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DESIGN AND OPTIMIZATION OF HYBRID RENEWABLE ENERGY SYSTEM FOR RURAL ELECTRIFICATION OF AN OFF-GRID COMMUNITY

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ABSTRACT

This study focuses on the technical feasibility and economic viability of an optimal hybrid renewable energy system, designed for the rural electrification of an off-grid community of Edem Urua, a remote village located in the southern part of Nigeria. Mathematical modelling method was used for modelling; energy resources such as solar, wind, and diesel-generator with battery storage were combined for the design and optimal sizing of system components using Ampere-Hour optimal design method. The simulation and optimization were carried out using the Hybrid Optimization of Multiple Electric Renewables (HOMER or Homer Pro) Microgrid Analysis Tool. System performance and techno-economics were determined using some objective functions such as cost of energy, net present cost, renewable penetration fraction (RPF), CO_2 emission, payback years and returns on investment (ROI). The various system configurations were compared and analyzed for technical feasibility and economic viability. Findings showed that three optimal system configurations, Solar-PV/Diesel-Generator/Battery-Bank (SDB), Solar-PV/wind/Diesel-Generator/Battery-Bank (SWDB) and Solar-PV/Wind/Battery-Bank (SWB) had little or no CO_2 emission and were the most cost effective and technically preferred solutions. The SDB had a net present cost of $233,867.86, cost of energy of $0.062/kWh, RPF of 95.219% and CO_2 emission of 8,231 kg/yr. The SWDB had a total NPC of $227,082, COE of $0.063/kWh, RPF of 97.34%, and CO_2 emission of 4,621 kg/yr while the SWB had a total NPC of $264,046.10, COE of $0.073/kWh, RPF of 100% and zero CO_2 emission. The result of this research was found to be in alignment with the recent “Race to Zero” global campaign/climate action by the United Nations Framework Convention on Climate Change (UNFCCC) to keep global temperature rise to 1.5°C through cutting of global CO_2 emissions by 45% by the year 2030 and to net-zero CO_2 emissions by the year 2050.

Keywords: Hybrid Renewable Energy System, Off-grid, Cost of Energy, CO_2 emission, HOMER Pro.

1.0 INTRODUCTION

1.1 Background of Study

Sustainable electrical energy is the backbone and vehicle that drives development in every country that wants to advance in development. Its lack in some off-grid communities in developing countries like Nigeria contributes immensely to the slow pace of their socio-economic development as it is very essential in the most critical activities of their day-to-day life, including education, transportation, entertainment, agriculture and healthcare. According to the International Energy Agency (IEA), the number of people that lacked access to electricity in 2019 was 758.98 million, representing 13% of the world’s population, out of which 589.46 million were from sub-Saharan Africa. Nigeria’s figure in the year under review stood at 89.63

million as reported by Ritchie and Roser (2020). The total available grid power of Nigeria in 2017 was 5074 MW for a population of over 200 million people with a peak demand of about 17,700 MW and a national electricity access rate of 58% with a significant difference between urban areas (78%) and rural areas (39%) as reported by Oladigbolu *et al*. (2020). The grid extension in rural areas is usually impossible due to rugged terrains, thick jungles, far distance to the nearest grid, and high cost of energy supply, low power consumptions, low-income families and inadequate road infrastructure. Consequently, most people in rural areas depend on alternative sources of electrical power supply, mostly petrol and diesel-generators, with its own side effects and disadvantages of high cost of fuel, noise pollution, greenhouse gas emissions, and above all, it requires frequent maintenance as opined by Yimen *et al*. (2020) and Oyedepo *et al*. (2018).

To facilitate rapid social-economic development of off-grid communities and make life meaningful and better for the people, availability of clean and sustainable electrical energy at affordable rate has become imperative. This can be achieved through an efficient usage of an optimal hybrid renewable energy system using solar photovoltaic (PV) array, wind turbine, diesel-generator with a battery bank as a storage device, based on the yearly weather and climatic conditions of such an off-grid community. This is exactly what this research work was set out to achieve for Edem Urua community.

1.2 Study Community

The study community is Edem Urua village, an off-grid community located in Iwerre Clan, Ini Local Government Area (LGA) of Akwa Ibom State, South-South Region, Nigeria with a population of about 650 people. It is surrounded by other communities of Ikweme, Mbiabong, Nturi, Obotme, Okpoto, Ukpa Okon. Ini LGA is bounded by Abia State to the north and to the south, by Obot Akara, Ikono and Ibiono Ibom Local Government Areas of Akwa Ibom State. Figures 1 and 2 show the geographical locations, while Table 1 displays the background information of the study community.

The major occupations of residents of Edem Urua community are trading, farming, small and medium-scale enterprises like furniture and upholstery, auto-mechanics, barbing and milling. Some of these can be mechanized, upgraded and value-added with adequate supply of affordable electrical energy. The estimated peak load demand of this community is expected to be about 40kW. Residents of this study community presently use petrol and diesel fuel generators as sources of electrical power supply with its attendant cost of acquisition, high prices of petrol and diesel fuel, high cost of operation and maintenance and emission of greenhouse gas CO_2.

