Catalyzing Uninterrupted Energy Availability in Nigeria through Decentralized Off-Grid Hybrid Energy Exploitation

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ABSTRACT
The Present use of centralized energy planning model in Nigeria lacks the capacity to meeting the energy need of Nigerian rural and urban communities, leading to environmental degradation as fossil fueled energy options are being adopted. This paper evaluated decentralized off grid hybrid energy model as feasible alternative solution to energy poverty and as catalyst for sustainable, round-the-clock energy availability in Nigeria using Abeokuta in Ogun state as a case study. Small hydro (SHP), solar PV, diesel generator (DG) and battery storage (BB) hybrid system was used for the study. HOMER (hybrid optimization model for electric renewable) was employed to determine the optimal result. The load profile of the area was arrived at through the use questionnaire and from load data of the community obtained from Nigeria's National Control Center (NCC), Oshogbo. The hydro data of Oyan river in Abeokuta used for the study and the solar data of the area were obtained from Ogun-Oshun River Basin Development Authority, Abeokuta and National Aeronautics and Space Administration (NASA)'s global satellite database respectively. The capital costs of system components were estimate as obtained from suppliers in Nigeria and Oversea. The optimal energy systems were selected on the basis of less levelised cost of energy (COE), less net present cost (NPC), less excess electricity, minimum annual capacity shortage and so on. A comparative analysis of the optimal configuration with an autonomous diesel generator with respect to environmental impact and economy was done to ascertain the ecological advantage of the off-grid hybrid model. The analysis favoured off grid PV-DG-BB-SHP hybrid system, wherein levelized cost of energy (COE) is $0.290, net present cost (NPC) $1,265,686,000 and renewable fraction (RF) 99.9%. The community annual energy need is 105,645,600 kWh/yr while the annual energy production of the hybrid energy model is 295,702,783 kWh/yr. The result shows environmentally benign hybrid energy model that can guarantee uninterrupted energy availability for Abeokuta. When fully exploited by government and policy makers in Nigeria and extended to other localities in the Nigerian state, constant energy availability, independence and growth are possible in all parts of Nigeria.

General Terms
Hybrid energy, Optimal topology, Comparative analysis, Economic metrics.

Keywords
Electricity supply, Renewable energy resources, Decentralized energy model, Energy growth.

1. INTRODUCTION
The increasing energy gap owing to population growth both in rural and urban areas in Nigeria reinforces the necessity of balancing local energy production and consumption. Population growth is accompanied by increasing socioeconomic activities which are energy dependent. Rural and urban areas which are the epicenters of national development lag in commensurate energy growth.

The centralized grid system in practice for decade in Nigeria has been highly incapacitated by measureless impediments creating an increasing expanse between energy demand and supply. Also, commercial energy-oriented development focuses on fossil fuels and centralized electricity generation. This has resulted in inequities and environmental degradation. Globally, these developments are upending this convectional method of centralized power infrastructure and disseminating power generation across hundreds of thousands of local clean energy resources avouched as the emerging paradigm of a decentralized power generation system.

Electricity systems globally are undergoing a paradigm shift towards decentralization. New frontiers of energy production that can guarantee energy growth, uninterrupted availability and self-sufficiency are being explored [1]. As countries seek to meet their emission reduction targets, electricity is being increasingly decarbonized by the infusion of renewables into the energy production mix. Using variety of decentralized renewable energy planning model is a step to ensuring energy growth and round-the-clock availability [2]

The answers to local problems generally lie in nurturing local solutions and capacities because, even in the course of expanding utility infrastructure, any energy growth projection is centered on limited geographies where it is feasible for the utility grid to reach and not otherwise. Therefore, the panacea for laying the foundation for energy independence, sustained energy growth and availability is to have recourse to energy sourcing from green energy endowments bestowed by nature. Decentralized off-grid hybrid energy solutions are promising options for sustainable energy growth in modern world, especially where the centralized grid system is bedeviled by lack of capacity to meeting the energy need of locals and urbans in all nook and cranny.

Despite high up-front investment costs, these systems can provide numerous benefits: they can substantially reduce overall energy costs by increasing self-consumption of renewable electricity produced on-site. They exhibit large synergy potential and high flexibility operationally, thus optimizing input resource utilization, stress reduction on the local grid, ensuring distribution and transmission losses reduction; and in effect creating a more reliable energy supply [3]

Decentralized off grid hybrid energy model has high reliability and resilience. Owing to their disseminated structural design, decentralized off grid hybrid energy systems can easily cope with individual failures from any of the network sources since each energy using node is served by multiple energy production units. Decentralized off grid systems can enable a democratization of energy access, thus fostering inequality reduction, community self-sufficiency and self-governance [4]. Today, there are already many successful implementations of decentralized off-grid hybrid energy (DOHE) system across various applications and with diverse technical topology. The implementations range from interconnected neighbourhoods in urban settings to remote or islanded areas [5-10]. The extant literatures lack a comprehensive review of the knowledge and potentials of DOHE systems in Nigeria. To fill these gaps, discussed in the present work is the feasibility of a decentralized off grid energy option for towns and small-scale applications in villages in Nigeria. An extensive evaluation of DOHE model by means of a hybrid power project of small hydro, photovoltaic (PV), diesel generator and battery storage is conducted in this paper using Abeokuta, Ogun state in Nigeria as a case study.

The first part of this study presents an overview of decentralized off grid hybrid energy technologies and the available renewable resources for possible design of DOHE system in the case study area. The hybrid system proposed consists of small hydro and solar photovoltaic (PV) panels. A diesel generator and a battery bank were included to provide back-up and energy storage for the system respectively. The later part presents the simulation results.

2. AN OVER VIEW OF DECENTRALIZED OFF-GRID HYBRID ENERGY TECHNOLOGIES

In Nigeria the demands for sustainable, round-the-cloth energy abundance are increasing, engendered by population and developmental growth. But the available infrastructures for providing commensurate energy, especially to rural areas have continued to diminish and have become grossly inadequate. This fact has necessitated the need to identify and promote the development and utilization of renewable energy technologies from sources such as wind, solar, small or mini hydropower on which decentralized off grid hybrid energy system can be developed for sustainable energy growth and socio-economic development of the unreached rural and urban areas of Nigeria [11].

