems, mainly in the form of hybrid mini- and microgrids, as well as stand-alone systems, utilizing solar PV units, a preferred model of electricity generation and supply in the few communities, which have been electrified these communities. Solar photovoltaics systems have been widely noted to provide a suitable option to meet electricity needs for off-grid locations. However, academic studies on off-grid hybrid solar minigrids are few and far between. This work seeks to contribute to this regard by providing a methodology carrying out the technical and an economic analysis on four options of power generation systems for application in a typical rural and remote location in Sierra Leone.

The power generation models considered for analysis include source(s) employing:

(1) DG only

(2) A combination of SPV and DG

(3) A combining SPV and BS

(4) A combination of SPV, DG, and BS

This study aimed at carrying out a comparative technical and an economic analysis for supplying reliable electricity to a remote village. The objectives of this study carried out the following: energy resources and electrical load demand assessment and simulation of energy models (also called scenarios) using homer software.

The comparative analysis is carried out based on results obtained from the simulation software—Hybrid Optimization for Multiple Electric Renewables (HOMER) software. Using HOMER software, simulations were carried out for each one of the four power systems considered. Specific economic characteristics including CC, the NPC, the LCOE, the technical characteristics of the system (including the sizes of each of the component included in a power system), as well as the electricity production characteristic (including the quantity of electricity produced and the overall and individual production characteristics) were analyzed in this study.

This paper presents methods and findings obtained from the simulation and analysis carried out. The remaining part of this manuscript is presented in the following format:

(i) Section 1 reviews existing literature on case studies of related projects that have been carried out on the subject across the sub-Saharan Africa continent and beyond

(ii) Section 2 defines the relevant study approach used to conduct the research, as well as the application of HOMER software

(iii) Section 3 provides a comparative analysis of the four scenarios based on the results obtained and further discusses key findings obtained from the simulation results for the various scenarios considered

(iv) Section 4 outlines the conclusions and recommendations drawn from the study

*1.1. Literature Review.* Due to the intermittency in power production from the use of SPV systems as a single source of power generation in their applications, hybrid power systems, combining SPV system with at least a generation source and or a storage device, have been widely researched and proposed as a suitable option to provide reliable power supply for off-grid applications worldwide [5]. Power generation using such systems can be from both renewable and nonrenewable energy resources including SPV systems, wind turbines, hydro power plants, diesel generator, steam turbines, or other nonconventional power generation sources.

Across Africa and beyond, a body of literature exists on techno-economic feasibility studies of SPV hybrid system, to assess their potential in terms of providing reliable electricity supply for off-grid communities across SSA. Many of these studies sought to assess the associated technical requirements and economic cost, carrying out a comparative analysis in order to determine the feasibility of different possible options of hybrid systems for the particular locations considered. For the existing studies cited in this work, assessments were carried out with the use of HOMER software—a specialized software designed to carry out feasibility study for hybrid mini- and microgrids. Existing literature on techno-economic studies across sub-Saharan Africa are cited as follows.

A work by authors [6] assessed the techno-economic feasibility of hybrid electricity systems including SPV, DG, and BS system for electricity generation for selected off-grid rural locations in Jos community, located in northern Nigeria. A similar study [7] considered as case study a remote village, Fouay, located in Benin. The authors of [8] carried out a comparative techno-economic assessment amongst three options of HES: hybrid SPV, stand-alone SPV, and stand-alone DG in northern Cameroon. Other similar case studies outside of Africa include works outside of Africa can be cited from [9–11]. Literature from the cited works have indicated the viability of hybrid SPV systems as a means creating electricity access to rural and isolated communities.

In Sierra Leone, academic literature on the techno-economic feasibility of solar PV systems are few. However, closely related research works include a study on grid-connected renewable system in Freetown [12] and a comparative study on hybrid renewable power generation [13].

## 2. Methodology and Materials

A breakdown of the study methodology is summarized in the following steps:

(i) Resources assessment and electrical load data collection

(ii) Daily electrical load data estimation

(iii) Simulation of the four power model scenarios

In the resources assessment phase, renewable energy generation resources were assessed in order to identify their potentials for power generation for the case study site. For this reason, both solar and wind energy resources were assessed. Data for the assessment were obtained from NASA online data set containing information on energy and climate resources for the location.

Homer software is used to carry out simulation, optimization, and sensitivity analyses for the four scenario of power systems considered. Sensitivity analysis is carried out on the most economical system to determine as well as carrying out a sensitivity analysis on the best-case system. The methodologies mentioned are discussed in subsequent sections.

*2.1. Profile of the Study Area.* Masunthu village is in Kambia district, northwestern part of Sierra Leone (longitude 9.1°W and latitude 12.6°N). The community has a land size of approximately 110,000 $m^2$ (Google Earth, 2021), with the community located at approximately 27 kilometres from the district's administrative headquarter town (Google maps data).

The community hosts 1,004 inhabitants, where 54% represents female inhabitants (Local village statistics, October 2021). The primary source of economic livelihood is subsistence farming, where value addition activities such as local garri production and soapmaking are carried out. The basic social facilities present include church, cinema, clinic, playing field, mosques, schools, shops, and water supply system.

The community is in an equatorial climatic zone with two distinctive seasonal weather patterns: rainy season (lasting from May to November) and dry season (lasting from December to April). The former is characterized by long periods of sunshine with average sunshine hours of between 4.5 and 6 hours a day, while the latter is characterized by higher levels of rainfall (between 2,000 and 3,000 mm) and frequency of cloudy days (Meteorological statistics, 2012). The vegetation type is tropical savannah grassland. Figure 1 shows ariel view of the Masunthu village.

