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MODELING AND ANALYSIS

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Off-grid hybrid renewable energy system for rural healthcare centers: A case study in Nigeria

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Abstract

Presented in this study is an optimal hybrid renewable off-grid energy system model that supplies a typical rural healthcare center across the six regions in Nigeria. A technical and economic evaluation was carried out to identify the optimal off-grid hybrid energy system combination based on photovoltaic (PV), wind, diesel generator and battery. Due to governments' fuel subsidy in many developing countries, the pump price of fuel is reduced and not a true reflection of what is obtainable in a deregulated market. In order to comprehensively capture the reality, the study considered the effect of subsidy removal by carrying out a sensitivity analysis on the fuel pump price. Therefore, the impact of a change in diesel fuel pump price and interest rates on the economic performance criteria of the optimal configuration is explored. Results show that across all the locations considered, PV/diesel/battery system is the most economically viable with a net present cost and renewable fraction (RF) ranging between \$12 779 and \$13 646 and 70%-80% respectively. The cost of energy (COE) is also estimated to range between 0.507 and 0.542 \$/kWh.

KEYWORDS

hybrid renewable energy system, levelised cost of energy, net present cost, rural healthcare center, techno-economic analysis

1 | BACKGROUND

Reliable and sustainable energy supply is critical and inevitable to the survival of modern civilization. Adequate and sustainable energy enhances socio-economic development. Energy supply is a prerequisite for improving basic services such as healthcare and water supply which are essential to humanity.[1] Unreliable power supply which is peculiar to many developing nations particularly in Africa has been reported to be grossly responsible for the poor socio-economic growth.[2] This is usually predominant in rural communities.[3] One reason for this is that grid extension to rural communities is expensive. Furthermore, the cost of extending the grid to these communities if added to the electricity tariffs becomes unaffordable and may precipitate energy poverty in such communities. Moreover, an envisaged poor return-on-investment further discourages investors from investing in grid extension for rural communities. As such many governmental and utility interventions for grid extension are directed toward urban centers where capacity expansion is cheaper and profitable for the utility company.

Many consumers in rural areas in developing countries depend on conventional sources which are powered by fossil fuels (captive generator) which are proven to be one of the major sources of greenhouse gases (GHGs).[4] Furthermore, the depletion of fossil fuel and cost are major concerns that necessitate alternative means of energy supply. Interestingly, renewable energy is considered to be cost-effective and environmental friendly.[5] Investigations have confirmed that renewable energy sources enhances economic sustainability in developing countries such as Iran, Malaysia, India, and Senegal.[6] Sound health is also an important factor that boosts economic growth and development; a healthy population indicates higher economic output and consequently a higher GDP.[7]

Access to adequate energy supply in health facilities has a direct relationship with improved healthcare services. As a result, the health outcomes of people living in rural areas in many developing countries remain poor due to lack of reliable energy supply. Moreover, a previous study shows that access to electricity supply for healthcare facilities in sub-Saharan Africa countries is poor and unreliable.[8] A 2013 study shows that about 26% of health facilities in some sub-Saharan countries (Nigeria, Ethiopia, Tanzania, Kenya, Uganda, Ghana) have no access to electricity and only 28% of the health facilities in these countries have access to reliable electricity.[8] Consequently, health workers in rural healthcare clinics (RHC) are daily faced with several challenges ranging from poor infrastructure to unreliable energy supply leading to the wastage of medical supplies thereby hindering access to quality care.[9] Even with the availability of state-of-the-art medical equipment essential for the delivery of quality healthcare services, access to a reliable modern and clean electricity is critical for their operations.[8] Health facilities require reliable electricity for water supply, temperature control, lighting, ventilation and the recent initiatives to improve rural health and combat the growing noncommunicable diseases epidemic in developing countries.

Furthermore, majority of households in rural areas depend majorly on open fire and stoves using wood, charcoal, and kerosene for cooking and lighting. Further complicated by poor ventilation, people are exposed to and inhale toxic gases which adversely impact on their health and well-being. According to the World Health Organization, about 4 million people die yearly from conditions related to household air pollution.[10] Household pollution is responsible for a huge number of deaths from noncommunicable diseases such as pneumonia, lung cancer, chronic obstructive pulmonary diseases, and heart diseases in developing countries.[10] Moreover, optimal cares for these conditions are indirectly inhibited due to continuous power outages. Many health facilities without electricity rely largely on off-grid fossil-powered generators, kerosene lamps, and candles. In cases where there is access to grid, power outages are frequent, and as such health facilities are forced to utilize their back-up generators which are not cost effective due to high cost of fuel and maintenance.

Power interruptions may lead to interruption of treatment plans and a reliable use of electrical laboratory equipment. For areas solely relying on fossil fuel-powered generators, the noise pollution and GHG emissions are major challenges. Furthermore, the frequent increase in fuel pump price and scarcity also make the option of fossil fuel-powered generation in RHCs unsatisfactory. Therefore, the role of adequate clean power supply for remote primary health centers is highly essential. Adopting a more reliable and sustainable energy source accompanied with measures to prevent wastage and ensure efficient energy consumption can potentially address the challenges encountered in rural health facilities. Renewable energy technology such as the photovoltaic (PV) solar power and small scale wind turbine are increasingly considered to be a safer and cheaper alternative for energy supply.[11] Moreover, the development of more efficient power saving medical equipment such as PV solar-powered refrigerators, water pumps, lighting devices, and laboratory equipment provides the opportunity for improved access to quality healthcare services. Many research efforts have been directed toward the techno-economic evaluation of hybrid renewable energy system (HRES), however, only a few are specifically directed toward supplying rural healthcare center. The next two paragraphs present some of the studies that have addressed the optimization of HRES for RHCs.

A study which incorporates uncertainties of both load and solar irradiation in the optimization of off-grid HRES for a healthcare facility in Congo was presented using Monte Carlo simulation.[12] Simulation results show that a cost and emission reduction of 28% and 54% can be achieved respectively. In another study, the determination of an optimal HRES alternative for a typical RHC in three off-grid villages in Nigeria were carried out.[13] Hybrid PV/wind/diesel/battery was acknowledged as the most feasible system for two of the three locations while hybrid PV/diesel/battery is the optimal for the third location that was considered in the study. A study which evaluated and compared the cost of electrifying a RHC using a decentralized hydrogen-based fuel cell and grid source for electricity generation has been conducted.[14] The authors were able to determine the break-even distance that will make the decentralized hydrogen-based fuel cell profitable and cost effective for the case study as 43.8 km. Babatunde et al,[15] proposed the use of off-grid solar photovoltaic for powering a RHC in North-West Nigeria. The study estimated the reliability, energy yield, losses, state of charge as well as load demand increase in the proposed PV system. The possibility of adopting wind turbine and solar PV technologies for energy generation and the determination of their optimal configuration in six RHCs across Nigeria has also been studied.[16]

Furthermore, Olatomiwa et al[17] in a recent paper discussed the problems caused by inadequate electricity supply in RHCs. The study further proposed a framework for the design and optimization of standalone HRES for a hypothetical healthcare center which is assumed unconnected to a grid. The role that demand side management plays in the reduction of load size, optimal configuration of HRES, life cycle cost, and GHGs in RHCs was the focal point of a study conducted by Babatunde et al.[18] The result of the study identified that investment in DSM activities will reduce the initial capital on HRES. A model that combines rank sum and WASPAS method was used to identify the best HRES location for RHCs in six communities in Nigeria.[19] In another contribution, Anayochukwu developed a framework for energy optimization map for RHCs in Nigeria.[20] Other studies similar to those discussed above has also been published.[21-24]

2 | OBJECTIVE OF STUDY

In many rural communities of developing economies, inadequate and lack of power supply is frequent and predominant. Consequently, many RHCs centers lack access to adequate power supply which is necessary to carry out certain essential daily operations. Majority of the clinics depend on diesel or gasoline powered generators that can only operate for a short period of time due to the operational expenses. In addition, the emission of GHGs can also cause health hazards and climate change. Many lives have been lost due to lack/inadequate power supply as rural physicians often refer many patients to urban clinics and many die in transit. To address this situation, an alternative power supply is essential for effective operation in rural communities. The studies earlier reviewed offer an elementary theoretical background upon which this study is built. There are several studies on the techno-economic evaluation of HRES, however, only a few are specifically directed toward supplying RHCs. Although some studies have presented the techno-economic aspect of hybrid renewable off-grid energy for RHCs, they do not present a comprehensive sensitivity analysis on the subject as regards fuel pump price and interest rate. Furthermore, none of these studies presented the relevant policies that can enhance the adoption of the optimal technologies.

