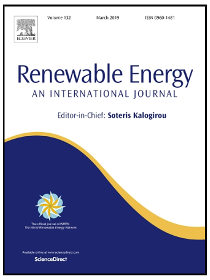

Optimal Mapping of Hybrid Renewable Energy Systems for Locations Using Multi-Criteria Decision-Making Algorithm

E.O. Diemuodeke, A. Addo, C.O.C. Oko, Y. Mulugetta, M.M. Ojapah

PII:	S0960-1481(18)31374-0
DOI:	10.1016/j.renene.2018.11.055
Reference:	RENE 10818
To appear in:	*Renewable Energy*
Received Date:	19 May 2018
Accepted Date:	13 November 2018

Please cite this article as: E.O. Diemuodeke, A. Addo, C.O.C. Oko, Y. Mulugetta, M.M. Ojapah, Optimal Mapping of Hybrid Renewable Energy Systems for Locations Using Multi-Criteria Decision-Making Algorithm, *Renewable Energy* (2018), doi: 10.1016/j.renene.2018.11.055

Optimal Mapping of Hybrid Renewable Energy Systems for Locations Using Multi-Criteria Decision-Making Algorithm

E.O. Diemuodeke[1*], A. Addo[2], C.O.C. Oko[1], Y. Mulugetta[3] and M.M. Ojapah[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, University of Port Harcourt, PMB 5323, Port Harcourt, Rivers State, Nigeria.

[2]The Energy Centre, College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

[3]Department of Science, Technology, Engineering & Public Policy (STEaPP), University College London, UK.

[*]*Corresponding Author*: oghenerouna.diemuodeke@uniport.edu.ng

Abstract

This paper presents the optimal mapping of hybrid energy systems, which are based on wind and PV, with the consideration of energy storage and backup diesel generator, for households in six locations in the South South geopolitical (SS) zone of Nigeria: Benin-city, Warri, Yenagoa, Port Harcourt, Uyo and Calabar. The optima hybrid energy systems are able to meet 7.23 kWh/day of a household's electrical energy. The hybrid energy system for each of the locations was optimally chosen based on HOMER software computation and TOPSIS multi-criteria decision-making algorithm that considers technical, economic, environmental, and sociocultural criteria. Wind energy potential was conducted for the six locations using the Weibull distribution function; the wind speed ranges between 3.21–4.19 m/s at 10m anemological height. The wind speeds and the wind characteristics were extrapolated for 30 m and 50 m hub heights. The solar resource potential across the six locations is also presented – ranges between 4.21 – 4.71 kWh/m^2/day. The best hybrid system for the locations in Benin-city, Yenagoa and Port Harcourt is the Diesel generator-PV-Wind-Battery system; whereas the best hybrid system for the locations in Warri, Uyo and Calabar is the PV-Wind-Battery system. The hybrid systems in Benin-city, Yenagoa and Port Harcourt emit CO$_2$; only 8.47%, 15.02% and 14.09% of the business as usual (the diesel generator). The payback time ranges between 3.7 – 5.4 years, using the business as usual cost of energy of 0.893 US$/kWh; whereas the cost of energy of the hybrid systems ranges between 0.459 – 0.562 US$/kWh, which compares well with available literature in the public domain. The design parameters of the optima hybrid energy systems are also presented. The methodology presented here will serve as a design tool for renewable energy professionals.

Keywords: Hybrid Renewable Energy, Multi-Criteria, TOPSIS, Techno-Economic, Environment, HOMER Software

1 Introduction

There is a consensus agreement that available useful modern energy is the driver of socioeconomic and technological developments in every society; electricity is the most demanded modern energy, which forms the nucleus of the Sustainable Development Goals (SDGs). Therefore, there is a strong need to provide electrical energy globally to about 1.3 billion people live without the electrical energy (Karakaya and Sriwannawit 2015). Of this total, over 600 million are in Sub-Saharan Africa countries, and Nigeria accounts for about 93 million; Nigeria has the world's largest electricity access deficit only after India, which has manifested in poor development progress (The World Bank 2017). Although Nigeria's electrification rate is on a steady increase, the rate of growth falls short of meeting electricity demand as the country's electrical energy generation growth rate is put at 93% over 20 years horizon, whereas Indonesia and Bangladesh growth rates are, respectively, put at 372% and 451% in the same time horizon (GIZ 2015). The rural communities are the worst hit by the deficit access to electricity in Nigeria, as about 59% of the rural dwellings live without electricity, with electricity availability of 16.1%(The World Bank 2018).