Table 1: Background information of Edem-Urua community

Particulars	Details
Country	Nigeria
State	Akwa Ibom
Local Government Area	Ini
Clan	Iwerre
Community	Edem-Urua
Latitude	5° 24′42.0″ N (5.411656)
Longitude	7° 49′29.0″ E (7.824727)
Elevation above sea level	110.42 m
Number of Households	102
Estimated Population	650
Main Socio-Economic activities	Farming, Small Businesses and Crafts

Figure 1: The geographical location of the study community of Edem-Urua 1.
(www.google.com/maps)

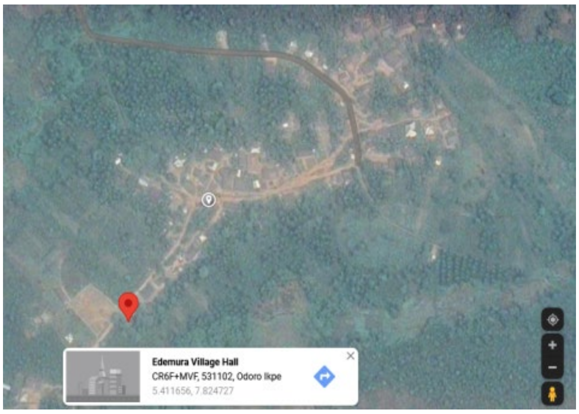

Figure 2: The geographical location of the study community of Edem-Urua 2.
(www.google.com/maps)

2.0 LITERATURE REVIEW

A lot of research works have been done in the area of design and optimisation of hybrid renewable energy systems, with attention paid mostly on the techno-economic analysis and changes in the some system input parameters. Most of these works which include (Samir, 2021), Oladigbolu, *et al*. (2020), Yimen *et al*. (2020), Kiros *et al*. (2020), Aghenta *et al*. (2019) were consulted in the course of carrying out this study, in order to gather reasonable information about the design, modelling, simulation and optimisation of hybrid renewable energy systems.

(Samir, 2021) presented a techno-economic analysis of four different configurations of HRES for energy sustainability of Hurghada City in Egypt with a daily peak load of 218kW, using Homer software. He concluded that the results obtained indicated that longtime planning of renewable energy resources for the study location was appropriate. In the work of Oladigbolu, *et al*. (2020), an optimal hybrid renewable power system was designed for the deployment of electrical power to a typical remote community located in the southern part of Nigeria using HOMER software for the simulation and analysis of the system. They performed analyses to compare and evaluate the performance of the proposed system with the performance of some other system configurations which include the stand-alone diesel generator system, solar PV/diesel/battery, solar PV/wind/diesel/battery, and hydro/wind/diesel/battery systems. Also, Yimen *et al*. (2020) proposed a two-step methodology to optimize and analyze a solar-PV/wind/battery/diesel hybrid energy system to meet the power demand of the study community of Fanisau, a remote and off-grid village in northern Nigeria, using the MATLAB environment for simulations and genetic algorithm for system optimization. Their optimisation results put forward solar PV system as a critical component for the HRES, to meet rural electrification challenges in sub-Saharan Africa.

Also, Kiros *et al*. (2020) designed and modeled a standalone hybrid renewable energy system for a remote Kutur Village in Ethiopia with about 120 households, using Homer software. In the work of Aghenta *et al*. (2019), a stand-alone PV-Diesel Generator hybrid power system was designed for a house in Nigeria using Building Energy Optimisation software (BEopt) for thermal modelling of the house, in order to get the actual energy need of the house which was 17,485 kWh per year (2 kW average loads). Homer software was used for optimisation and MATLAB/Simulink was used for dynamic simulation of the proposed PV system.

Some of the research gaps identified in these works are high cost of energy, high net present cost, designs not meeting load demand, non-inclusion of both commercial and community loads in load profiling, usage of present load profile of the rural study community, lower renewable penetration fraction, absence of 100% RPF, proposal of only one configuration of optimal system and usage of load demand value not related to study site. Few authors carried out techno-economic and emissions analyses of the optimal system that covered some aspects related to economic performance of the systems. This paper attempted to extend the coverage to economic performance factors relating to investment decision such as returns on investment, present worth, annual worth, internal rate of return and payback years.

This paper also attempted to fill most of these research gaps by designing optimal system with lower cost of energy, lower net present cost, higher RPF, zero unmet load, inclusion of both commercial and community loads in load profiling, usage of load profile of an electrified community that has the same socio-economic status with the study community, proposal and recommendation of three different configurations of the optimal system and usage of related load demand value. Such analysis extension could be essential to highlight the relevance of each configuration of optimal HRES as a better means to increase the rate of production of affordable energy for off-grid rural communities, therefore, attracting the attention of investors, stakeholders and decision-makers to the importance of its implementation. Unlike the available previous research works in this subject area, this research work proposed three different configurations of the optimal HRES for the study community.

3.0 METHODOLOGY

This research involves the design and optimization of a hybrid renewable energy system (HRES) using multi-level methodology. Mathematical modelling method was used for modelling, design and optimal sizing of system components was achieved by using Ampere-Hour optimal design method, while Homer Pro Microgrid Analysis Tool was used for simulation and optimisation. The optimal system was designed for the rural electrification of an off-grid community of Edem-Urua using the climatic data of the study community and the load profile of an electrified community of Itie-Ikpe that has the same socio-economic status with the study community of Edem Urua. The research methodology steps adopted and used are summarized in Figure 3.

3.1 Modelling of System Components

A hybrid renewable energy system consists of two or more of these various system components, such as solar PV array, wind turbine, diesel generator, hydro turbine, micro turbine and battery bank. Modelling is the first step in selecting various system components for optimal sizing of the entire energy system.

3.1.1 Mathematical Modelling of Solar-PV System

Power output of a solar-PV array is based on solar irradiance and ambient temperature. According to Salameh (2014), the power output in this model is calculated as;

$$P_{spv} = \eta_{spv}\, A_{spv}\, R_{spv} \tag{1}$$

Where η_{spv} = the solar-PV array power generation efficiency (%), A_{spv} = the Solar-PV array area (m^2), R_{spv} = the solar irradiation in tilted module plane (W/m^2). It was assumed in this study that solar-PV modules have a maximum power point tracking (MPPT) system and the temperature effects were ignored. The selected solar-PV array model has 500 W power capacity, module efficiency of 19.71%, lifespan of 25 years and installation cost of

\$189.73/kW. Table 2 shows the design results for the worst month solar radiation through the application of equation 1.