The aim of this study is to provide relevant techno-economic and environmental data that can contribute to knowledge on the implementation of HRES (PV, Wind, diesel generator, and battery) for effective operation of primary healthcare centers in Nigeria. Six rural communities in the six geo-political zones in Nigeria were hypothetically selected as case study. Due to the fluctuation in market oil prices and inflation rates, a sensitivity analysis is also conducted with respect to change in fuel pump price and interest rates. The effect of these two variables on the net present cost (NPC), renewable fraction (RF), and levelised cost of energy (COE) is also presented. The results of this study will help in policy formulation as well as investment decisions.

3 | SITE DESCRIPTION

Nigeria is enormously massive in terms of geographical land space; it is reported that the country occupies a total of 923, 768 square km with landscape of about 910.768 square km and water occupies the remaining 13 000 square km.[25] The land mass is classified into six geopolitical zones. Each of these zones has peculiar weather and climatic attributes varying widely from one another at different seasons of the year. This includes the length of the rainy season, the duration of solar irradiation per day and average annual solar irradiation per year, wind speed, etc. Thus implementing each of these zones becomes veritable and representative means of ensuring equitable assessment of the effectiveness of the research. The geographical area is broadly divided into six; namely the south-west, south-east, the south-south, the north-central, the northeast, and the north-west. A detail of the locations considered is shown in Table 1.

4 | SYSTEM DESCRIPTION

4.1 | Demand model

Healthcare facilities provide various health-related services and as much require specification of energy demand of equipment and other energy-consuming related activities. This study, adopts the energy demand profile for energy efficient equipment and process in RHC as provided by Ref. 15. The ratings and the operational schedule of the various medical equipment considered in this case study are given in Table 2. The time of use for the medical

TABLE 1 Hypothetical locations of RHCs considered

S/no.	Location	State/province	Region	Longitude	Latitude
1	Anyigba	Kogi	North-Central	7.4920N	7.1740E
2	Ile-Ife	Osun	South-West	7.4910N	4.5520E
3	Toro	Bauchi	North-East	10.0590N	9.0710E
4	Nsukka	Enugu	South-East	6.8430N	7.3730E
5	Okrika	Rivers	South-South	4.7410N	7.0850E
6	Kabo	Kano	North-West	11.8840N	8.1990E

TABLE 2 Equipment type, ratings, and duration of use[18]

S/no.	Equipment	Qty	Power (W)	Total (W)	Daytime (07:00-17:59)	Evening (18:00-21:59)	Night (22:00-06:59)	Total h/d	Total Energy (kWh/d)
1	Refrigerator-vaccine	1	40	40	5	3	2	10	0.4
2	Refrigerator-non-medical	1	125	125	2	2	1	5	0.625
3	Centrifuge	2	242	484	4	0	0	4	1.936
4	Microscope	2	20	40	6	0	0	6	0.24
5	Blood chemical analyzer	1	45	45	4	0	0	4	0.18
6	Hematology analyzer	1	230	230	4	0	0	4	0.92
7	CD4 machine	1	200	200	4	0	0	4	0.8
8	Radio	1	15	15	10	0	0	10	0.15
9	Tube fluorescent lights	4	18	72	8	0	0	8	0.576
10	Wall fan	5	65	325	8	0	0	8	2.6
11	halogen lamp (security)	1	50	50	0	3	8	11	0.55
12	Desktop computer	1	65	65	4	0	0	4	0.26

equipment is divided into three time bands namely: daytime (07:00-17:59), evening (18:00-21:59), and night (22:00-06:59). The average energy demand for the RHC under consideration is 9.24 kWh/d and the peak load which occurs between 2 PM to 3 PM for all the months is estimated at approximately 1.4 kW. Figure 1 displays the daily energy consumption pattern for the 12 months in a year. As can be seen, the main part of energy consumption occurs between 9 AM and 6 PM. This is because the clinic opens around 8 AM and closes around 5 PM daily. Vital medical equipment such as refrigerator operates intermittently at night. The peak load occurs in February while the minimum demand occurs in the month of November.

4.2 | Meteorological resources

The solar irradiation, wind speed, and ambient temperature of the locations under study were obtained from the National Aeronautics and Space Administration (NASA) website. The average monthly solar radiation data, wind speed and ambient temperature for the studied locations are shown in Figures 2 and 3, Table 3 respectively. The average solar irradiation received in kW/m^2/d at each location is: Anyigba (6.16), Ile-Ife (6.12), Toro (6.40), Nsukka (6.05), Okrika (4.21), and Kabo (5.87).

4.3 | System components

The proposed HRES includes diesel generator, PV, wind turbine, battery, and a converter. The generator considered in the paper has the general specifications as provided in the HOMER software. The investment and replacement cost of the modeled generator is \$280/kW, its operation & maintenance (O & M) cost is 0.5\$/h, and its operational lifespan is 15 000 hours. The base case fuel cost is \$0.58 per L.

Different values for the cost of PV module have been reported in the Nigerian market. This include \$3200/kW,[17] \$4250/kW.[18] The capital cost for solar PV panel used in this research is \$4250/kW with a replacement cost and O &M costs of \$4200/kW and \$10/y respectively. We further conducted a sensitivity analysis for PV module price (between \$1275 and \$4250) to determine the feasible HRES alternatives (the result of which is presented in the Appendix). A derating factor of 80% is applied to the model. This factor decreases the electrical production of the panel by 20%. This study considered the temperature effect on the output of the panel. It, therefore, assumed that the temperature coefficient of power is −0.5%/°C, nominal operating cell temperature of 47°C, and efficiency at the standard test condition is taken as 15.15%. The battery input parameters are given as: the price of each battery is \$269; replacement cost and O &M costs are set to \$260 and \$5/y respectively. The parameters of the other system components are presented in Table 4. The search space