The renewable energy technologies relate to small and micro hydro, wind turbines, solar photovoltaic and hybrid systems. For large and dispersed rural communities as in the case of Nigeria, decentralized power generation systems, wherein electricity is generated at consumer end and avoiding transmission and distribution costs, offers a better solution.

Decentralization of electricity generation provides a new economy guaranteeing employment availability once renewable energy is mainstreamed in the economy. There is a large potential for growth in renewable energy industry. Promotion of renewable technology through decentralization will expedite the use of cleaner forms of energy production.

There is a growing worldwide acceptance that decentralized electric generation will reduce capital investment needs compared to central generation with its supporting transmission and distribution systems. In addition, decentralized generation can lower the cost of electricity, reduce pollution, reduce production of greenhouse gas and decrease vulnerability of the electric system to extreme weather and militant attacks. It is believed that the share of decentralized off grid hybrid energy technology in global power generation will increase dramatically in coming years, with important benefits to all segments of the population and significant environmental benefits. More often than not, decentralized off grid hybrid energy system is synonymous with cleaner electricity which indeed is one of DOHE system's main benefits [3]

The various renewable energy technologies include solar photovoltaic panels such as crystalline-silicon technologies and thin-film technologies; roof-top/local wind turbines; small-scale local hydro power, such as small-scale tidal or run-of the river; geothermal energy; renewable energy-powered fuel cells; thermal based technologies, including biomass-fired engines, biomass-fired steam turbines, gas turbines and micro turbines; plug-in electric hybrid vehicles and so on.

3. REVIEW OF RENEWABLE ENERGY RESOURCES FOR DOHE SYSTEM IN NIGERIA

3.1 Wind

Wind energy is one of the fastest growing technologies in energy generation industry worldwide. Wind resources can be converted into electricity using the appropriate technology. Wind generation technology is more cost-effective resource among different renewable energy technologies [12]. According to the works done by scholars, Nigerian North-west has the highest wind speeds ranging from 3.88 m/s to 9.39 m/s at Yelwa and Kano respectively. Following this is North-east zone with Jos having a lead with a wind speed of 9.47m/s. In the South-east zone of Nigeria represented by Enugu and Ogoja have 5.73 m/s and 2.80 m/s respectively. The South-western part of the country has 1.77 m/s in Ondo and 4.5 m/s in cities like Lagos Island, Shaki and Lagos Mainland. Minna and Bida in the North-central geo-political zone have wind speed of 5.36 m/s and 2.46 m/s respectively. Then the South-south zone from the research shows that Calabar has the highest wind speed of 4. 65 m/s, while Port-Harcourt has the least wind speed in the zone with a value of 3.30 m/s [12-14].

3.2 Biomass

Nigeria is rich in Biomass. From the study carried out by [15], Nigeria has large biomass potential estimated to be at least 3.2 EJ (3.2x1018J) in 2010. Some biomass sources are agro-residues, livestock wastes, municipal solid wastes and forest residues. The energy potential is expected to continue to grow from about 3.2 EJ in 2010 to about 5.5 EJ in 2020 and even about 29.8 EJ in 2050.

3.3 Solar Resources

Nigeria’s annual average daily solar radiation is about 5.25 kW/m2/day at the coastal area and 7.0 kW/m2/day at the northern boundary. This corresponds to about 1.082 million tons of oil equivalence per day and about 4 thousand times the current daily crude oil production. Also, this value amounts to about 13 thousand times the natural gas daily production based on energy unit. According to [16] this huge energy resource from the sun is available for only about 26% of the day, while [17] averaged it as 5.535 kWh/m2 /day based on land area of 924 x 103 km2 for the country. Nigeria annual incident solar energy average is 1.804 x 1015 kWh. This annual solar energy insolation value is equivalent to about 27 times the nation total conventional energy resources in energy units [18].

3.4 Small Hydro Power

There are many small rivers with Small hydro power potential in different locations in Nigeria. Some locations were identified with a total power generation capacity of 12,190 MW [15]. There are other small rivers in various communities in the country that have potential for small hydro power development such as Oyan river in Ogun state, Ogunpa river in Oyo state, Aye river in Lagos state, Osun river in Osun state, Owena river in Ondo state and Ele river in Ekiti state all in Southwest geopolitical zone of Nigeria

4. DESCRIPTION OF THE STUDY AREA: ABEOKUTA-OGUN STATE

Abeokuta lies at latitude 7.258° N and longitude 3.250° E. It covers an area of 16,762 square km and had a population of 707,277 in 2013 census [19]. Agriculture is the economic mainstay of the area. The local industries include but not limited to fruit canning plants, plastics, breweries, sawmills, and an aluminum products factory. Included in this are irrigation and food-processing.

One of the small rivers in the area is Oyan river situated at latitude 7.258o N and longitude 3.25o E. The lake is in the savannah region, with sparse trees and grasses and low fertility. It covers 4,000 hectares and has a catchment area of 9,000 km.2 Oyan dam (Figures 1) was constructed across the Oyan river—a tributary of the Ogun river. It has potential for use in irrigation and power generation. The dam is operated by the Ogun-Osun River Basin Development Authority. It was met to support the 3,000-hectare Lower Ogun Irrigation Project. The dam has a crest length of 1044 m, height 30.4 m, gross storage capacity of 270 million m3 and an installed capacity of 9MW [20].

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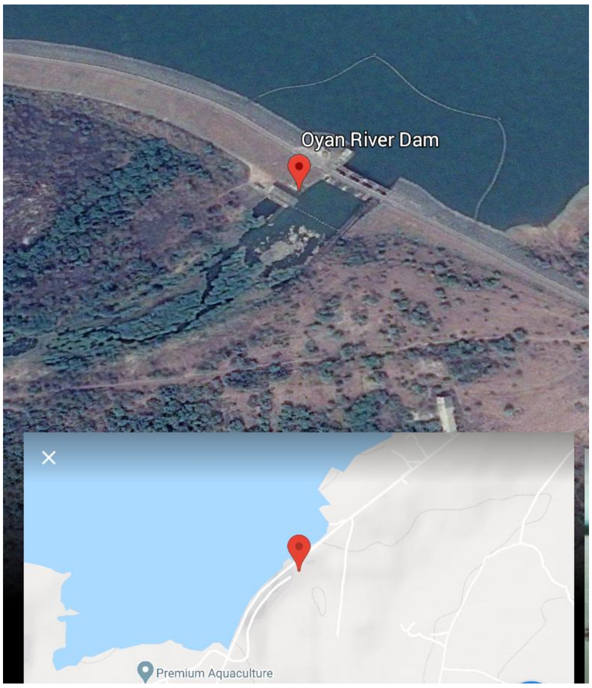