Nigeria is located on the west coast of Africa, with a projected population of about 170 million people. Nigeria occupies an important position in the sub-Saharan Africa – in terms of primary energy supply, population, economy and politics. Nigeria covers 923,770km^2 geographical area, with six geopolitical zones, as shown in Figure 1, and of which total land area is 910,770km^2, with extensive coastline of approximate area of 853km^2. The South-South Geopolitical zone (SS zone), the geographical Niger delta, see Figure 1, occupies about 7.5% of the Nigeria's geographical area ($\approx 69{,}283$ km^2), and houses 6 states (Akwa-Ibom, Bayelsa, Cross-River, Edo, Delta and Rivers) of the 36 states of Nigeria – the circles in Figure 2 indicate strategic towns in the Niger Delta region. The region is rich in both renewable and non-renewable natural resources – large proportion of Nigeria's oil and gas reserves and production is from the region. Significant proportion of the SS zone is domicile in rugged coastline terrains, which, normally, do not support grid-connected electricity supply, with just 8.5% rural electrification and 17.8% electricity availability, the lowest, only after the South-East geopolitical zone (15.3% availability), in Nigeria (The World Bank 2018). The Niger Delta rural poor rely heavily on firewood, petrol, diesel, kerosene, candle and others crude fuels to meet their heating and lighting needs, which have adverse effects on health of inhabitants and climate change mitigation.