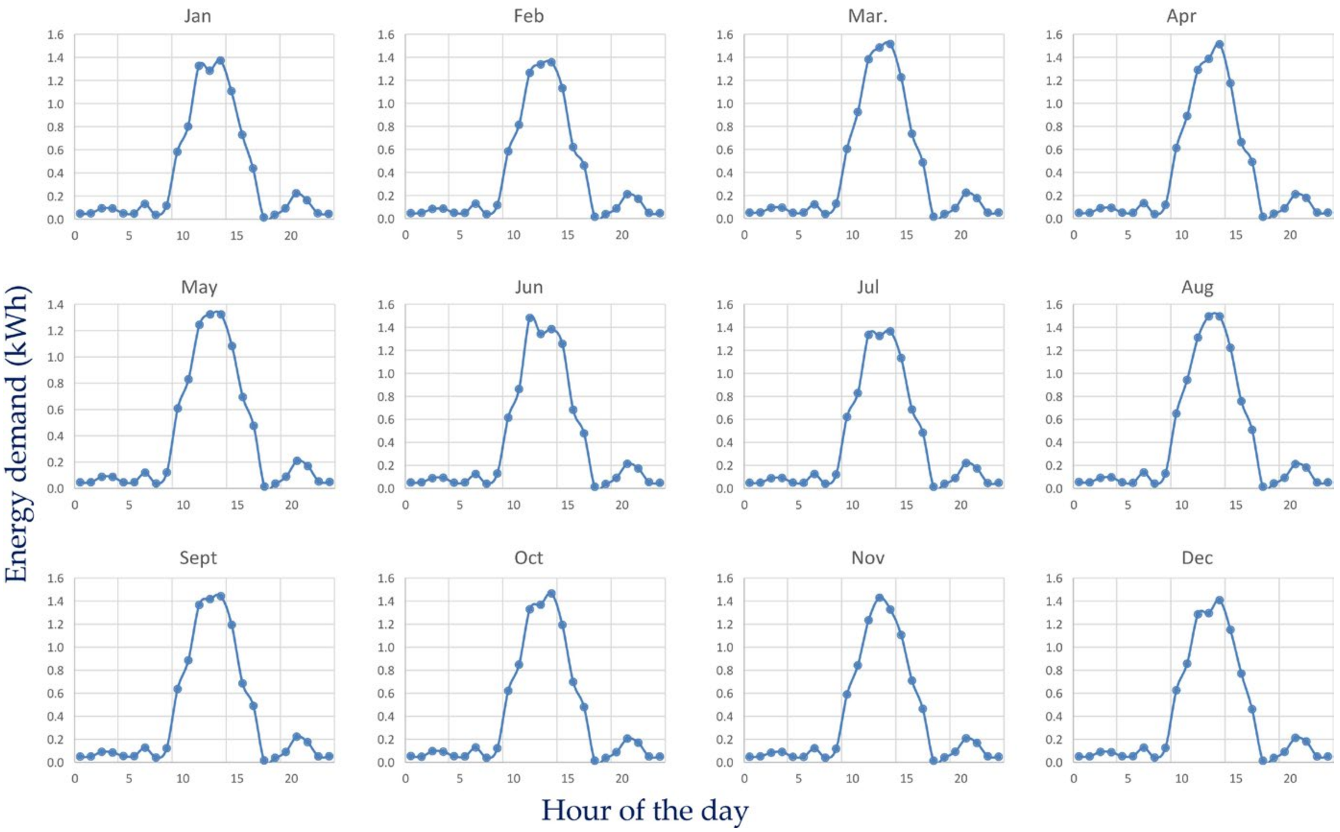

FIGURE 1 Scaled data daily load profile

for each system component is given in Table 5. The project lifetime is considered as 20 years and the annual real interest rate is assumed to be 12%. More information about the parameters of the components used in hybrid energy system is presented in Ref. 18. The assumption in this study is that the capacity shortage factor is zero so that there is no unmet load. This increases system reliability as it is a vital component in the health sector. HOMER ranks the optimal system based on the Net Present Cost (NPC) returned for each system. The NPC is the discounted sum of the investment, replacement, and maintenance costs over the operational life of the system.

4.4 | Optimization process

HOMER searches for the energy system that adequately meets electrical energy demand at minimum total NPC subject to other specified technical constraints. It can also perform sensitivity analyses of input variables. HOMER simulates the operational characteristics of a system by ensuring energy balance controls for each time step of the year. For each time step, the electric and thermal load in the time step is compared to the energy that the system is able to supply in that step. When batteries and fuel-powered generators are added to the system, for each time step, HOMER prioritizes the operation of the generator whether to charge or discharge the batteries using load following (LF) or cycle charging (CC). Once the demand is met by the combination of the components, the lifecycle cost (discounted sum of the initial investment, replacement, operation and maintenance, fuel and interest costs) of the system is estimated. Furthermore, sensitivity analysis can be performed on the input that is stochastic in nature. For this study, the HOMER software is adopted.

Based on the intended aim, various evaluation criteria can be used to appraise the performance of a hybrid energy system. These include economic (NPC, levelised cost of energy (COE), simple payback period), technical (reliability) or environmental (emission minimization, renewable energy fraction). Although the results of other evaluation performance criteria are presented in this study, the NPC is used in raking the optimal system. The NPC is estimated using Equation (1).

$$\mathrm{NPC} = \mathrm{ICC} - \sum_{y=1}^{Y} \frac{\mathrm{CF}_y}{(1+r)^y} \tag{1}$$

where ICC, r, and CF_y are initial capital cost, interest rate, and cash flow during the time steps y, respectively. The LCOE according to HOMER is the ratio of the average production cost to the energy served in kWh (Equation 2).

$$\mathrm{LCOE} = \frac{C_{\mathrm{ann,tot}} - C_{\mathrm{boiler}} H_{\mathrm{served}}}{E_{\mathrm{served}}} \tag{2}$$

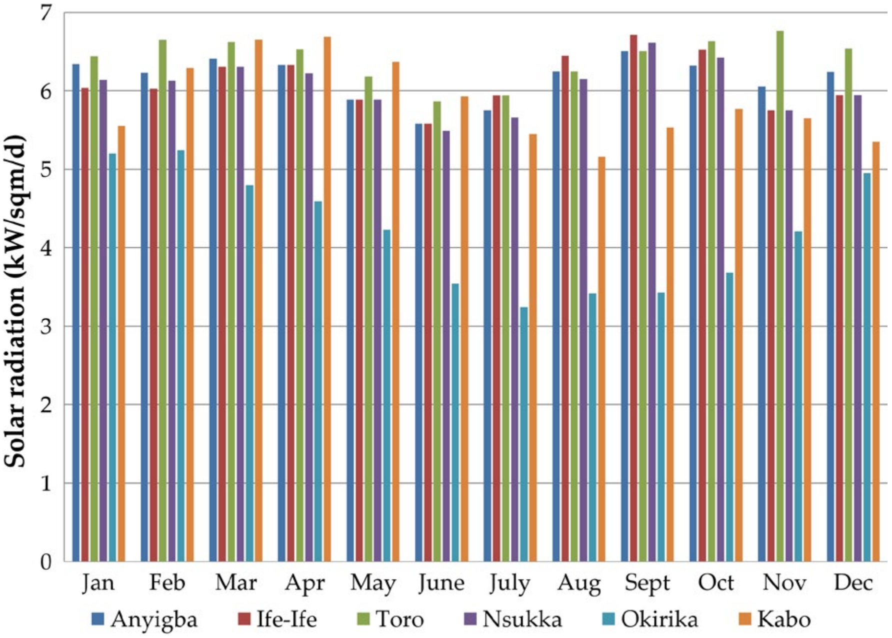

FIGURE 2 Monthly solar irradiation data of the study sites

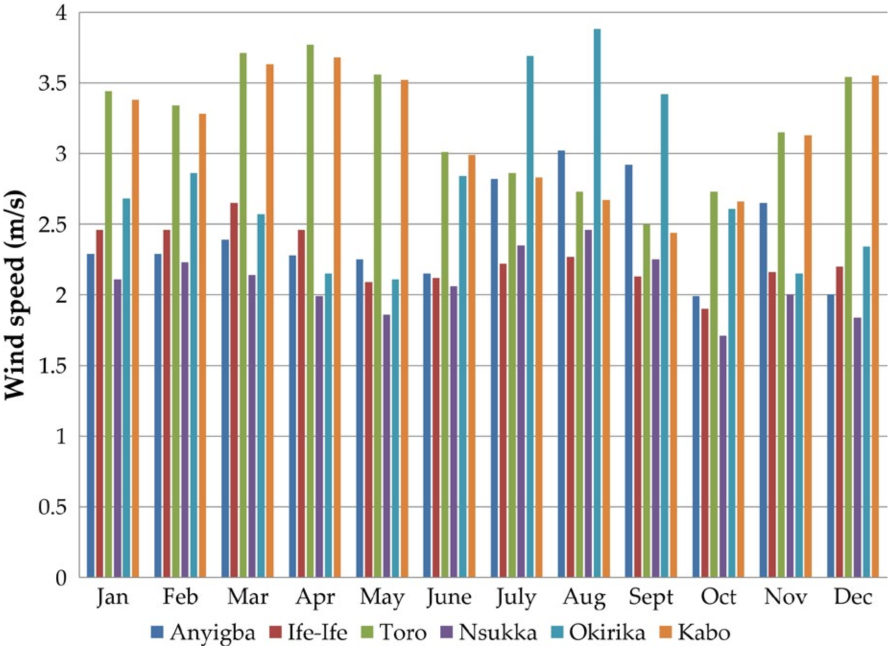

FIGURE 3 Wind speed data of the study sites

where is C_{boiler} the marginal cost of the boiler in $/kWh, the annual cost of the system is represented as $C_{\text{ann,tot}}$ in $/y, E_{served} is total electrical load served in kWh/y and H_{served} is total thermal load served (kWh/y). In this case study, since our system is not supplying a thermal load, the value of H_{served} is equal to zero. Since out analysis did not consider deferrable loads, the renewable fraction is based on the amount of the renewable energy that is used in serving the primary load. The renewable fraction is the fraction of the energy supplied to the load that comes from renewable sources. The renewable fraction equation is given by:

$$F_{\text{ren}} = 1 - \frac{E_{\text{nonren}} - E_{\text{grid,sales}} + H_{\text{nonren}}}{E_{\text{served}} + H_{\text{served}}} \tag{3}$$

Where, E_{nonren} nonrenewable electrical production (kWh/y), $E_{\text{grid,sales}}$ energy sold to the grid (kWh/y), H_{nonren} nonrenewable thermal production (kWh/y), E_{served} total electrical load served (kWh/y), H_{served} total thermal (kWh/y), load served. In this study, $E_{\text{grid,sales}}$, and $H_{\text{nonren}} = 0$.

