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Optimal planning and electricity sharing strategy of hybrid energy system for remote communities in Nigeria

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ABSTRACT

In recent times, renewable energy-based power systems are being used to address energy poverty or shortage that is experienced in developing countries. To improve these systems' applicability, they are used to design a hybrid energy system. It is against this backdrop that this paper focuses on how hybrid energy systems can be designed optimally to address electricity sharing between domestic and productive use in remote communities. This paper, therefore, proposes a mixed-integer multi-objective optimization model for electricity sharing between domestic and productive use in remote communities. The model considered the number of solar photovoltaic (PV) systems acquisition, the total cost of energy utilized, and the cost of CO_2 emissions avoided. A genetic algorithm was used to optimize these decision variables. The proposed model evaluation was carried out using data from three remote communities in South-West Nigeria. The results obtained from the model show that the number of installed solar PV systems in the first, second, and third communities is 74, 76 and 73 solar PV systems, respectively. For 25 years planning period, the first community required 29,554.05 kWh, the second community required 28,280.20 kWh, and the third community required 28,608.70 kWh. The average values for productive use of electricity from the conventional energy sources for the first community was 0.358, for the second community was 0.338, and for the third community was 0.348. In terms of the maximum productive use of electricity from the solar PV system, the first and second communities had the same value (0.39), while the third community's maximum had a value of 0.40. The developed model will be useful for evaluating the expected number of functional solar PV systems required, managing the quantity of electricity supply from the national grid and the generators, and planning electricity sharing for domestic and productive use within the selected communities.

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Introduction

Electricity generation from renewable sources is a promising option for electrifying remote communities around the world [1]. Apart from its eco-friendly nature, it provides the opportunity for modular design which depends on the energy need and consumption pattern of an intended user [2]. Interestingly, for more than ten years, the prices of solar PV panels, for example, have been slashed [3]. A recent study has reported that less than one billion people still do not have access to the electricity grid with the largest energy access deficit experienced in sub-Saharan Africa [4]. These are among the important features and factors that make renewable electricity interesting and attractive for a localized power system in several communities in the world. It is on this basis that efforts are made to address energy availability and affordability challenges in sub-Saharan Africa, where energy poverty and the shortage is being experienced. Solar photovoltaic (PV) systems have been identified as the most suitable and affordable renewable energy system for this region [5].

The implementation of solar PV systems is not without challenges. Some of the challenges associated with these systems implementation in developing countries are poor design, lack of maintenance, and lack of funding. These have been reported in existing scholarly works, and are recognized as the major causes of solar PV system failure in several communities. It is necessary to examine and address these problems, to forestall a negative impression about solar power systems in developing countries.

In Nigeria— a country within the sub-Sahara African region, there are increased failure rates of renewable energy systems, especially solar photovoltaic systems. One of the reasons for this failure is that many of the installations have been done without proper consideration for the site characteristics. Most at times, attention is only paid to cost-reflective design, without adequate considerations for their long-term viability. The vast majority of the renewable energy systems in the country suffer from technical problems because they are not designed according to standards, i.e. the best practices are compromised because of the high initial capital cost of the renewable energy systems. As such, one or more key components of sustainability are being ignored, which invariably result in poor performance or failure or unreliable systems. Hence, this study concentrates on how a hybrid energy system may be designed and planned for remote communities, as a contribution towards addressing the issue of the poor technical design of solar electricity systems, while also considering economic and environmental performances for the proposed system.

Many scholarly works have been presented and published on off-grid electricity generation with particular emphasis on solar PV systems, which are relevant to this study. A study has discussed off-grid PV power systems for remote electrification and emissions mitigation focusing on India – as a case study [6]. A review of sizing methodologies for PV array and battery in a standalone power system has been presented [7]. A study has also been recently published on solar electrification solutions for remote areas in Yemeni [8]. A review of PV systems has been discussed with emphasis on the technical design aspect, operation, and maintenance [9]. PV microgrid design has been discussed for electrifying remote locations [10]. The optimization and comparison analysis of solar PV panels has been presented using three different villages as test cases [11]. The design of a solar-PV-diesel power system has been discussed for a remote part of Australia [12]. Long-time performance analysis of a standalone PV system under real conditions has been published with an emphasis on a remote island [13].

The technical and economic analyses of off-grid hybrid renewable energy systems have been discussed for powering a remote area in Sri Lanka [14]. The technical and economic evaluation of microgrid projects for remote electrification has been published, emphasizing the redesign of Koh Jik off-grid [15]. A hybrid renewable power system analysis has been discussed for realizing sustainable remote electrification in Benin, based on solar PV and diesel sources [16]. The optimal design and techno-economic assessment of a grid-independent microgrid have also been presented [17]. A techno-economic study has been presented on power generation systems for off-grid locations of Gilutongan Island, Cordova, Cebu, and the Philippines [18]. A solar PV power generation system with energy storage has been discussed for remote locations of Myanmar [19]. The methodology for energy need assessment has been presented with an emphasis on the effective design and deployment of mini-grids for electrifying remote areas [20]. The optimal sizing of PV/wind/diesel/battery system has been discussed, which focuses on how to supply energy to off-grid locations in Rafsanjan in Iran [21].

A study has also discussed the development and evaluation of a stand-alone hybrid power using the Rohingya refugee camp in Bangladesh as a case study [22]**.** The authors analysed the techno-economic performance of generator, solar PV and wind systems with battery storage. The technical, economic, and the environmental impact analysis of bioethanol production based on banana has been discussed in [23]**.** The authors maintained a position that bioethanol promises an economically feasible and environmentally friendly option for producing electricity [24]**.** The potential of power generation based on chicken waste-based biodiesel has also been discussed in [24]; the authors focused on the economic and environmental aspects using a location in Bangladesh as a case study.