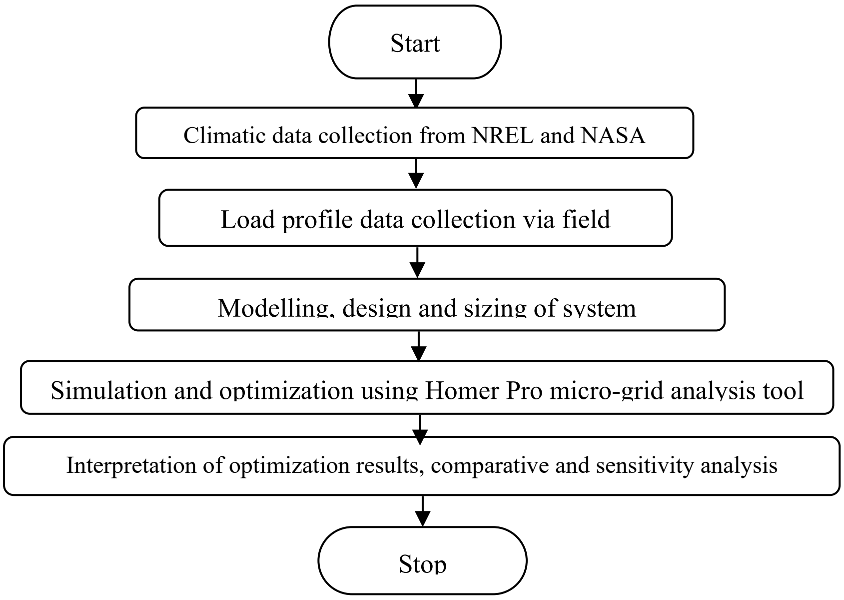

Figure 3: Flow diagram of the research process.

Table 2: Solar-PV array sizing results for the worst month solar radiation (By Design)

Peak Daily Energy Demand (kWh/d)	Battery Efficiency	Required PV Array Energy Output/day (kWh/d)	PV Module Power Output (kW)	Peak Sun Hrs	Energy Output/ module/day (kWh/d)	Operating Temp Derating Factor	Effective Energy Output/ Module/ Day (kWh/d)	Number of Module Required	Capital Cost per kW (\$)
562.25	0.85	661.4706	0.5	3.70	1.85	0.8	1.48	446.9	189.8

3.1.2 Mathematical Modelling of Wind Power System

Salameh (2014) declares that the instantaneous power output of the wind turbine generator is given as;

$$P_{out} = \left(\frac{1}{2}\right) \times \rho \times A \times (V^3) \times C_p \times \eta \qquad (2)$$

Where ρ = Air density (kg/m^3), A = Area of the wind turbine blades (m^2), V = Wind speed (m/s), C_p = Aerodynamic power coefficient = 0.593, which represents the efficiency of the wind turbine and η = the efficiency of the generator if no gearbox is used and the combined gearbox generator efficiency if gearbox is used. The selected wind turbine model has 80 kW rated power, cut-in speed of 2.5 m/s, rated speed of 12 m/s, cut-out speed of 30 m/s, swept area of 530 m^2, hub height of 40 m, lifespan of 25 years and installation cost of \$30,000/unit. Table 3 shows wind turbine design results through the application of equation 2.

Table 3: Wind turbine design results

Peak Daily Energy Demand (kWh)	Estimated Number of Hours of usage	Peak Load Demand (kW)	Design Peak Load Demand (kW) = (Peak Load Demand/0.6)	Wind Turbine Generator Efficiency	Wind Turbine Rating (kW)	Extractable Power Output (kW)	Capacity Factor (CF)	Recommended WT Capacity (kW)
562.25	24	23.42708	39.04513889	0.85	45.93546	9.1923	0.115	80

3.1.3 Battery Model

The selected battery model is DAH solar battery with rated capacity of 210 Ah, 12V, 85% charge efficiency, 80% depth of discharge (DOD), 33.2 A maximum charge current, 335 A maximum discharge current, lifespan of 5 years and installation cost of $79.88/unit. Table 4 displays the battery optimal design results.

Table 4: Battery optimal sizing result (By design)

Average Daily Energy (Wh)	Battery Voltage (12V)	Average Daily Amp-Hour Demand	Days of Storage	Required Usable Capacity (Amp-Hours)	Depth of Discharge (DoD)	Amp-Hours Capacity of Selected Battery	Useful Battery Capacity (Amp-Hours)	Units Of Battery Required
562250	12	46854.2	3	140563	0.8	210	168	836.682
562250	12	46854.2	2	93708.3	0.8	210	168	557.788
562250	12	46854.2	1	46854.2	0.8	210	168	278.894

3.1.4 Diesel-Generator Model

An 80 kW, 100 kVA diesel-generator was used with a unit capital and replacement cost of $4,992.64, an operations and maintenance cost of $0.003/hour and a lifetime of 25 years. Table 5 shows the diesel-generator optimal design results.

Table 5: Diesel-Generator design results

Peak Daily Energy Demand (kWh)	Estimated No of Hours of Supply	Peak Load Demand (kW)	Design Peak Load Demand (kW) = (Peak Load Demand /60%)	Power Factor	Design kVA Rating	Selected Generator Rating(kVA)	Cost /Unit ($)
562.25	16	35.14063	58.56770833	0.8	73.2096	100	4,992.64

3.1.5 Converter Model

For this study, a generic converter power model with an average installation unit cost of $349.38/kW and a lifetime of 5 years was considered, as advised by Yimen *et al*. (2020).

3.2 Calculation Procedures and Cost Functions of Homer Pro Microgrid Analytical Tool

The flow chart of the overall optimization process is displayed in Figure 4 while the following equations 3 to 8 are used in the simulation and optimization process. Total Net Present Cost is the sum of present costs of the system incurs over its lifetime, minus the present value of revenues the HRES earns.