5 | SIMULATION AND OPTIMIZATION RESULTS

This section provides the result obtained by using the load data of a typical RHC, the component parameters and the

TABLE 3 Monthly ambient temperature data of the study sites

Month	Anyigba	Ile-Ife	Toro	Nsukka	Okrika	Kabo
Jan	27.0	25.9	23.7	26.2	25.6	23.0
Feb	27.3	26.2	25.6	26.5	26.0	24.9
Mar	26.5	25.8	28.0	26.1	26.0	28.0
Apr	26.1	25.6	27.5	26.0	26.1	28.1
May	25.8	25.5	26.3	25.8	26.0	26.9
June	24.9	24.6	24.7	24.9	25.3	25.0
July	24.2	23.7	23.7	24.2	24.5	23.9
Aug	24.1	23.6	23.6	24.1	24.2	23.9
Sept	24.3	24.0	24.2	24.3	24.5	24.6
Oct	24.6	24.4	25.0	24.6	24.8	25.7
Nov	24.7	24.5	25.5	24.6	25.0	25.9
Dec	25.9	25.1	24.1	25.1	25.3	23.6
Average	25.45	24.91	25.16	25.20	25.28	25.29

TABLE 4 System component parameters[18]

Component	Investment cost	Replacement cost	Annual O & M cost	Operational lifetime
PV	\$4250/kW[a]	\$4200/kW	10 \$/y	20 y
Wind turbine	\$4500/kW	\$4500/kW	\$0.05/hr	20 y
Diesel Generator	\$280/kW	\$280/kW	0.5 \$/hr	15 000 h
Battery	\$269 (4 V, 1900 Ah)	\$260	\$5/y	4 y[b]
Converter	\$621.8/kW	\$569/kW	\$3/y	15 y

[a] Sensitivity analysis for PV module price is conducted between \$1275 and \$4250 and the results are presented in the Appendix.

[b] The battery is replaced every 4 years.

TABLE 5 Search space of system components

S/no.	PV panels (kW)	Wind turbine (no.)	Diesel gen. (kW)	Battery (quantity)	Converter (kW)
1	0	0	0	0	0
2	2	1	1	1	1
3	3	3	2	2	2
4	5		3	3	3
5	10			4	
6				5	

meteorological data of the sites under investigation. The first objective of the section is determining and presenting the energy systems with the minimum cost across the sites under review. The effect of fluctuation in fuel pump price and the interest rate on the economic parameters are also discussed in this section. In 1992, the fuel pump price was about 0.02 USD/L. At present (2018) gasoline pump price in Nigeria is between 0.47 and 0.58 USD/L. Hence, the percentage increase in gasoline pump price over 27 years is approximately 2250%. This is an average of 83% per year with irregular spikes over the 27 years period (Figure 4). Since the currency exchange rate and inflation rate will not be constant over the operational years of the proposed project, it is therefore necessary to conduct a sensitivity analysis with respect to change in fuel pump price and interest rates.

5.1 | Economic

The techno-economic and environmental result of the simulation for the selected sites is presented in Table 6. Across all six locations, various configurations were returned as potential optimal. At all the sites, PV/DG/Battery is being returned as the optimal in terms of NPC and LCOE. The PV/DG/Battery and PV/Wind/Battery ranks best in terms of

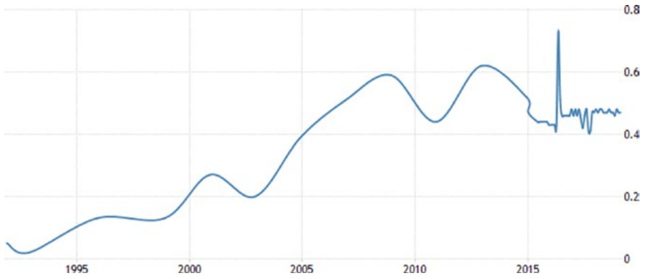

FIGURE 4 Fluctuation in gasoline pump price in Nigeria from 1992 to 2018[26]

environmental performance both with 100% renewable fraction and zero fuel consumption across all locations. Figure 5 shows the trend of NPC and LCOE across all the sites. It could be seen that Okrika had the highest NPC and LCOE ($13 646 and 0.542 $/y). This is due to the low level of solar and wind resources received at this location. Ile-Ife and Toro had the least NPC and LCOE ($12 779 and 0.507 $/y respectively) -an indication of high viability. None of the number 1 ranked best system has a wind turbine in its configuration. It is more expensive to site and run the optimal system in Okrika than all other sites.

5.2 | Electricity production

Electricity produced by various system architectures is dependent on the diverse mix of the hybrid system. In this study, the annual electricity produced, excess energy, unmet load, renewable energy penetration, and renewable fraction were evaluated. Details of this are given in Table 5 and Figure 6. For the optimal system configuration for all locations, the shortage capacity is zero, thereby unmet load is negligible. From Figure 6, it is seen that Anyigba has 84% PV, 16% DG; Ile-ife-84% PV, 16% DG, Kabo-83% PV, 17% DG; Nsukka-84% PV, 16% DG; Okrika-74% PV, 26% DG; Toro 84% PV, 16% DG. Toro has the highest excess electricity production of 86.1 kWh/y while Anyigba had the least-37.9 kWh/y. The excess electricity can be sold to the grid if the system does not operate in the islanding mode. From the analysis (Table 5), it is obvious that 100% of the RHC load can be supplied with PV/DG/Battery and PV/Wind/Battery. The diesel generator at Okrika run more in terms of operational hours and consume the highest diesel fuel when compared to other sites. Kabo and Okrika returned only four feasible options (Table 5). This is likely due to the fact that these site (Kabo and Okrika) has the least value of solar irradiation out of the six locations considered (since this is the only renewable energy source that contributed at lowest NPC).

5.3 | Sensitivity analysis

Since the price of oil fluctuates both in the local and international market, more outage may occur due to the addition of load and/or reduction in meteorological climatic resources, it is necessary to carry out a sensitivity analysis on the system. In doing this, the effect of a change in diesel price on the NPC of the optimal system configuration is carried out. The effect of interest rate on the NPC of the optimal system configuration for the location is also investigated. The fuel pump price is varied between 0.4 and 1 $/L for the optimal system configurations for the six locations considered in this study. It is observed that the higher the pump price the higher the NPC (Figure 7). Toro still remains the center with the lowest NPC while the center with the highest NPC is Okrika. Figure 8 shows the effect of change in interest rate (between 0% and 12%) on NPC. The 0% interest rate is added to accommodate "equity participation" for the funding of such projects. In equity participation, the financial institution loans money to an investor, the investor will pay back the loan without interest but instead shares the profit with the financial institution.[27] It can be easily observed that for all locations considered, there is a decrease in the NPC as the interest rate increases. Except for Okrika, the NPC for all other locations are close in terms of the values. As usual, the RHC in Okrika had the highest NPC.

Figure 9 shows the influence of a change in interest rate on renewable fraction and LCOE for the six locations. For all locations, it can be seen that the LCOE is directly proportional to the interest rate. At Anyigba the RF was constant at 78% between 0% and 4% interest rates before increasing to 81% and remaining constant till 12% interest rate. The renewable faction at Ile-Ife shows a different pattern with RF being constant between 0 and 4% interest rate before dropping to around 78% at 6% interest rate. This then rises to around 81% between 10% and 12%. Kabo and Nsukka share a similar pattern with RF being constant between 0% and 2% interest rate before increasing at 4% and remaining constant till 12% interest rate. At Okrika, the RF is constant for all interest rates. It can be observed that at Toro, the RF was 79% between 0% and 6% before dropping to about 78% for interest rates between 10% and 12%. It is worth to note that there is no significant difference in the optimal configuration as the interest rates increases (Table 7). This may be due to the fact that HOMER orders cost-optimal solutions according to NPC, which in turn is sensitive to interest rates. This can affect the renewable fraction as technologies may be reordered and the contribution from nonrenewable sources could also increase/decrease. As such, technologies and their respective contributions may be reordered to minimise NPC.