The above-mentioned studies are of relevance to this current paper. However, most of these recent scholarly publications in the aspect of energy development for remote communities are found to majorly concentrate on the technical modelling and simulation and the economic considerations. In some of the papers that proposed standalone PV and hybrid systems for off-grid locations, different design and simulation strategies have been employed, while few of these studies provided reviews of systems sizing techniques and methodologies that have added value to the literature. This present paper, therefore, proposes an optimal hybrid design approach that is based on solar PV, diesel generator and the national grid, which takes a different perspective from the existing scholarly works earlier mentioned. This approach accounts for the amount of electricity for domestic and productive use in remote communities.

This study objective is, therefore, to optimize the electricity sharing between domestic and productive uses in rural communities – this objective is within the energy planning problem. The basis of energy planning is understanding the intended community's prevailing energy situation and the local conditions, which is necessary to achieve a sustainable electricity system [25, 26]. After visiting the selected remote communities in Nigeria, it was observed that a steady electricity supply for the community is achievable using a hybrid energy system. Based on the feasibility study carried out, we observed that electricity from a national grid, solar PV (mono-crystalline silicon module), and diesel generator can be used to design a hybrid system for these communities. Also, the maintenance of this system can be achieved using income from productive electricity use in these communities. Also, we observed that sparse information exists on electricity sharing for domestic and productive use, especially in Nigeria. Hence, this study proposed a mixed-integer non-linear mathematical model was designed for electricity sharing between the domestic and productive uses in remote communities. The genetic algorithm (GA) was used to generate optimal values for the model's decision variables. GA was selected as a solution method for the proposed based on its ability to generate Pareto solutions for non-linear models - other benefits of GA are contained in [25].

The remaining part of the paper is organized as follows: Section 2 focuses on methods and materials, Section 3 presents the results and discussion, while Section 4 concludes the paper.

Methods and material

Problem description

Obtaining relevant data about the technical, economic, and environmental dimensions of clean energy, serves as a basis for planning, modelling, and implementing a sustainable clean electricity supply system in a community. When these data are made available to decision-makers, appropriate policy directions for achieving renewable energy sustainability can be drafted. The process of generating these data for the nonlinear relationship among technical, economic, and environmental criteria for clean energy supply systems involve the use of complex mathematical expressions. For example, the contribution of productive use to CO_2 emission is nonlinear. And this is also true about the relationship among the annualized life-cycle cost of clean energy parameters, which is an economic criterion [26].

The lack of access to the national grid, or modern and steady energy supply in several remote communities, is one factor that has led to their increased dependence on the fossil fuel-based electricity systems [27,28]. This is due to the need to cater for their energy needs for domestic and productive purposes. This is due to the need to cater for their energy needs both domestic and productive purposes. While the energy demand for domestic use includes powering TVs, electric fans, radios, lighting fittings, charging phones, rechargeable lanterns, etc., the energy need for productive use includes supplying electricity for small businesses such as barbing, meat and fish refrigeration, water pumping, etc. The increased use of fossil fuel systems leads to an increase in CO_2 emissions. Therefore, there is a need to minimize the utilization of fossil fuel systems in remote communities and also strengthen the productive use of clean energy. To achieve this objective, the assessment of energy from a renewable energy system, national grid, and fossil fuel are considered in this study. This will provide useful insights to policy-makers on the possible energy mix resulting from these sources. It will, therefore, allow them to understand the situation and proffer a robust solution to the lack of energy supply to remote communities.

As interesting as this idea may sound when the above-mentioned relationship is modelled with productive and domestic use of energy, it is a non-linear relationship. For example, the present worth for a renewable energy system can be modelled only with a non-linear expression. This is because the compound interest for investment is computed using an exponential function. Still, on the issue of the relationship, the amount of CO_2 emission from different energy centres can only be determined using a non-linear function, for example, detailed analysis of CO_2 emission could require considering CO_2 emission from productive and domestic energy use. It is also possible to analyze CO_2 emission from a community-wide perspective. And this could be motivated by the need to penalize communities with high CO_2 emission rates. Another non-linear relationship in energy system analysis is a relationship among installation cost, operation and maintenance cost and interest rate, life-cycle cost.

During the development of the proposed model, the following assumptions are made.

- The expected amount of energy for productive use in a community is known [29].
- Energy demand for productive use increases from one period to another period [30].
- Diesel is used as a fossil fuel for a generator [31].
- The level of economic activities in a remote community affects the distribution of clean energy resources [32, 33].
- The importance of clean energy system installation varies from one community to another [34].
- There is a restriction on the maximum number of clean energy systems that can be installed in a period: Finance constraint is among the major cause of this restriction [35].
- The addition of a new solar PV system is done periodically [36].
- Productive use of electricity is for commercial purposes, while domestic use of electricity is for household purposes.

Model formulation

The definitions of the index and variables used to present the proposed optimization model are presented as follows:

Symbol	Definition	Symbol	Definition
t	Planning periods	l	Community
T	Total planning period	L	Total number of communities
y^1_{lt}	Amounts of clean energy allocated for productive use in remote community i at period t.	y^2_{lt}	Amounts of clean energy allocated for domestic use in remote community i at period t.
z^1_{lt}	Amounts of energy from fossil fuel for allocated for productive use in remote community i at period t.	z^2_{lt}	Amounts of energy from fossil fuel for allocated for domestic use in remote community i at period t.
S_{lt}	Number of installed clean energy systems in community l at period t	G_{lt}	Capacity of diesel generator in community l at period t
D_{lt}	Number of generators in community l at period t	C^1_l	Daily operation and maintenance cost of a clean energy system in community l per day
C^2_l	Hourly expenses of electricity for community l	C^3_l	Hourly operation and maintenance cost of a generator in community l
h^1_{lt}	Number of hours of electricity is supplied from a national grid in community l at period t	h^2_{lt}	Number of hours of a generator is operated per day in community l at period t
Q^1_{lt}	Quantity electricity a national grid supplied to a household per hour in community l at period t (kWh).	Q^2_{lt}	Quantity electricity a diesel generator supplied to a household per hour in community l at period t (kWh).
E_1	Average amount of CO_2 emitted by a generator is used per day (kg/kWh)	E_2	Average hour a generator is used per day (kg/kWh)
f_{lt}	Failure rate of clean energy systems in community l at period t	x_{lt}	Number of newly installed clean energy systems in community l at period t
r_{lt}	Number of restored clean energy systems in community l at period t	υ_t	Expected number of clean energy systems at period t
$MRRT$	Mean to time to restore	I_l	Importance of community l
P_{lt}	Quantity of electricity demand for domestic use in community l at period t	$\bar{P}_{lt}$	Quantity of electricity demand for productive use in community l at period t
C	Unit cost of CO_2 emission	β_l	Rated capacity of clean energy systems in community l
η_t	Expected number of newly installed clean energy system at period t		