Before calculating the total net present cost and the cost of energy, the total annualized cost C_{tac} is first defined as;

$$(C_{tac})\,(N_{batt},\ N_{spv},\ N_{wind},\ \ N_{conv},\ P_{genrated}) = T_{min} \tag{3}$$

Where,

$$T_{min} = \sum_{k\in\{batt,\ spv,\ wind,\ gen,\ conv\}}\left(C_{icc,k} + C_{o\&m,k} + C_{repl,k} + C_{dfc,k} - C_{sv,k}\right) \tag{4}$$

Where $C_{icc,k}$ = Initial Capital Cost, $C_{o\&m,k}$ = Operations and Maintenance cost, $C_{repl,k}$ = replacement cost, $C_{dfc,k}$ = diesel fuel cost, $C_{sv,k}$ = salvage value of the component. Then, the net present cost C_{npc} is defined as;

$$C_{npc} = \frac{C_{tac}}{CRF(i,N)} \tag{5}$$

and the cost of energy is defined as;

$$C_{coe} = \frac{C_{tac}}{P_{als}} \tag{6}$$

where $CRF(i,N)$ = Capital recovery factor, P_{als} = The overall annual load served, The Capital recovery factor $CRF(i,N)$ is defined as;

$$CRF(i,N) = \frac{i(1+i)^N}{(i+1)^N - 1} \quad (7)$$

Where i = The annual interest rate, N = The lifetime of the HRE system (number of years) The annual interest rate is defined as;

$$i = \frac{i' - f}{1+f} \quad (8)$$

Where, i'= is nominal interest rate which is the rate at which we can borrow money, f = is inflation rate.

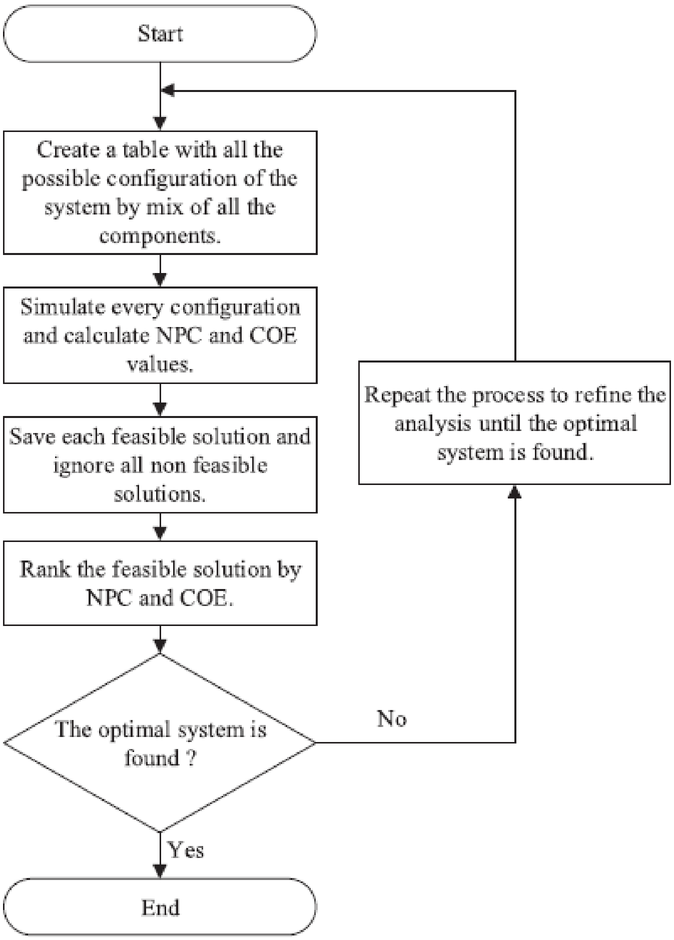

Figure 4: Flowchart of the overall optimisation process (Samir, 2020)

4.0 RESULTS

Summary of various results of this research are displayed and analysed in the following subsections.

4.1 Energy Usage and Load Profile of the Study Community

Table 6 shows the summary of load demand of the study community while the hourly load profiles are displayed in Figures 5, 6 and 7.

Table 6: Load demand summary

Load Category	kWh/d
Household	363.416
Commercial	165.582
Community	33.251
Total Load Demand	562.249