TABLE 6 Techno-economic and environmental results at 0.58$/L pump fuel price (base case)

	Technical						Economic				Environmental		
	PV (kW)	Wind Turbine	DG (kW)	Battery	Converter (kW)	Dispatch strategy	Initial capital	Operating cost ($/y)	Total NPC	LCOE ($/kWh)	Renewable fraction	Diesel (L)	Diesel[a] (h)
Anyigba	2	0	2	2	2	LF	10 733	277	12 805	0.508	0.81	322	1012
	2	1	2	2	2	LF	15 233	155	16 389	0.651	0.92	127	398
	3	0	0	4	3	CC	15 692	110	16 516	0.656	1	0	0
	3	1	0	3	3	CC	19 923	109	20 739	0.823	1	0	0
	10	3	1	0	2	CC	57 469	517	61 330	2.435	0.71	509	3275
Ile-Ife	2	0	2	2	2	LF	10 733	274	12 779	0.507	0.81	318	995
	2	1	2	2	2	LF	15 233	155	16 392	0.651	0.92	127	401
	3	0	0	5	3	CC	15 961	123	16 882	0.67	1	0	0
	3	1	0	4	3	CC	20 192	122	21 106	0.838	1	0	0
	10	3	1	0	2	CC	57 469	519	61 346	2.435	0.71	512	3294
Kabo	2	0	2	2	2	LF	10 733	281	12 829	0.509	0.8	327	1016
	2	1	2	2	2	LF	15 233	177	16 552	0.657	0.9	160	498
	3	0	0	5	3	CC	15 961	123	16 882	0.671	1	0	0
	3	1	0	5	3	CC	20 461	135	21 472	0.853	1	0	0
Nsukka	2	0	2	2	2	LF	10 733	276	12 792	0.508	0.81	320	1002
	2	1	2	2	2	LF	15 233	156	16 398	0.651	0.92	129	405
	3	0	0	5	3	CC	15 961	123	16 882	0.67	1	0	0
	3	1	0	4	3	CC	20 192	122	21 106	0.838	1	0	0
	10	3	1	0	2	CC	57 469	517	61 329	2.435	0.71	509	3273
Okrika	2	0	2	2	2	LF	10 733	390	13 646	0.542	0.7	483	1456
	2	1	2	2	2	LF	15 233	251	17 104	0.679	0.84	270	822
	5	0	0	5	3	CC	24 461	143	25 531	1.014	1	0	0
	5	1	0	3	3	CC	28 423	129	29 389	1.167	1	0	0
Toro	2	0	2	2	2	CC	10 733	274	12 779	0.507	0.78	326	888
	2	1	2	2	2	LF	15 233	155	16 391	0.651	0.93	127	403
	3	0	0	4	3	CC	15 692	110	16 516	0.656	1	0	0
	3	1	0	3	3	CC	19 923	109	20 739	0.824	1	0	0
	10	3	1	0	2	CC	57 469	511	61 282	2.433	0.71	501	3224

CC, cycle charging; DG, diesel generator; LF, load following.

[a] Diesel-operational hours of diesel generator.

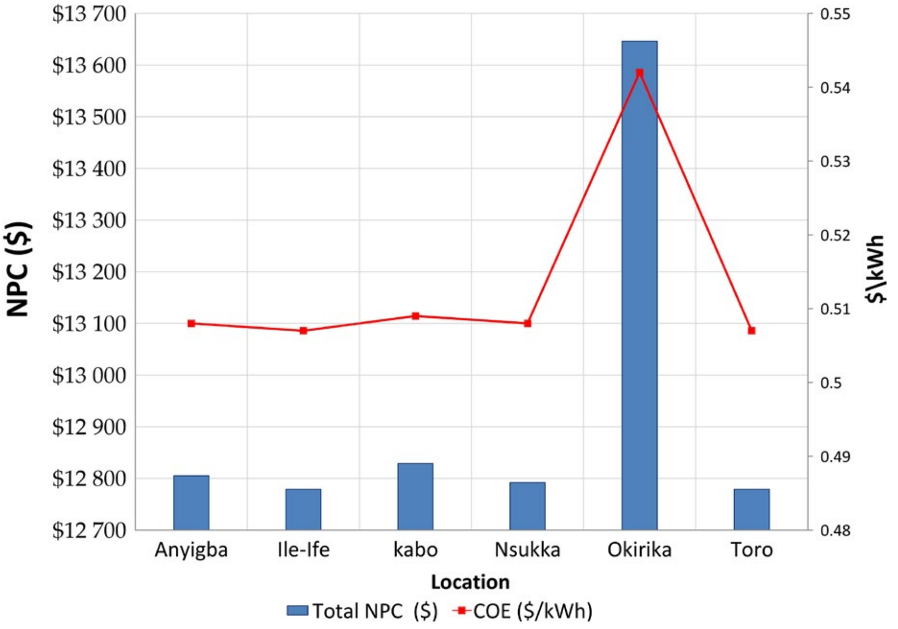

FIGURE 5 Results of NPC and LCOE across the locations for the optimal system configuration

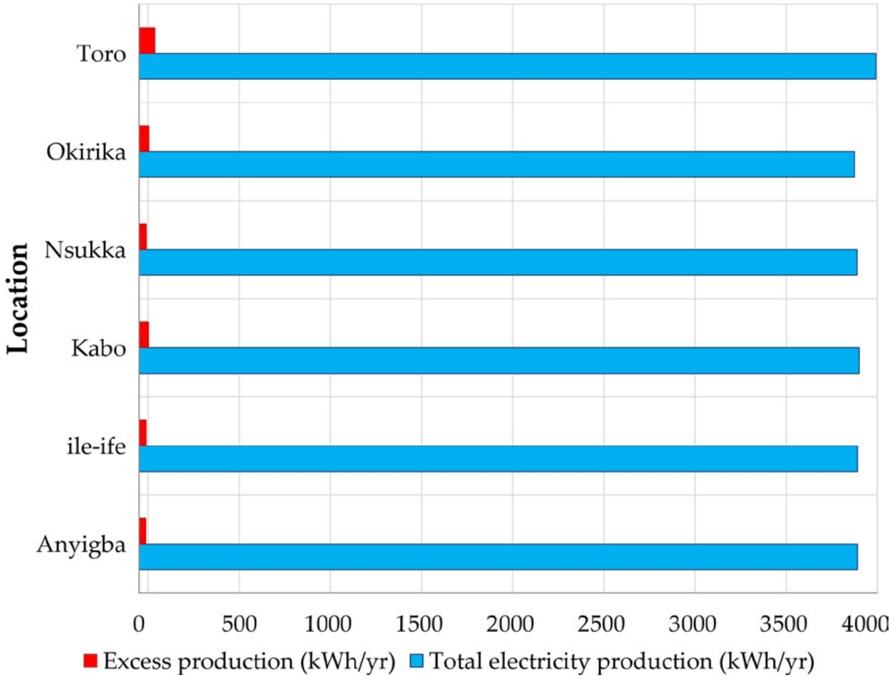

FIGURE 6 Energy production and excess energy across the locations for the optimal system configuration

6 | POLICY DISCUSSION

The sustainability of HRES technologies in alleviating energy poverty for RHCs is a major area where little has been achieved. Hence, the inability of operators and stakeholders to replicate the successes in other viable mini-grid projects is a source of concern for decision makers. It has been discovered that many of the renewable mini-grid technologies that have worked on a commercial scale could not be replicated due to the absence of adequate policies, maintenance structure, sustainable operation as well as financing.[28] For example, over 35 000 biogas plants were constructed in Nepal between 1992 and 1998. The technology was largely embraced by small and lower-income farmers due to the implementation of subsidies and affordable financing.[28] It was reported that a joint sustainability effort on the part of the owners, installers as well as programme staff was the brain behind the excellent performance of the scheme. The scheme also made sure the users received financial incentives.[28,29] On the contrary, the replicability of Bio-gas plant in sub-Saharan Africa experienced challenges. Similarly, some factors responsible for sustainability of HRES for RHC applications include inadequate policies and