Using the above notations, the proposed model is described in the following sub-sections:

Objective function

The amount of energy used for productive activities in a community is expressed as Eq. (1). The performance of a solar photovoltaic power generation is affected by certain factors such as ambient temperature, dust, shading, degradation, wiring losses, etc. [37]. In solar PV systems design, the de-rating factor is usually employed to account for losses due to dust, degradation, etc. Therefore,β_l accounts for the power output and the de-rating factor of a PV module in this study.

$$Z_1 = 365\left(\sum_{t=1}^{T}\sum_{l=1}^{L}\left(y^1_{lt}\right)\times 24\times\beta_l S_{lt}+\sum_{t=1}^{T}\sum_{l=1}^{L}\left(z^1_{lt}\right)\left(h^1_{lt}Q^1_{lt}+h^2_{lt}Q^2_{lt}D_{lt}\right)\right) \tag{1}$$

The total cost of electricity the communities consumed during the planning period is expressed as Eq. (2).

$$Z_2 = 365\left(\sum_{l=1}^{L}\sum_{t=1}^{T}C^1_l\beta_l S_{lt}+\sum_{l=1}^{L}\sum_{t=1}^{T}C^2_l h^1_{lt}Q^1_{lt}+\sum_{l=1}^{L}\sum_{t=1}^{T}C^3_l h^2_{lt}Q^2_{lt}D_{lt}\right) \tag{2}$$

The penalty cost of emitted CO_2 is expressed as Eq. (3).

$$\left(\left(\mathrm{z}^1_{\mathrm{it}}+\mathrm{y}^1_{\mathrm{it}}\right)+\left(\mathrm{z}^2_{\mathrm{it}}+\mathrm{y}^2_{\mathrm{it}}\right)\right)=\left(\mathrm{c}_{\mathrm{i}}\mathrm{S}_{\mathrm{it}}+\mathrm{G}_{\mathrm{it}}+\phi_{\mathrm{it}}\right) \tag{3}$$

The objective functions are subject to energy demand, system failure, and system sizing constraints as represented by Eqs. (4) to (16). Eq. (4) represents the relationship between the amount of energy demanded and generated in a community.

$$\sum_{l=1}^{L}\left(P_{lt}+\bar{P}_{lt}\right)=365\left(\sum_{l=1}^{L}24\times\beta_l S_{lt}+\sum_{l=1}^{L}h_{1l}Q^1_{lt}+\sum_{l=1}^{L}h_{2l}Q^2_{lt}D_{lt}\right)\forall t \tag{4}$$

The relationship between the amount of energy used for productive and domestic uses in the community is expressed as Eq. (5).

$$\left(\left(\mathrm{z}^1_{\mathrm{it}}+\mathrm{y}^1_{\mathrm{it}}\right)+\left(\mathrm{z}^2_{\mathrm{it}}+\mathrm{y}^2_{\mathrm{it}}\right)\right)=\left(\mathrm{c}_{\mathrm{i}}\mathrm{S}_{\mathrm{it}}+\mathrm{G}_{\mathrm{it}}+\phi_{\mathrm{it}}\right)\left(\left(\mathrm{z}^1_{\mathrm{it}}+\mathrm{y}^1_{\mathrm{it}}\right)+\left(\mathrm{z}^2_{\mathrm{it}}+\mathrm{y}^2_{\mathrm{it}}\right)\right)=\left(\mathrm{c}_{\mathrm{i}}\mathrm{S}_{\mathrm{it}}+\mathrm{G}_{\mathrm{it}}+\phi_{\mathrm{it}}\right)\forall t \tag{5}$$

The relationship between clean and conventional energy sources in a period is expressed as Eq. (6).

$$\beta_l S_{lt}\geq h_{2l}Q^1_{lt}+h_{1l}Q^2_{lt}D_{lt}\ \forall l,\forall t \tag{6}$$

Eqs. (7) and (8) account for energy sharing for productive and domestic use for the energy generated from clean energy and conventional energy sources, respectively.

$$y^1_{lt}+y^2_{lt}=1\ \forall t \tag{7}$$

$$z_{lt}^{1} + z_{lt}^{2} = 1\,\forall t \tag{8}$$

Eq. (9) places a limit on the minimum number of clean energy systems in a community.

$$\sum_{l=1}^{L} S_{lt} \geq \upsilon_t\,\forall t \tag{9}$$

Eq. (10) is used to establish the relationship between a community's importance, and the number of clean energy systems at a period. Eq. (11) accounts for the relationship between new, existing and restored clean energy systems in a location.

$$I_l S_{lt} \geq I_{l+1} S_{l+1t}\,\forall t \tag{10}$$

$$S_{lt} = r_{lt} + x_{lt} + (S_{lt-1} - f_{lt-1})\,\forall l, \forall t \tag{11}$$

Eqs. (12) to (14) are used to model the number of repaired systems, the number of newly installed systems, and the minimum number of the newly installed system in a location, respectively.

$$r_{lt} = MTTR * f_{lt}\,\forall l, \forall t \tag{12}$$

$$\sum_{l=1}^{L} x_{lt} \leq \eta_t\,\forall t \tag{13}$$

$$\sum_{t=1}^{T} x_{lt} \geq 1\,\forall l \tag{14}$$

Eqs. (15) and (16) give the expressions of the proposed model's non-negativity constraints.