Fig 1: Oyan river dam

5. RENEWABLE RESOURCES FOR DOHE SYSTEM AND LOAD DEMAND OF THE STUDY AREA

5.1 Hydro Resources of the Study Area

The hydro parameter of Oyan river was used in hybrid with other resources for this investigation. The hydro parameters for this river were obtained from Ogun-Oshun River Basin Development Authority covering a 10 years period. From the data analysis Oyan river has an annual average stream flow of 5,537.50 L/S. The peak is around August recording 14630 L/S. Its dry season is from November to December and January to early April as shown in Table 1 and Figure 2.

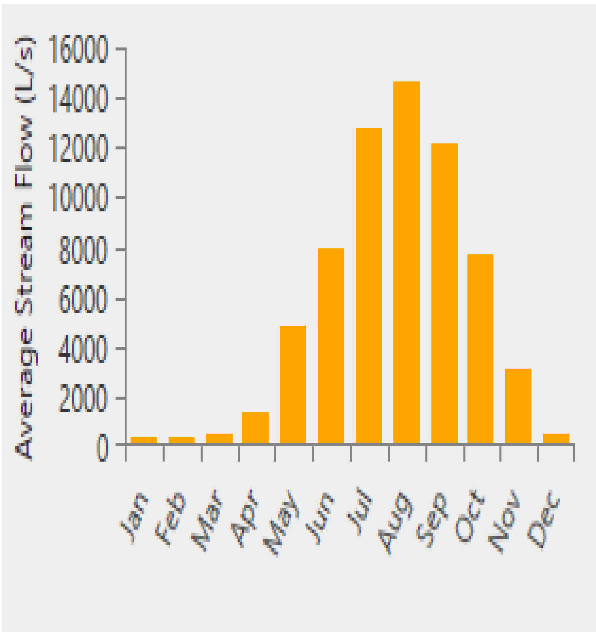

Fig 2: Oyan river average stream flow

Table 1 Average monthly hydro and solar resources data of Abeokuta

	Hydro data		Solar data	
Month	**Discharge (L/S)**	**Head(L)**	**Solar Radiation (kW/m^2)**	**Clearness index**
Jan	410	280	5.28	0.525
Feb	360	250	5.36	0.516
March	530	330	5.29	0.503
April	1350	690	5.32	0.521
May	4890	1100	5	0.518
June	7980	1620	4.48	0.481
July	12730	2440	4.08	0.433
August	14630	2930	3.6	0.363
Sept	12210	2330	4.3	0.416
October	7750	1770	4.91	0.474
Nov	3070	1070	5.31	0.526
Dec	540	360	5.27	0.532
Annual Average	5537.5	1264.167	4.85	0.484

5.2 Solar Resources of the Study Area

The solar radiation data for this investigation was obtained from National Aeronautic Satellite Administration (NASA) surface meteorology for latitude 7.258^o N and longitude 3.250^o E [21]. The solar radiation varies throughout the year, ranging between 5.280 $kWh/m^2/day$ and 5.000 $kWh/m^2/day$ from the months of January to May, and between 5.310 $kWh/m^2/day$ and 5.270 $kWh/m^2/day$ from the months of November and December, which are the periods of dry season in Abeokuta.

The analysis also shows corresponding typical values of monthly average clearness indices of relative stability from the months of January to May and November to December. The annual average clearness index and solar radiation are 0.484 and 4.85 $kWh/m^2/day$ respectively. The daily solar radiation and clearness index are shown in Table 1 and the chart in figure 3.

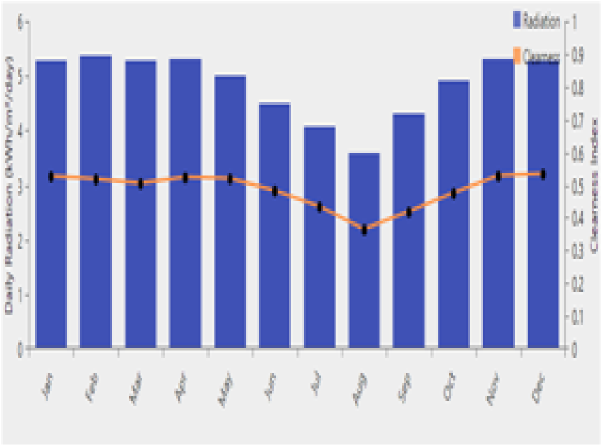

Fig 3: Daily average global horizontal radiation

5.3 Abeokuta Area Load Profile

The load profile of the area was estimated through questionnaire and record obtained from Nigeria's power supply authority National Control Centre (NCC), Oshogbo. The daily load profile of Abeokuta town is shown in Figure 4. The average daily energy need of the area is 289,440.40 kWh and a daily average power of 12,060 kW, while the peak load is 35,000 kW.

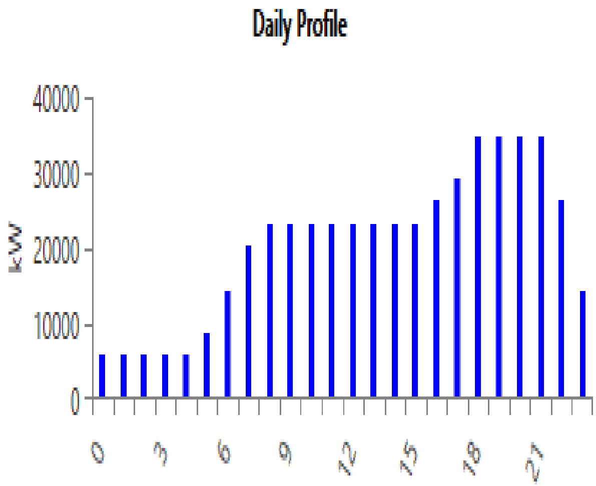

Fig 4: Abeokuta daily load profile

6. MATHEMATICAL MODELLING OF THE PROPOSED DOHE SYSTEM COMPONENTS

The hybrid energy system components are mathematically modelled as described below. The proposed DOHE model comprises small-hydro generating system, solar PV system, diesel generator unit and a battery storage system. The theories are given below based on the works of [22, 23].