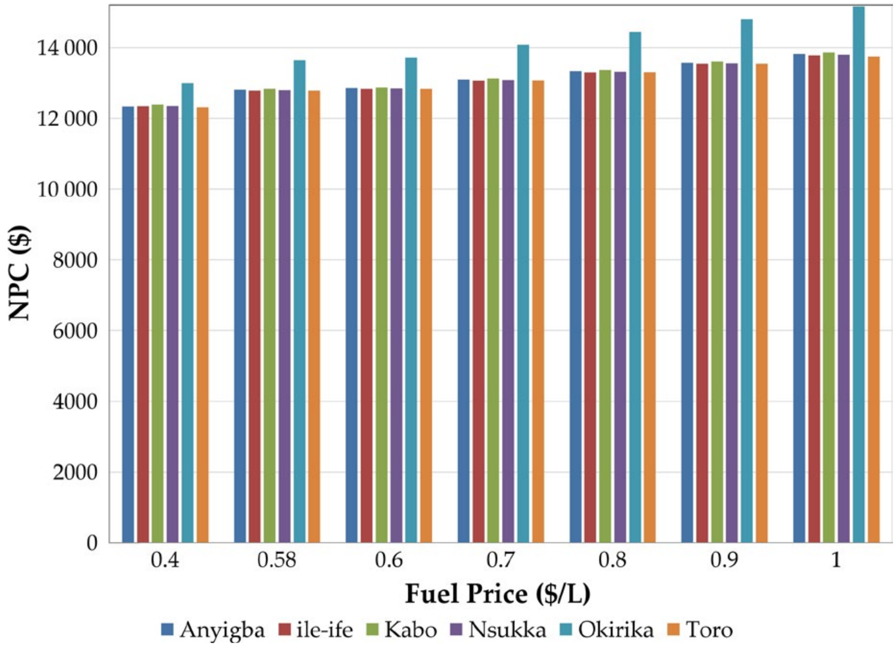

FIGURE 7 Effect of change in fuel pump price on NPC

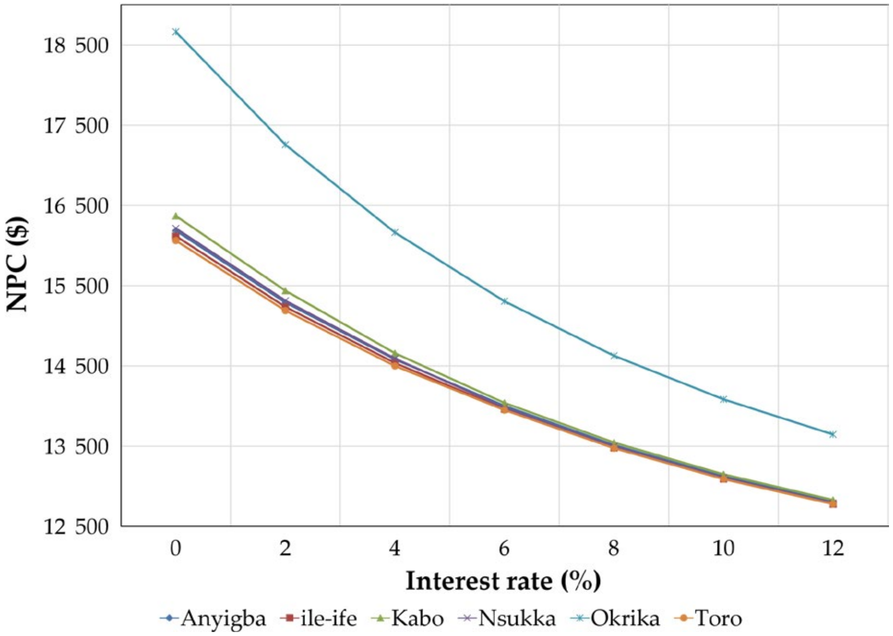

FIGURE 8 Effect of change in interest rate on NPC

regulatory framework, wrong business model, quality control, lack maintenance culture etc.

6.1 | Effective policy initiatives and incentives

In order to achieve success in the deployment of an off-grid hybrid renewable energy system (HRES) for RHCs, effective policy frameworks are essential. It is therefore essential to adopt and incorporate the relevant policy framework when deploying renewable energy for supplying the energy demands of RHCs. There are vast international institutional regulatory frameworks and policies as it relates to the development and implementation of HRES for RHCs. However, the modification of such policies to fit into the local scenario is very important. Using successful models from other countries, the establishment of a national and local policy for powering RHC with HRESs is essential. The government, however, must support these policies with absolute political will, relevant policies, incentives as well as commitment. Some of these policies include monetary incentives (eg, soft loans, exemptions from import duty) and reduction/removal of fossil fuel subsidy. These policies have the tendencies to encourage the penetration of HRES in RHCs.

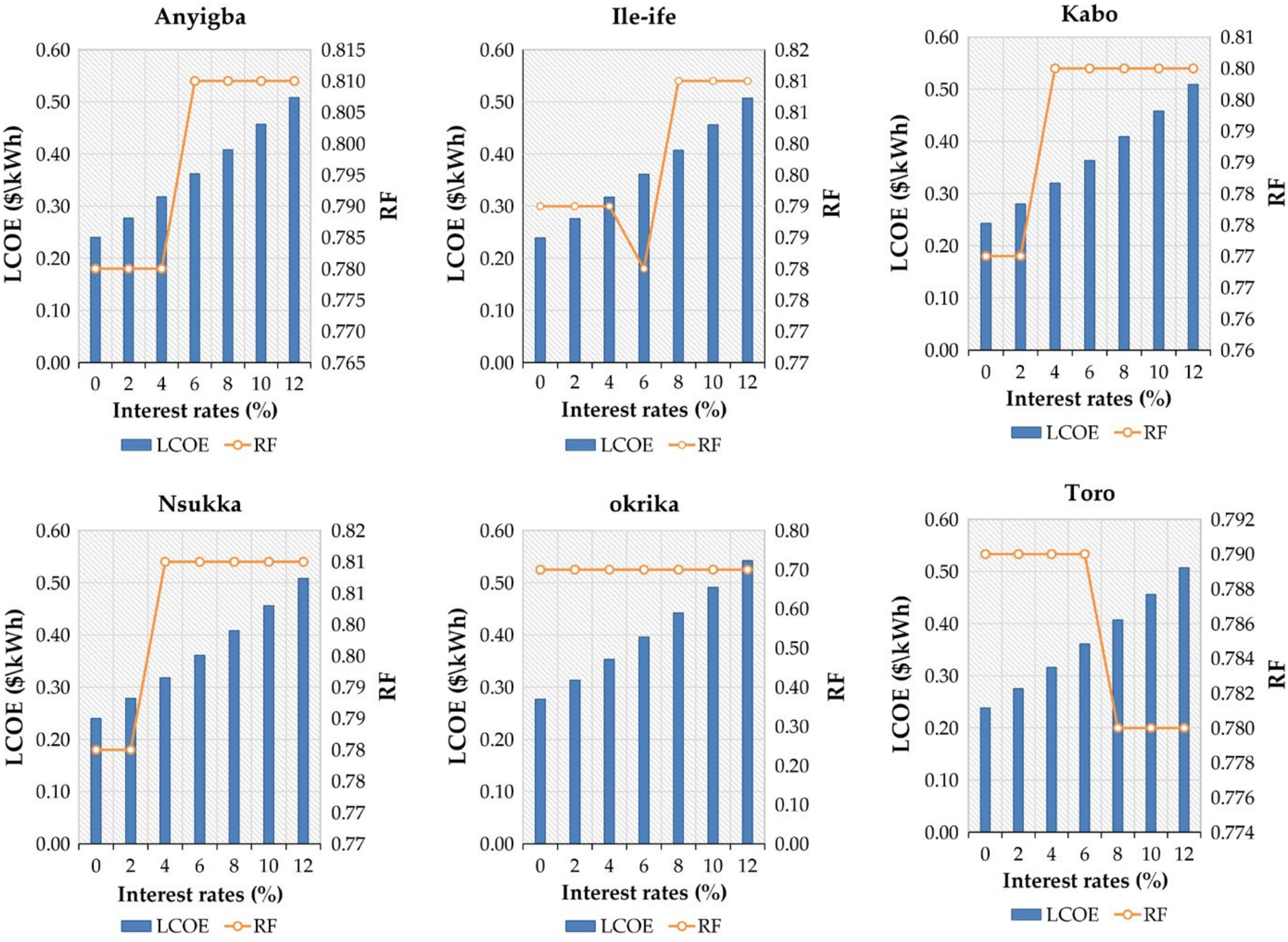

FIGURE 9 The influence of interest rate on LCOE and RF

6.2 | Development and adoption of relevant business models

Energy business in developing countries is a lucrative business. This is due to the inability of government in these countries to meet energy demand. The government's inability is due to nonavailability of funds. Though HRES has been identified to be more economically viable when compared to the stand-alone diesel generators in RHCs, the huge upfront investment cost is often seen as a major barrier. This is because the initial capital for setting up the renewable system is usually far greater than that of its conventional alternative such as diesel-powered generators. Hence, putting together a sustainable financial base for funding and operating HRES for RHCs can be difficult despite the emergence of efficient financial analysis tools. Financial schemes for these systems should be designed to accommodate income generating techniques to enhance sustainability. In other words, the project should be able to pay back within a reasonable time frame. This can be achieved by "setting realistic tariffs and encouraging Public-private-partnerships (PPPs). Through designing and implementation of suitable financial business model, many rural health facilities will have access to sustainable renewable energy.