*2.2. Electricity Situation.* The community is located off-grid and approximately 80.4 km (50 miles) from the closest national transmission grid (Google Earth, 2021), the Bumbuna hydro power transmission line. Primary energy use in the village meets the needs for domestic cooking, lighting, and powering of electronic devices (radio and phone charging). According to the United Nations multi-tier framework for energy access, electricity access for the village is categorized under the "Tier-1" framework [14], where pico-solar lanterns and torchlights with small photovoltaic cells and batteries are used to provide nighttime lighting for households. Charging of phones is accessed through a local telecentre for 0.1 USD per charge cycle per phone. Electricity generated from a 250 Wp solar module supplies power to an existing underground water pumping system used for community water supply purposes.

*2.2.1. Solar Energy Resources Assessment.* Table 1 summarize data on solar and wind energy potential of the case study area. The information from the data indicates solar energy as a source with viable potential for electricity generation. Wind power generation is infeasible due to low average wind speeds.

*2.2.2. Electrical Load Assessment.* Load assessments were completed in order obtain information necessary for estimating the expected daily electrical energy demand for the village. The assessment used a survey questionnaire developed in principle with the standard GIZ procedure minigrid sizing. A total of 50 questionnaires were issued and interviews were conducted with representatives from households, small businesses, and other social facilities that include schools and religious houses. Part A of the questionnaire asked general questions on the villagers' present means of meeting their needs for lighting, cooking, phone charging, and other uses of electricity. The load consumers were categorized into three categories, including household, commercial, and community loads. Table 2 shows the summary of village electrical loads.

Based on predictable factors such as villagers' daily routine and their expected consumption patterns, a few

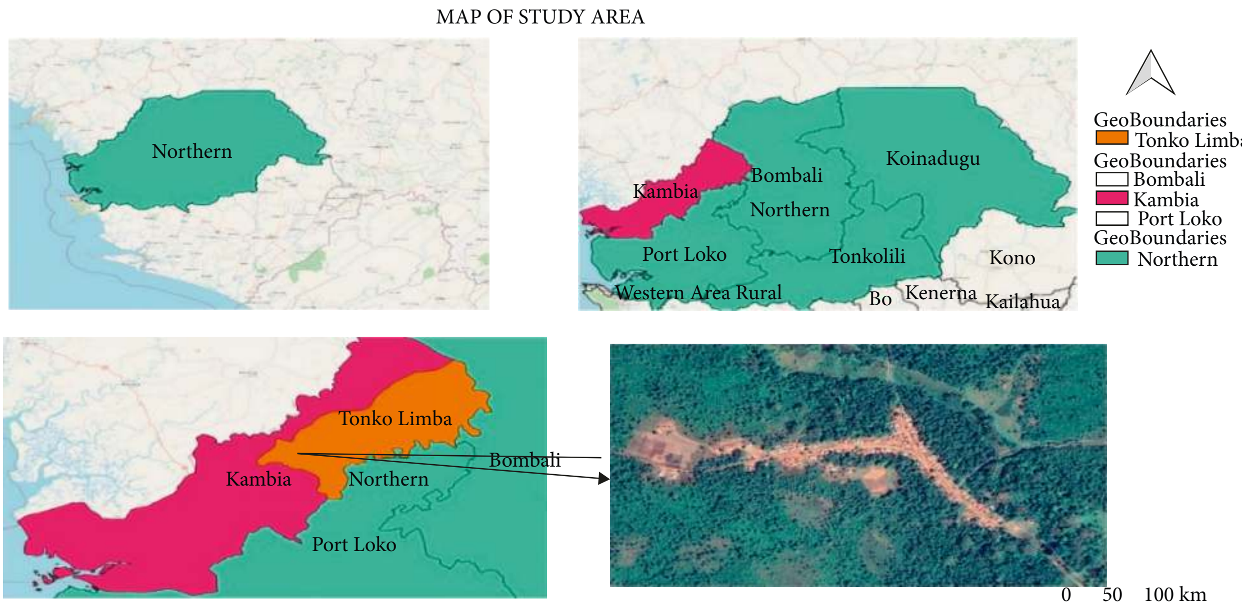


FIGURE 1: Ariel view of the Masunthu village. Source: Google maps.

TABLE 1: Solar and wind energy characteristics of Masunthu.

| Month | Air temperature (°C) | Earth temperature (°C) | Atmospheric pressure (kPa) | Relative Humidity (%) | Wind speed (m/s) | Daily solar radiation: horizontal (kWh/m$^2$/d) | Equivalent number of no-sun days |
|---|---|---|---|---|---|---|---|
| January | 26.000 | 25.9 | 99.4 | 73.3 | 3.600 | 5.600 | 4.31 |
| February | 28.170 | 26.8 | 99.4 | 77.0 | 3.640 | 6.130 | 2.22 |
| March | 29.510 | 27.0 | 99.3 | 80.3 | 3.880 | 6.440 | 2.13 |
| April | 29.420 | 26.9 | 99.3 | 83.0 | 3.950 | 6.300 | 1.57 |
| May | 27.980 | 26.4 | 99.5 | 85.9 | 3.540 | 5.480 | 2.92 |
| June | 26.190 | 25.4 | 99.6 | 87.7 | 3.760 | 4.740 | 6.48 |
| July | 24.880 | 24.3 | 99.7 | 87.5 | 4.710 | 4.340 | 5.08 |
| August | 24.530 | 23.9 | 99.7 | 88.0 | 5.150 | 4.060 | 4.57 |
| September | 25.020 | 24.5 | 99.6 | 88.0 | 4.140 | 4.560 | 4.35 |
| October | 25.630 | 25.1 | 99.5 | 87.5 | 2.990 | 4.760 | 4.31 |
| November | 25.640 | 25.4 | 99.4 | 85.5 | 2.570 | 4.890 | 4.27 |
| December | 24.940 | 25.1 | 99.4 | 80.1 | 3.340 | 5.280 | 3.5 |
| Annual | **24.6** | **25.5** | **99.5** | **83.7** | **3.77** | **5.22** | **45.71** |

Source: International Energy Agency, 2021.