6.1 Small-hydro Generator Mathematical Model

Equation 1 represents the electrical power produced by small hydropower generator [24, 25]

$$P_{SHP}(t) = \Pi_{Hydro} \frac{9.81 \text{ x } Q \text{ x } P_{Water} \text{ x } h}{1000} \tag{1}$$

and the total energy in kWh is given by (2)

$$E_{SHP}(t) = p_{SHP}(t) \text{ x } t \quad (2)$$

Where $P_{SHP}(t)$ stands for the electrical power generated by small hydro power generator, where Π_{Hydro} presents the hydro efficiency, Q discharge in m^3/s, P_{Water} is the water density, h stands for the height or head in (m),

$E_{SHP}(t)$ means the electrical energy produced by small hydropower generator and t is time given in hour.

6.2 Solar Photovoltaic Generator Mathematical Model

Using the solar radiation available, the hourly energy output of the PV generator (E_{PVG}) can be calculated according to (3) [24, 25]

$$E_{PVG} = G(t) \text{ x } A \text{ x } P \text{ x } \Pi_{PVG} \quad (3)$$

The assumption made is that the temperature effects (on PV cells) are ignored. Where $G(t)$ represents the hourly irradiance in kWh/m,^{2} A stands for the surface area in m^2, P is the PV penetration level factor and Π_{PVG} is the PV generator efficiency.

6.3 Diesel Generator Mathematical Model

The energy generated by diesel generator on hourly basis (E_{DEG}) with nominal capacity (P_{DEG}) is given by expression (4) [24]

$$E_{DEG}(t) = P_{DEG}(t) \text{ x } \Pi_{DEG} \quad (4)$$

Where $\prod_{DEG}$ is the efficiency of the diesel generator. The diesel generator is set to operate between 80 and 100% of their kW rating for better performance and higher efficiency

6.4 Converter Mathematical Model

In the proposed scheme the power converter is a combination of both rectifier and inverter. The battery units and solar PV generator are linked to the DC bus while the hydro and diesel generating systems are coupled to the AC bus. The predominant electric load types in this design are AC loads.

6.4.1 Inverter

The inverter model for photovoltaic generator and battery bank are given in equations (5) and (6)

$$E_{PVG-IN}(t) = E_{PVG}(t) \text{ x } \Pi_{INV} \quad (5)$$

$$E_{BAT-INV}(t) = \left[\frac{E_{BAT}(t-1) - E_{Load}(t)}{\Pi_{INV} \text{ x } \Pi_{DCHN}} \right] \quad (6)$$

Where $E_{PVG-IN}(t)$ hourly energy output from inverter (in case of solar PV) in kWh, $E_{PVG}(t)$ hourly energy output of the PVg, Π_{INV} efficiency of inverter, $E_{BAT-INV}(t)$ hourly energy output from inverter (in case of battery) in kWh, $E_{BAT}(t-1)$ energy stored in battery at hour t-1 in kWh and Π_{DCHG} battery discharging efficiency.

6.4.2 Rectifier

The rectifier is used to transform the surplus AC power from the small hydro unit and diesel electric generator to DC power at constant voltage, when the energy generated by the hybrid energy system exceeds the load demand. The rectifier model is defined by equations (7), (8) and (9) [24].

$$E_{REC-OUT}(t) = E_{REC-IN}(t) \text{ x } \Pi_{REC} \quad (7)$$

$$E_{REC-IN}(t) = E_{SUR-AC}(t) \quad (8)$$

At any time

$$E_{SUR-AC}(t) = E_{SHP}(t) + E_{DEG}(t) - E_{Load}(t) \quad (9)$$

where $E_{REC-OUT}(t)$ is the hourly energy output from rectifier in kWh, $E_{REC-IN}(t)$ is the hourly energy input to rectifier in kWh, Π_{REC} is the efficiency of rectifier, $E_{SUR-AC}(t)$ is the amount of surplus energy from AC sources in kWh, $E_{DEG}(t)$ is the hourly energy generated by diesel generator, E_{Load} (t) is the hourly energy consumed by the load side in KWh and $E_{SHP}(t)$ is the electrical energy generated by small hydropower generator.

6.5 Charge Controller Mathematical Model

The charge controller senses when the batteries are fully charged and automatically stops the charging process or limits the amount of energy flowing to the batteries from the energy source. The charge controller mathematical model is as shown in (10) and (11) [24]

$$E_{CC-OUT}(t) = E_{CC-IN}(t) \text{ x } \Pi_{CC} \quad (10)$$

$$E_{CC-IN}(t) = E_{REC-OUT}(t) + E_{SUR-DC}(t) \quad (11)$$

Where $E_{CC-OUT}(t)$ is the hourly energy output from charge controller in kWh, $E_{CC-IN}(t)$ is the hourly energy input to charge controller in kWh, Π_{CC} is the efficiency of charge controller $E_{REC-OUT}(t)$ is the hourly energy output from rectifier in kWh and $E_{SUR-DC}(t)$ is the amount of surplus energy from DC sources in kWh.

6.6 Battery Bank Mathematical Model

The battery state of charge (SOC) is defined as the total daily summation of the charge/discharge transfers. The battery is both a load and energy source. It is a source of energy when discharging and a load when charging. At any time, t, the present state of battery bears a relationship to the previous state of charge and to the energy production and consumption scenarios of the system for the duration of the time from t -1 to t. In the charging process, that is when the cumulative energy output of all generators is in excess of the load demand, the available battery bank capacity at time, t, is represented by (12) [25, 26]

$$E_{BAT}(t) = E_{BAT}(t-1) - E_{CC-OUT}(t) \text{ x } \Pi_{CHG} \quad (12)$$

Where $E_{BAT}(t)$ the energy is stored in battery at hour t in kWh, $E_{BAT}(t-1)$ is the energy stored in battery at hour t-1 in kWh and Π_{CHG} is the battery charging efficiency On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at time, t, can be expressed by (13) [26]