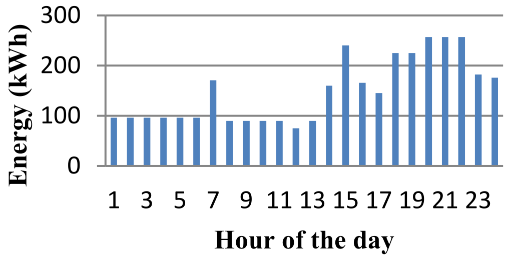

Figure 5: Hourly households load profile

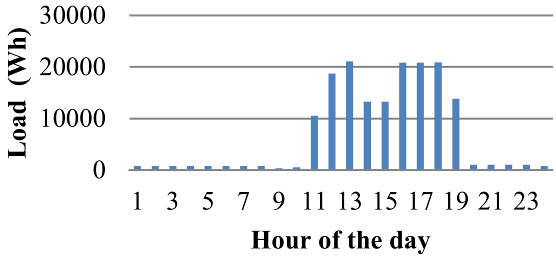

Figure 6: Hourly commercial load profile

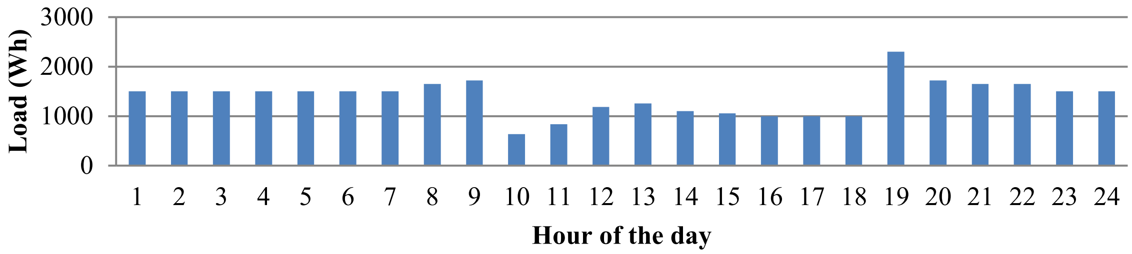

Figure 7: Hourly community load profile

4.2 Solar Energy Potential of the Study Community

The solar radiation data used for this study is the monthly average solar global horizontal irradiance data, measured in 10-minute time interval over the period of sixteen years as shown in Figure 8 and obtained from NREL-National Renewable Energy Laboratory and NASA-National Aeronautics and Space Administration and considered in the Homer Pro as the solar resource input. The maximum solar radiation is for the month of December with a daily average radiation of 5.02 kWh/m^2/d, whereas the minimum average radiation occurred in the month of July with radiation of 3.70 kWh/m^2/d while the average of 4.51 kWh/m^2/d was also obtained with the clearness index of the site as shown in Table 7. In this research work, the clearness value varies from 0.38 to 0.54.

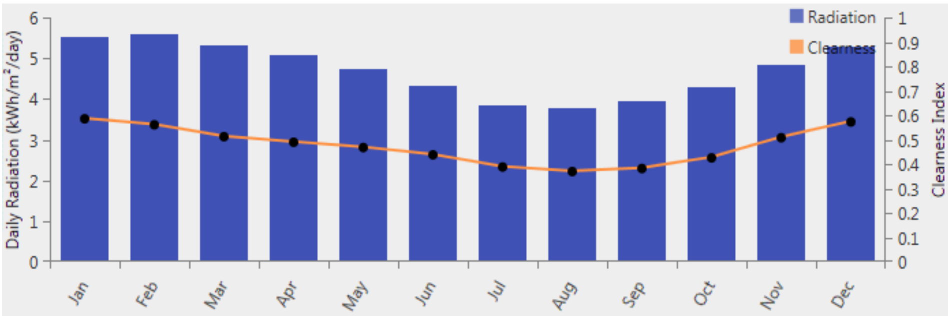

Figure 8: Monthly solar radiation and clearness index (Homer Pro (2017)

Table 7: 16-year average monthly global solar radiation for Edem Urua (2004 to 2019)

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Average
Solar Radiation - NASA (kWh/m^2/d)	5.01	4.83	4.80	4.85	4.66	4.15	3.70	3.74	4.08	4.49	4.80	5.02	4.51
Clearance Index from NASA	0.53	0.48	0.46	0.47	0.46	0.42	0.38	0.37	0.40	0.45	0.50	0.54	0.45

4.3 Wind Energy Potential of the Study Community

The wind speed data used in this research work is a 16-year data (2004 to 2019). This data was recorded over 24 hours for the whole 16 years by NASA and downloaded from NASA Prediction of Worldwide Energy Resources (POWER) database. It was measured at 40 meter above the surface of the earth and 10 meter anemometer height. The average annual wind speed was 3.83 m/s, with a minimum wind speed of 2.77 m/s in the month of December and a peak speed of 4.76 m/s in June. The wind speed potential of the study area is shown in Table 8.

Table 8: Average monthly wind Speed of Edem Urua (2004 to 2019)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Aver
Average Wind Speed (m/s) (From NASA)	3.33	3.35	3.62	3.93	3.63	4.76	4.7	4.67	4.41	3.71	3.08	2.77	3.83

4.4 Consideration of Various Configurations

The eleven possible scenarios are as follows; Solar-PV/Diesel-Generator/Battery-Bank (SDB), Solar-PV/Wind/Diesel-Generator/Battery-Bank (SWDB), Solar-PV/Wind/Battery-Bank (SWB), Solar-PV/Battery-Bank (SB), Wind/Diesel-Generator/Battery-Bank (WDB), Solar-PV/Wind/Diesel-Generator (SWD), Wind/Diesel-Generator (WD), Diesel-Generator/Battery-Bank (DB), Solar-PV/Diesel-Generator (SD), Diesel-Generator only (D) **(Base Case)** and Wind/Battery-Bank (WB).

Above are the different configurations of the optimal HRES computed and ranked by the simulation tool Homer Pro, according to the values of the COE and total NPC with the system components displayed in Figure 9.

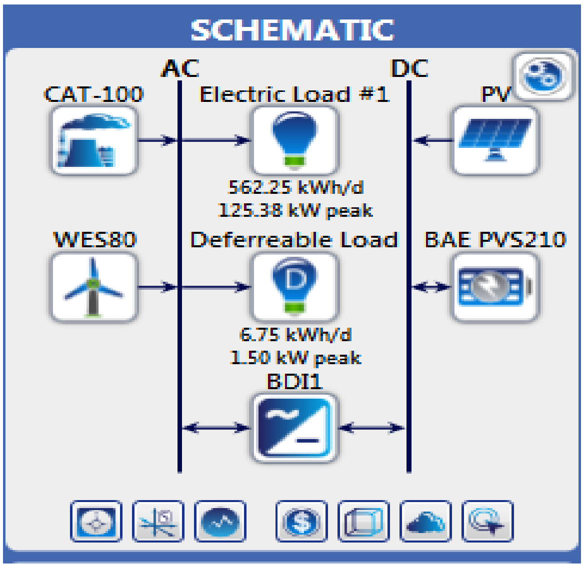

Figure 9: HRES configuration components (Homer Pro, 2017)

4.5 Simulation and Optimisation Results

Tables 9 and 10 display the abridged form of most feasible HRES configurations that satisfy the input constraints imposed on the system by the designer. These feasible configurations are shown in an increasing order of the cost of energy COE from the top to the bottom. The top three scenarios which are the most cost effective configurations are proposed and recommended.

