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Technical and economic appraisal for harnessing a proposed hybrid energy system nexus for power generation and CO2 mitigation in Cross River State Nigeria

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ABSTRACT

By creating hybrid energy systems and obtaining a framework that equally satisfies a continuous operation for renewable energy technology, this study presents renewable and sustainable energy options as an integral method to energy transitioning in Cross River State, Nigeria. For a needed load of 2424.25 kWh/day in Cross River State, this study focused on proposing a designed hybrid energy system (HES) nexus, mitigating CO2, and appraisal of the technical and economic viability. To accomplish this, HOMER software was utilized in simulating the ideal components that suggested a HES nexus. The software enabled the selection of the optimal HES using various renewable energy sources since it predicts future electrical demand, wind speed, solar irradiation, and temperature. Economic results obtained showed that the proposed HES's Levelized cost of energy (LCOE), net present cost (NPC), and operating cost (OC) were \$0.89/kWh, \$10,138,702 and \$134,084.37 respectively. Further technical appraisal showed that the renewable energy conversion systems (RECs) make up 78.74% of the proposed HES. The photovoltaic (PV) arrays were primarily responsible for the hybrid energy system's electricity output. The annual electrical energy output was 1,984,111kWh (89.4%), produced by the PV arrays. The generic fuel cell produced the least, at 29,957kWh/year, accounting for just 1.35% of the total electricity produced. However, the wind power plant produced 205,365kWh/year annually. Furthermore, comparing the HES with diesel-powered generators, the system achieves a net-zero carbon emission status. Therefore, it has proven to be the most reliable energy as it will solve the problem of energy insecurity and reduces carbon emissions in Cross River State, Nigeria.

1. Introduction

The reduction of CO2 emissions in the atmosphere will have a good impact on the environment and it will restrain the effects of global warming [1]. CO2 emissions have increased rapidly, and this rapid growth has led to environmental problems like natural disasters, climate change, ozone layer depletion, health challenges, as well as reduction in annual gross domestic product (GDP) growth [2], [3]. These effects make the emission of excessive CO2 a major problem, and mitigating its effects has been on the world's radar as one of its major challenges in the 21st century [4]. Today, energy is being produced, consumed and developed all over the world and it is changing constantly, as the evidence from this transformation can be seen in its application and growth of renewable technologies in developing countries [5]–[9].

[10] Developed the carbon emission reduction index (CERI) and applied the refined Laspeyres technique in order to mitigate the pressure of CO2. The results obtained showed that the cities contributed largely to the emission of CO2. As we know, economic globalization and integration characterizes our world today, embodied by some varying economic agreements [11]. The Paris agreement which constitutes the mitigation of greenhouse gases emission to attain a climate impartial world as stated by [12], will help in achieving net zero emission and sustainable energy transitioning in countries across the world by 2030. Due to the diminishing rate in the reserves of fossil fuels and a heightened increase in the emission of CO2, countries that are still developing are edging closely towards an adoption of large-scale alternative renewable energy sources [13], [14]. According to [15], with the current global usage of the available crude oil and gas reserves, these resources will diminish in the next 53 years and 52 years respectively, hence the need to transition into renewable and more sustainable energy sources. A study carried out by [16] has established the effective transitioning from fossil fuels to renewable energy sources for CO2 mitigation and environmental sustainability in South Asia.

According to [17], a global net sum of 1474.4 billion metric tons of CO2 was emitted into our atmosphere between the years 1751 - 2014. Further decomposition in percentages as depicted in Fig. 1, shows that about 35.74% (519.5 billion metric tons) were from liquid fuel, 47.37% (698.5 billion metric tons) from the consumption of coal, and 13.74% (202.5 billion metric tons) were gotten as a result of gas consumption. Furthermore, cement production produced 2.74% (40.4 billion metric tons), while gas flaring produced about 0.92% (13.50 billion metric tons). This analysis showed that the total percentage of CO2 emitted to the atmosphere during that period came through the consumption of fossil fuels and stood at 97.26%. CO2 emissions have been notably responsible for some environmental issues, and depleting economic growth and ozone layer.

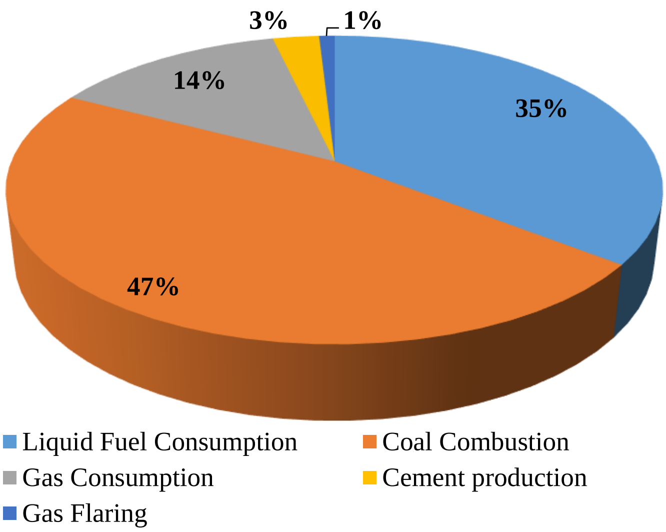


Fig. 1. Global CO_2 emission rate distribution [17]

It was also reported by the World Health Organization (WHO) in May 2018, that about 90% of the world's population breathe in polluted air due to the widespread of CO2 in the atmosphere. One of the reliable options that might tackle the mitigation of CO2 emissions is the deployment of a hybrid energy system. A hybrid energy system is a system that integrates several types of non-renewable and renewable energy systems [18]. It allows for overall system cost effectiveness, system maintenance, emission levels reduction, increase in reliability and availability [18]. Hybrid energy systems are reliable and it can also be analytically designed by HOMER software for optimum results, which runs simulations hourly to get the best match for demand and supply [19].

[18] designed a hybrid energy system to fulfill the escalating pace that the growing demand for energy created due to inadequate supplies. The hybrid system was designed for local accomplishment and the sources were widely considered as time and load were varying necessities. Sizing

methodologies, configuration, criteria selection, control and energy management were the imperative areas that were well thought-out in the course of this study. [20], proposed that a genetic algorithm-based optimization for sizing components of a hybrid energy system that would be used for standalone applications. MATLAB toolbox was used to formulate the program with the aim of reducing the net present cost (NPC) of the system and lighting up the rural areas. [21] investigated the uncertainty of grid-independent hybrid energy system optimization and its impact on the economy. After many obstacles to decentralizing the energy sector in developing countries, this study proposed a contribution that scrutinizes a three grid-independent hybrid renewable energy economy that will generate electricity and produce heat for loads on small scale. [22] focused on building a hybrid energy system with smart grid concepts. A fuzzy logic controller was introduced to implement a new demand strategy that determines electricity tariffs based on battery state charge and customers previous responses. The study also sought to resolve the problems of energy demands due to inadequate energy supplies over the years, and proposed ways to reduce the net present cost of a hybrid energy system while decentralizing the energy sector in developing countries.

Various states in Nigeria have the potential for the production of renewable energy in a hybrid nexus because of the abundance of solar radiation and wind speed resources (See Fig. 2); thus, motivating this study for proper integration of renewable energy options into Nigeria's energy sector. This study is focused on developing a technical driven appraisal for harnessing a proposed hybrid energy system nexus, designed using HOMER software for the mitigation of CO2 within Cross River State, Nigeria.

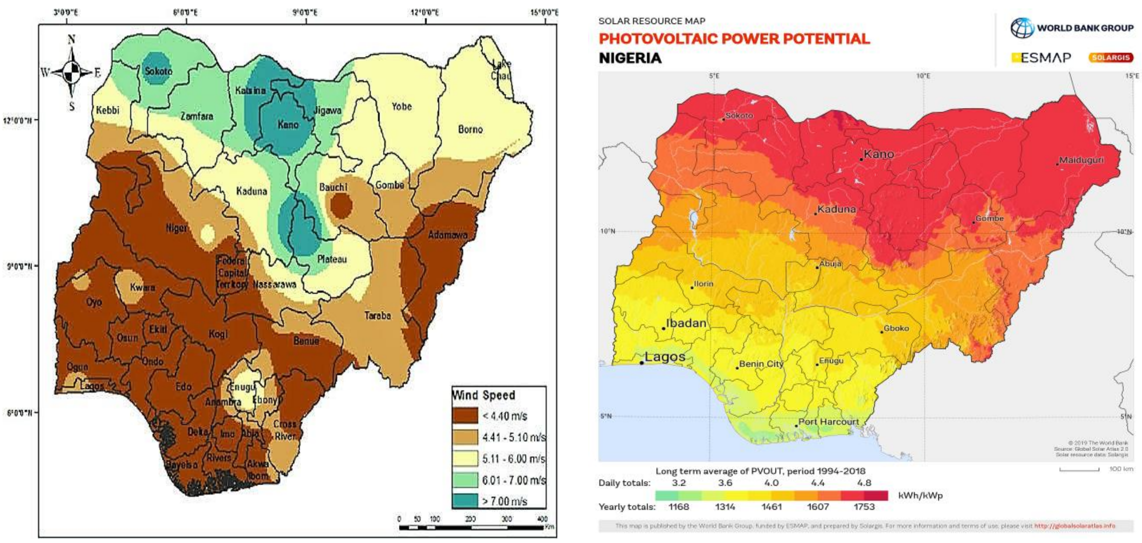


Fig. 2. Nigeria's renewable energy resource potential (a) Wind speed (b) Solar photovoltaic (Photo credit: Solargis)

1.1. Specific Objectives

The study aimed at utilizing renewable energy resource data within Cross River State, to appraise the technical and economic viability of a proposed hybrid energy system design in nexus for power generation.