TABLE 2: Summary of village electrical loads.

| Type | Number |
|---|---|
| Church | 1 |
| Mosque | 1 |
| Health clinic | 1 |
| School | 2 |
| Cinema | 1 |
| Shop | 3 |
| Street lighting | 15 |
| Tailoring centre | 1 |
| Household | 91 |

assumptions were made in the estimation of the total electrical load.

The assumptions include the following:

(i) Power ratings of equipment are assumed to be of standard average sizes, to cater for the probability of the use of nonenergy saving electrical devices: computer (120 W), fan (65 W), fridge (120 W), light (10 W), and phone (5W).

(ii) Only low power consuming Alternating Current (AC) loads were considered in the sizing process.

(iii) Load types were categorized into two seasonal loads: (1) summer loads and (2) winter loads (representing load consumption in the dry and rainy seasons, respectively).

(iv) The hourly load consumption was calculated using the following formula:

$$\text{Horly Load consumption (kWh)} = \text{Elecrtical Load}\,(kW)^{*}\,\text{Time of use (hour)}. \quad (1)$$

Table 3 shows the load demand category.

### 2.3. Homer Software Simulation

*2.3.1. Simulation Scenarios.* Simulation scenarios is found in Table 4. Economic specifications for solar panel is given in Table 5.

*2.3.2. Description of HOMER Software.* HOMER software is an optimization tool developed in 1993 by the National Renewable Energy Laboratory (NREL), widely used to carry out techno-economic feasibility studies for both off-grid and grid-connected applications worldwide [15]. HOMER software carries out three key functions: simulation, optimization, and sensitivity analysis [16]. Figure 2 shows the Homer software and user interface. Specific technical and economic parameters as inputs that include:

(i) Load and energy resources input. The daily electrical load consumption is used as an input to generate the daily electrical load profile (load consumption).

(ii) Power system component input. These include the details of aggregate components that make up a power generation or a storage system, including their technical and cost specifications where necessary.

(iii) Specific economic inputs. Project lifetime, inflation rate, interest rate, and diesel fuel price

HOMER runs multiple *simulations* on a selected power generation model, in the process, optimizing the technical and economic performance of the system over an entire calendar year of 365 days.

Technical output calculated by HOMER include the following: the total size of the system, specifications and performance of the individual components, power produced, economic outputs calculated that include the LCOE, and the annualized and total NPC and CC. GHG emissions calculations are also made. The key economic parameters are defined as follows.

The NPC of a generation system gives the sum of all associated income and outlay costs over the lifetime of the project.

The Levelized Cost of Energy (LCOE) is the minimum cost of energy beyond which an investment made is infeasible. LCOE compares investment alternatives amongst two or multiple projects. In HOMER, LCOE is defined as the average cost per kWh of useful energy.

### 2.4. Simulation Input Parameters

*2.4.1. Components*

*Solar PV panel.* Solar module converts irradiance into electricity using the photoelectric effect. HOMER calculates the size required and the power output of the SPV array. Table 5 shows the economic specifications for solar panel.

*Power converter.* A power converter converts between alternating current (AC) and direct current (DC) voltage. The input characteristics of the selected power converter are summarized in Table 6. The required size of the converter is calculated by using HOMER.

*Diesel generator.* Diesel generator when used in hybrid system can serve as a source of secondary or backup power supply. The economic input characteristics of the diesel generator are given in Table 7.

*Battery bank.* The battery bank stores and supply energy when needed. Technical and economic inputs for the battery unit are as specified in Table 8.

*2.4.2. Specific Economic Inputs and Sensitivity Inputs.* The specific project economic inputs used in the simulation are summarized as given in Table 9 which shows the economic input for diesel generator.

The price of diesel fuel, discount rate, as well as the inflation rates were obtained from national figures as of October 2021 [17]. In order to carry out the sensitivity analyses, values higher and lower than the original ones were selected. Observable project economic output variables include LCOE, NPC, and CC.

Diesel fuel prices in Sierra Leone are susceptible to unstable surges in market prices. As of October 2021, the pump-price of a litre of diesel fuel is 0.75 USD.

The nominal discount rate of 24% was used, as this represents the interest rate charged on financial lending provided by the Central Bank of Sierra Leone. The real discount rate used is calculated in homer as given in equation (2):

$$R = \frac{(r - f)}{(1 + f)}, \quad (2)$$

Table 3: Load demand category.

| Category | Load type | Summer (kWh/day) | Winter (kWh/day) |
|---|---|---|---|
| 1. Community load | Church | 1.21 | 1.21 |
| | Health centre | 20.43 | 20.43 |
| | Mosque | 1.18 | 1.18 |
| | School (2) | 13.42 | 7.81 |
| | Street lighting (15) | 6.6 | 6.6 |
| | Total (kWh/day) | 42.84 | 34.19 |
| 2. Commercial load | Cinema | 4.18 | 4.18 |
| | Shop (3) | 5.31 | 4.24 |
| | Training centre | 2.83 | 1.79 |
| | Total (kWh/day) | 12.32 | 10.21 |
| 3. Household load | DVD | 6.75 | 6.75 |
| | Fan | 18.66 | 0 |
| | Fridge | 6.50 | 6.50 |
| | Light | 33.67 | 33.67 |
| | Phone | 8.41 | 8.41 |
| | Radio | 26.70 | 26.70 |
| | TV | 22.50 | 22.50 |
| | Total (kWh/day) | 123.21 | 104.53 |
| Daily load (kWh/day) | | 178.37 | 148.93 |

Table 4: Simulation scenarios.

| Scenario | Configuration |
|---|---|
| Scenario a (SA) | DG only |
| Scenario B (SB) | PV + DG |
| Scenario C (SC) | PV + BS |
| Scenario D (SD) | PV + DG + battery |

Table 5: Economic specifications for solar panel.

| | |
|---|---|
| Capita cost ($/kW) | 800 |
| Replacement cost | N/A |
| O&M ($) | 10 |
| Lifetime (years) | 25 |


Figure 2: HOMER software user interface.