Table 9: Summarized optimisation results of the optimal system (Categorized)

Configurations	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	RPF (%)	CO2 Emission (kg/yr)	Capacity Shortage (kWh/ yr)	Unmet Load (kWh/ yr)	Excess Elec. Prod. (kWh/yr)
Scenario 1	223,867	0.062	6,522.59	109,541	95.21	8231	0.00	0.00	250,169
Scenario 2	227,082	0.063	5,828.32	124,924	97.34	4621	0.00	0.00	222,628
Scenario 3	264,046	0.073	6,162.24	156,035	100.0	0	195.72	15.86	418,626
Scenario 4	295,836	0.082	6,323.19	185,004	100.0	0	173.75	106.16	762,475
Scenario 5	404,929	0.113	14,141.7	157,056	74.72	42925	0.00	0.00	113,946
Scenario 6	640,203	0.178	26,097.7	182,767	38.41	105623	0.00	0.00	677,326
Scenario 7	670,984	0.187	31,150.0	124,992	22.69	132031	0.00	0.00	235,019
Scenario 8	690,980	0.192	38,773.0	11,366	0.00	166873	0.00	0.00	1970.25
Scenario 9	693,568	0.193	32,815.0	118,385	18.95	137121	0.00	0.00	678,456
Scenario 10	775,292	0.216	43,947.0	4,992	0.00	192331	0.00	0.00	32,359
Scenario 11	965,945	0.269	21,304.0	592,531	100.0	0	202.09	178.90	833,242

Homer Pro (2017)

Table 10: Summarized optimisation results of the optimal system components

Configuration	Solar-PV Array (KW)	Wind Turbine (kW)	Diesel-Gen. (kW)	Battery	Converter (kW)
Scenario 1	340		80	242	59
Scenario 2	269	1	80	246	55
Scenario 3	414	1		317	63
Scenario 10			80		

Homer Pro (2017)

4.6 Optimisation Analysis of the Proposed Optimal System Configurations (Scenarios 1, 2 and 3)

The top three most cost effective configurations of the optimal HRES are analysed in the following subsections in terms of their electrical energy productions and economics.

4.6.1 Scenario 1 Analysis

The optimal system configuration of scenario 1 is Solar-PV/Diesel-Generator/Batter-Bank (SDB) with its architecture displayed in Table 10. Scenario 1 configuration reduces the COE by 71.3% as compared to the base case Scenario 10 of diesel-generator only and it is the most cost-effective configuration in terms of COE. From all the eleven different configurations, Scenario 1 is considered as the best configuration of the optimal solution, taking into account the COE as the topmost comparison benchmark. Also, Scenario 1 reduced the total NPC by 71.12% compared to the base case of Scenario 1 (Diesel-Generator only) and it is also the most cost-effective configuration in terms of NPC. Using the total NPC and COE as the comparison benchmarks, Scenario 1 is selected and recommended for implementation.

Electrical Energy Production of Scenario 1

The details of the annual power generation of scenario 1 are shown in Table 11 with the electricity power produced by individual power units of the optimal HRES configuration as shown.

Table 11: Electricity production of scenario 1 (kWh/yr)

Scenario 1 Components	Electricity Production of Scenario 1 (kWh/yr)	Percentage (%)
Solar-PV Array	470,621	98.00
Diesel-Generator	9,840	2.00
Total	480,460	100.00

As displayed in Figure 10, the Solar-PV array potential is high from the month of October through May but low in the month of June through September with the majority of the load

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demand (98%) being carried by it, attesting to the presence of abundant solar renewable energy source at the study location.

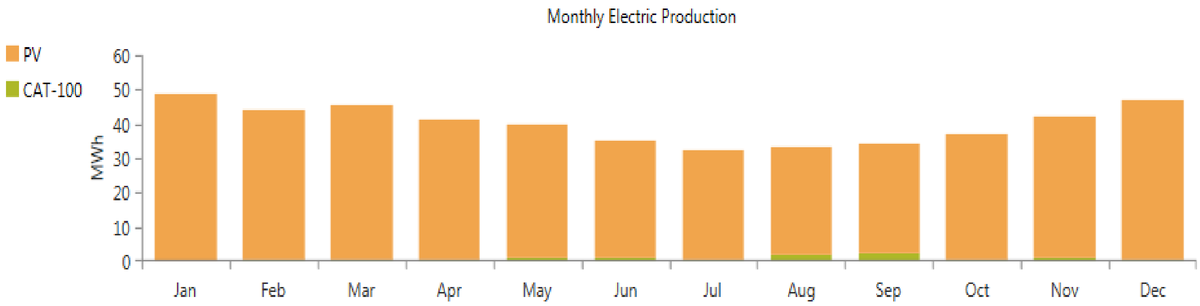

Figure 10: Electrical details of scenario 1 (Homer, 2017)

4.6.2 Scenario 2 Analysis

Apart from Scenario 1, another attractive configuration of the optimal HRES, which we may be tempted to select and recommend, is Scenario 2 because of its RPF of 97.34% which has a 2.24% improvement from what was obtainable in Scenario 1 with RPF of 95.21%, operating cost of $5,828 with 10.65% reduction and CO_2 emission of 4,621 kg/year with 43.86% reduction from what was obtainable also in Scenario 1. This configuration closely follows the recommended Scenario 1 configuration in terms of COE, NPC and initial capital with 0% capacity shortage and zero unmet load as well.

Electrical Energy Production of Scenario 2

The monthly average electrical energy generation of Scenario 2 configuration is displayed in Figure 11 with the solar-PV array contributing 371,788 kWh/yr (83.10%) to the total energy production 447,641 kWh/yr, a 15.20 % decrease from what solar-PV array contributed in Scenario 1. Also, as displayed in Table 12, diesel-generator contributed 5,459 kWh /yr (1.2%), to the total energy production, representing a 39% reduction from its contribution in Scenario 1 which is the first ranked cost effective optimal HRES configuration while the wind turbine contributed 70,394 kWh/yr to the total energy production. This shows that the electrical energy production from the solar-PV array is very high almost throughout the year with a little drop in the months of July and August.