The specific objectives include;

- Appraise obtained data (CO2 distribution data, energy load data, technical and environmental data of various energy sources) to predict the viability of a hybrid energy system for CO2 mitigation in the study area.
- Design a hybrid energy system model using HOMER based on obtained data for the study area.
- Simulation of the technical viability of the proposed hybrid energy system.
- Investigation of the economic feasibility options and the levelized cost of the system in the study area for potential investors.

- Contribute to Nigeria's energy transitioning plan and global CO2 mitigation based on Paris agreement for net zero greenhouse gas emissions with a proposed hybrid energy system.

1.2. Literature Review

The dispensation where the need to combat carbon emission from fossil fuel to renewable energy has become pertinent globally, because of accountability on the continuous anthropogenic global warming and environmental depletion [23]. These problems can be handled by utilizing renewable energy sources: solar, geothermal, biomass, wind, etc., which are currently available geographically contrasting the conventional fossil fuels resources that are limited in specific regions [24].

[25] proposed to mitigate CO2 using fuel transition on Danish combined heat and power (CHP) with its district heating plants. The model formulated analyzed how the transitioning from coal to forest biomass or natural gas was greatly influenced by carbon dynamics. [25] also stated that for fossil fuel to transition into biomass to mitigate the amount of CO2 emitted, time is going to be measured relatively. The study conducted by [10] was substantial to evaluate the mitigation of CO2 in China's residential division. Developing a carbon emission reduction index (CERI) was the contribution to mitigating carbon emissions whilst applying Laspeyres technique. [26] investigated the potential implications of CO2 emissions and proposed a systematic empirical assessment of evidences of innovation induced in energy and technology.

[27] carried out an investigation on the strategies to be able to mitigate the consumption of energy and the emission of greenhouse gases, and acquire sustainable neighborhoods. A sensitivity analysis was carried out to determine the environmental impacts on the future climate change and the results showed that only countries with flourishing economies emit the highest levels of CO2. [28], modeled evidence from quantile-on-quantile approach to meet the globalization of CO2 emission nexus in Australia. The results proved that there was a linkage positively between carbon emissions and economic growth at some quantiles. According to [29], renewable energy consumption contributes comparatively to the mitigation of CO2 emissions in a global perspective. Utilizing renewable energy is crucial for the exploitation of developing or under developed countries. Consequentially in this research, it was discovered that in some developing countries, carbon emissions reduced extensively because of the use of renewable energy and not by enhancing energy-use efficiency.

[17] also examined the effects of CO2 emissions on economic growth and also the effects of transitioning from non-renewable energy to renewable energy. A generalized method of moments (GMM) of a two-step approach and its empirical results showed the relationship between CO2 and economic growth which also shows the sustainability of the environment. Also, according to [11], CO2 emissions have severe environmental consequences as well as consequences on trade openness. [11] modeled the study to help mediate the process effects of CO2 emission on economic trade and technology. Furthermore, the study concluded that improving renewable energy utilization will decrease carbon emissions and energy intensity. Equally, [26] sought to merge qualitative economic evaluation with qualitative socio-technical transitions for a more fruitful research area.

Transitioning from non-renewable energy sources to renewable energy sources is the major process in spearheading the fight for the mitigation of carbon emissions and finding a more sustainable renewable energy option. [15] investigated the role energy storage system handles in the transitioning of energy from fossil fuel resources to renewable energy source. The study presented a transitioning prospect of the world's energy from non-renewable energy to renewable energy with technological advances in the storage capacity for the energy system. [30] focused on proving that the transitioning to renewable energy has an impact on the importation of oil in south Asia's economy. The results simply imposed critical policy implications for the energy security realization and the sustainability of the environment, energy transition has a huge impact on the economies of south Asian countries. However, according to [16], environmental value across south Asia can be sustained or improved considerably by transitioning from non-renewable sources of energy to renewable energy sources, and can integrate regional trade. This study proved that financial development and urbanization will boost the emission of CO2 into our atmosphere on the long run.

Other studies on transitioning gave insights on the importance of transitioning globally to renewable energy sources. Whereas this study gives a practical approach to help mitigate these emissions as a major contribution in Nigeria's energy sector and energy transition plan, while meeting the energy demand of Cross River State. The reviewed literatures have also established that carbon emissions play a vital economic role and mitigating these emissions would lead to a more sustainable technological advancement and proper economic growth of the world. Contributing to the feat, this study also shows how carbon emissions can be mitigated through using a poly-integrated hybrid energy system for Cross River State. This is in line with the Paris agreement and United Nations sustainable development goals (SDGs) 7 and 11.

2. Method

The simulation was set up using HOMER software. The software allows the user to carryout load profiling, energy resource assessment, selection of all possible components needed for the HES design configuration, and automatically generate the data needed to run the simulation. Input parameters utilized for the simulation includes; the load profile and energy resource assessment data of the study area respectively, depicted in Fig. 3 to Fig. 7. The design specification data of the HES components were also considered input parameters to run the HOMER simulation for the technical and economic appraisal as presented in Table 1 to Table 4.

2.1. Technical and economic appraisal

HOMER software was used to design and appraise the technical and economic feasibility of the hybrid energy system, to examine if the loads (thermal and electrical) can be met. Meteorological data gotten from the study locations, in Cross River State as well as the technical specifications of the various integrated components of the hybrid energy system were used for the appraisal.

To determine the levelized cost of energy (LCOE) for the hybrid system, a model developed by [24] was used as presented in Eqn. (1) to (4). The net present cost (NPC) of the hybrid system is expressed as:

$$NPC = \frac{C_{ta}}{CRF\ (i, P_t)} \tag{1}$$

Where; C_{ta}, CRF, P_t, and i represents the total annual cost of system (N/year), capital recovery cost, project lifetime, and interest rate respectively.

The capital recovery cost is expressed as:

$$CRF\ (i, n) = \frac{i\ (1+i)^n}{(1+i)^n - 1} \tag{2}$$

Where: n is the number of project years

Salvage cost (SC) as obtained from [31] is expressed as:

$$\text{SC} = C_{RC}\frac{T_{re}}{T_{co}} \tag{3}$$

Where; C_{RC}, T_{re}, and T_{co} represents the replacement cost of equipment, remaining lifetime of equipment, and lifetime of equipment respectively.

Furthermore, the Levelized Cost of Energy (LCOE) as obtained from [24] is evaluated using eqn. (4).

$$LCOE = \frac{C_{tot}}{E_{tot}} \tag{4}$$

Where; E_{tot} is the annual electricity consumption

2.2. Appraised study area

Cross River State is located at the southern part of Nigeria. A tourism state whose coordinates are 5.8702˚N, 8.5988˚E on the equator and has a good potential for renewable energy resource formation as shown in Fig. 3, Fig. 4, and Fig. 5 respectively. The monthly average solar, wind and temperature data resource respectively for the State was obtained from NASA surface meteorology and solar energy database. The scaled annual average of the renewable energy sources in the eighteen (18) Local Government areas of Cross River State are depicted in Fig. 6.

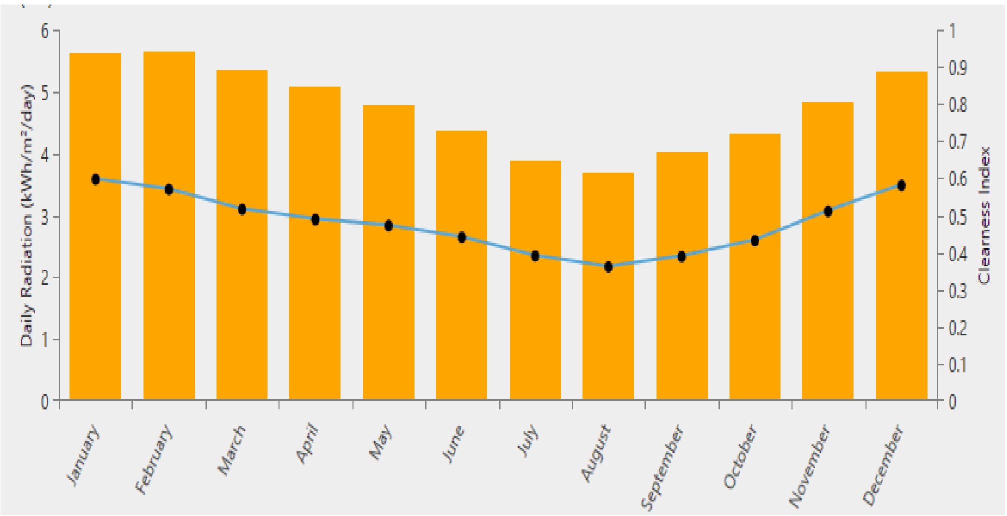


Fig. 3. Monthly average GHI solar resource data for Cross River State (Credit: NASA surface meteorology and solar energy database)