6.3 | Quality control

It is expected that the various component and construction of the renewable energy system should conform to relevant international and national standards. Some of these standards include: IEC 61730-2, IEC 61730-1, IEEE 1361, IEC 62109-1, IEC 62109, IEC 61347-1-4, IEC/TS 62257, etc.[30] Furthermore, the WHO has its own standard PQS, which represents a technical-assurance reference for the WHO and UNICEF regular supplies.[30] The use of inferior products and materials such as solar PV panels, turbine, storage devices, and converters is one of the factors that contribute to HRES failure in Nigeria. This can also affect HRES for RHCs across the country if not monitored. The provision of adequate procurement standards is essential, as the absence of such, usually results in mix-up on the part of vendor and frequently results in delivery of substandard HRES. The provision of

TABLE 7 Effect of interest rates on optimal configuration

Location	Interest rate	0%	2%	4%	6%	8%	10%	12%
Anyigba	PV (kW)	2	2	2	2	2	2	2
	DG (kW)	2	2	2	2	2	2	2
	Battery	3	3	3	2	2	2	2
	Converter	2	2	2	2	2	2	2
Ife	PV (kW)	2	2	2	2	2	2	2
	DG (kW)	2	2	2	2	2	2	2
	Battery	3	3	3	2	2	2	2
	Converter	2	2	2	2	2	2	2
Kabo	PV (kW)	2	2	2	2	2	2	2
	DG (kW)	2	2	2	2	2	2	2
	Battery	3	3	2	2	2	2	2
	Converter	2	2	2	2	2	2	2
Nsukka	PV (kW)	2	2	2	2	2	2	2
	DG (kW)	2	2	2	2	2	2	2
	Battery	3	3	2	2	2	2	2
	Converter	2	2	2	2	2	2	2
Okrika	PV (kW)	2	2	2	2	2	2	2
	DG (kW)	2	2	2	2	2	2	2
	Battery	2	2	2	2	2	2	2
	Converter	2	2	2	2	2	2	2
Toro	PV (kW)	2	2	2	2	2	2	2
	DG (kW)	2	2	2	2	2	2	2
	Battery	3	3	3	3	2	2	2
	Converter	2	2	2	2	2	2	2

self-explanatory technical and user manuals should be provided to accompany equipment. In a similar manner, it is essential that such a project be given to qualified contractors that can deliver quality work.

6.4 | Operation and maintenance

In developing countries, many of the HRES are designed and implemented by consultants. Conversely, many of the RHCs are owned and operated by local governments. Consequently, it is the sole responsibility of the local government to operate and maintain the HRES used to power the RHCs. This situation is however challenging for many local councils because most of them do not have budgets that can accommodate adequate maintenance. If the HRES is not well serviced, it can lead to premature failure of the systems. In order to avoid this, support maintenance funds should be made available for implemented HRESs through public-private-partnership. It is also essential and cost effective to adequately train local staffs on the operation and maintenance of the HRES. These trainings can be done concurrently during the installation of the HRES. Furthermore, training on the operation and management of energy storage device is essential. This will help prioritize the use of energy stored for critical medical equipment and services. The provision of HRES service manuals for end-users of health facilities and technicians is essential. This will aid operators in remote monitoring or documentation of faults and problems.

10 | CONCLUSION

This paper evaluates the RHC demand supply based on the possibility of 100% RES. Different evaluation performance criteria such as NPC, LCOE, renewable fraction and the excess electricity, have been considered to select the best combination of HRES. Six hypothetical RHC centers across the six geopolitical zones in Nigeria has been used has a case study. By considering various scenarios of fuel pump price and interest rate, the optimal generation mix of the power sources has been evaluated. Results show that the optimal mix based on NPC at all location consists of PV/Diesel generator and battery of various output power rating. This implies that if cost minimization is the objective, the diesel generator will play an integral part in the system. Though at higher NPC, the results also show the feasibility of 100% renewables at all locations considered in this research. Based on the optimal results, the most economically viable location is Ile-Ife and Toro while the least economically viable location is Okrika which receives the lowest solar irradiation. In terms of the renewable fraction, Anyigba and Nsukka are the most preferred location with 81% renewable energy penetration in the generation mix at both locations. The sensitivity analysis shows that the interest rate is directly proportional to the LCOE and inversely proportional to the NPC. Furthermore, as the fuel pump price increases, the NPC also increases as also reported by Olatomiwa[13] and Babatunde et al.[15] Generally, the results of this study compares favorably with the outcome of similar studies[13,15-18,20,22-24] where renewable energy is returned as the most economically feasible system for RHCs.

Future studies are expected to consider the application of decision-making tools in the selection among alternatives returned as optimal for different locations. Other storage facilities and renewables will also be considered as further studies. Future research can be directed towards proposing a comprehensive model which considers the Social, Technical, Environmental, Economic, and policy (STEEP) aspect of electrifying RHCs.

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APPENDIX

Various values for the cost of PV module related to Nigeria have been presented in the literature. Some of them include \$3200/kW,[17] and \$4250/kW.[18] For the purpose of this study, the capital cost for solar PV panel is \$4250/kW with a replacement cost and O &M costs of \$4200/kW and \$10/y respectively. A sensitivity analysis for PV module price (between \$1275 and \$4250) is further conducted to determine the feasible HRES alternatives. Results of the sensitivity analysis for PV module price for all locations (between \$1275 and \$4250) are presented in this section.

PV price (\$/kW)	PV (kW)	Wind turbine (no)	Gen. (kW)	Battery (no)	Converter (kW)	Dispatch strategy	Initial capital	Operating cost (\$/y)	Total NPC	COE (\$/kWh)	RF	Diesel (L)	Diesel* (h)
Anyigba													
1275	3	0	1	2	2	LF	\$3282	95	\$3993	0.159	0.98	35	217
	3	0	0	4	3	CC	\$4217	110	\$5041	0.2	1	0	0
	3	1	1	1	2	CC	\$7513	118	\$8397	0.333	0.95	73	382
	3	1	0	3	3	CC	\$8448	109	\$9264	0.368	1	0	0
	10	3	1	0	2	CC	\$19 219	517	\$23 080	0.916	0.71	509	3275
1913	3	0	1	2	2	LF	\$3920	95	\$4630	0.184	0.98	35	217
	3	0	0	4	3	CC	\$4854	110	\$5678	0.225	1	0	0
	3	1	1	1	2	CC	\$8151	118	\$9034	0.359	0.95	73	382
	3	1	0	3	3	CC	\$9085	109	\$9902	0.393	1	0	0
	10	3	1	0	2	CC	\$21 344	517	\$25 205	1.001	0.71	509	3275
2295	3	0	1	2	2	LF	\$4302	95	\$5013	0.199	0.98	35	217
	3	0	0	4	3	CC	\$5237	110	\$6061	0.241	1	0	0
	3	1	1	1	2	CC	\$8533	118	\$9417	0.374	0.95	73	382
	3	1	0	3	3	CC	\$9468	109	\$10 284	0.408	1	0	0
	10	3	1	0	2	CC	\$22 619	517	\$26 480	1.051	0.71	509	3275
3315	3	0	1	2	2	LF	\$5322	95	\$6033	0.24	0.98	35	217
	3	0	0	4	3	CC	\$6257	110	\$7081	0.281	1	0	0
	2	1	2	2	2	LF	\$8943	155	\$10 099	0.401	0.92	127	398
	3	1	0	3	3	CC	\$10 488	109	\$11 304	0.449	1	0	0
	10	3	1	0	2	CC	\$26 019	517	\$29 880	1.186	0.71	509	3275
Ile-Ife													
1275	3	0	1	2	2	LF	\$3282	98	\$4014	0.159	0.98	40	240
	5	0	0	2	3	CC	\$4529	104	\$5308	0.211	1	0	0
	3	1	1	1	2	CC	\$7513	121	\$8417	0.334	0.95	78	400
	3	1	0	4	3	CC	\$8717	122	\$9631	0.382	1	0	0
	10	3	1	0	2	CC	\$19 219	519	\$23 096	0.917	0.71	512	3294
1913	3	0	1	2	2	LF	\$3920	98	\$4652	0.185	0.98	40	240
	3	0	0	5	3	CC	\$5123	123	\$6044	0.24	1	0	0
	3	1	1	1	2	CC	\$8151	121	\$9055	0.359	0.95	78	400
	3	1	0	4	3	CC	\$9354	122	\$10 268	0.408	1	0	0
	10	3	1	0	2	CC	\$21 344	519	\$25 221	1.001	0.71	512	3294
2295	3	0	1	2	2	LF	\$4302	98	\$5034	0.2	0.98	40	240
	3	0		5	3	CC	\$5506	123	\$6427	0.255	1	0	0
	2	1	2	2	2	LF	\$8263	155	\$9422	0.374	0.92	127	401
	3	1	0	4	3	CC	\$9737	122	\$10 650	0.423	1	0	0
	10	3	1	0	2	CC	\$22 619	519	\$26 496	1.052	0.71	512	3294