$$I_l, S_{lt}, x_{lt}, f_{lt}, h_{lt}^{1}, h_{lt}^{2} \geq 1\,\forall l, \forall t \tag{15}$$

$$y_{lt}^{1}, y_{lt}^{2}, z_{lt}^{1}, z_{lt}^{2} \geq 0\,\forall l, \forall t \tag{16}$$

Description of case study

The proposed model's applicability was tested using information from three remote communities in Nigeria. The first community is the Divine grace community (L1), the second community is Alubarika community (L2), while the third community is Idera community (L3). All the communities are in Ogun State, Nigeria. They have access to the national grid, but the duration of electricity supply from the grid per day is between 2 to 5 hours, which is highly erratic – meaning that they are not being supplied electricity every day. To address their electricity problem, these communities usually depend on diesel generators as a source of electricity supply. This study, therefore, considers the possibility of including solar PV systems in the energy mix, which is why the analysis is based on a hybrid energy supply of the national grid, solar PV, and generator. A solar PV system rating is 10kW – with 40 panels [38]. Nigeria is blessed with abundant solar energy resources all over its six geo-political zones, which favors the crystalline silicon photovoltaic technology [39]. Several existing solar microgrid systems in the country are based either on mono-crystalline or poly-crystalline silicon modules.

Based on the technical visits to the mentioned communities, it was gathered that most of the households in the communities have at least 5 electric bulbs, a television set, radio, and refrigerator. Also, electric iron, fans, and laptop computers are among the appliances in some of the other households, as well. Most of the businesses in these communities are small-scale businesses, and some of which use electrical appliances such as deep freezers, electric clippers, electric dryers, and electric sewing machines. Hence, a significant proportion of electricity usage in these communities is used for domestic use. In these communities, the average capacity of a diesel generator is 6 kVA, with a power factor of 0.9. This implies that the generator has an active power capacity of 5.4 kW. Often, a household operates its generator for 6 hours per day, usually in the evening time and operating more than these hours during the weekends. Given that the generator is reasonably reliable, it will produce 11,826 kWh of electricity per year. The generator will require an average of 1.17 litres of diesel per hour. Given that the amount of CO_2 from a litre of AGO is 2.392 kg, this generator will emit about 2.8 kg of CO_2 into the environment [40]. The cost of carbon emission is taken as ₦2.88 per kg [41].

The duration of electricity that the national grid supplies to a household are a function of the number of hours of the supply and the average electricity a household consumes per hour. The per capita per month of electricity consumption in southwest Nigeria is 23 kWh [42]. For a household with 5 persons, this study considered a solar PV system with 14 panels. The annual output of this system is 9,909 kWh [38]. The solar PV system operation and maintenance cost is taken as $5 per annual [43]. Genetic algorithm (GA) – a metaheuristic optimization algorithm described in Appendix A is used as a solution method for the proposed model. In this study, we considered a population size of 50 and a generation size of 100. The GA crossover probability was 0.5 and its mutation probability was 0.4. A tournament selection method was used to determine individual chromosomes that will survive to the next generation. These values have been used for the analysis, whose significance has produced some results in [25].

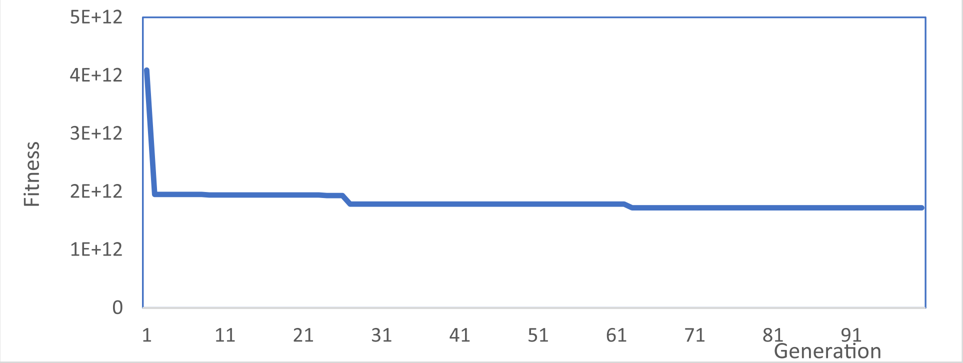

Fig. 1. Convergence plot for the genetic algorithm.

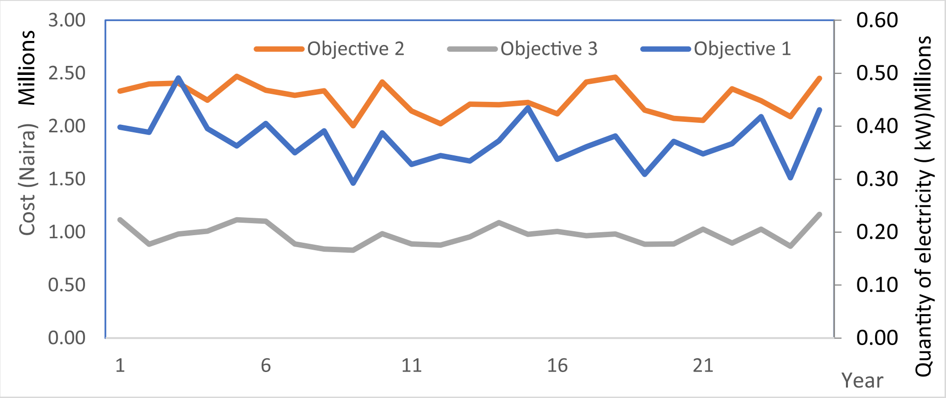

Fig. 2. Optimal values of the objective functions for different periods.