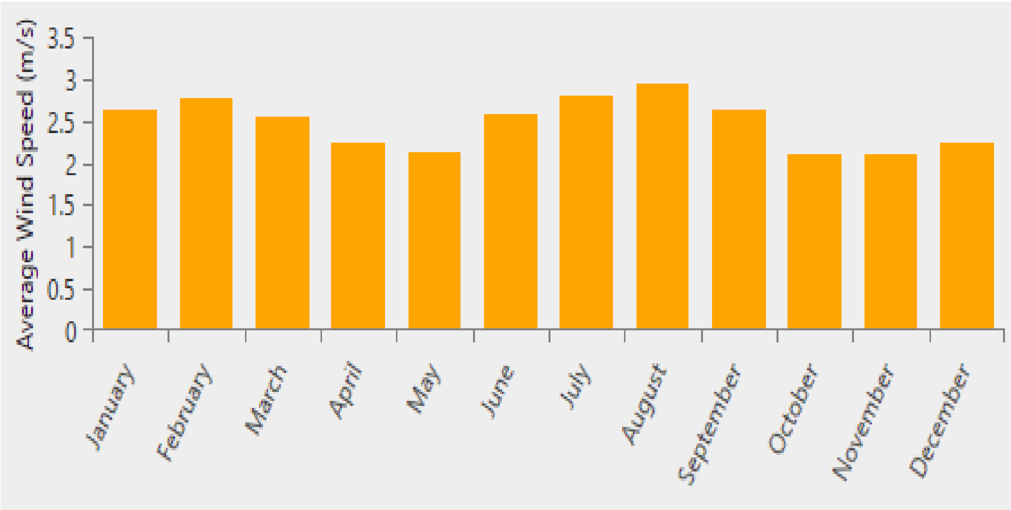


Fig. 4. Monthly average wind speed resource for Cross River State (Credit: NASA surface meteorology and solar energy database)

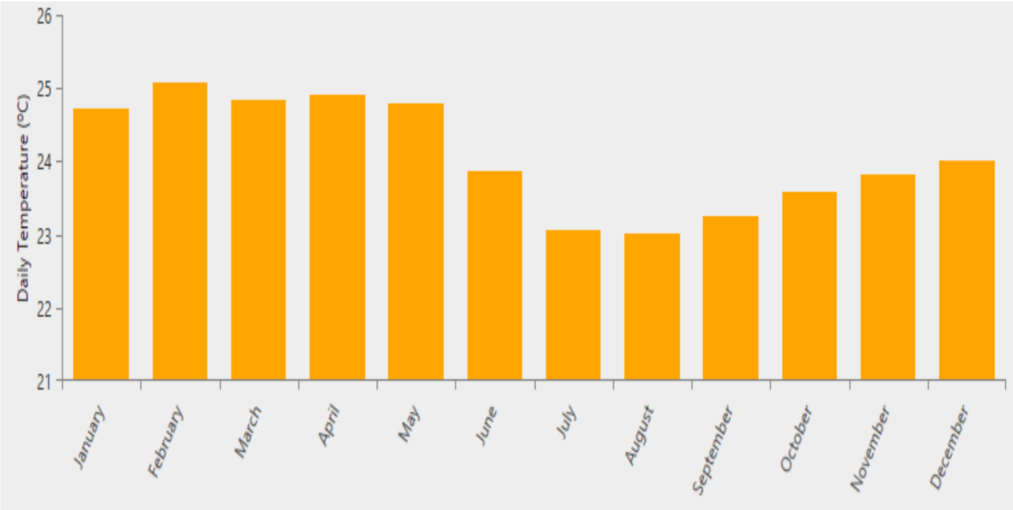
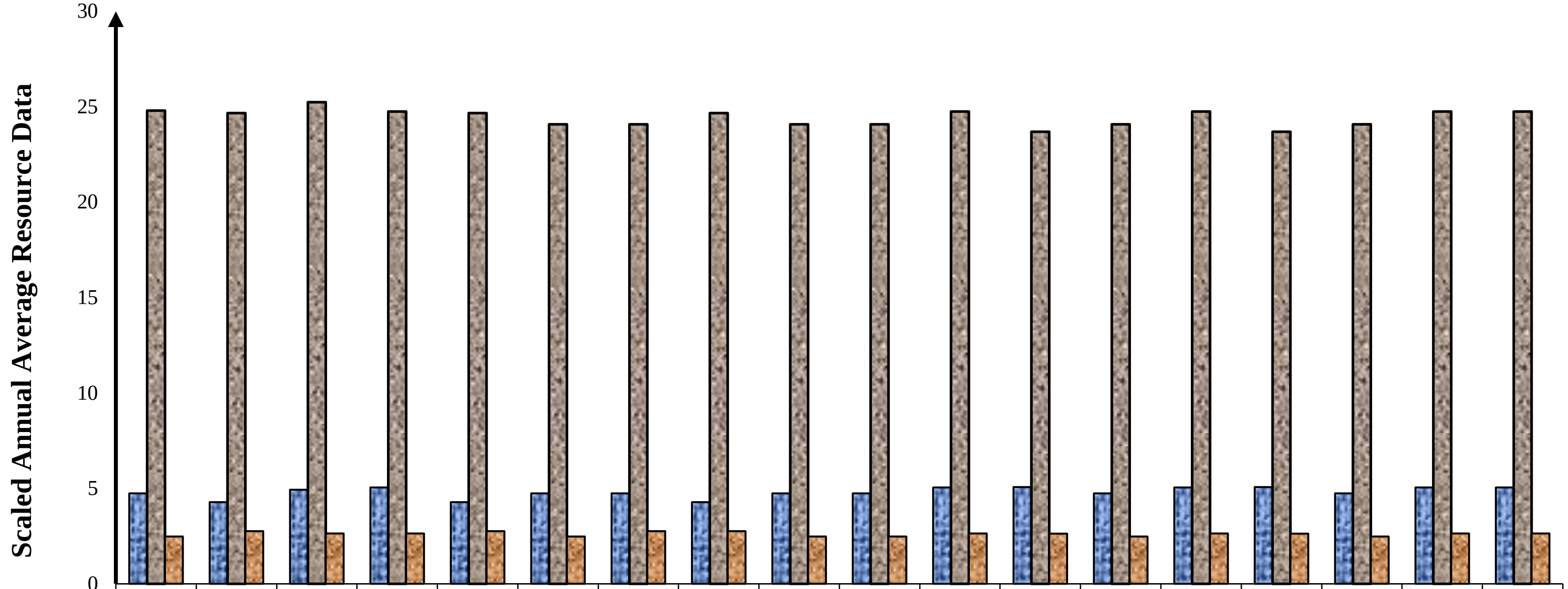


Fig. 5. Monthly average temperature resource for Cross River State (Credit: NASA surface meteorology and solar energy database)



	Akampka	Akpabuyo	Abi	Bekwarra	Bakassi	Biase	Cal. Munincipality	Cal. South	Etung	Ikom	Obubra	Obudu	Odukpani	Ogoja	Obanliku	Yakurr	Yala	Boki
Solar GHI (kW/m2/day)	4.74	4.28	4.93	5.05	4.28	4.74	4.74	4.28	4.74	4.74	5.05	5.07	4.74	5.05	5.07	4.74	5.05	5.05
Temperature oC	24.8	24.67	25.24	24.75	24.67	24.08	24.08	24.67	24.08	24.08	24.75	23.69	24.08	24.75	23.69	24.08	24.75	24.75
Wind Resource (m/s)	2.48	2.76	2.64	2.64	2.76	2.48	2.76	2.76	2.48	2.48	2.64	2.63	2.48	2.64	2.63	2.48	2.64	2.64

Fig. 6. Scaled annual average renewable energy resource data in Cross River State (Credit: NASA surface meteorology and solar energy)

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Based on the renewable energy resource data presented in Fig. 6, two different study locations within Cross River State as depicted in Fig.7 were considered in designing the proposed poly-integrated hybrid energy system. The potential areas include, Akpabuyo, and Obudu LGAs for wind energy, and solar energy resource respectively.