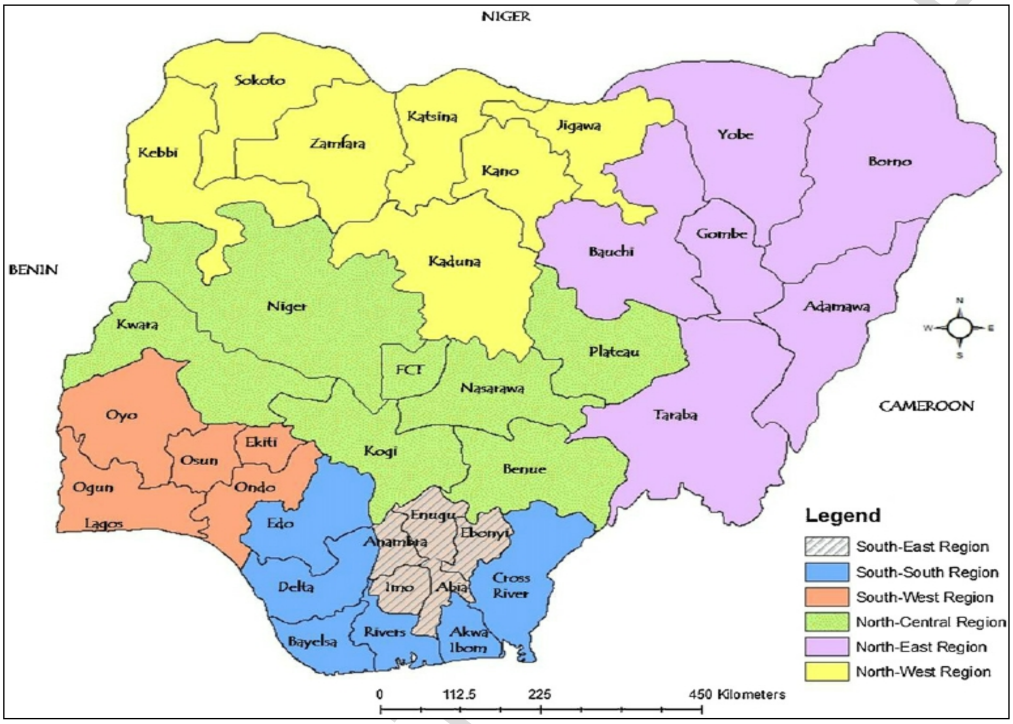

Figure 1 Nigeria Map Showing Geo-Political Zones

Life Cycle Analysis (LCA) of the Nigerian electricity sector revealed that there is a significant environmental impact, which is strongly associated with the overwhelming use of fossil fuels in the energy mix (Gujba, Mulugetta, and Azapagic 2010). The environmental impact is expected to be more significant with the continuous utilisation of absolute fossil fuel driven energy systems, especially in the rural coastline communities that rely on firewood and diesel generators to meet their energy needs. Therefore, a promising solution to the energy starvation of the rural areas and climate change would be the deployment of a decentralised energy projects through the utilisation of renewable energy (RE) sources(Sokona, Mulugetta, and Gujba 2012; Khare, Nema, and Baredar 2016; Thiam 2011), as a majority of the rural coastline areas has dispersed settlements in rugged terrain with relatively low energy demand(Mahmoud and Ibrik 2006; Thiam 2011; Aslani, Helo, and Naaranoja 2013). The Nigerian Ministry of Power has identified RE technologies utilisation as a way of curbing the energy and power crisis, and climate change bedevilling Nigeria (Federal Ministry of Power 2015). Besides, the trend in energy utilisation globally is towards drastic reduction in the dependence on the depleting and expensive fossil fuels (Khare, Nema, and Baredar 2016; Lal, Dash, and Akella 2011; Lambert, Gilman, and Lilienthal 2006; Leonforte and Pero 2015; Siddaiah and Saini 2016; de Christo et al. 2016; Federal Ministry of Power 2015), primarily due to their adverse impact on the environment such as their global warming potential (GWP), greenhouse gas (GHG) emissions, which normally lead to many negative effects including climate change, receding of glaciers, rise in sea level, and loss of biodiversity.

Wind and solar energy technologies are the fastest growing RETs for power generation in recent years, as demonstrated in Figure 2. The trend of the wind and solar energy capacity seen in Figure 2 will continue to be steady due to technological ‘disruption’ which has seen the cost of wind turbine and PV at an all-time low, and decreasing (IRENA 2017). The implication is that the levelised cost of energy will continue to come down to an affordable rate, even as a standalone application, which will see the aggressive acceptance of the RETs in the rural communities. Reduced project execution time of solar and wind energy conversion technologies also favour the general adoption of solar and wind energy interventions – this is very crucial in the Nigeria’s administrative structure due to abandonment of projects (Babatunde and Dandago 2014). However, wind and solar are considered variable renewable energy technologies because they can only independently supply energy intermittently without a storage device (Zhou et al. 2018). The variability challenge requires the hybridisation of wind-PV to play a complementarily role that guarantees reliable power supply (Rezaei, Mostafaeipour, and Qolipour 2018). The concept of hybrid energy system is gaining technical and financial recognitions globally, especially for the off-grid applications, since it is based on more than one source of energy conversion technology. The hybrid energy system may be cheaper than a standalone energy system (wind or PV) because the energy storage system for a standalone system may be oversized for reliability of energy supply, which would manifest in huge overall system cost (Gan, Shek, and Mueller 2015). However, balancing the hybrid system configuration optimally based on available energy resources is paramount.