$$E_{BAT}(t) = E_{BAT}(t-1) - E_{Needed}(t) \quad (13)$$

Where $E_{Needed}(t)$ stands for the hourly electric load desired or energy needed at a specific time. On the assumption that d be the ratio of minimum permissible SOC voltage limit to the maximum SOC voltage read at the battery terminals when it is charged to the full, then DOD or Depth of Discharge is given by expression (14)

$$DOD = (1- d) \times 100 \quad (14)$$

DOD is an appraisal of the level of energy withdrawn from a storage device, expressed as a percentage of full capacity. SOC has a maximum value of 1, and the minimum SOC is ascertained by maximum depth of discharge (DOD), as expressed by (15) [24]

$$soc_{Min} = 1 - \frac{DOD}{100} \quad (15)$$

6.7 Power Generation Mathematical Model

The sum total of hybrid power generated at any time t, is expressed by (16) [24, 25]

$$P(t) = \sum_{SHP-1}^{N_H} P_{SHP} + \sum_{PVG=1}^{N_P} P_{PVG} + \sum_{DEG=1}^{N_D} P_{DEG} \quad (16)$$

Where P_{SHP} is electrical power generated by small hydropower generator, P_{PVG} is the electrical power generated by the solar PV generator, P_{DEG} is the rated power output by diesel generator, N_H stands for the numerical quantity of small-hydro generators unit , N_P is the numerical quantity of PV cells unit and N_D is the numerical quantity of diesel generators unit.

7. THE PROPOSED DECENTRALIZED OFF- GRID HYBRID ENERGY (DOHE) MODEL

HOMER tool used for the simulation and optimization requires six types of data. These are meteorological data, load profile, renewable energy resources data, equipment characteristics, economic and technical data. The hourly values of global solar radiation, small hydro monthly average stream flow data obtained were synthesis to hourly data based on the algorithm used in HOMER. The parameters, characteristic, properties, types, size, cost and model of the hybrid system components are dependent on the peak load demand of the study area. Figure 5 shows the schematic of the proposed DOHE model of the study area. Accordingly, the components' parameters, properties and model of the location are subsequently discussed.

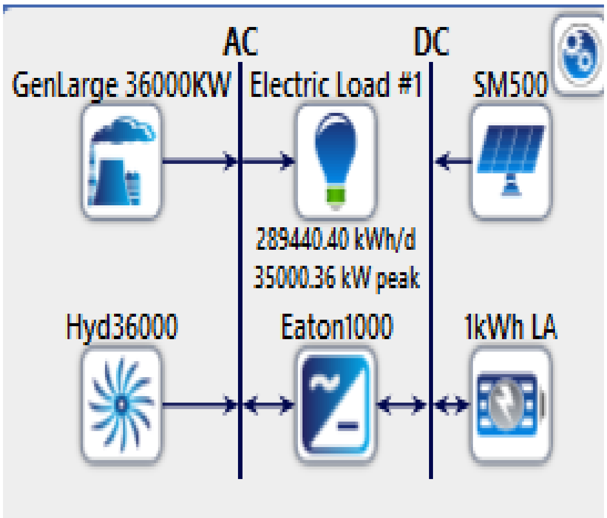

Fig 5: The proposed scheme of the DOHE model for Abeokuta

7.1 Hydro Turbine Model

Turbine model was selected to match the peak load demand of the area. Certain assumptions were also taken regarding available head, design flow rate, maximum and minimum flow ratios and efficiency of the turbine used in the location. HOMER treats these as input variables and hence allows for adjustment to suit the design. The life time of the small hydro model in the simulation was taken as 25 years. The size considered was 38 MW and nominal capacity of 2550.6 kW. The designed flow rate and available head were assumed to be 15,000 L/s and 25 m respectively.

7.2 Photovoltaic Model

The connected maximum power derived is a parallel and series combination. The photovoltaic tracking systems were assumed to be excluded in this study. This is to establish the worst-case scenario for the location. The effect of temperature was omitted in the project also. HOMER allows difference sizes to be considered for load matching. The sizes therefore considered ranged from 37 to 66 MW. The life time was taken as 25 years and a derating factor of 96% was assumed.

7.3 Diesel Generator Model

Different Diesel generator model abound. The selection of a model was in consideration for the size of the load of the community. The generator used for the study location is a diesel powered generator. The price of diesel fuel is $0.629/L in accordance with the federal government of Nigeria official pump price as at November, 2021. A sensitivity value of $0.635/L was applied to allow for fluctuation in the diesel price. The diesel generator serves as back-up system. It operates at times of inadequate output from hydro and solar systems to meeting the load and when the battery storage has been exhausted. A 38 MW genset was considered for this research, with maximum flow ratio of 25% and 25 years life time.

7.4 Storage Battery

The storage battery chosen was Generic 1kWh Lead Acid. HOMER software datasheet gives the minimum state of charge of the batteries as around 20%. The round-trip efficiencies are in the neighborhood of 80%. Batteries are considered pivotal in decentralized off-grid power systems. It helps to minimize the starting/stopping frequency of the diesel generator such that the problems of premature wears are eliminated and thus able to satisfy load demand amidst renewable sources fluctuations. HOMER allows for number of quantities of batteries to be considered to match the load. The quantities considered range between 20 and 80. The voltage for each is 12V, maximum capacity 83.4 Ah and life throughput 800.00 kWh

7.5 Power Converter

A power converter as used for the study works both as an inverter and a rectifier depending on which direction power flows. In this present study, the size of the converter was carefully selected to accommodate the peak load in the areas. The sizes of converters used ranged between 1 and 80 MW. The life time was chosen as 15 years with inverter efficiency of 98%.

7.6 The System Economics

The optimal result of the evaluation is also hinged on economic parameters, such as cost of energy, net present cost etc. This necessitates cost assessments of the components of the hybrid power system. The capital costs of all the system components including PV module, hydro turbine, diesel generator, converter and battery were quotes from component manufacturers and suppliers in Nigeria and Oversea. The hydro turbine and generators prices were based on quotes from Alibaba, a major supplier of hydro turbines worldwide [27]. The batteries, power converters and solar modules price estimates were quotes from Solar Shop, Jumia and Eco business [28, 29]. All initial costs such as installation, commissioning, replacement, operating & maintenance costs summary for the site are presented in Table 3.