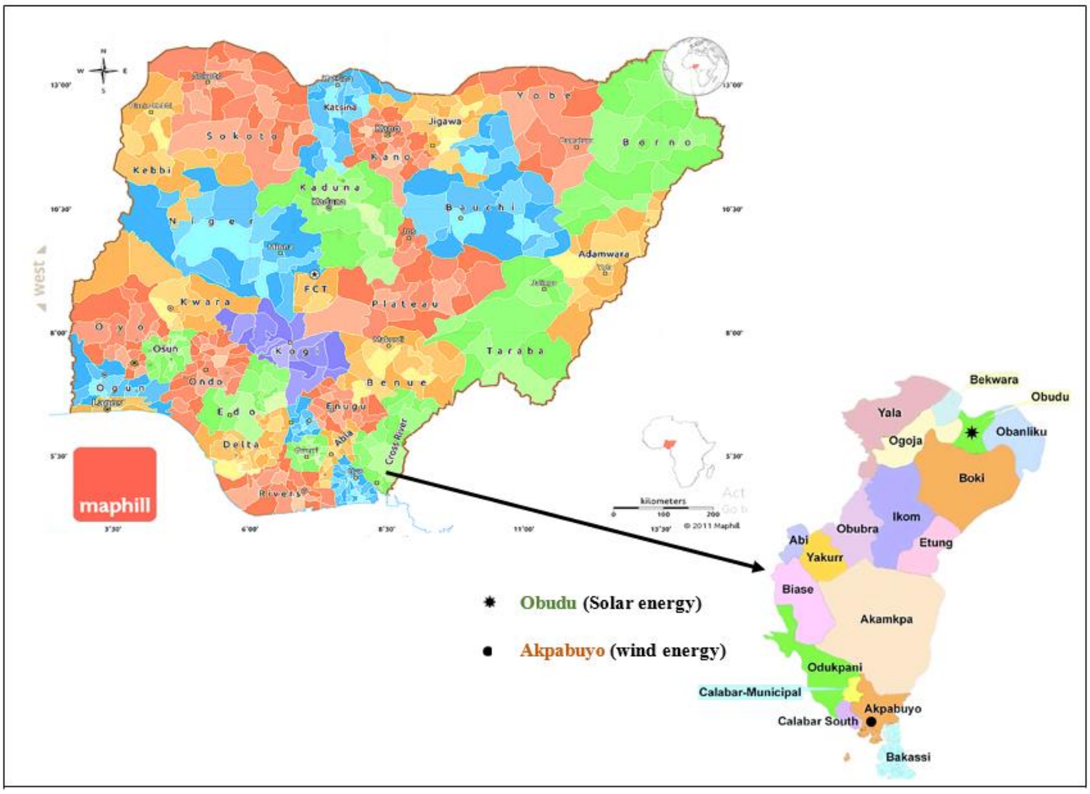

Fig. 7. Selected study areas with high solar and wind energy resource in Cross River State

2.3. Energy Load Assessment

Energy load assessment was further carried out to estimate the load consumption with regards to commercial consumption of energy in Cross River State. The commercial load for Cross River State was estimated at 2424.25kW/day and 348.08 kW at peak periods. The estimated seasonal average load profile for Cross River State is depicted in Fig. 8.

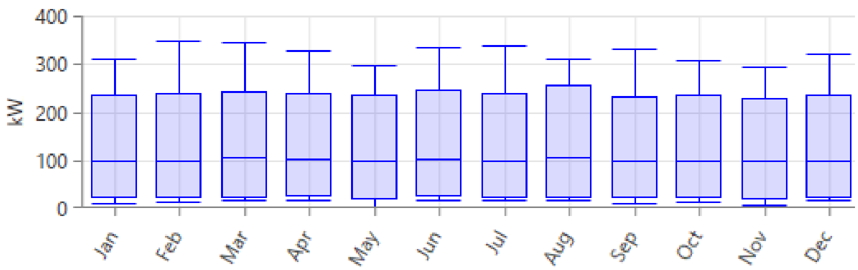

Fig. 8. Monthly profile of energy consumption for Cross River State (Credit: NASA surface meteorology and solar energy database)

2.4. Hybrid energy system modeling

Various energy system components were integrated to a hybrid (renewable and non-renewable) energy system (HES) configuration. The configuration for the designed HES is depicted in Fig. 9. This consist of solar photovoltaic panels (solar farm), battery storage, wind turbines (wind farm), converter, and the load according to the given load area.

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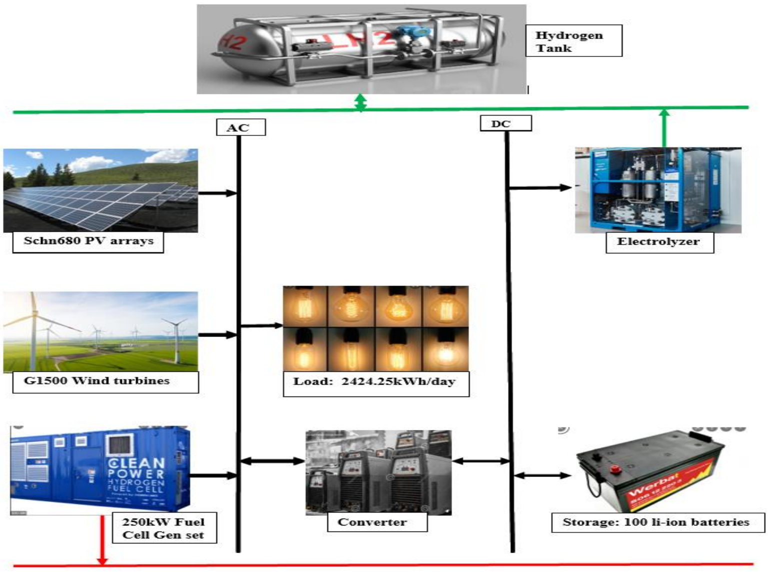

Fig. 9. Schematic of a proposed hybrid energy system (Credit: HOMER)

2.4.1. Solar Photovoltaic (PV) Modules

The solar PV module contains photovoltaic cells that convert radiations into electricity from the sun. The power output of the module can either be computed and or obtained based on manufacturer's specification. [32] suggested that the output power of the solar array is linearly proportional to the incident solar radiation on the panel. The output power of a PV module can be calculated using eqn. (5) as proposed by [33], [34].

$$P_{output} = Y_{pv} f_{pv} \left[\frac{G_T}{G_{T,STC}}\right] \left[1 + \alpha_p \left(T_c - T_{C,STC}\right)\right] \quad (5)$$

Where: Y_{pv} = PV arrays rated capacity or output power under standard test conditions (kW)

f_{pv}, G_T, and $G_{T,STC}$ represents the derating factor of PV (%), incident solar radiation on PV array (kW/m^2), and incident solar radiation under standard situations (1kW/m^2) respectively. While α_p, T_c, and $T_c STC$ represents the temperature coefficient of power (%/ ˚C), PV cell temperature, Cell temperature of the PV under standard test conditions (25˚C) respectively. Where the effect of temperature on the performance of the PV array is neglected, α_p can be presumed as zero leaving equation (5) to be reduced to;

$$P_{output} = Y_{pv} f_{pv} \left[\frac{G_T}{G_{T,STC}}\right] \quad (6)$$

The sizes of the photovoltaic panels considered in this study as presented in Table 1, depended on the irradiation resource of the given area. The selected photovoltaic array cost of installation, replacement, and maintenance was not ignored.

Table 1. Solar panel technical parameters (Credit: HOMER)

Description	Value
Panel type	Flat plate
Abbreviation	Schn680
Rated capacity (kW)	680.08
Temperature coefficient	-0.4100
Operating temperature (̊C)	45.00
Efficiency (%)	17.30
Capital cost ($/year)	3000
Replacement cost ($/year)	3000
O and M cost ($/year)	10

2.4.2. Wind Turbines

The output power of the wind turbine is highly dependent on the wind speed at hub height. The wind speed was evaluated through a quadratic model in eqn. (7) to (8), obtained from [14], [35]–[37].

$$P_w(V_v) = \left\{ P_n \cdot \frac{V_v^2 - V_v^2}{V_n^2 - V_d^2}, V_d < V_v < V_n \right\} \tag{7}$$

$$P_n, V_n \leq V_v < V_c \; O, V_v \leq V_d \; et \; V_v > V_c$$

Where P_w, P_n, V_d, V_c, and V_n represents the output power of the wind, nominal power, cut-in speed, cut-off speed, and rated wind speed respectively.

The wind speed at specific height is expressed as:

$$\frac{V_{(z)}}{V_{(z\alpha)}} = \left(\frac{Z}{Z_\alpha}\right)\alpha \tag{8}$$

Where $V_{(z)}$, and $V_{(z\alpha)}$ are the wind speed at new level, and mean wind speed at anemometer level respectively. While Z_α and α are the power indices.

Wind frequency distribution as obtained from [38], is given by:

$$f_{(v)} = {}^{K}/_{C} \cdot (V/C)^{k-1} \cdot exp\left[-({}^{V}/_{C})\right]^{k} \tag{9}$$

Where V, C, and K represents the wind speed (m/s), Weibull scale parameter, and Weibull shape factor respectively. In this study, the wind turbine selected was based on the wind speed of the selected area. The technical specification of the selected wind turbine is depicted in Table 2. The procurement cost, alternate cost, and maintenance cost of the wind turbines were measured yearly.

Table 2. Wind turbine technical parameters (Credit: HOMER)

Description	Value
Name	Generic 1.5MW
Abbreviation	G1500
Hub height (m)	80
Capital cost ($)	3,000,000
Replacement cost ($)	3,000,000
O and m cost ($)	3,000,000
Lifetime (years)	20

2.4.3. Battery Storage

The generic 100kWh Li-ion battery storage selected has some technical specifications as presented in Table 3, and is required to provide electrical storage for the system. The converter adopted has its primal function to convert electrical current between alternating current (AC) and direct current (DC) [35]. The state of charge (SOC) is expressed as:

$$SOC_{(t)} = \frac{C_{bat(t)}}{C_{batmax(t)}} \tag{10}$$

Where $(0 \leq SOC \leq 1)$, C_{bat} and C_{batmax} are the battery capacity at a time (t) and battery's maximum capacity respectively. If $SOC = 1$, then battery is fully charged. If $SOC = 0$, battery is empty.The nominal capacity batman $(C_{bat(t)})$ which is the battery's charging and discharging process, was evaluated using eqn. (11) to (14).

$$C_{bat(t)} = C_{bat(t-1)} + \left(p_{tot(t)} - P_{cha(t)} + P_{ge(t)}\right)n_{ac} / \, dc \; n_{cha}\Delta t - \text{charging} \tag{11}$$

$$C_{bat(t)} = C_{bat(t-1)} + \left(P_{tot(t)} - P_{cha(t)}\right)\Delta t \; ndc/ac \; n_{decha} \tag{12}$$

Where P_{cha}, P_{ge}, and n_{decha} represents the power demand, power produced by diesel generator, and efficiency of discharging battery respectively.

$$C_{batmin(t)} \leq C_{bat(t)} \leq C_{batmax} \tag{13}$$

$$C_{batmin} = DOD \times C_{batn} \tag{14}$$

Where $C_{batmin}$is the minimum capacity, and $DOD$is the deep discharge coefficient = 0.5. The battery life as calculated by HOMER is expressed by [39];

$$R_{batt} = MW \left[\frac{W_{batt} \cdot Q_{lifetime}}{Q_{thrpt}} R_{batt} \cdot f\right] \tag{15}$$

Where R_{batt}, $Q_{lifetime}$, Q_{thrpt}, and $R_{batt} \cdot f$ represents the battery life (years), lifetime throughput for one battery (kWh), annual battery throughput (kWh/year), and battery float life (years), respectively.