Table 6: Economic specifications for power converter.

| | |
|---|---|
| Capital ($/kW) | 350 |
| Replacement cost ($/kW) | 350 |
| O&M ($) | — |
| Lifetime (years) | 15 |

Table 7: Economic input characteristics for diesel generator.

| Generator fuel | Diesel |
|---|---|
| Capital ($/kW) | 850 |
| Replacement cost ($/kW) | 850 |
| O&M ($/hr) | 0.02 |
| Lifetime (hrs) | 20,000 |

Table 8: Techno-economic input for battery storage.

| Name | EnergySafe SX |
|---|---|
| Capacity (Ah) | 411 |
| Voltage (V) | 12 |
| Throughput (kWh) | 2,589 |
| Depth of discharge (%) | 70 |
| Number of parallel strings | 4 |
| Capital ($) | 250 |
| Replacement cost | 250 |
| O&M | — |
| Lifetime (years) | 6 |
| Efficiency (%) | 97 |

Table 9: Economic input for diesel generator.

| Table of sensitivity input variables | | |
|---|---|---|
| Variable | Value | Sensitivity input values |
| Interest rate/discount rate (%) | 24 | 30, 15, 4 |
| Inflation rate (%) | 10.2 | 13, 6, 3 |
| Diesel fuel price ($) | 1 | 0.95, 1.25 |
| Project lifetime (years) | 25 | |

Table 10: Characteristics of controller.

| Type | HOMER cycle charging/load following |
|---|---|
| Capacity (kW) | — |
| Capital ($) | 3000 |
| Replacement cost | 3000 |
| O&M ($) | — |
| Lifetime (years) | 15 |

where $R$ is real discounted rate, $r$ is nominal discounted rate, and $f$ is the expected inflation rate (18).

*2.4.3. Operational and Control Strategies.* Both the cycle charging and the load following dispatch strategies were selected in different simulation processes [18]. In the simulation, the load following strategy was used for SB, whereas cycle charging was used for cases of SC and SD. Table 10 shows the characteristics of controller.

## 3. Results and Discussion

*3.1. Daily Electrical Load Profile.* Figure 3 gives the daily electrical load profile for Masunthu village. A total daily consumption of 178 kWh was estimated. Community, commercial, and household loads account for 24, 7, and 67%, respectively, of the total consumption.

Electrical energy demand is lowest between periods of 00:00 and 08:00, as Villagers register their typical sleeping time during this period. There is also an expected rise in demand between 05:00 am and 06:00 am, mainly due to the muslim villagers rising to attend their daily religious prayers.

During energy demand for household is expected to be low as villagers attend to their daily occupations; meanwhile, electricity demand from commercial and community loads is expected to increase.

Peak energy demand is expected to occur in the evening hours between 7:00 pm and 10:00 pm due to an increase in the expected household demand. Consumption is estimated to vary on a seasonal basis, with electricity demand in summer estimated to be higher than that in the winter due to an increasing use of electrical power consuming appliances.

Simulation was done for each one of the four individual scenarios. The schematics of scenario for different configurations obtained from the simulation are, shown as given in

Table 11: Architectures of the four simulation scenarios.

| | System architecture for the different simulation scenarios | | | | |
|---|---|---|---|---|---|
| | DG (kW) | SPV (kW) | BS (units) | Converter (kW) | Controller |
| Scenario A | 35 | — | — | — | — |
| Scenario B | 30 | 56.2 | — | 17.7 | Load following |
| Scenario C | — | 77 | 108 | 30.2 | Cycle charging |
| Scenario D | 30 | 45 | 68 | 31 | Cycle charging |

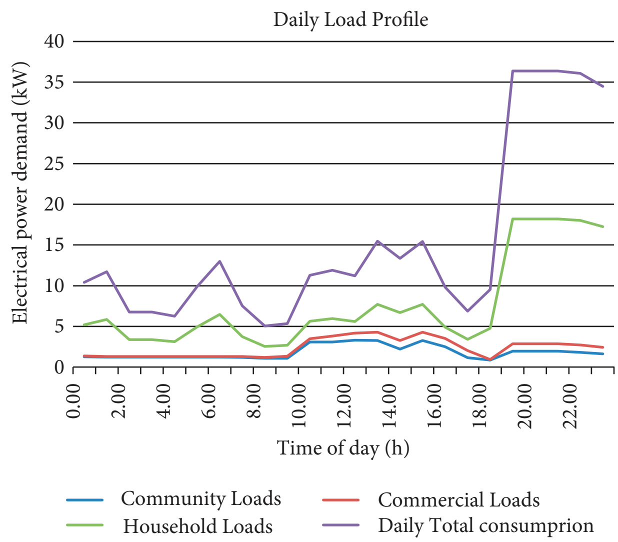


Figure 3: Daily electrical load profile of the village.

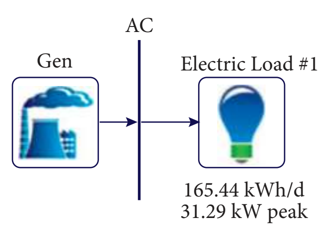


Figure 4: Schematic of scenario A.