Table 3. Cost summary of the hybrid components

Components	Price	Initial Costs ($)	Replacement Costs ($)	O&M Costs ($)
Hydro Turbine	$/kW of capacity	600	480	12
PV Module	$/kW of capacity	2,000	1600	24
Diesel Generator	$/kW of capacity	400	320	8
Converter	$/kW of capacity	360	288	4.32
Battery	1 qty	300	240	3.6

8. RESULTS AND DISCUSSION

The simulation result presented many hybrid topologies for possible design of DOHE system in Abeokuta study area. The best energy solution was selected using the indices of less net present cost (NPC), less cost of energy (COE), high renewable fraction (FR), less excess electricity and less fuel consumption with maximum annual capacity shortage and minimum renewable fraction being the worst constraint cases. From the categorized simulation result table (Table 3), the most cost effective system that meets the selection criteria is PV-DG-BB-SHP configuration. That is, the system configuration with the least levelized cost of energy (COE) and least net present cost (NPC). The capital cost of the project is $378 million, operation cost $16.6 million, NPC $1.27 billion and Levelized COE being $0.290 /kWh. The renewable resources fraction is 99.9 %. The energy production shares of the energy generators making the winning hybrid system are discussed in the subsequent sections.

Table 3. Optimization result

Export... Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.
Categorized Overall

Architecture						Cost				System		GenLarge 36000K			
SM500 (kW)	GenLarge 36000KW (kW)	1kWh LA	Hyd36000 (kW)	Eaton1000 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fue (L)
170,060	2,000	666,229	2,551	42,598	CC	$1.27B	$0.290	$16.6M	$578M	99.9	15,480	30.0	60,000	15,4
252,956	2,000	703,482		38,356	CC	$1.51B	$0.345	$18.7M	$732M	99.9	15,630	31.0	60,500	15,6
	35,000	351,470	2,551	31,719	CC	$39.2B	$8.96	$943M	$152M	0	29,290,054	3,247	113,520,592	29,2
	35,000	371,554		32,813	CC	$41.5B	$9.48	$999M	$137M	0	31,080,494	3,442	120,466,864	31,0

8.1 Small Hydro Output

The small hydro output or contribution of the winning DOHE system configuration is shown in Figure 6. The nominal capacity is 2.551 kW, capacity factor 30.20% and total electric production 6,737,068 kWh/yr. The hydro penetration is 6.38 % and LCOE is $0.142/ kWh. The maximum output is 2,424 kW and happens in the months of August and September when the river has the highest stream flow.

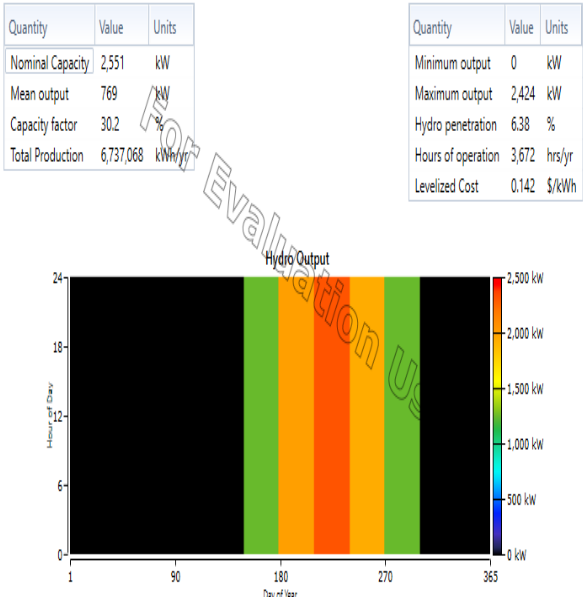

Fig 6: Hydropower power Output of the of the proposed DOHE system

8.2 Diesel Generator Output

The Figure 7 shows diesel generator power output and power share of the proposed DOHE system. From the generator power distribution, generator power production was sparse. The hours of operation per year were 30 hrs which is less than half an hour in a day. Generator participating in this hybrid power system generated mean power output of 2000 kW, minimum electrical output of 2000 kW and maximum electrical output of 2000 kW. The amount of diesel fuel consumed was around15,480 litres per annum as depicted in Figure 7.

The main disadvantage of the inclusion of diesel generator in power systems is the environmental pollution, high running cost and noise. Emissions per years for this hybrid system were CO_2 40,592 kg/yr, CO 210 kg/yr, Unburnt Hydrocarbon 11.1 kg/yr, Particular Matter 1.8 kg/yr, $SO_2$99.2 kg/yr and NO 40.2 kg/yr. The use of renewable sources of energy decreases the hours of run of the DG. This, in effect, reduces the kilograms of pollutants emitted to the atmosphere. The quantity of emitted pollutants by the DG is diminutive considering that the RF of the hybrid model is 99.9% and thus insignificant environmental impact.

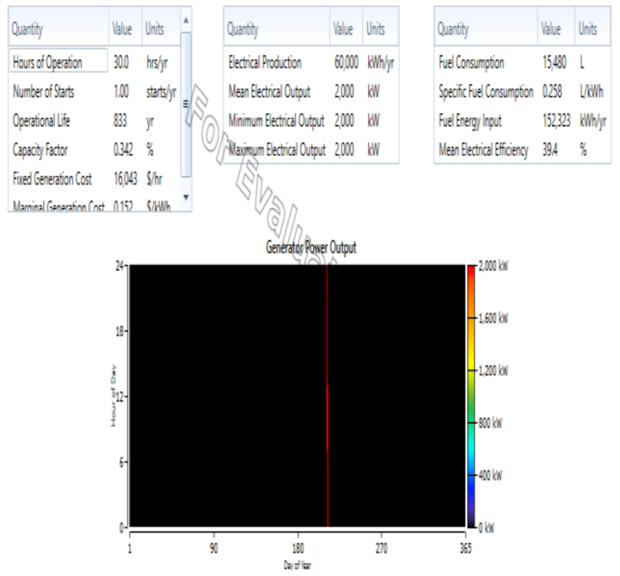

Fig 7: Diesel generator output of the proposed DOHE system

8.3 Solar PV Output

Solar PV output share of the proposed DOHE system is displayed in Figure 8. From the result the rated capacity of PV module is 170,060 kW. The mean output is 32,980 kW and the capacity factor is 19.4%. The total energy production is 288,904,715 kWh/y. Hours of operation were 4,380 hrs and levelized cost of energy $0.0426/kWh. Electricity generation is higher during dry season when solar radiation and clearance index are high.