Table 3. Battery technical parameters (Credit: HOMER)

Description	Value
Nominal voltage (V)	600
Nominal capacity (kWh)	100
Maximum capacity (Ah)	167
Round trip efficiency (%)	90
Maximum charge current (A)	167
Maximum discharge current (A)	500
Lifetime (years)	15
Throughput (kWh)	300,000
Capital cost ($)	70,000

2.4.4. Fuel cell generator

The fuel cell generator selected with specification depicted in Table 4, is a stored hydrogen-powered engine generator that drives the electric motor. The fuel consumption of the generator was evaluated using eqn. (16), as developed by [40].

$$F = F_o Y_{gen} + F_1 P_{gen} \tag{16}$$

Where F, F_o, Y_{gen}, F_1, and P_{gen} are the fuel consumption (L), generator's fuel curve intercept coefficient, generator's rated capacity (kW), fuel curve slope for the generator (L/h/kW), and generator's output (kW) respectively. The fuel curve, and efficiency curves of the generator are presented in Fig. 10 and Fig. 11**.**

Table 4. Generator technical parameters (Credit: NREL)

Description	Value
Fuel	Stored hydrogen
Capacity (kW)	250
Slope (kg/hr/kW)	0.2100
Intercept (kg/hr/kW)	0.000
Heat recovery (%)	60
Capital cost ($)	3000
Replacement cost ($)	2500
O and M ($)	0.010

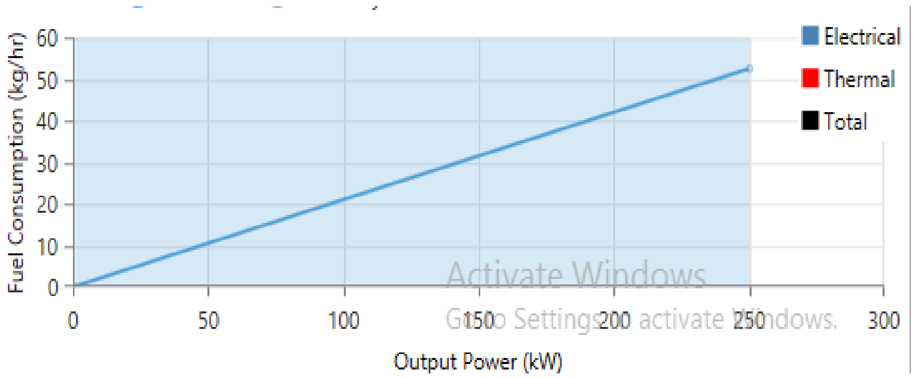

Fig. 10. Fuel curve of the generator (Credit: NREL)

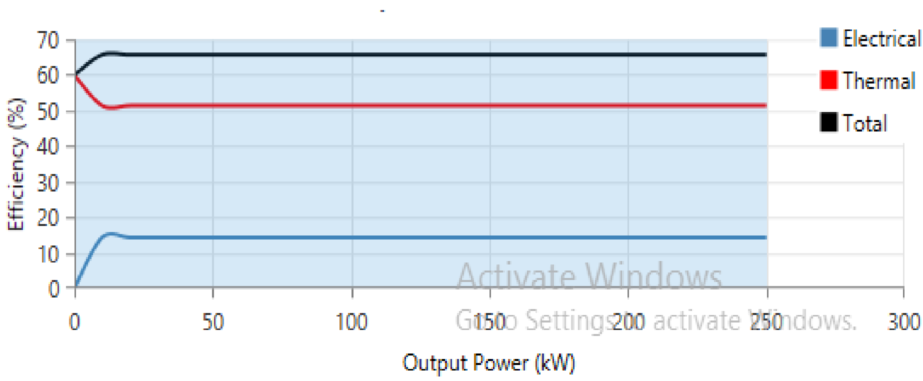

Fig. 11. Efficiency curve of the generator (Credit: NREL)

2.4.5. Converter

The generic system converter was selected for the HES in this study. Its inverter input efficiency is 95% and has a lifespan of 15 years. Also, its rectifier input relative capacity is 100% with a 95% efficiency. For 1kW capacity, the capital and replacement costs are $300.

2.4.6. Electrolyzer

The Electrolyzer is responsible for generating hydrogen by electrolysis of water. The generic electrolyzer was selected for the HES. It has a lifetime of 15 years and 85% efficiency with a 0.0% minimum load capacity, its capacity is 1kW and the capital cost is $1400/kW, $1200/kW, O and M $30/kW.

2.4.7. Hydrogen Tank

The hydrogen tank selected is the generic hydrogen tank with 50% relative to tank size and a capital cost of $65,000.

3. Results and Discussion

The results obtained from the simulation based on the technical data of the appraised study areas and technical specifications of selected components that constitutes the HES configuration is presented for a 25 years analysis period. The optimal and preferred system was selected by the HOMER software. The hybrid hydrogen powered system was optimized to meet the demand of electrical energy and mitigate CO2 in the system and Cross River State. A sensitivity analysis that ascertains the financial cost effects on the viability of the HES is also presented.

3.1. Result of economic appraisal

The results obtained for the LCOE, NPC and operating cost (OC) for the hybrid energy system are 0.89 USD, 10,138,702 USD, and 134,084.37 USD respectively. Table 5 presents the cost summary of the entire HES.

Table 5. Net present summary cost of the HES components

Component	Capital (USD)	Replacement (USD)	O and M (USD)	Fuel (USD)	Salvage (USD)	Total (USD)
Generic 1.5MW	2,000,000	956,422.05	387,825.50	0.00	539,005.16	2,663,676.67
Generic 100kWh Li-ion	1,602,800	1,104,299.92	560,795.67	0.00	207,840.39	2,842,038.64
Generic Electrolyzer	80,000	50,912.86	38,782.55	0.00	9,582.31	154,07.17
Generic Fuel Cell 250kW	350,000	0.00	9,986.51	0.00	126,591.35	473,373.79
Hydrogen Tank	45,000	0.00	12,927.52	0.00	0.00	54,549.26
System Converter	74,030.18	39,894.55	0.00	0.00	7,508.56	88,491.32
Schn680 with Generic PV	3,355,775.60	0.00	230,789.59	0.00	0.00	3,910,595.32
System	6,007,605.78	2,151,529.38	1,215,252.30	0.00	890,527.78	10,138,702

The Schneider ConextCore 680kW with Generic PV (PV arrays) amounted to 44.6% of the capital cost of the system, taking the chunk of the capital cost. The wind turbines (G1500), the battery (G100kW Li-ion), the generic fuel cell 250 kW generator, the electrolyzer, hydrogen tank, and converter account for 24.9%, 21.6%, 6.2%, 1.2%, 0.6%, and 0.8% of the capital cost respectively. Fig. 12 shows the net present and annualized cost summary of the components. It is clearly shown that the composition of renewable energy conversion systems (RECs) makes up for 78.74% of the entire hybrid energy system.

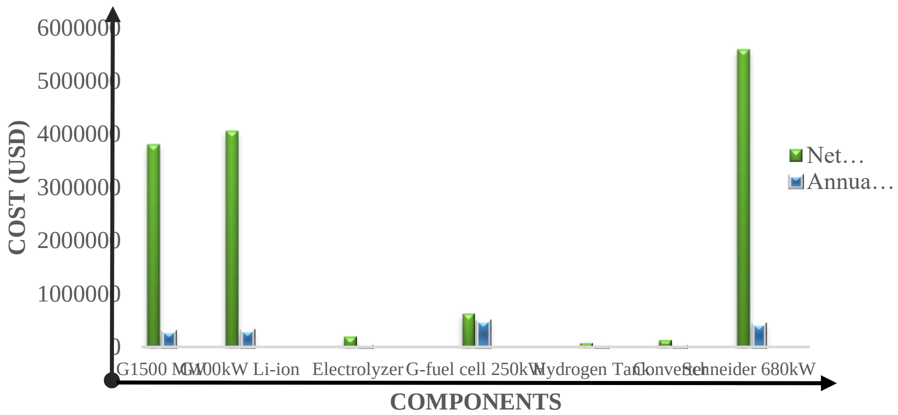

Fig. 12. Cost summary of components

3.2. Result of the technical appraisal

The HES was appraised based on the various energy system components. This includes; solar photovoltaic panels (solar farm), battery storage, wind turbines (wind farm), converter, and the load. The plant layout of the proposed HES is depicted in Fig. 13.