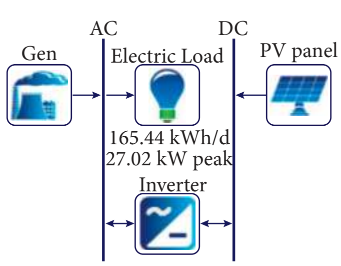


Figure 5: Schematic of scenario B.

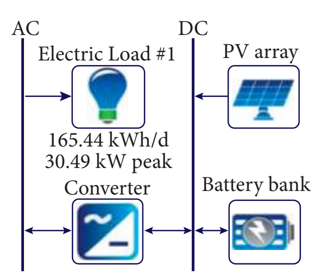


Figure 6: Schematic of scenario C.

Figures 4–7. Table 11 shows the architectures of the four simulation scenarios. Table 12 shows the technical and economic characteristics of the four scenarios.

A breakdown of the NPC over a 25-year period obtained for each of the scenarios are given as shown in Figures 8–11.

SA ($496,336) gives the highest NPC amongst the four scenarios simulated, due to its high associated cost of fuel and maintenance cost. SD ($152,491) gives the lowest NPC, slightly lower as compared to the NPC obtained for SC ($153,349). The NPC obtained for SB ($309,541) doubles those obtained for SC and SD.

The high cost of battery storage component required makes SC ($110,131) the system with the highest initial

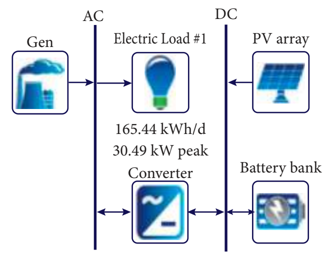


FIGURE 7: Schematic of scenario D.

TABLE 12: Technical and economic characteristics of the four scenarios.

| | Scenario type | | | |
|---|---|---|---|---|
| Architecture | Scenario A (SA) Diesel only | Scenario B (SB) PV + diesel | Scenario C (SC) PV + battery | Scenario D (SD) PV + diesel + battery |
| NPC ($) | 496,336 | 309,541 | 153,350 | 152,491 |
| CC ($) | 29,750 | 78,147 | 110,131 | 97,482 |
| LCOE ($/kWh) | 0.955 | 0.677 | 0.337 | 0.336 |
| O&M ($) | 23,201 | 24,141 | 937 | 1,266 |
| Total electricity production (kWh/yr.) | 91,869 | 137,090 | 112,728 | 75,121 |
| Excess electricity produced (kWh/yr.) | 31,483 | 75,877 | 47,952 | 10,165 |
| Renewable fraction | 0 | 0.10 | 1 | 0.87 |
| Fuel consumption (L) | 38,816 | 21,730 | 0 | 2,302 |
| Greenhouse gas emission (kg/yr.) | 103,103 | 57,733 | 0 | 6,117 |

TABLE 13: Summary of technical specifications of the most optimal system.

| Components | Specification |
|---|---|
| PV array | 45.5 kW |
| Battery | 68 units |
| Diesel generator | 31 kW |
| Converter | 28 kW |

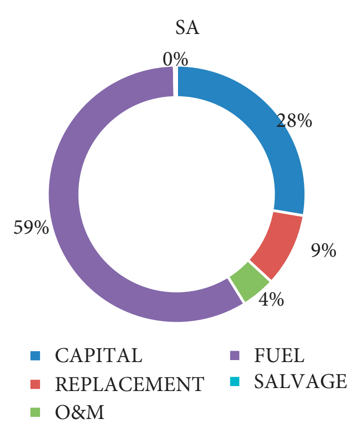


FIGURE 8: NPC breakdown for SA.

capital cost. Initial capital cost is relatively lowest with SA ($29,750).

SD ($/kWh 0.336) gives then lowest LCOE, almost equal to the LCOE of SC ($/kWh 0.337). The highest LCOE is associated with SA ($0.995/kWh), which generates power using DG only, followed by SB ($/kWh 0.677).

SC possesses the least lifetime O&M cost ($937) due to the use of a completely renewable energy system. SB

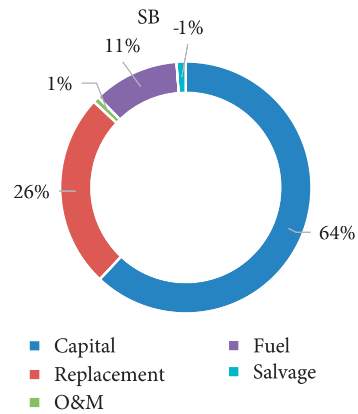


Figure 9: NPC breakdown for SB.

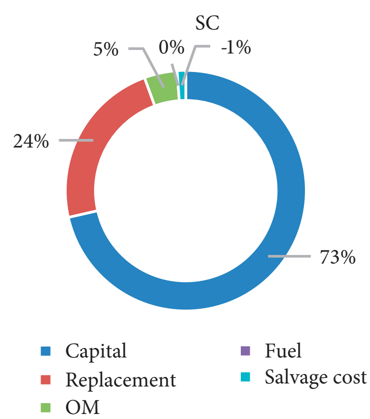


Figure 10: NPC breakdown for SC.

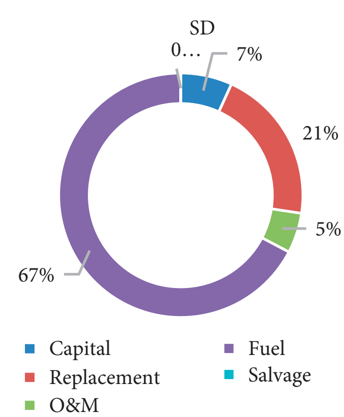


Figure 11: NPC breakdown for SD.