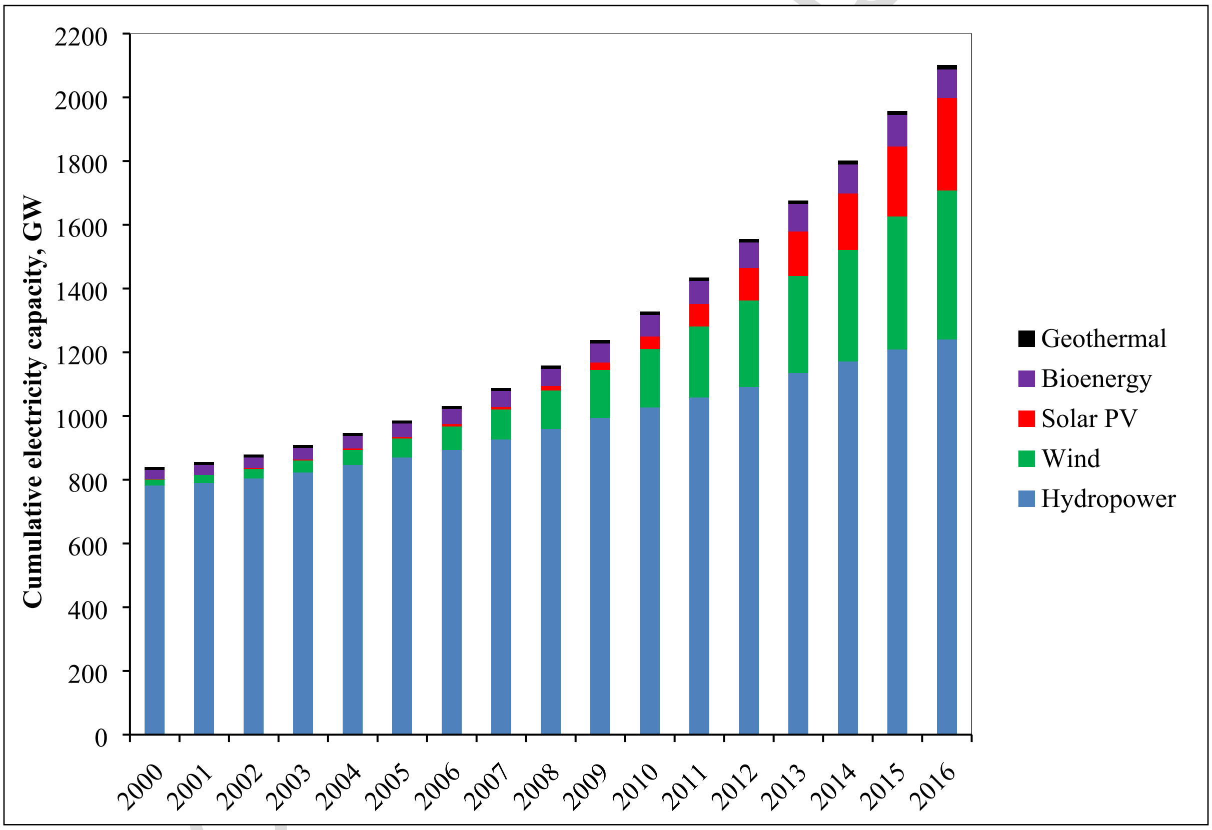

Figure 2 World’s cumulative renewable electrical power capacity (IRENA 2016)

Dawoud, Lin, and Okba (2017) present a review on hybrid PV-wind turbine energy system with the consideration of storage device and/or energy backup supply (diesel generator). The authors maintained that the reliability of the hybrid system is enhanced with the consideration of the battery storage; that an optimal batteries storage bank capacity is required to supply the facility’s energy demand during cloudy and non-windy days. New efficient ways of energy practice of solar-Wind hybrid system were also presented. Hybrid PV-Wind-Diesel-Battery system for telecommunication applications has been investigated in Khan, Yadav, and Mathew (2017). The authors investigated five different hybrid systems – PV-Wind-Diesel-Battery, PV-Diesel-Battery, PV-Wind-Diesel, Wind-Diesel and PV-Diesel. But the investigation is only on technical and economic considerations.

Singh and Fernandez (2017) present optimal hybrid PV and wind energy conversion technologies couple with energy storage unit for a remote area located in India. Popular optimisation tools (Cuckoo Search, Genetic Algorithm and Particle Swarm Algorithm) were considered for the analysis, which only balance available solar and wind resources against capital cost of the systems to obtain the combination of the hybrid system that gives the minimal cost of energy generated. Effects of resource availability and system capital cost on the cost of energy generated were investigated. Ramli, Bouchekara, and Alghamdi (2018) present the optimal sizing of a PV-Wind-Diesel tied with battery bank to supply reliable and uninterrupted power for a city in Saudi Arabia. The multi-objective self-adaptive differential evolution optimisation algorithm was used for the investigation. The major consideration of the optimisation process is on energy management strategy required to coordinate the size of different components of the hybrid system.

Fantastic as the testimonies of hybrid renewable energy rural electrification suffice, there are cases where their adoptions do not solve the energy challenges of the rural poor, especially in the Global South, e.g. sub-Saharan Africa rural communities (Cloke, Mohr, and Brown 2017; Akuru et al. 2017). This observation can be attributed to the consideration of limited set of criteria, normally technical and economic only, without the consideration of the end users' personalities, which obscure the decision outcomes of renewable energy projects – design and implementation decisions(Mulugetta et al. 2005). Specifically, decisions on appropriate rural energy intervention projects are constrained by technical, economic, financial, environmental and sociocultural issues. Rezaei, Mostafaeipour, and Qolipour (2018) investigated optimal location of a hybrid wind-solar plant using fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) based on multi-criteria consideration. The study ranked seven locations suitable for wind-solar electrification project without establishing the appropriate hybrid system for each of the locations. However, the TOPSIS analysis has been shown as a veritable optimisation tool for multi-criteria decision-making space – environmental, technical, economic, financial and sociocultural as they are related to rural energy application (Şengül et al. 2015; Cayir Ervural, Evren, and Delen 2018; Rezaei, Mostafaeipour, and Qolipour 2018; Diemuodeke, Hamilton, and Addo 2016).