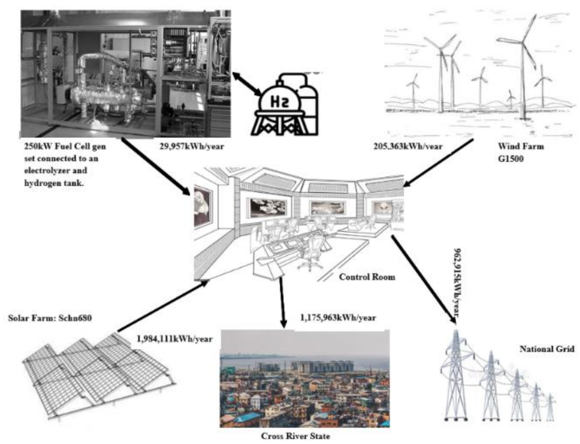

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Fig. 13. Proposed HES plant layout

3.2.1. Appraised load result

Fig. 14 shows the daily load profile of Cross River State using data obtained from NREL. The demand for power peaks between the 8th hour and 19th hour when commercial activities are high. The estimated daily commercial load for the Cross River State is 2424.25kWh/day, with an average load of 101.01kW and peak load of 348.08kW.

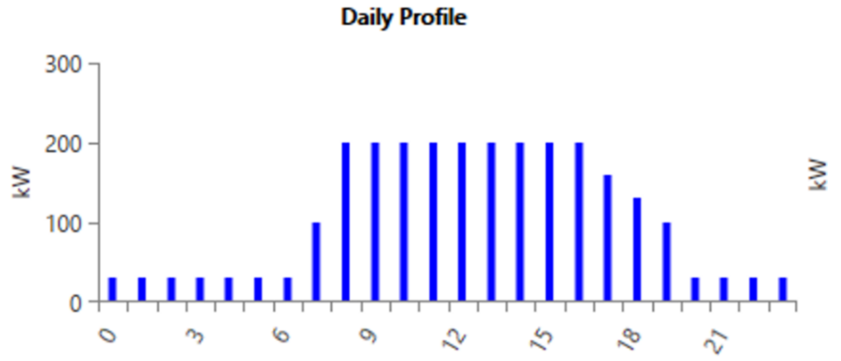

Fig. 14. Commercial daily load profile for Cross River

3.2.2. Appraised results for the solar photovoltaic arrays and the battery storage

Electricity production from the hybrid energy system is mainly from the photovoltaic arrays. The PV arrays generated 1,984,111kWh/year accounting for 89.4% of the electrical energy produced annually. The wind power plant also produced 205,365kWh/year per year accounting for 9.25% of electricity produced. The generic fuel cell produced the least of 29,957kWh/year accounting for 1.35% of electricity produced. Fig. 15 shows the monthly average electricity production of each plant.

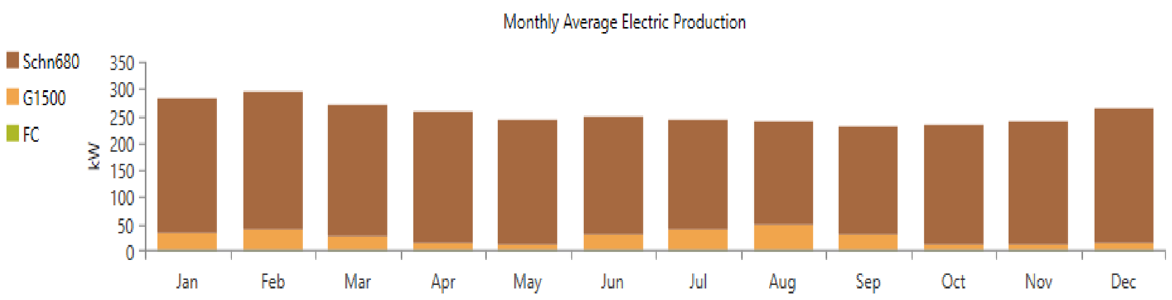

Fig. 15. Monthly electricity production for the hybrid energy system

Fig. 16 and Fig. 17 depicts the monthly state of charge for the battery of the proposed hybrid energy system. The months of February, April, and July produces the least battery charge records as seen in Fig. 16. The battery achieves an average of 90 to 100% charge between the 6th to 18th hour of the day. This translates to high battery charge during the day as a result of high solar irradiance within this period (see Fig. 17). Furthermore, day 192 to 225 experiences 18% to 22% charge. These could be due to high load demands resulting to either inadequate power to charge the battery or high discharge during peak load demands. Another reason could be low power generation due to unfavorable weather conditions during those months. The battery has a high discharge during the day because of high load demands.

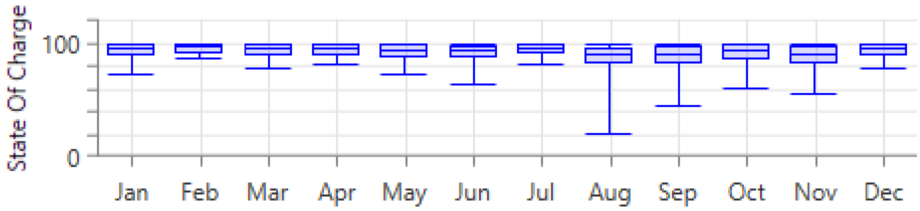

Fig. 16. Monthly state of charge for the battery of the hybrid energy system

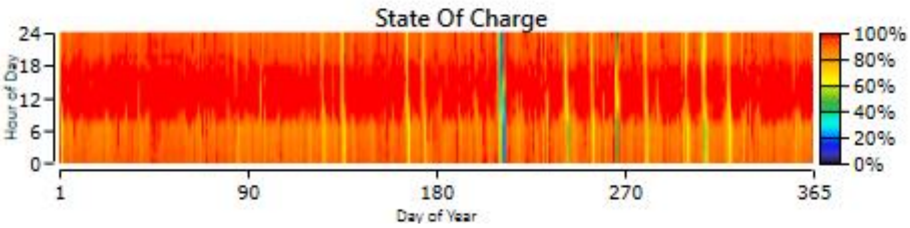

Fig. 17. Yearly state of charge for the battery of the hybrid energy system

The solar photovoltaic panels of the HES are made up of special cells that generates electric current form sunlight and are linked together as a solar farm. When the sun shines on the cells, an electric field is created. The more powerful the sun, the more energy is produced. Fig. 18 shows the photovoltaic power output of the peak periods which begins from the 6th hour of the day to the 18th hour of the day. The PV array operates at a value of 4,456 hours/year with a levelized cost of $0.218/kWh. The Schneider ConextCore XC 680kW with generic photovoltaic panels generates a total of 1,984,111 kWh/year of electricity. The mean output discharge is 5,436kW/day. Effectually, the ConextCore XC produces more energy during the peak hours because of the amount of usage during these hours.

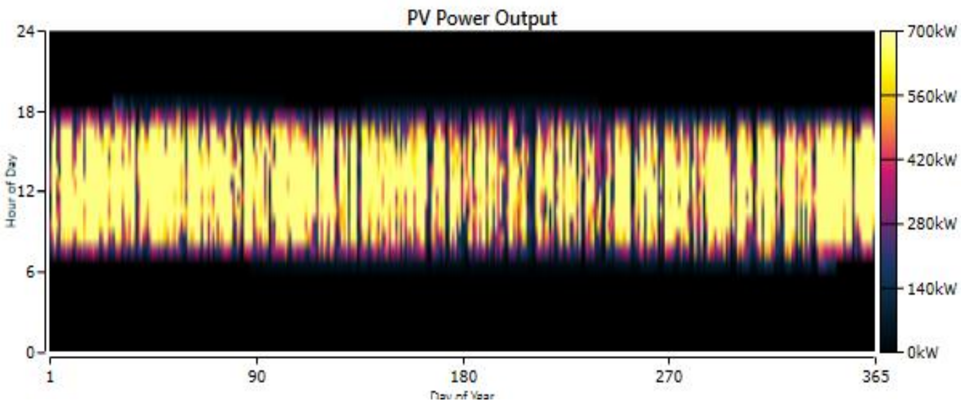

Fig. 18. PV power output of the hybrid system

3.2.3. Appraised results for the wind turbine

The wind turbine configured to the HES, operates on the principle of wind to power (Wind Energies). Fig. 19 depicts the wind turbine power output. The generic 1.5 MW (G1500kW) total electricity production is 205,365kWh/year with a maximum output of 1,059kW and 1.341 hours/year hours of operation, also garnering a levelized cost of $1.43 kWh. The peak hours are from the 8th hour to the 14th, generating between 243kW to 720kW of power. Connected to the HES, it also contributes to the REC percentage of energy produced in the system and as such gives output at various hours of the day.