Table 12: Electricity production of scenario 2 (kWh/yr)

Scenario 2 Components	Electricity Production of Scenario 2 (kWh/yr)	Percentage (%)
Solar-PV Array	371,788	83.10
Diesel-Generator	5,459	1.20
Wind Turbine	70,394	15.70
Total	447,641	100.00

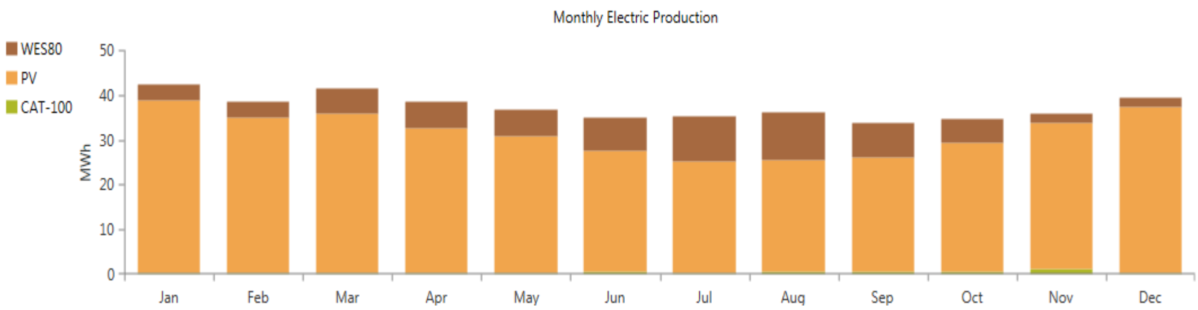

Figure 11: Electrical summary of scenario 2 (Homer Pro, 2017)

4.6.3 Scenario 3 analysis

Following Scenario 1 and 2 in the perking order of cost effectiveness is Scenario 3, with its optimization results displayed in Tables 9 and 10. However, taking into consideration its 100% RPF with 5.03% improvement from what was obtainable in Scenario 1 and zero CO_2 emission, Scenario 3 is adjudged the best for implementation in terms of renewable penetration. If we are to achieve total clean energy production, sustain our green environment and say a big "NO" to environmental pollution and the problem of climate change we all face today globally, scenario 3 is the best pick. However, it has a capacity shortage of 195.72 kWh/yr and unmet load of 15.86 kWh per year.

Electrical energy production of scenario 3

Table 13 and Figure 12 display the details of electricity production of scenario 3 with total annual electrical energy production is 644,002 kWh. The Solar-PV contributed 573,608 kWh/year (89.1%) while the wind turbine contributed 70,394 kWh/yr representing 10.9% of the total annual energy production. This also reiterates the good solar energy potential of the study community. Apart from the higher cost issues with this Scenario 3, excess electricity production of 418,626.80 kWh/yr representing 65.0% of the total energy production is also a setback compared to 52.1% and 49.7% for Scenario 1and 2 respectively.

Table 13: Electricity production of scenario 3 (kWh/yr)

Scenario 3 Components	Electricity Production of Scenario 3 (kWh/yr)	Percentage (%)
Solar-PV Array	573,608	89.1
Wind Turbine	70,394	10.9
Total	644,002	100

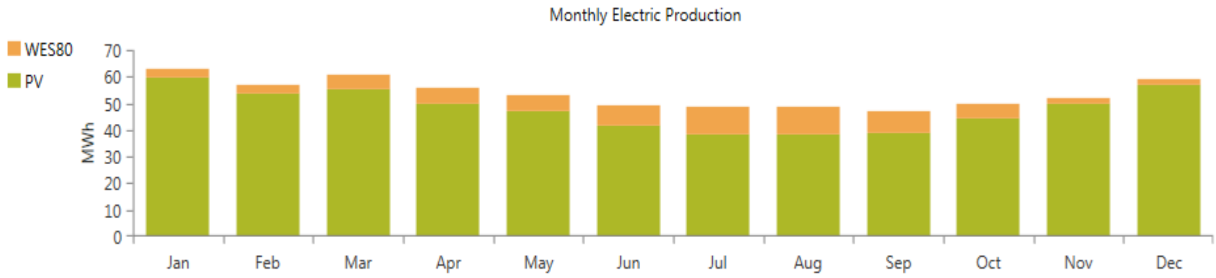

Figure 12: Electrical Summary of Scenario 3 (Homer Pro, 2017)

4.6.4 Comparative Analysis of Scenarios 1, 2 and 3 in Terms of Economics

Tables 14 gives detailed information about the economics of the three top-ranked optimal HRES configurations in terms of payback years and return on investment.

Table 14: Economics of the proposed optimal system configurations

Metric	Scenario 1	Scenario 2	Scenario 3
Present Worth ($)	551,425.00	548,211.00	511,247.00
Annual Worth ($)	31,460.00	31,277.00	29,168.00
Return on Investment (%)	31.90	27.90	21.00
Internal Rate of Return (%)	37.60	33.10	26.00
Simple payback (yr)	2.53	2.85	3.52
Discounted payback (yr)	2.67	3.02	3.77

The economics of the three proposed configurations are displayed in Table 14. Carefully observing the various decision variables under these three Scenarios, Scenario 1, having the highest rate of return on investment and smallest payback time is adjudged the best for implementation.

4.8 Cost Analysis of Grid Extension to Edem Urua Community

The estimation of cost of grid extension for connecting Edem-Urua community to the national grid was done by an electrical engineering company TYJ Engineering Co. Limited, Uyo, Nigeria. The distance of Edem Urua community from an existing grid (33 kV line at Itie Ikpe community) is about 5 km; a rough survey was conducted to select the type of assemblies to be used for the 33 kV transmission line constructions with about 2 km low tension distribution line and erection of 1 unit of 100 kVA power distribution transformer also needed. Hence, the cost of grid extension is analyzed by using an interlinked spread Microsoft excel sheet, the result obtained is as shown in Table 15. The total initial capital cost, as indicated in Table 15, includes salaries, wages and fees, transportation costs, cost of materials, overhead cost, is therefore N71,522,000.00 which is equivalent of $173,968.67 with $0.083/kWh cost of energy which is the current tariff in Nigeria, about 25.3% increase from $0.062/kWh obtainable in Scenario 1 configuration as seen in Table 15.