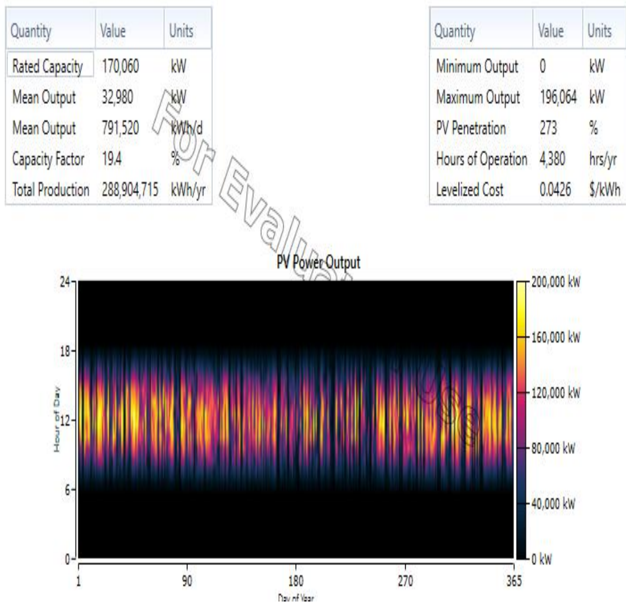

Fig 8: Monthly output of the solar PV component of the proposed DOHE system

8.4 Monthly Average Electric Production of the System Architecture

The percentage of energy production of the main energy sources of the proposed DOHE system is shown in Figure 9. The major part of the energy comes from PV accounting for 97.7% and 2.28% from SHP. The rest 0.020% came from diesel generator. It is evident as shown in Figure 9 that PV system has the highest percentage energy production than others in the hybrid power system. When the photovoltaic array energy production exceeds energy demand, the excess energy is channeled to charge the battery bank if the battery bank is in a low state of charge, otherwise it increases the bus frequency and automatically reduces the power feed from a photovoltaic array to the buss. If on the contrary, the photovoltaic array generates less energy than is needed, the batteries provide the needed energy margin.

Most load profile indicate peak load in the evening time, but solar energy is available only during daytime particularly at peak sun hour. To compensate for this short fall and ensure system reliability is the reason for the inclusion of DG through cycle charging (cc) dispatched strategy. The effectiveness of this selected energy solution for the study area accounts for the low percentage DG incursion in the energy generation process. Even though the small-hydro percentage power production is less than PV, this DOHE system can ensure round-the-clock energy availability of around 100% resulting in only around 0 hour of power outage in a year when it comes into effect in Abeokuta.

The system architecture of the 25 years DOHE system design is presented in Table 3. It shows the capacities and sizes of the energy generators and accessories in the hybrid system, and the required number of batteries for installation.

Table 3. The proposed DOHE system architecture

Component	**Name**	**Size**	**Unit**
Generator	Generic Genset	2,000	kW
PV	SolarMax Generic PV	170,060	kW
Storage	Generic 1kWh Lead Acid	666,229	strings
System converter	Eaton Power Xpert	42,598	kW
Hydroelectric	Generic Hydro	2,551	kW
Dispatch strategy	HOMER Cycle Charging		

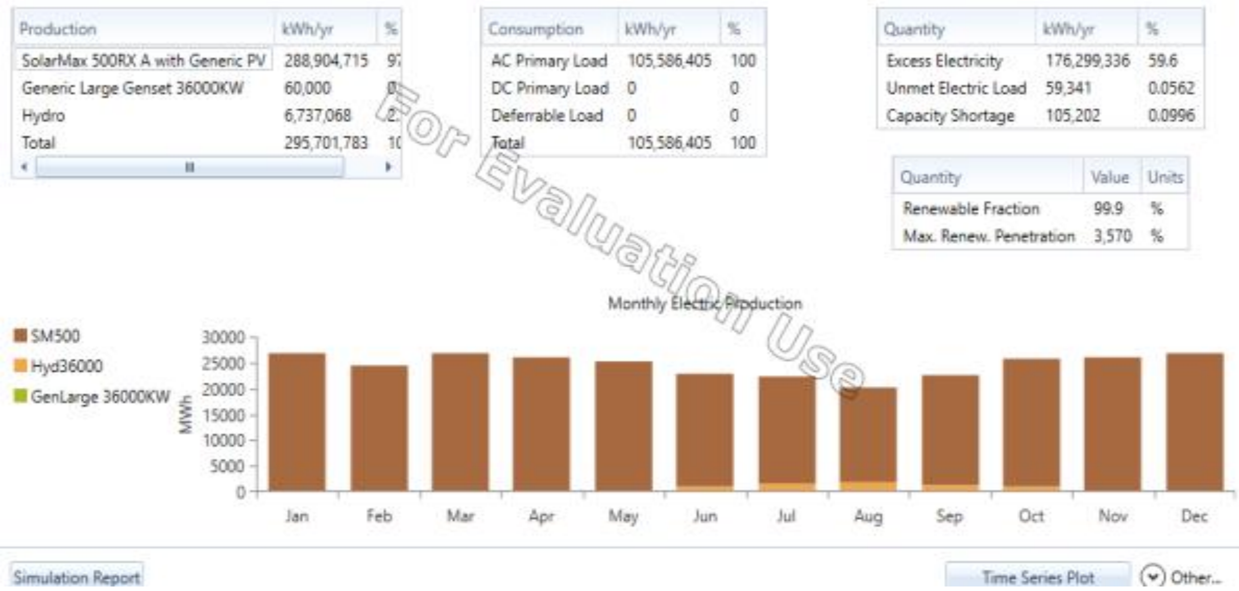

Fig 9: Monthly average electric production of the proposed DOHE system

9. COMPARING DOHE SYSTEM WITH AN AUTONOMOUS DIESEL GENERATOR

9.1 Emission Comparison of the DOHE Project with a Lone Diesel Generator

The hybrid power system (PV-DG-BB-SHP) when compared with a lone diesel generator for DOHE design option for the study location saved 32,971,028 litres of fuel consumption per annum. The hybrid power project also eliminated the release of 86457471kg of carbon dioxide emission per annum and 447,285 kg of carbon monoxide per annum, about 99.95% decrease in both CO_2 and CO emissions to the environment. The pollutants were CO_2 40,592kg/yr, CO 210kg/yr, Unburned Hydrocarbon 11.1kg/yr, Particulate Matter 1.8kg/yr, SO_2 99.2kg/yr and NO 40.2 kg/yr. This analysis is shown in Table 4