($24,141) that combines SPV and DG gives the highest O&M cost, closely followed by SC ($23,201).

The highest total annual energy generated is obtained with SC (112,728 kWh/yr.), which accounts also for the highest excess electricity produced (75,877 kWh/yr.). SD (75,121 kWh/yr) generates the least amount of electricity and produces relatively minimum excess energy.

*3.2. The most optimal system.* Table 13 shows the summary of technical specifications of the most optimal system. Among the four different scenarios considered in this study, SD comprising SPV/DG/BS system is taken to be the most optimal system with the following characteristics based on a relative comparison:

system with the lowest NPC and LCOE

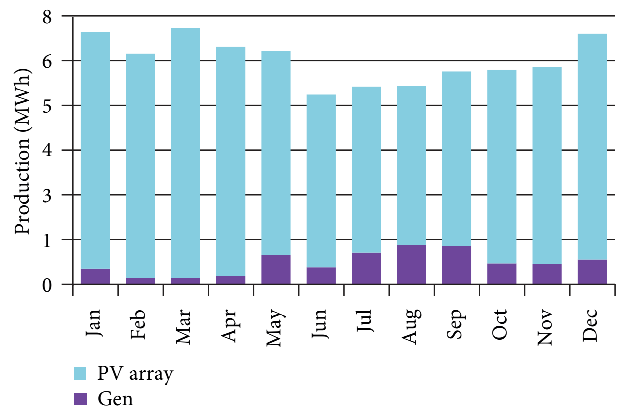


Figure 12: Annual electricity production.

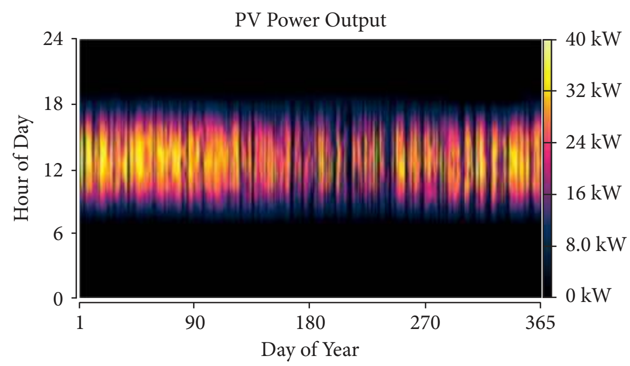


Figure 13: Power output from PV array.

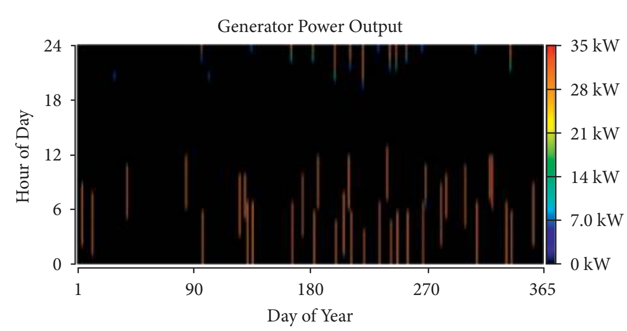


Figure 14: Power output from DG.

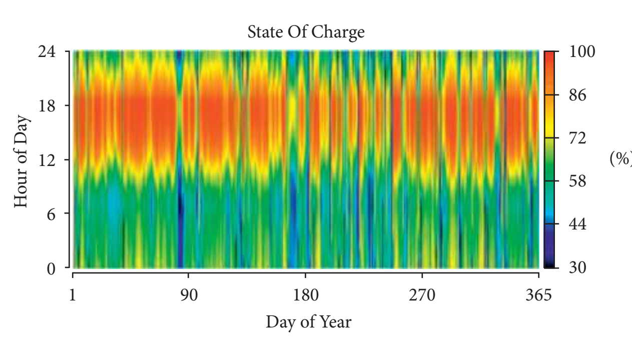


Figure 15: Battery state of charge.

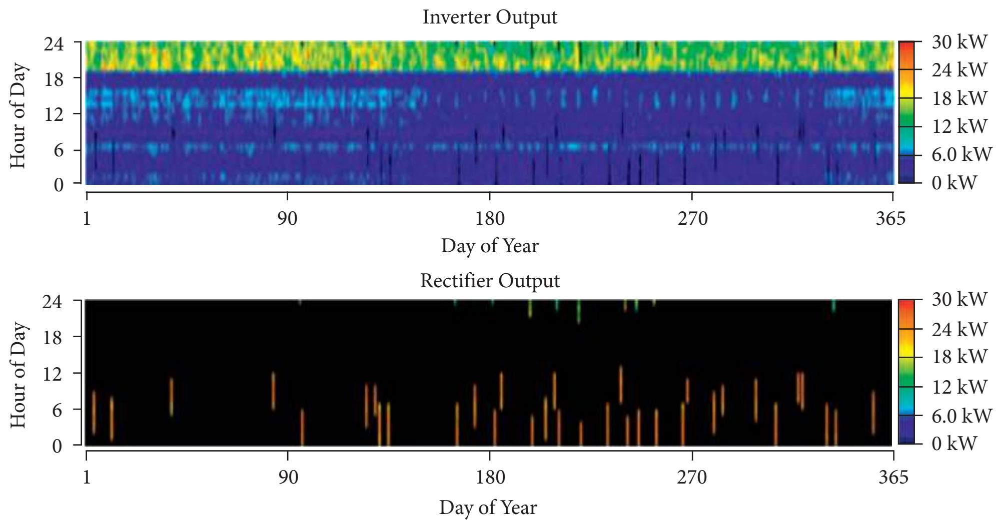


Figure 16: Converter power output.