The deployment of RE technologies (RETs) is dependent on the availability of RE sources in the chosen locality. Precise data (resource and load) are of most importance in the design and planning of RETs in a given site. Many research works have been devoted to RETs with battery energy storage system for rural communities (Baghdadi et al. 2015; Bhandari et al. 2014; Engin 2013). Therefore, the driving force for this present work is the exploration of hybrid energy system, which is based on wind and PV, with the consideration of energy storage and backup diesel generator for households in six locations in the South-South geopolitical (SS) zone of Nigeria. The hybrid energy system for each of the locations will be optimally chosen based on a multi-criteria decision-making algorithm that considers technical, economic, environmental, and sociocultural issues.

2 Materials and Methods

The methodology is segmented into three phases, as shown in Figure 3 – Phase 1: resource assessment, load demand assessment and cost assessment; Phase 2: optimal design using HOMER[1] software platform; and Phase 3: location based optimal system configuration using multi-criteria decision-making (MCDM) algorithm based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which has seen many applications in renewable energy deployment (Şengül et al. 2015; Cayir Ervural, Evren, and Delen 2018; Çolak and Kaya 2017; Sindhu, Nehra, and Luthra 2017; Kumar et al. 2017). The outputs from the facility energy demand, resource analysis and the cost data serve as input data to the HOMER software platform. The outputs from HOMER software and other data related to technical, economic, financial, environmental and sociocultural serve as input data in the multi-criteria decision-making algorithm, the TOPSIS analysis. The alternatives considered are diesel generator energy system (GES), diesel generator-battery energy system (GBES), PV-battery energy system (PBES), wind-battery energy system (WBES), diesel generator-PV-battery energy

---

[1] The HOMER, which stands for Hybrid Optimisation Model for Electric Renewable, was developed by the US NREL for both grid-tied and stand-alone energy applications

system (GPBES), diesel generator-wind-battery energy system (GWBES), PV-wind-battery energy system (PWBES) and diesel generator-PV-wind-battery energy system (GPWBES).

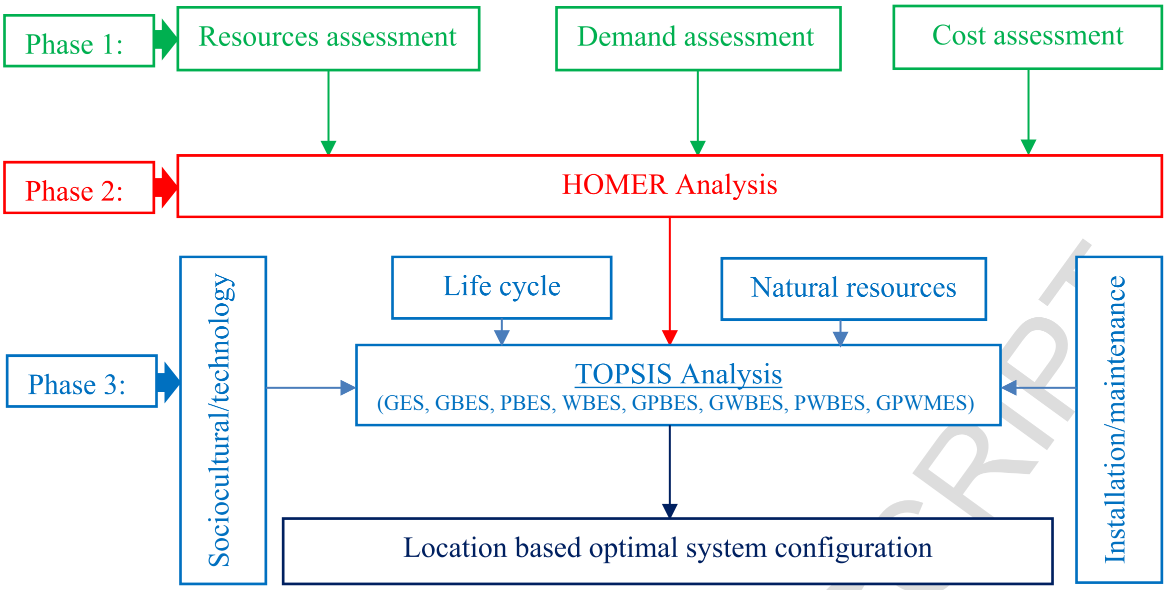

Figure 3 Methodology

2.1 Assessment

The household load demand assessment, solar and wind resources assessment and cost assessment are presented in the subsequent subsections.