Table 4. Ecological advantage by emissions in kg/yr

System architecture	PV-DG-BB-SHP	Autonomous diesel generator
Generator operational hour (hrs)	30	8,760
Fuel consumption (L)	15, 480	32,986,508
CO2 (kg/yr)	40,592	86,498,063
CO (kg/yr)	210	447,495
Un-burned hydrocarbons (kg/yr)	11.1	23,750
Particulate matter (kg/yr)	1.8	3,826
Sulfur dioxide (kg/yr)	99.2	211,441
Nitrogen oxides (kg/yr)	10.2	85,765
Total Emission (kg/yr)	40,924	87,270,340

9.2 Comparing the Economy of the Optimal DOHE System Configuration with an Autonomous Diesel Generator (DG)

Comparative economic analysis between the PV-DG-BB-SHP hybrid option and an autonomous diesel generator option for designing decentralized power generation system for the study area was done to appraise the merit of green energy resources adoption for DOHE system implementation over a lone diesel generator. That is, comparing the cost effect of a decentralized power generation using an autonomous diesel generator instead of hybrid power system for the study area. This comparison is presented in Table 5.

In Abeokuta area, the initial capital cost of using an autonomous DG is $14 million, with COE of $ 23.45/kWh. The DG consumes 32,986,508 litres of diesel annually corresponding to $20.75 million. The NPC and the COE is on the high side for the DG by comparison; but it has the merit of having lower investment cost compared to the hybrid power system. Although the investment cost is low when compared to the hybrid system, the profit margin in investment cost of DG over the hybrid power system is overshadowed by the hike in DG operational cost, fuel cost, and NPC. All this put together increases the COE. This ultimately justifies preference for a hybrid power system for DOHE system design aside from the environmental degradation associated with using DG. The COE of the DG option for the area is extremely high, unsustainable and unattainable to the communities compared to the hybrid system which represents an almost completely green energy power system that is environmentally benign and highly affordable to the communities. Hence the hybrid systems present better option for implementation

Table 5. Economic comparison between the proposed DOHE hybrid topology and diesel generator

System configuration	PV-DG-BB-SHP	DG
Initial capital cost ($)	578 million	14.0 million
Net present cost ($)	1.27 billion	103.0 billion
L. C. O. E ($)	0.290/kWh	23.45 /kWh
Operating cost ($)	16.6 million	2.48 billion
Generator hours of operation(hrs)	30	8,760
Fuel consumption per annual (L)	15,480	32,986,508
Cost of fuel/annual ($0.629/L)	9,736.92	20.75 million

9.3 Economic Metric and Break-Even Period of the DOHE System

Arriving at the optimal configuration is also based on its economic advantage over the base system (diesel generator). The prospect of return on investment (R.O.I) and simple payback year catalyze investment in DOHE systems. A positive R.O.I figure means that net returns exceed total costs. A negative R.O.I figure means the investment produces a loss. The DOHE system project produced positive R.O.I of 432.2 % as shown in Table 6. The payback is an indication of how long it would take to recover the difference in investment costs between the optimal hybrid system and the base case system. An investment with a short payback period is considered to be better, since the investor's initial outlay is at risk for a short period of time. The simple payback in years occurred in 0.23 year. This means, the investment break even in less than year. The Present worth is the difference between the NPC of the base case system and the winning hybrid system. A positive value indicates that the current system saves money over the project lifetime compared to the base case system. The result is also positive, meaning that DOHE system by far outwits an autonomous diesel generator system usage as energy solution for the community.

Table 6. The hybrid system economic metrics

Metric	Value
Present Worth ($)	$101,269,400,000
Annual Worth ($/Yr)	$2,446,429,000
Return on Investment (%)	432.2
Internal Rate of Return (%)	437.5
Simple Payback (Yr)	0.23
Discounted Payback (Yr)	0.22

10. CONCLUSION

The decentralized off-grid hybrid energy model evaluated spanned a 25 years period of possible uninterrupted power supply; an indication that these hybrid pilot power plants have capacity for efficient and sustainable energy production and aiding the decarburization of energy generation. Decentralized off-grid PV-BB-DG-SHP pilot project investigated came with little or no emission, making them environmentally friendly. It readily falls in place in meeting the drive toward an emission free society [30].

Considering the mountainous, riverine and convoluted geographical locations of most rural and some urban areas in Nigeria that cannot be reached by the centralized power system, the yearning of these communities for energy and the global concern about environmental degradation, the adoption of decentralized off-grid renewable energy systems represent a promising strategy to tackling energy poverty in Nigeria.

Abeokuta is one of the economic hubs of the Nation with abundant socioeconomic activities that have been in doldrums owing to incessant power outages. Outages engendered by lack of power on the utility grid. DOHE system is an efficient alternative that guarantees reliability and independence from the utility grid. It is time the entire gamut of stakeholders– government, policymakers, financiers and entrepreneur– made concerted efforts at implementing DOHE system in this area to light and revitalize the socioeconomic activities of the study area and, also, made effort at integrating DOHE system into the country's electricity architecture. Decentralization is sweeping the landscape of electricity systems globally. DOHE technology is catching and evolving as catalyst for energy growth and independence

One case study area was used in this research and gave positive result. The capacity of renewable hybrid power projects for DOHE system in other geopolitical zones in Nigeria can be accessed using other hybrid energy resources. Many small rivers abound in other localities within Nigeria which have the potentials for DOHE system design and implementation. Dedicated efforts and necessary incentives by stakeholders are needed to fast track research into DOHE system feasibility in these other geographical zones of Nigeria with a view to meeting the energy needs of the Nigerian populace through decentralized renewable energy options. Doing so will not only be keeping pace with the global shift towards decentralization and de-carbonization but also effectuating continuous energy availability in all nook and cranny of the Nigeria.

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