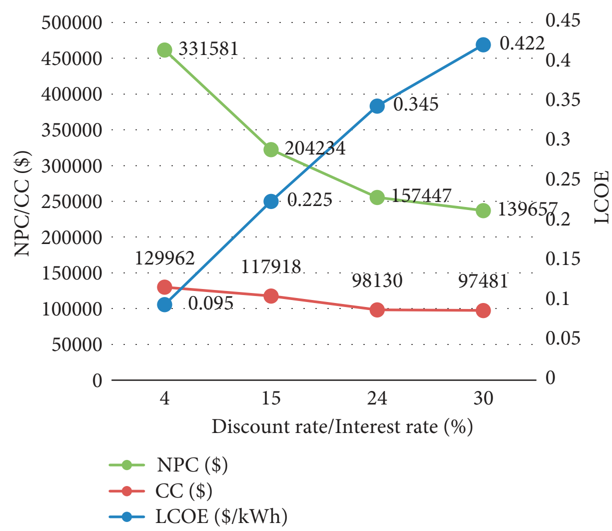


Figure 17: Sensitivity output for discount rate.

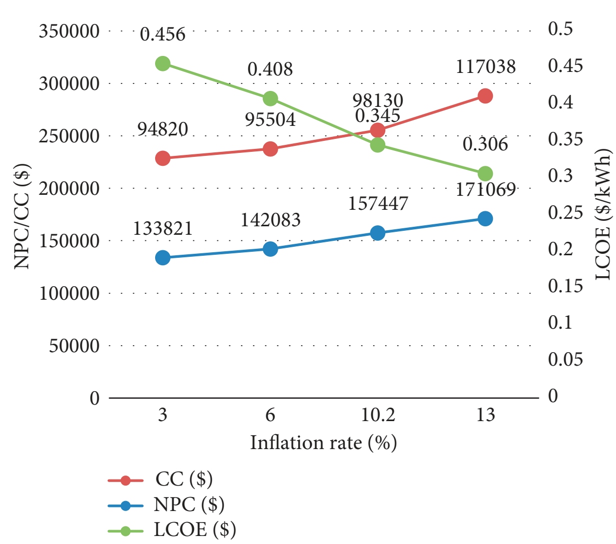


Figure 18: Sensitivity output for inflation rate.

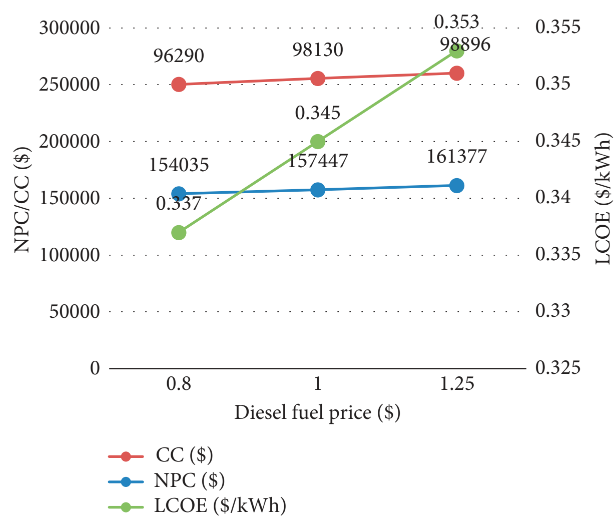


Figure 19: Sensitivity output for diesel fuel price.

Technically maximizes the use of renewable energy

Emits minimum amount of GHG relative to SA and SB

The proposed hybrid PV system for village electricity is expected to supply a daily load of 165 kWh, with a peak load of 30 kW. Electrical power from the system is generated using SPV and DG. The system has a renewable energy fraction of 88% and significantly minimizes GHG emissions relative to SA and SB that employ a DG only.

The proposed system has an expected annual power output of 75,295 kWh. The power produced from the SPV array in this model 68,002 kWh/yr. while the DG produces 7,257 kWh/yr. The months of March and June have the lowest and highest expected PV power output, respectively. Output from the DG is expected to be low during the dry season due to limited use and increases during the rainy season as the generator runtime increases. Figures 12, –16 show the performance curves for the system.

*3.3. Results from Sensitivity Analysis.* Figures 17–19 show the results obtained for the sensitivity analyses for model SD [19–22].

## 4. Conclusions

This study carried out a comparative technical and economic feasibility analysis among four different options (configurations) of power generation systems using generation options of SPV, DG, and BS systems using homer software. Homer software was used to carry out simulation, optimization, and sensitivity analyses on each of the selected power system configuration. The scenario considered power generation by diesel generator only, a hybrid system consisting of DG and BS, hybrid system comprising SPV and BS, and a three-way hybrid power system comprising SPV/DG/BS.

With a national rate of inflation of 10.2%, a discount rate of 24%, and a price of $1 per litre of diesel fuel, simulations results obtained hybrid system, model SD, as the most optimal system representing the least NPC and LCOE. The proposed system comprises45.5 kW PV array, 31 kW DG, and 68 lead-acid batteries. Economically, the model accounts for the cheapest energy generation, with a total NPC of $152,491 and LCOE of $0.336/kWh. Technically, the model is expected to generate an annual electrical energy of 75,121 kWh. This model also considerably reduces the annual amount of GHG emissions (6,117 kg) when compared to power generation using DG only (21,730 kg) or the hybrid system combining PV and DG (57,733 kg).

Hybrid SPV systems play an important role in rural and remote area power generation and supply; as such, this study recommends there is need for further scientific and academic studies to be carried on assessing the feasibility of such power systems for similar application across other locations of rural Sierra Leone.