2.1.1 Demand assessment

Estimation of hourly electrical energy demand (energy demand profile) of a given facility is paramount in the optimal sizing of RE system (Boait, Advani, and Gammon 2015), since the RE sources are normally transient in supply. Electrical energy demand of coastline communities in the SS zone has been conducted in Diemuodeke et al. (2017). In conducting the demand, appropriate questionnaires were designed to capture all aspects of energy consumption and basic family background of a given household. Community visitations and interviews were undertaken to assess existing and future electrical energy demand of representative coastline communities. Within the sampled area, 12 coastline communities (two each from a state) were systematically chosen to cover the entire SS zone. The two communities selected from each of the six states feature the existing electrical energy demand (EED) and the attribute of future electrical energy demand (FEED). Candidate households for the estimation of EED have diesel generating sets without access to 24 hour electricity; whereas households for the estimation of FEED have 24 hours supply of electricity, which they derived from nearby oil producing companies' facilities (e.g. field logistic base). In all, 240 households were considered for the estimation of the household energy demand (twenty households were randomly selected from each of the 12 candidate rural coastline communities). The featured households' energy demand appliances are: ceiling fan, table fan, TV, portable stereo, fluorescent light, CD player, pressing iron, A/C, washing machine and others (e.g. phones, rechargeable lanterns, laptops, etc). The energy demand estimation in Diemuodeke et al. (2017) considered all available appliances, which is against the consideration of only appliances of up to 100W power rating in the estimate by Adeoti, Oyewole, and Adegboyega (2001) for the South-West geopolitical zone.

The average hourly electrical load requirement of an appliance per household in a given day, E_{kj} (Wh/household/day), was computed by Equ.(1). Equ.(1) was independently used for the EED and FEED cases (Diemuodeke et al. 2017).

$$E_{kj} = \frac{\sum_{i}^{N_H} P_{ij}^{k}}{N_H}; j = 0,1,2,\ldots,23 \qquad (1)$$

where P(kW) is the power consumed by an appliance in a given hour, N_H is total number of household, k is a superscript representing the given appliance, i is the current household, j is the current hour of the day.

The average hourly energy demand per household per day, E_{kj} (Wh/household/day), was computed according to Equ.(2).

$$E_j = \sum_k^A E_{kj}; j = 0,1,2,\ldots,23 \qquad (2)$$

where A is total number of appliances.

The average daily energy requirement, E (kWh/household/day), was obtained by Equ.(3)

$$E^m = \sum_{j=0}^{23} E_j; m \in \{EEL, FED\} \qquad (3)$$

The average of EED and FEED energy demand scenario, which represents the future base energy demand (FBED), was computed according to Equ.(4).

$$E_A = \frac{E^{EEL} + E^{FED}}{2} \qquad (4)$$

2.1.2 Resource Assessment

2.1.2.1 Wind assessment

There are two methods available in evaluating wind potential – (i) measured values at meteorological stations, and (ii) use of probability distribution function. The probability distribution function has been widely applied, due to its simplicity and less computation. Under the probability distribution function, the Weibull distribution is favoured and adjudged best for regional wind energy estimation due to its flexibility and simplicity (Quan and Leephakpereeda 2015; Mohammadi and Mostafaeipour 2013; Babayani et al. 2016).

Wind speed distribution is a pertinent factor in the evaluation of wind resource potential for power generation in a given location (Genchi et al. 2016). The Weibull probability density function of observed wind speed data can be computed as (Mohammadi and Mostafaeipour 2013; Genchi et al. 2016; Babayani et al. 2016):

$$f_p(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \qquad (5)$$

where k (-) is the shape factor, c (m/s) is the scale factor, and v [m/s] is wind speed.

The Weibull's cumulative distribution function can be expressed as follows:

$$f_c(v) = 1 - e^{-\left(\frac{v}{c}\right)^k} \qquad (6)$$

There are several methods to evaluate the Weibull factors – graphical method, moment method, standard deviation method, maximum likelihood method, energy pattern factor method and power density method (Mohammadi and Mostafaeipour 2013). However, the standard deviation is adopted in this analysis due to its straightforward and flexible computational approach.