Results and discussion

Fig. 1 shows the convergence plot of the GA that was used to solve the formulated model, while Fig. 2 shows the optimal values of the different objective functions for 25 years. In terms of productive use of electricity, the selected communities consumed about 9,304,426.59 kW during the 25 years planning period. On an annual basis, these communities need about 372,177.06 kW for productive use. However, Fig. 2 shows that 491,301.62 and 292,731.92 kW are the maximum and minimum amount of electricity that these communities will need for productive use.

Table 1 shows the distributions of the number of functional solar PV systems that are expected on an annual basis for the different communities. The communities installed 287 solar PV systems at the end of 25 years. The results show that the model was able to track each community's solar PV systems increase – this shows the practicality of the model. The model captures the expected fluctuations of the number of newly installed solar PV systems in each community. Also, the proposed model's results for the number of failed solar PV systems followed a stochastic pattern that captures a real-world failure rate of engineering systems.

The results in Table 1 show that the second community (L2) installed more solar PV systems (76 solar PV systems) than the other communities – the first community (L1) installed 74 solar PV systems, while the third community (L3) installed 73 solar PV systems. However, the maximum (4 solar PV systems) and minimum (2) number of newly installed systems are the same for all the communities. In addition, this table shows that there are several periods when the same number of solar PV systems are installed in the communities, for example, 3 solar PV systems were installed in Year 3, 5,7, 18, and 19, while these communities installed 2 solar PV systems in Year 12 and 25. The characteristic of the number failed solar PV systems shows that apart from Year 5, there is no other period that has the same number of failed systems. Table 1 shows that more solar PV systems failed in the first community, in this case, 55 solar PV systems, than in the other two communities. Fifty-four solar PV systems failed in the second community, while 52 solar PV systems failed in the third community. One solar PV system failed in a year, while the maximum number of system failures for the third community is 3 solar PV systems.

Table 2 shows the communities' annual electricity usage from conventional energy sources - national grid and generators. The results in this table show that the proposed model captured the stochastic distribution from these sources. From this table, the quantity of maximum electricity supplied from the national grid to first community (1,460 kWh) is greater than that of the other communities – 1,438.1 kWh for the second community and 1,452.7 kWh for the third community. On the

Table 1
Solar PV distribution.

Year	Existing			New			Failure		
	L1	L2	L3	L1	L2	L3	L1	L2	L3
1	30	21	17	0	0	0	3	2	1
2	33	24	20	4	4	4	2	1	2
3	37	28	23	3	3	3	3	3	1
4	39	30	27	4	3	3	2	1	3
5	43	34	29	3	3	3	2	2	2
6	47	38	33	4	4	3	2	2	3
7	49	42	37	3	3	3	1	3	3
8	54	44	39	4	4	3	3	1	2
9	55	48	42	3	4	3	1	3	2
10	57	52	46	2	3	3	1	2	2
11	61	55	49	3	4	3	3	2	3
12	63	57	49	2	2	2	2	2	1
13	66	60	52	3	3	2	3	1	1
14	68	64	56	2	3	3	2	3	2
15	72	67	59	3	3	2	3	1	2
16	74	71	63	3	4	4	2	3	2
17	77	74	66	2	3	4	3	3	2
18	81	77	70	3	3	3	3	2	3
19	84	78	73	3	3	3	3	2	3
20	86	83	76	4	2	3	1	3	2
21	90	85	78	3	4	4	2	3	2
22	95	87	82	4	3	3	3	2	2
23	97	91	86	4	2	4	1	2	3
24	99	93	87	3	4	3	1	2	2
25	103	96	88	2	2	2	3	3	1

Table 2
Number of hours of electricity supply from conventional energy sources.

Year	National grid (kWh)			Generator (kWh)		
	L1	L2	L3	L1	L2	L3
1	1460.00	1270.20	1383.35	2390.75	2492.95	1894.35
2	730.00	919.80	1317.65	2492.95	2514.85	2014.80
3	1284.80	1043.90	1069.45	2544.05	2292.20	2197.30
4	1120.55	1332.25	1157.05	2069.55	2536.75	1934.50
5	1233.70	1387.00	1441.75	2460.10	2310.45	2423.60
6	1350.50	1303.05	1427.15	2405.35	2478.35	1919.90
7	956.30	1164.35	901.55	2328.70	2387.10	1985.60
8	1073.10	857.75	923.45	2142.55	2230.15	2467.40
9	1310.35	751.90	854.10	1839.60	1981.95	2025.75
10	1259.25	1105.95	974.55	2376.15	2138.90	2555.00
11	897.90	1270.20	992.80	2003.85	1938.15	2317.75
12	1335.90	861.40	927.10	1912.60	1978.30	2007.50
13	1390.65	908.85	1222.75	1927.20	2284.90	2219.20
14	1248.30	1332.25	1452.70	2084.15	2211.90	2102.40
15	1321.30	1438.10	813.95	2036.70	2270.30	2168.10
16	901.55	1394.30	1408.90	1938.15	2332.35	1883.40
17	1346.85	963.60	1120.55	2157.15	2496.60	2409.00
18	1394.30	744.60	1350.50	2482.00	2259.35	2460.10
19	989.15	1204.50	879.65	2033.05	2022.10	2230.15
20	1142.45	970.90	1124.20	1872.45	2168.10	2003.85
21	1365.10	1405.25	1040.25	2018.45	2095.10	1843.25
22	1168.00	792.05	985.50	2321.40	2266.65	2303.15
23	1091.35	1387.00	1222.75	1887.05	2182.70	2449.15
24	784.75	1098.65	1189.90	1952.75	1963.70	2182.70
25	1397.95	1372.40	1427.15	2277.60	2492.95	2357.90

contrary, the third community had the highest minimum quantity of electricity supplied per year from the national grid (813.95 kWh). The first and the second communities' minimum quantity of electricity supplied per year from the national grid are 760 and 744.6 kWh, respectively. In terms of total electricity supplied, the first community's total electricity supplied is 29,554.05 kWh for 25 years, the second community's total electricity supplied is 28,280.20 kWh for 25 years, and the third community's total electricity supplied is 28,608.70 kWh for 25 years (Table 2).