Based on the sensitivity analysis, this study recommends fiscal and economic policies and incentives such as reducing the discount rate charged should be considered on financial lending provided towards SPV projects for rural villages that can significantly lower the capital cost of such projects, thus lowering the cost of energy produced. This has the tendency of increasing adoption rate of community households, which are mostly low-income earners.

## Nomenclature

| | |
|---|---|
| AfDB: | African Development Bank |
| BS: | Battery storage |
| CC: | Capital cost |
| DG: | Diesel generator |
| GDP: | Gross domestic product |
| GHG: | Greenhouse gas |
| HES: | Hybrid electricity system |
| HOMER: | Hybrid optimization for multiple electric renewables |

HRES: Hybrid renewable energy system
IEA: International energy agency
IRENA: International renewable energy agency
LCOE: Levelized cost of energy
NPV: Net present value
PV: Photovoltaic,
RE: Renewable energy
SA: Scenario A
SB: Scenario B
SC: Scenario C
SD: Scenario D
SDG: Sustainable development goals
SE4ALL: Sustainable energy for all
SL: Sierra Leone
SPV: Solar photovoltaic
SSA: Sub-Saharan Africa
UN: United Nations
UNDP: United Nations Development Program
WB: World Bank.

## Data Availability

The data are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## References

[1] D. F. Barnes, *The Challenge of Rural Electrifi Cation*, Resources for the Future, Washington, D.C., U.S, 2007.
[2] J. Peters, M. Sievert, and M. A. Toman, "Rural electrification through mini-grids: challenges ahead," *Energy Policy*, vol. 132, no. May, pp. 27–31, 2019.
[3] A. Zomers, "The challenge of rural electrification," *Energy for Sustainable Development*, vol. 7, no. 1, pp. 69–76, 2003.
[4] S. A. Hirmer, H. George-Williams, J. Rhys, D. McNicholl, and M. McCulloch, "Stakeholder decision-making: understanding Sierra Leone's energy sector," *Renewable and Sustainable Energy Reviews*, vol. 145, Article ID 111093, 2021.
[5] J. F. Manwell, "Hybrid energy systems," *Encyclopedia of Energy*, 2004.
[6] M. S. Adaramola, S. S. Paul, and O. M. Oyewola, "Assessment of decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria," *Energy for Sustainable Development*, vol. 19, no. 1, pp. 72–82, 2014.
[7] O. D. T. Odou, R. Bhandari, and R. Adamou, "Hybrid off-grid renewable power system for sustainable rural electrification in Benin," *Renewable Energy*, vol. 145, pp. 1266–1279, 2020.
[8] N. E. Mbaka, N. J. Mucho, and K. Godpromesse, "Economic evaluation of small-scale photovoltaic hybrid systems for mini-grid applications in far north Cameroon," *Renewable Energy*, vol. 35, no. 10, pp. 2391–2398, 2010.
[9] C. L. Azimoh, P. Klintenberg, F. Wallin, B. Karlsson, and C. Mbohwa, "Electricity for development: mini-grid solution for rural electrification in South Africa," *Energy Conversion and Management*, vol. 110, pp. 268–277, 2016.
[10] M. H. Jahangir and R. Cheraghi, "Economic and environmental assessment of solar-wind-biomass hybrid renewable energy system supplying rural settlement load," *Sustainable Energy Technologies and Assessments*, vol. 42, Article ID 100895, 2020.
[11] C. Li and W. Yu, "Techno-economic comparative analysis of off-grid hybrid photovoltaic/diesel/battery and photovoltaic/battery power systems for a household in Urumqi, China," *Journal of Cleaner Production*, vol. 124, pp. 258–265, 2016.
[12] D. A. Konneh, M. E. Lotfy, R. Shigenobu, and T. Senjyu, "Optimal sizing of grid-connected renewable energy system in Freetown Sierra Leone," *IFAC-PapersOnLine*, vol. 51, no. 28, pp. 191–196, 2018.
[13] D. Konneh, H. Howlader, R. Shigenobu, T. Senjyu, S. Chakraborty, and N. Krishna, "A multi-criteria decision maker for grid-connected hybrid renewable energy systems selection using multi-objective particle swarm optimization," *Sustainability*, vol. 11, no. 4, p. 1188, 2019.
[14] T. World Bank, "Turning the Lights on Across Africa," 2013, https://openknowledge.worldbank.org/handle/10986/16623.
[15] A. Kassam, "HOMER software: training guide for renewable energy base station design | mobile for development," *Homer Manual*, vol. 21, 2010.
[16] Homer Energy, "Homer pro," *Manual Homer Energy*, pp. 1–241, 2019.
[17] A. B. Johnny, *Consumer Price Index*, 2021.
[18] S. A. Shezan, K. N. Hasan, A. Rahman, M. Datta, and U. Datta, *Selection Of Appropriate Dispatch Strategies For Effective Planning And Operation Of a Microgrid*, 1–9, *Sierra Leone*. (n.d.), 2021.
[19] A. Henry, *Electricity Sector Reform Roadmap*, 2017, https://rise.esmap.org/data/files/library/sierra-leone/Energy%20Access/EA%2014.1B.pdf.
[20] Homer's, "Calculations," 2021, https://www.homerenergy.com/products/pro/docs/latest/homers_calculations.html.
[21] E. Muh, *A Comparative Assessment of Hybrid Renewable Energy Systems for Sustainable Rural Electrification in Cameroon*, Pan African University Institue of Water and Energy Sciences, Algeria, North Africa, 2017.
[22] *Rural Electrification | the Alliance for Rural Electrification*, 2022, https://www.ruralelec.org/rural-electrification.