In the standard deviation method, the Weibull factors can be obtained as (Paul, Oyedepo, and Adaramola 2012; Mohammadi and Mostafaeipour 2013):

$$k = \left(\frac{\sigma}{\overline{v}}\right)^{-1.086} \qquad (7)$$

and

$$c = \frac{\overline{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \qquad (8)$$

where $\overline{v}$ (m/s) and σ (-) are respectively the mean wind speed and standard deviation of wind speed at a given location specified at any timescale, which can be respectively computed as follows:

$$\bar{v} = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{9}$$

and

$$\sigma = \left[\left(\frac{1}{N-1}\sum_{i=1}^{N}\left(v_i - \bar{v}\right)^2\right)\right]^{1/2} \tag{10}$$

Also, $\Gamma(x)$, which is the gamma function, is defined as (Paul, Oyedepo, and Adaramola 2012):

$$\Gamma(x) = \int_0^{\infty} e^{(-u)} u^{(x-1)} dx \tag{11}$$

The optimum wind speed ($\bar{v}_{op}$), which represents the wind speed that carries the maximum amount of wind energy, can be computed accordingly as (Genchi et al. 2016):

$$\bar{v}_{op} = c\left(1 + \frac{2}{k}\right)^{1/k} \tag{12}$$

The power of the wind, P (W), flowing through a sweep area of a wind turbine is proportional to the cube of wind speed and can be calculated by the following equation:

$$P = \frac{1}{2}\rho A v^3 \tag{13}$$

where ρ (kg/m^3) is the density of air, which is normally taken as 1.225 (kg/m^3) (Mohammadi and Mostafaeipour 2013; Paul, Oyedepo, and Adaramola 2012), and A (m^2) is the sweep area of the rotor blades.

The wind power density, $\bar{P}$ (W/m^2) is, therefore, given as:

$$\bar{P} = \frac{P}{A} = \frac{1}{2}\rho v^3 \tag{14}$$

The expression for wind power density based on the Weibull probability density is given as (Okeniyi, Ohunakin, and Okeniyi 2015):

$$\bar{P} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{15}$$

The wind speed parameters could be extrapolated to higher anemometer altitudes, since wind blows fast with increase in altitude. The calculation procedures for extrapolating wind speed parameters at height h are done, respectively, for the shape factor, scale factor, average wind speed, and wind power density, as follows (Mohammadi and Mostafaeipour 2013):

$$k_h = \frac{k}{\left[1 - 0.088\ln\left(\frac{h}{10}\right)\right]} \tag{16}$$

$$c_h = c\left(\frac{h}{10}\right)^{[0.37 - 0.088\ln(c)]} \tag{17}$$

$$\bar{v}_h = c_h \Gamma\left(1 + \frac{1}{k_h}\right) \tag{18}$$

and

$$\bar{P}_h = \frac{1}{2}\rho c_h^3 \Gamma\left(1 + \frac{3}{k_h}\right) \tag{19}$$

It should be noted that the above extrapolation expressions are used after which the parameters at 10m anemometer height (k,c, $\bar{v}$ and $\bar{P}$) have been established.

The coefficient of variation (COV) is the ratio of standard deviation to mean wind speed, which demonstrates the variability of wind speed. The coefficient of variation is mathematically defined in percentage as (Mohammadi and Mostafaeipour 2013; Babayani et al. 2016):

$$COV = \frac{\sigma}{\bar{v}} \times 100 \tag{20}$$

2.1.2.2 Solar assessment

The global solar irradiance estimated in Diemuodeke et al. (2017) for the same locations sufficed. PV arrays generate direct current (DC) voltage when solar irradiance incident on the PV arrays, and the power output from the PV can be computed as follows (Olatomiwa 2016; Lambert, Gilman, and Lilienthal 2006):

$$P_{out} = P_{rated} \times f_{pv}\left(\frac{G}{G_{ref}}\right) \times \left[1 + K_{T,pv}\left(T_c - T_{ref}\right)\right] \qquad (21)$$

where P_{rated} (kW), f_{pv} (%), G_{ref} (kW/m^2), G(kW/m^2), $K_{T,pv}$, T_{ref} and T_c are the PV rated power at standard test condition (STC), the PV derating factor, the radiation at STC, the global solar irradiance incident on the PV surface, the temperature coefficient of the PV module, the cell temperature at STC and PV cell temperature, which can be approximated as $T_c = T_{amb} + 0.0256G$ according to Duffie and Beckman (Duffie and Beckman 1991), respectively; T_{amb} is the ambient temperature. The effects of wind and humidity on the solar PV performance were not considered since studies have shown that they have moderate effects on the PV module efficiency (Kaldellis, Kapsali, and Kavadias 2014; Bhattacharya, Chakraborty, and Pal 2014).