The results in Table 2 show that the total electricity supplied by the generator for the second community (53954.3 kWh) is greater than that of the first (56,326.8 kWh) and third (54,355.8 kWh) communities. But the maximum per annual

Table 3
Domestic use of electricity.

Year	Solar PV (%)			Conventional energy sources (%)		
	L1	L2	L3	L1	L2	L3
1	0.56	0.50	0.54	0.55	0.52	0.56
2	0.59	0.52	0.52	0.56	0.52	0.57
3	0.53	0.54	0.57	0.55	0.60	0.53
4	0.60	0.52	0.55	0.53	0.58	0.55
5	0.50	0.56	0.56	0.52	0.53	0.51
6	0.53	0.51	0.53	0.57	0.51	0.58
7	0.55	0.60	0.55	0.56	0.57	0.55
8	0.60	0.54	0.59	0.60	0.60	0.51
9	0.50	0.59	0.50	0.54	0.55	0.51
10	0.54	0.59	0.51	0.54	0.56	0.54
11	0.57	0.52	0.58	0.50	0.58	0.56
12	0.57	0.50	0.57	0.56	0.55	0.51
13	0.52	0.54	0.58	0.57	0.51	0.51
14	0.57	0.54	0.60	0.57	0.51	0.57
15	0.59	0.54	0.50	0.58	0.57	0.50
16	0.52	0.53	0.51	0.52	0.54	0.53
17	0.53	0.55	0.54	0.51	0.55	0.52
18	0.51	0.56	0.53	0.56	0.50	0.51
19	0.56	0.59	0.53	0.50	0.57	0.52
20	0.55	0.51	0.55	0.57	0.54	0.54
21	0.54	0.58	0.58	0.53	0.57	0.55
22	0.52	0.59	0.59	0.52	0.59	0.55
23	0.52	0.58	0.56	0.58	0.55	0.58
24	0.55	0.56	0.58	0.51	0.50	0.51
25	0.59	0.57	0.52	0.53	0.51	0.55

electricity supplied from the generators for the third community (2,555 kWh) is greater than that of the first (2,544.05 kWh) and the second (2,536.75 kWh) communities. On the other hand, the second community had the highest minimum per annual electricity supplied from the generators is 1,938.15 kWh. The first and third communities' minimum per annual electricity supplied from the generators are 1,839.60 and 1,843.25 kWh, respectively (Table 2).

Table 3 shows the optimal allocation of the proportion of clean and conventional energy sources for domestic use. The maximum (0.6) proportion of domestic electricity use in these communities is the same, except for the third community's conventional energy source results (Table 3). Also, the results in this table show that the minimum proportion of clean and conventional energy sources that are used for domestic use is the same (0.5). The first community's average proportion of clean energy that is used for domestic use is 0.548. These communities' average domestic energy use from the conventional energy sources is 0.545 for the first community, 0.5472 for the second community, and 0.5368 for the third community.

Table 4 shows the distribution of the proportion of energy from the solar PV systems and conventional energy sources for productive use. The results in Table 4 shows that the minimum productive use of electricity from the solar PV systems in the second and third communities is the same (0.30), but these minimum values occurred at different periods. To be more explicit, the second community had its minimum values in Year 1 and 22. On the other hand, the third community has its minimum values in Year 6 and 15. This minimum value is less than that of the first community's minimum value, which is 0.31 at Year 8, 13, 14, and 19 (see Table 4). This reoccurring minimum value in the first community made it to have the lowest average productive use value (0.344) for the clean energy from the solar PV system. On the other hand, the third community has the highest average productive use value (0.351) for clean energy from the solar PV system. The second community's average productive use value for the solar PV system is 0.348.

In terms of the maximum productive use of electricity from the solar PV system, the first and second communities had the same value (0.39), while the third community's maximum productive use of electricity from the solar PV system value is (0.40) – see Table 4 for more details. Table 4 shows that the maximum productive use of electricity from the solar PV systems and the conventional energy sources for the second and third communities are the same (Table 4). This assertion is also true for these communities' minimum values of productive use of electricity from these energy sources. The first community's maximum and minimum values for productive use of energy from the conventional energy sources are 0.40 and 0.30, respectively. Finally, the average values for productive use of electricity from the conventional energy sources for the first community are 0.358, for the second community is 0.338, and for the third community is 0.348.

Contributions of the proposed model

The following are some of the proposed model's contributions:

i. The model may be used to evaluate the expected number of functional solar PV systems required in a community. It also can determine the expected number of solar PV systems that a community will use to meet its load demand growth.

Table 4
Productive use of electricity.

Year	Solar PV (%)			Conventional energy sources (%)		
	L1	L2	L3	L1	L2	L3
1	0.39	0.30	0.34	0.36	0.32	0.36
2	0.34	0.35	0.38	0.37	0.30	0.39
3	0.34	0.36	0.33	0.33	0.31	0.32
4	0.33	0.34	0.34	0.34	0.36	0.34
5	0.39	0.31	0.40	0.37	0.33	0.33
6	0.35	0.32	0.30	0.36	0.35	0.33
7	0.39	0.37	0.38	0.39	0.36	0.38
8	0.31	0.36	0.36	0.40	0.34	0.32
9	0.32	0.37	0.34	0.39	0.37	0.32
10	0.32	0.31	0.38	0.40	0.32	0.36
11	0.36	0.39	0.37	0.35	0.33	0.40
12	0.32	0.38	0.40	0.37	0.31	0.34
13	0.31	0.36	0.33	0.34	0.36	0.31
14	0.31	0.38	0.39	0.35	0.38	0.36
15	0.37	0.31	0.30	0.30	0.36	0.30
16	0.32	0.37	0.32	0.35	0.31	0.40
17	0.37	0.35	0.33	0.30	0.34	0.37
18	0.38	0.35	0.40	0.33	0.31	0.37
19	0.31	0.39	0.34	0.38	0.35	0.35
20	0.33	0.32	0.39	0.35	0.31	0.33
21	0.34	0.35	0.31	0.36	0.34	0.38
22	0.34	0.30	0.31	0.38	0.39	0.33
23	0.39	0.35	0.35	0.38	0.37	0.32
24	0.33	0.37	0.35	0.39	0.30	0.30
25	0.35	0.36	0.34	0.30	0.34	0.39

ii. Planning of electricity sharing for domestic and productive use within a community may be managed using the proposed model. Beyond this use, the proposed model can analyse the contributions of clean and conventional energy sources towards domestic and productive use.
iii. The proposed model may be used to manage the quantity of electricity supply from the national grid and generators. This will give energy demand planners an idea of the estimated annual cost of diesel consumption.
iv. The number of generators that a community will need to complement the expected energy from solar PV systems and the national grid may be estimated using the proposed model.