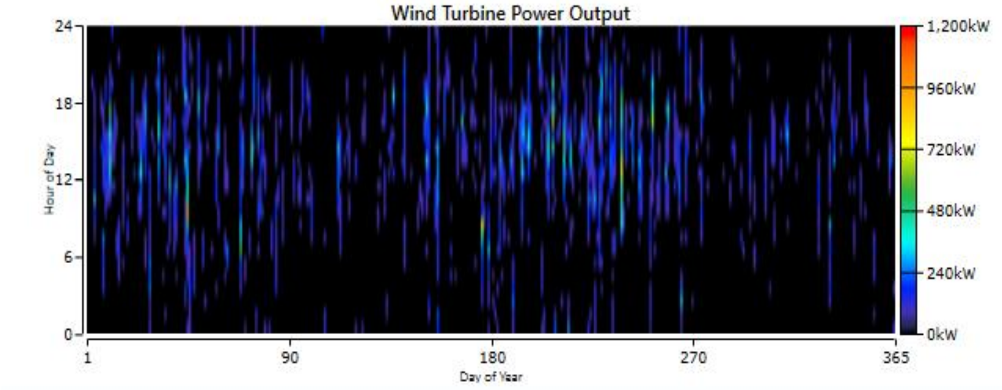

Fig. 19. Wind turbine power output of the system

3.2.4. Appraised results for fuel cell and electrolyzer

The generic fuel cell (hydrogen powered) produces a total of 29,957kW/year of electricity, with its maximum electrical output at 250kW. Thermal energy produced is 107,845kWh/year and maximum thermal output is 900kW. The generic fuel cell used is an electrochemical system that directly converts the chemical energy of a conventional fuel into direct current electrical energy. The fuel cell generator is made up of two permeable electrodes connected by a conducting electrolyte. The hydrogen at the anode gives up electrons to the electrode and enters the electrolyte as a positive ion (H+), whereas the oxygen at the cathode takes electrons and enters the electrolyte as a negative ion (O-) (O2- or OH-) (Fuel Cell Systems). The hydrogen powered fuel cell consumes 6,291kg of fuel (stored hydrogen) with a specific fuel consumption of 0.210kg/kWh. Its hours of operation are 309 hours/year. Fig. 20 shows the power output of the fuel cell. The peak hours of output in this component if from the 18th hour towards the 20th hour of the day. Also contributing to the REC, but the fuel cell requires just its stored hydrogen and as such gives output when natural renewable sources are at low levels in the system.

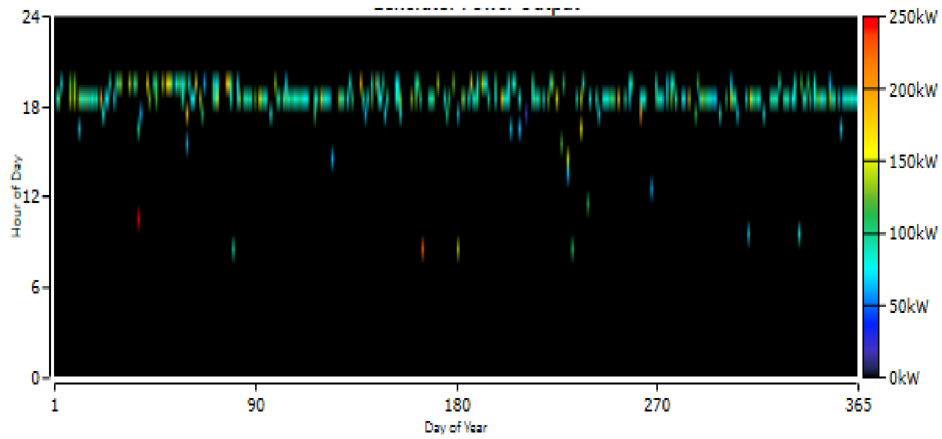

Fig. 20. Power output of the fuel cell of the HES

Furthermore, the electrolyzer generates hydrogen gas through electrolysis. The remaining oxygen is either released into the atmosphere or captured and stored to supply other industrial processes [41]. The Electrolyzer integrated in the proposed HES, produces 6,281kg/year of hydrogen that is consumed by the fuel cell for power generation. The levelized cost of hydrogen is $178/kWh. Its input energy is 291,470kWh/year with a specific consumption of 46.4kWh/kg and 3192 hours/year of hours of operation. Zero carbon emissions were also achieved. Fig. 21 and Fig. 22 depicts the hydrogen production by the electrolyzer and the electrolyzer input power respectively. The electrolyzer input is highest in the months of January through March, July and December. This invariably affects the production of energy in months of low electrolyzer inputs. From the 8th to 18th hour of the day, the electrolyzer's input is highest which means that the fuel cell generator's output during these hours of the day is also high.

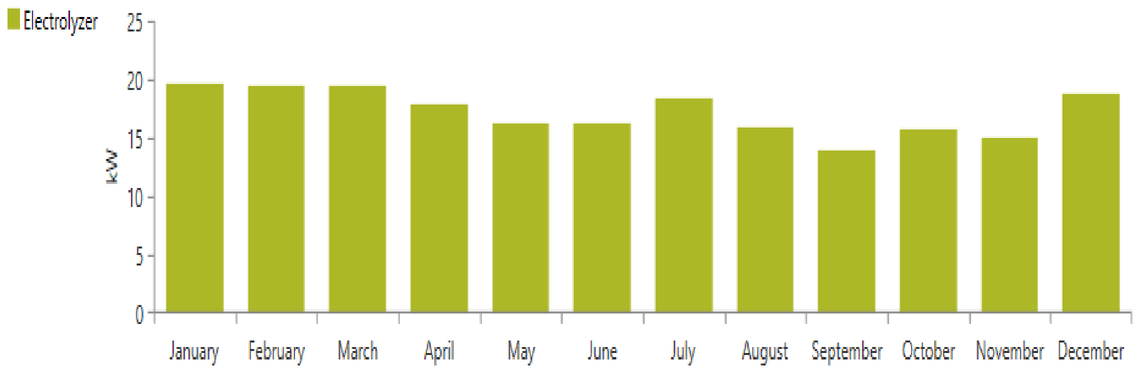

Fig. 21. Hydrogen production by electrolyzer

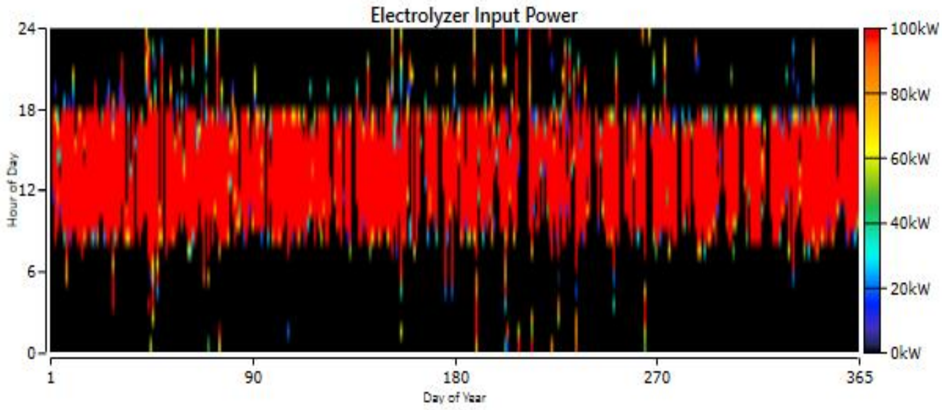

Fig. 22. Input power of the electrolyzer

Fig. 23 and Fig. 24 also depicts the monthly storage of hydrogen stored, and the daily discharge of hydrogen annually. The hydrogen tank (HT) has a storage capacity of 100kg with an energy storage capacity of 3,333kWh. The HT stores the manufactured hydrogen from the electrolysis and distributes it when needed by the fuel cell to carry out operations. The months of March and June records the highest amount of hydrogen stored in the tank. During the high discharge months, the HT discharges hydrogen for maximum output from the fuel cell (FC) generator, thus increasing work in the FC generator.

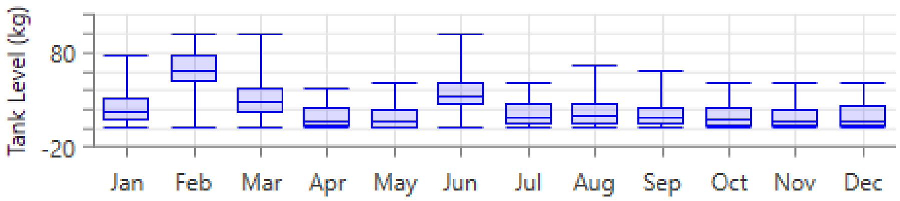

Fig. 23. Monthly storage of hydrogen

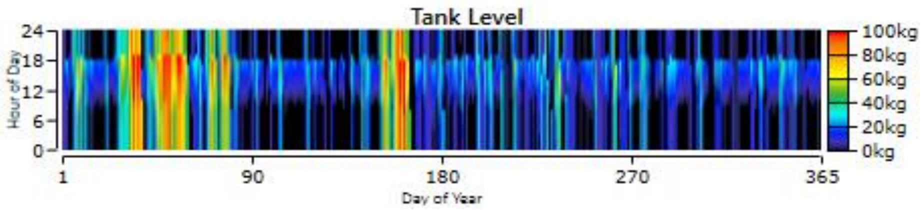

Fig. 24. Daily discharge of hydrogen

3.2.5. Appraised results for HES converter

The system converter has an inverter and rectifier capacity of 313 kW each. The maximum output for the inverter is 269kW giving out energy of 162,138kWh/year at 4,389 hours/year. However, the rectifier maximum output is 313kW, giving in energy of 534,163kWh/year at 4,192 hours/year. Fig. 25 and Fig. 26 depicts the output of the inverter and rectifier. The output of both rectifier and inverter are both high during the 6th and 18th hours of the day.