Table 15: Grid extension to Edem Urua community

Cost Description	Salaries, Wages and Fees (₦)	Transportation Cost (N)	Cost of Materials (N)	Total Cost (N)
33 kV High Tension Transmission Line Extension	2,000,000.00	240,000.00	42,370,600.00	44,610,600.00
415/230 V Low-Tension Distribution Lines at Edem-Urua Community	1,000,000.00	150,000.00	13,411,000.00	14,561,000.00
Design and Construction of a 33/0.415 kV Power Sub-Station at Edem Urua Community	1,110,000.00	0.00	4,738,400.00	5,848,400.00
Total	4,110,000.00	390,000.00	60,520,000.00	65,020,000.00
	Interest To Be Capitalised			0.00
	Overhead Cost (10%)			6,502,000.00
Grand Total	Total Initial Capital Cost (N)			71,522,000.00
	Equivalent in USD ($)			173,968.67
	Cost of Energy (N)			34.23
	Equivalent in USD ($)			0.083

5.0 DISCUSSION

This research work presents solution to the problem of lack of affordable and clean electrical energy in a remote off-grid community of Edem Urua, a rural village in the southern part of Nigeria. The solution is in the form of a design of an optimal HRES, using the renewable energy resources available in the study community. Based on the results obtained in this research study, three configurations of the optimal HRES are hereby proposed as shown in Table 16.

Table 16: Optimisation results of the proposed configurations of the optimal HRES with Base Case and Grid Extension

Configuration	System Architecture	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	RPF (%)	CO_2 Emission (kg/yr)	Capacity Shortage (kWh /yr)	Unmet Load (kWh/yr)	ROI (%)	Pay back Years
Scenario 1	SDB	223,868	0.062	6,522.59	109,541	95.21	8231	0.0	0.0	31.9	2.53
Scenario 2	SWDB	227,082	0.063	5,828.32	124,924	97.34	4621	0.0	0.0	27.9	2.85
Scenario 3	SWB	264,046	0.073	6,162.24	156,035	100.0	0	195.7	15.9	21.0	3.52
Scenario 10 (Base Case)	D	775,293	0.216	43,947.2	4,993	0.00	192331	0.0	0.0	0.0	N/A
Grid Extension	GE	N/A	0.083	N/A	173,969	N/A	N/A	0.0	0.0	N/A	N/A

Comparing the results of this research study with some previous works done by some great researchers like Yimen, *et al,* (2020) that proposed a similar solar-PV/wind/battery/diesel hybrid energy system to meet the power demand of Fanisau, a remote and off-grid village of Fanisau in northern part of Nigeria with an evaluated daily electricity demand of 484.729 kWh/day, their research results put forward solar-PV system as a critical component for the HRES in that part of the country while the results of our research study put both the solar-PV array and wind turbine as the critical components of the optimal system responsible for 100% renewable penetration. Also their techno-economic analysis clearly showed that the optimized system was more cost-effective and environmental friendly than the diesel-generator stand-alone system and grid extension with the total net present cost (NPC), cost of energy (COE) and total initial capital cost of $572,382, $0.25/kWh and $323,870 respectively, as against the similar results of this study, with total net present cost (NPC), cost of energy (COE) and total initial capital cost of $223,868, $0.062/kWh and $109,541 respectively.

This comparative analysis clearly shows that the cost of energy in the southern part of Nigeria is cheaper than what is obtainable in the northern part of the country and the cost of setting up a HRES in the northern part of Nigeria is on the high side unlike what is obtainable in the southern part for relatively same value of load demand. Talking about CO_2 emission, Yimen *et al.* (2020) proposed-HRES would save 122,062.85 kg/year of CO_2 compared to the base case of diesel-generator-only system while we recorded 184,100 kg/year CO_2 emission savings. Our base case of diesel-generator only produced 192,331 kg/year CO_2 emission and the optimal HRES produced 8,231 of CO_2 emission. Their daily load demand was evaluated at 484.73 kWh/d and annual load demand of 176,926 kWh/year while for this research study, 562.25 kWh/d was the evaluated primary daily load demand while 207,683 kWh/year was the total annual load demand. Both studies established the fact that HRESs could play a critical role in the sustainable electricity supply in rural areas of sub-Saharan Africa.

6.0 CONCLUSIONS

From the results of this research study, it is concluded that the most cost effective optimal system is Solar-PV/Diesel-Generator/Battery Bank (SDB) configuration with a total NPC of $223,867.86, a 14.11 % reduction from what was obtainable from Scenario 2 and 71.12% reduction from the base case of diesel-generator only, a COE of $0.062/kWh with a 1.59% reduction from Scenario 2 and 71.3% reduction from the base case of DG only (Scenario 10). Another attractive configuration that can be implemented is Solar-PV/wind/Diesel-Gen/Battery-Bank (SWDB). This configuration is also cost effective with a total NPC of $227,082, COE of $0.063/kWh, operating cost of $5,828 with a 10.65% reduction in what was obtainable in Scenario 1 and a RPF of 97.34% with a 2.24% improvement from Scenario 1. Also, another attractive configuration from the list of proposed optimal system configurations, which can be implemented, is Solar-PV/Wind/Battery Bank (SWB). The major point of attraction here is its 100% RPF with zero CO_2 emission. This configuration is also cost effective with a total NPC of $264,046.10, COE of $0.073/kWh, RPF of 100%, (5.03% improvement from what was obtainable in Scenario 1) and Zero CO_2 emission with an 100% reduction from what was obtainable in Scenario 1.

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