Conclusions

As urbanization encroaches remote communities, there is a need to monitor electricity consumption rates for domestic and productive use in these communities. Hence, this study proposed a multi-objective optimisation model. The proposed model is a non-linear programming model that optimized electricity sharing between domestic and productive use in remote communities. It considered the need to optimize the number of solar photovoltaic systems acquisition, the total cost of energy utilized for domestic use, and the cost of CO_2 emissions avoided during an electricity sharing process. The developed model was evaluated using data from three remote communities in Southwest Nigeria. A genetic algorithm optimization technique was used as a solution method for the proposed model because of its nonlinear characteristics. Based on the generated results, the following conclusions are made:

- At the end of 25 years planning period, the first community (L1) had 103 functional solar PV systems, the second community (L2) had 96 functional solar PV systems, and the third community (L3) had 88 functional solar PV systems.
- The second community installed more solar PV systems (74) than the other communities. The first community installed 76 new solar PV systems, while the third community installed 73 new solar PV systems.
- In terms of generator usage, the first community used their generators for fewer hours (147.82 hr) than the other communities. The total hour for generator usage in the second community was 154.32 hr, while the third community used their generators for 148.92 hr.
- The productive usage of electricity from the solar PV systems in the third community was higher (0.344) than that of the first (0.349) and the second (0.351) communities.
- The first community's productive usage of electricity from the national grid and generators was higher (0.368) than that of the second (0.348) and the third (0.358) communities' productive usage of electricity from the national grid and generators.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Appendix A. Genetic algorithm [25]

Step 0: Create parents, define the population size, generation size, mutation probability, crossover probability, termination criteria
Step 1: Determine the fitness of current parents.
Step 2: Use the current parents to perform a crossover operation – i.e., create new individuals.
Step 3: Subject the newly created individuals to a mutation operation.
Step 4: Evaluate the fitness of the mutated individuals and then perform a selection operation.
Step 5: Check the algorithm's termination criteria.

References

[1] A.K. Pradhan, S.K. Kar, M.K. Mohanty, Off-grid renewable hybrid power generation system for a public health centre in rural village, Int. J. Renew. Energy Res. 6 (1) (2016) 282–288.
[2] E.E. Gaona, C.L. Trujillo, J.A. Guacaneme, Rural microgrids and its potential application in Colombia, Renew. Sustain. Energy Rev. 51 (2015) 125–137, doi:10.1016/j.rser.2015.04.176.
[3] M. Sugiyama, "Photovoltaic power generation," in Energy Technology Roadmaps of Japan: Future Energy Systems Based on Feasible Technologies Beyond 2030, 2016.
[4] E. Panos, M. Densing, K. Volkart, Access to electricity in the World Energy Council's global energy scenarios: An outlook for developing regions until 2030, Energy Strateg. Rev. (2016), doi:10.1016/j.esr.2015.11.003.
[5] D.E. Ighravwe, M.O. Babatunde, Selection of a mini-grid business model for developing countries using CRITIC-TOPSIS with interval type-2 fuzzy sets, Decis. Sci. Lett. 7 (4) (2018), doi:10.5267/j.dsl.2018.1.004.
[6] P. Sandwell, et al., Off-grid solar photovoltaic systems for rural electrification and emissions mitigation in India, Sol. Energy Mater. Sol. Cells (2016), doi:10.1016/j.solmat.2016.04.030.
[7] T. Khatib, I.A. Ibrahim, A. Mohamed, A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system, Energy Convers. Manag. (2016), doi:10.1016/j.enconman.2016.05.011.
[8] M. Hadwan, A. Alkholidi, Solar power energy solutions for Yemeni rural villages and desert communities, Renew. Sustain. Energy Rev. (2016), doi:10.1016/j.rser.2015.12.125.
[9] L. Hernández-Callejo, S. Gallardo-Saavedra, V. Alonso-Gómez, A review of photovoltaic systems: design, operation and maintenance, Solar Energy (2019), doi:10.1016/j.solener.2019.06.017.
[10] S. Mothilal Bhagavathy, G. Pillai, PV microgrid design for rural electrification, Designs (2018), doi:10.3390/designs2030033.
[11] M. Fadaeenejad, M.A.M. Radzi, M. Fadaeenejad, M. Zarif, Z. Gandomi, Optimization and comparison analysis for application of PV panels in three villages, Energy Sci. Eng. (2015), doi:10.1002/ese3.52.
[12] T. Jamal, M.A. Shoeb, G.M. Shafiullah, C.E. Carter, T. Urmee, A design consideration for solar PV-diesel remote electricity network: Australia perspective, in: Proceedings of the IEEE PES Innovative Smart Grid Technologies Conference Europe, 2016, doi:10.1109/ISGT-Asia.2016.7796491.
[13] T. Ma, H. Yang, L. Lu, Long term performance analysis of a standalone photovoltaic system under real conditions, Appl. Energy (2017), doi:10.1016/j.apenergy.2016.08.126.
[14] M.L. Kolhe, K.M.I.U. Ranaweera, A.G.B.S. Gunawardana, Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka, Sustain. Energy Technol. Assess. (2015), doi:10.1016/j.seta.2015.03.008.
[15] G. Veilleux, et al., Techno-economic analysis of microgrid projects for rural electrification: A systematic approach to the redesign of Koh Jik off-grid case study, Energy for Sustain. Dev. (2020), doi:10.1016/j.esd.2019.09.007.
[16] O.D.T. Odou, R. Bhandari, R. Adamou, Hybrid off-grid renewable power system for sustainable rural electrification in Benin, Renew. Energy (2020), doi:10.1016/j.renene.2019.06.032.
[17] D. Thomas, O. Deblecker, C.S. Ioakimidis, Optimal design and techno-economic analysis of an autonomous small isolated microgrid aiming at high RES penetration, Energy (2016), doi:10.1016/j.energy.2016.09.119.
[18] L. Lozano, E.M. Querikiol, M.L.S. Abundo, L.M. Bellotindos, Techno-economic analysis of a cost-effective power generation system for off-grid island communities: A case study of Gilutongan Island, Cordova, Cebu, Philippines, Renew. Energy (2019), doi:10.1016/j.renene.2019.03.124.
[19] H. Kim, T.Y. Jung, Independent solar photovoltaic with Energy Storage Systems (ESS) for rural electrification in Myanmar, Renew. Sustain. Energy Rev. (2018), doi:10.1016/j.rser.2017.09.037.
[20] V. Gambino, R. Del Citto, P. Cherubini, C. Tacconelli, A. Micangeli, R. Giglioli, Methodology for the energy need assessment to effectively design and deploy mini-grids for rural electrification, Energies (2019), doi:10.3390/en12030574.
[21] A. Maleki, A. Askarzadeh, Optimal sizing of a PV/wind/diesel system with battery storage for electrification to an off-grid remote region: A case study of Rafsanjan, Iran, Sustain. Energy Technol. Assess. (2014), doi:10.1016/j.seta.2014.04.005.
[22] T. Chowdhury, et al., Developing and evaluating a stand-alone hybrid energy system for Rohingya refugee community in Bangladesh, Energy 191 (2020) 116568.
[23] N. Hossain, et al., Experimental investigation, techno-economic analysis and environmental impact of bioethanol production from banana stem, mdpi.com (2019), doi:10.3390/en12203947.
[24] P. Barua, T. Chowdhury, H. Chowdhury, R. Islam, N. Hossain, Potential of power generation from chicken waste-based biodiesel, economic and environmental analysis: Bangladesh's perspective, SN Appl. Sci. 2 (3) (2020) 330.
[25] D.E. Ighravwe, S.A. Oke, K.A. Adebiyi, A weighted goal programming model for maintenance workforce optimisation for a process industry, Asia-Pac. J. Sci. Technol. 22 (4) (2017).
[26] S. Ashok, Optimised model for community-based hybrid energy system, Renew. Energy 32 (7) (2007) 1155–1164.