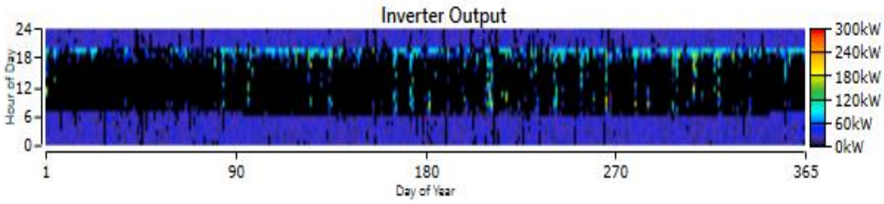

Fig. 25. Inverter output of the hybrid energy system

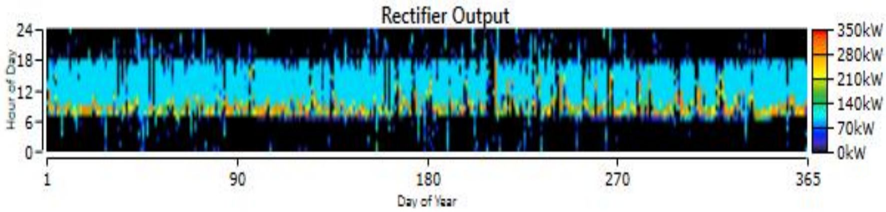

Fig. 26. Rectifier output of the hybrid energy system

3.3. Sensitivity Analysis

Sensitivity analysis was further carried out to determine the effect of some parameters on the viability of the HES project in Cross River State. Variations in discount rates (10%, 14%, 18%, and 22%) and inflation rates (4%, 8%, 12%, and 16%) were used to ascertain or predict their effects on the HES proposed.

The discount rate in this instance, can be the opportunity cost or laid-off cost of the capital as determined by the percentage of capital value. Opportunity cost of capital is the return on investments made elsewhere that is inevitable as a result of investing capital; it is also the rate below which an investment is not cost-effective [42]. As depicted in Fig. 27, the LCOE of the HES is directly proportional to the discount rate; as it increases from 1.02 USD to $2.84/kWh when there is a discount flow from 10 to 22% respectively. This indicates that the discount rate cannot be overlooked if the affordability and the cost effectiveness of the project are taken into consideration.

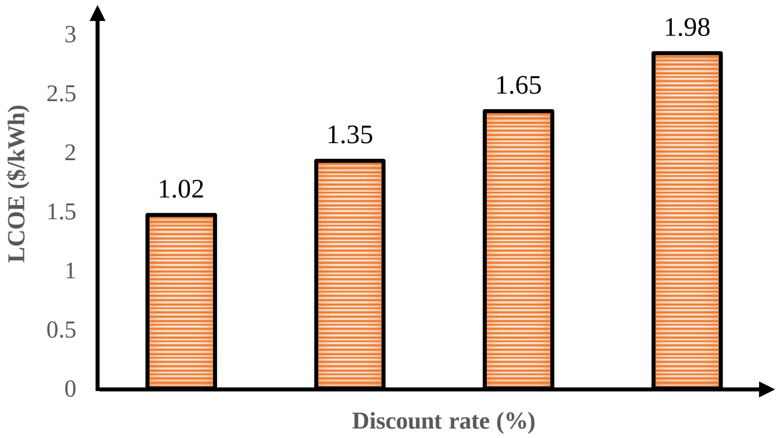

Fig. 27. Discount rate effect on LCOE of the HES

The effect of inflation on the LCOE of the HES is also significant. As depicted in Fig. 28, increasing the inflation rate, decreases the LCOE, implying that the rate of inflation is a key parameter in the project's viability.

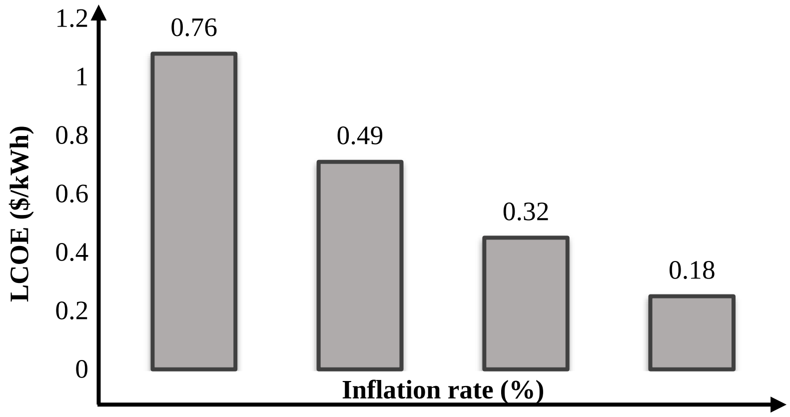

Fig. 28. Inflation rate effect on the LCOE of the HES

3.4. Emission appraisal

Carbon dioxide (CO2) accounts for the vast majority of greenhouse gas emissions from the energy sector, but methane (CH4) and nitrous oxide (N2O) are also emitted in smaller amounts. These gases are produced when fossil fuels such as coal, oil, and natural gas are burned to generate electricity. Sulfur hexafluoride (SF6), an insulating chemical used in electricity transmission and distribution equipment, accounts for less than 1% of the sector's greenhouse gas emissions [43].

The hybrid energy system proposed in this study provides a solution to greenhouse gases emissions and also provides electrical energy for consumption in the given potential area (Cross River State). The appraised rate of these emissions from the proposed HES is shown in Table 6.

Table 6. Emission rates from the proposed HES

Quantity	Value	Units
Carbondioxide	0	kg/year
Carbon monoxide	0	kg/year
Unburned hydrocarbons	0	kg/year
Particulate matter	0	kg/year
Sulfur dioxide	0	kg/year
Nitrogen oxides	0	kg/year

Nigeria seeks to upsurge her supply of renewable electricity from 13% of total electricity generation in 2015 to 23% in 2025 and 36% in 2030, this is under the renewable energy master plan (REMP). The REMP also implements a set of market and fiscal motivations to support redistribution. This system shows a practical approach to the REMP gaining a considerable percentage in electricity production whilst also sustaining the environment with zero emissions.

4. Conclusion

A hybrid energy system nexus for CO2 mitigation has been designed and proposed after a technical and economical appraisement for a 25-year period. Technical specification data of the different components that made up the HES nexus along with the meteorological data of high potential areas for the considered energy resources were used for the appraisal. The highly potential areas of wind energy, and solar energy resources in Cross River State that were identified and adopted for the design of the HES nexus were Akpabuyo, and Obudu respectively. The configuration for the designed HES nexus consists of Schn680 solar photovoltaic arrays, 250kW Fuel cell generating set, 100kWh Li-ion battery storage, G1500 (1.5MW) wind turbines, converter, a hydrogen tank, an electrolyzer, and the load according to the given load area. The composition of renewable energy conversion systems makes up for 78.74% of the entire HES nexus. The following conclusions are made.

- The estimated load consumption with regards to commercial consumption of energy in Cross River State was 2424.25kW/day, with an average load of 101.01kW, and peak load of 348.08kW.
- LCOE, NPC and operating cost (OC) obtained for the HES were 0.89 USD/kWh, 10,138,702 USD, and 134,084.37 USD respectively. The solar PV arrays amounted to 44.6% of the capital cost of the HES. The G1500 wind turbines, G100kW Li-ion battery, 250 kW fuel cell generator, the electrolyzer, hydrogen tank, and converter account for 24.9%, 21.6%, 6.2%, 1.2%, 0.6%, and 0.8% of the capital cost respectively.
- The electricity production from the HES is mainly from the photovoltaic arrays. The PV arrays generated 1,984,111kWh/year accounting for 89.4% of the electrical energy produced annually. The wind power plant also produced 205,365kWh/year per year accounting for 9.25% of electricity produced. The generic fuel cell produced the least of 29,957kWh/year accounting for 1.35% of electricity produced.
- The hydrogen powered fuel cell consumes 6,291kg of fuel (stored hydrogen) with a specific fuel consumption of 0.210kg/kWh, operating at 309 hours/year. However, the hydrogen tank (HT) has a storage capacity of 100kg with an energy storage capacity of 3,333kWh.
- The Electrolyzer integrated in the proposed HES nexus, produces 6,281kg/year of hydrogen that is consumed by the fuel cell for power generation at a specific consumption of 46.4kWh/kg and 3192 hours/year of hours of operation.
- The HES converter has an inverter and rectifier The maximum output for the inverter is 269kW giving out energy of 162,138kWh/year at 4,389 hours/year. However, the rectifier maximum output is 313kW, giving in energy of 534,163kWh/year at 4,192 hours/year.
- Sensitivity results shows that discount rates and inflation rates have a significant effect on the HES proposed are key variables in the project's viability.
- Net zero emissions of carbon, NOx, Sox, particulate matter, and unburden hydrocarbons, were also achieved by the HES.
- HOMER software has proven to be a viable tool used in designing and appraising the technical and economic feasibility of the HES.

It is concluded that the proposed HES nexus for Cross River State is technically and economically viable with net zero CO2 emissions and other greenhouse gases.

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Declarations

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