(Continues)

APPENDIX (Continued)

PV price ($/kW)	PV (kW)	Wind turbine (no)	Gen. (kW)	Battery (no)	Converter (kW)	Dispatch strategy	Initial capital	Operating cost ($/y)	Total NPC	COE ($/kWh)	RF	Diesel (L)	Diesel* (h)
3315	3	0	1	2	2	LF	$5322	98	$6054	0.24	0.98	40	240
	3	0	0	5	3	CC	$6526	123	$7447	0.296	1	0	0
	2	1	2	2	2	LF	$8943	155	$10 102	0.401	0.92	127	401
	3	1	0	4	3	CC	$10 757	122	$11 670	0.463	1	0	0
	10	3	1	0	2	CC	$26 019	519	$29 896	1.187	0.71	512	3294
Kabo													
1275	3	0	1	2	2	CC	$3282	132	$4267	0.169	0.93	94	402
	3	0	0	5	3	CC	$4486	123	$5407	0.215	1	0	0
	3	1	1	2	2	LF	$7782	107	$8579	0.341	0.98	35	205
	3	1	0	5	3	CC	$8986	135	$9997	0.397	1	0	0
1913	3	0	1	2	2	CC	$3920	132	$4905	0.195	0.93	94	402
	3	0	0	5	3	CC	$5123	123	$6044	0.24	1	0	0
	3	1	1	2	2	LF	$8420	107	$9217	0.366	0.98	35	205
	3	1	0	5	3	CC	$9623	135	$10 634	0.422	1	0	0
2295	3	0	1	2	2	CC	$4302	132	$5287	0.21	0.93	94	402
	3	0	0	5	3	CC	$5506	123	$6427	0.255	1	0	0
	2	1	2	2	2	LF	$8263	177	$9582	0.38	0.9	160	498
	3	1	0	5	3	CC	$10 006	135	$11 017	0.437	1	0	0
3315	3	0	1	2	2	CC	$5322	132	$6307	0.25	0.93	94	402
	3	0	0	5	3	CC	$6526	123	$7447	0.296	1	0	0
	2	1	2	2	2	LF	$8943	177	$10 262	0.407	0.9	160	498
	3	1	0	5	3	CC	$11 026	135	$12 037	0.478	1	0	0
Nusukka													
1275	3	0	1	2	2	LF	$3282	98	$4014	0.159	0.98	40	239
	5	0	0	2	3	CC	$4529	104	$5308	0.211	1	0	0
	3	1	1	1	2	CC	$7513	124	$8442	0.335	0.94	83	432
	3	1	0	4	3	CC	$8717	122	$9631	0.382	1	0	0
	10	3	1	0	2	CC	$19 219	517	$23 079	0.916	0.71	509	3273
1913	3	0	1	2	2	LF	$3920	98	$4652	0.185	0.98	40	239
	3	0	0	5	3	CC	$5123	123	$6044	0.24	1	0	0
	3	1	1	1	2	CC	$8151	124	$9080	0.361	0.94	83	432
	3	1		4	3	CC	$9354	122	$10 268	0.408	1	0	0
	10	3	1	0	2	CC	$21 344	517	$25 204	1.001	0.71	509	3273
2295	3	0	1	2	2	LF	$4302	98	$5034	0.2	0.98	40	239
	3	0	0	5	3	CC	$5506	123	$6427	0.255	1	0	
	2	1	2	2	2	LF	$8263	156	$9428	0.374	0.92	129	405
	3	1	0	4	3	CC	$9737	122	$10 650	0.423	1	0	0
	10	3	1	0	2	CC	$22 619	517	$26 479	1.051	0.71	509	3273
3315	3	0	1	2	2	LF	$5322	98	$6054	0.24	0.98	40	239
	3	0	0	5	3	CC	$6526	123	$7447	0.296	1	0	0
	2	1	2	2	2	LF	$8943	156	$10 108	0.401	0.92	129	405
	3	1	0	4	3	CC	$10 757	122	$11 670	0.463	1	0	0
	10	3	1	0	2	CC	$26 019	517	$29 879	1.186	0.71	509	3273

(Continues)

APPENDIX (Continued)

PV price ($/kW)	PV (kW)	Wind turbine (no)	Gen. (kW)	Battery (no)	Converter (kW)	Dispatch strategy	Initial capital	Operating cost ($/y)	Total NPC	COE ($/kWh)	RF	Diesel (L)	Diesel* (h)
Okrika													
1275	3	0	2	2	2	LF	$3508	198	$4988	0.198	0.88	196	602
	5	0	0	5	3	CC	$5336	143	$6406	0.254	1	0	0
	3	1	2	2	2	LF	$8008	141	$9061	0.36	0.94	91	279
	5	1	0	3	3	CC	$9298	129	$10 264	0.408	1	0	0
1913	3	0	2	2	2	LF	$4145	198	$5625	0.223	0.88	196	602
	5	0	0	5	3	CC	$6398	143	$7469	0.297	1	0	0
	3	1	2	2	2	LF	$8645	141	$9699	0.385	0.94	91	279
	5	1	0	3	3	CC	$10 360	129	$11 326	0.45	1	0	0
2295	3	0	2	2	2	LF	$4528	198	$6008	0.238	0.88	196	602
	5	0	0	5	3	CC	$7036	143	$8106	0.322	1	0	0
	3	1	2	2	2	LF	$9028	141	$10 081	0.4	0.94	91	279
	5	1	0	3	3	CC	$10 998	129	$11 964	0.475	1	0	0
3315	3	0	2	2	2	LF	$5548	198	$7028	0.279	0.88	196	602
	5	0	0	5	3	CC	$8736	143	$9806	0.39	1	0	0
	2	1	2	2	2	LF	$8943	251	$10 814	0.429	0.84	270	822
	5	1	0	3	3	CC	$12 698	129	$13 664	0.543	1	0	0
Toro													
1275	3	0	1	1	2	CC	$3013	121	$3920	0.156	0.93	96	513
	3	0	0	4	3	CC	$4217	110	$5041	0.2	1	0	0
	3	1	1	1	2	LF	$7513	95	$8226	0.327	0.98	37	227
	3	1		3	3	CC	$8448	109	$9264	0.368	1	0	0
	10	3	1	0	2	CC	$19 219	511	$23 032	0.914	0.71	501	3224
1913	3	0	1	1	2	CC	$3651	121	$4557	0.181	0.93	96	513
	3	0	0	4	3	CC	$4854	110	$5678	0.225	1	0	0
	3	1	1	1	2	LF	$8151	95	$8863	0.352	0.98	37	227
	3	1		3	3	CC	$9085	109	$9902	0.393	1	0	0
	10	3	1	0	2	CC	$21 344	511	$25 157	0.999	0.71	501	3224
2295	3	0	1	1	2	CC	$4033	121	$4940	0.196	0.93	96	513
	3	0	0	4	3	CC	$5237	110	$6061	0.241	1	0	0
	3	1	1	1	2	LF	$8533	95	$9246	0.367	0.98	37	227
	3	1	0	3	3	CC	$9468	109	$10 284	0.408	1	0	0
	10	3	1	0	2	CC	$22 619	511	$26 432	1.049	0.71	501	3224
3315	3	0	1	1	2	CC	$5053	121	$5960	0.237	0.93	96	513
	3	0	0	4	3	CC	$6257	110	$7081	0.281	1	0	0
	2	1	2	2	2	LF	$8943	155	$10 101	0.401	0.93	127	403
	3	1	0	3	3	CC	$10 488	109	$11 304	0.449	1	0	0
	10	3	1	0	2	CC	$26 019	511	$29 832	1.184	0.71	501	3224

*Diesel-operational hours of diesel generator.