[27] D. Akinyele, Techno-economic design and performance analysis of nanogrid systems for households in energy-poor villages, Sustain. Cities Soc. 34 (2017) 335–357.

[28] L. Olatomiwa, R. Blanchard, S. Mekhilef, D. Akinyele, Hybrid renewable energy supply for rural healthcare facilities: An approach to quality healthcare delivery, Sustain. Energy Technol. Assess. 30 (2018) 121–138.

[29] S. Asumadu-Sarkodie, P.A. Owusu, Forecasting Nigeria's energy use by 2030, an econometric approach, Energy Sources, Part B Econ. Planning, Policy 11 (10) (2016) 990–997.

[30] Y. Wolde-Rufael, Energy demand and economic growth: the African experience, J. Policy Model. 27 (8) (2005) 891–903.

[31] A.V. Anayochukwu, E.A. Nnene, Simulation and optimization of hybrid diesel power generation system for GSM base station site in Nigeria, Electron. J. Energy Environ. 1 (1) (2013) 37–56.

[32] M. Wei, S. Patadia, D.M. Kammen, Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? Energy Policy 38 (2) (2010) 919–931.

[33] O. Odularu, C. Okonkwo, Does energy consumption contribute to economic performance? Empirical evidence from Nigeria, J. Econ. Int. Financ. 1 (2) (2009) 44–58.

[34] J. Malen, A.A. Marcus, Promoting clean energy technology entrepreneurship: The role of external context, Energy Policy 102 (2017) 7–15.

[35] D. P. Goldman, J. J. McKenna, and L. M. Murphy, "Financing projects that use clean energy technologies: an overview of barriers and opportunities," 2005.

[36] F. Dincer, The analysis on photovoltaic electricity generation status, potential and policies of the leading countries in solar energy, Renew. Sustain. Energy Rev. 15 (1) (2011) 713–720.

[37] P. Mohanty, T. Muneer, M. Kolhe, Solar Photovoltaic System Applications: A Guidebook For Off-Grid Electrification, Springer, 2015.

[38] E. Sage, "How many solar panels do I need for my home?," 2020. .

[39] D.O. Akinyele, R.K. Rayudu, R.H.G. Tan, Comparative study of photovoltaic technologies based on performance, cost and space requirement: Strategy for selection and application, Int. J. Green Energy (2016), doi:10.1080/15435075.2015.1112287.

[40] A.Q. Jakhrani, A.R.H. Rigit, A.-K. Othman, S.R. Samo, S.A. Kamboh, Estimation of carbon footprints from diesel generator emissions, in: *Proceedings of the International Conference on Green and Ubiquitous Technology*,, 2012, pp. 78–81.

[41] H. Masondo, "The benefits of cleaner energy and reducing greenhouse gas emissions," 2014. .

[42] N. B. of Statistics, "LSMS-Integrated Surveys on Agriculture General Household Survey Panel 2015/2016," 2016.

[43] C.A. Hossain, N. Chowdhury, M. Longo, W. Ya\"\ici, System and cost analysis of stand-alone solar home system applied to a developing country, Sustainability 11 (5) (2019) 1403.