2.1.3 Cost assessment

Wind turbine: The Bergey Excel 1-R wind turbine is selected for the analysis. This wind turbine is perfect for low wind speed and off-grid applications; cut-in wind speed is 2.5 m/s. The capital cost of suggested wind turbine is US$3000/kW at 50m hub height; replacement cost is $2600/kW and annual maintenance cost is $50/kW, which are based on customer proforma invoice. The expected lifespan of the wind turbine panel is assumed to be 20 years.

PV Arrays: The MLU250HC PV module is suggested for the current analysis. The suggested panel is rated 250W$_p$ (at 1000 W/m^2 and 25^{o}C) and 31 V with estimated capital, replacement and maintenance costs of US$2.5/W$_p$, US$1.9/W$_p$ and US$100/year, respectively. This cost includes support structure, civil work, balance of system and land cost, which is based on extensive research on the PV panel cost estimate. A derating factor of 90%, which is associated with high operating temperature, and 14% module efficiency were applied to the electrical production from the PV panel. The expected lifespan of the PV panel is assumed to be 25 years.

Diesel generator: The generic diesel generator cost is based on market survey data as follows: unit cost of generator is 600US$/kW (including civil and electrical installation), replacement cost is 500US$/kW, fuel cost 1.10US$/Litre, maintenance cost is 0.015US$/hour and service life is 15,000hours.

Batteries: The battery serves as the energy storage medium during the day and supplies energy during capacity shortage. The Trojan T-105 battery was suggested for the current analysis. The suggested battery has the following nominal performance specifications: 6 V maximum power voltage, 230Ah (1.38 kWh) capacity and 85% battery efficiency. It has a life span of 5 years. The estimated cost for the battery is US$300 and US$240 for capital and replacement, respectively.

Converter: Normally, the electric power produced by the PV is in direct current (DC) power form, which is directly stored in the battery through the charge controller. The converter embodies the inverter and the charge controller. The inverter converts the DC to alternative current (AC) power and is capable of meeting the power rating of the household. Its efficiency is assumed to be 90%, with estimated unit cost of US$0.30/W. The lifespan of the inverter is assumed to be 15 years.

Financial costs: The prevailing discount rate under Nigeria's stable economy is adopted as 9% (Diemuodeke et al. 2017; Gujba, Mulugetta, and Azapagic 2010), which represents a ten-year historic average (2007-2016) (Trading Economics 2017). The project lifespan is considered to be 20 years. However, many literature in the open domain have shown that PV modules are warranted in the range between 25 and 30 years (Ouedraogo et al. 2015).

2.2 HOMER analysis

The system configuration of the hybrid system for remote area power supply system comprises wind turbine, PV arrays, batteries, inverter, charge controller and balance-of-system, as shown in Figure 4.

To assess the feasibility and the optimal design of the hybrid system, the HOMER software is used for the modelling. The optimisation computational algorithms of the HOMER software allow the rapid and robust techno-economic evaluations of various energy technology options by accounting for the cost of energy alternatives and availability of renewable energy resources. The HOMER software has high computation fidelity within the comity of energy systems engineers. The HOMER uses the load demand, the resources, the components details (with costs), the constraints, the systems control and the emission data as an input to simulate various feasible configurations and ranked by the net present value (NPV). The NPV, which is the present cost of system minus the sum of revenues, serves as the objective function, with charging and discharging of the energy storage device, power balance and other techno-economic considerations representing the constraints. HOMER obtains the best system configuration after balancing energy demand and supply for each hour of the system simulation (Shahzad et al. 2017).

The NPV the system can be related to the Annualised Life Cycle Cost (ALCC) of the system, which represents the present day worth of money, as (Oko et al. 2012)

$$ALCC = F(i,N)NPV \tag{22}$$

where $F(i,N)$ is the system capital recovery factor, which is related as;

$$F(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{23}$$

The cost of electricity (COE), which represents the average cost per kWh of the electrical energy generated by the system, can be calculated as;

$$COE = \frac{ALCC}{E_s} \tag{24}$$

where E_s (kWh/year) is the actual electrical energy served by the system.

Another parameter for measuring economic merit of an energy system is the break-even point (BEP) or the payback time (PBT), in years. The BEP is the number of years it takes to recover an investment's initial cost, which is calculated on the simple analysis case as follows

$$PBT = \frac{C_{INV}}{E_s * UEC} \tag{25}$$

where C_{INV} is the initial capital investment and UEC (\$/kWh) is the cost of energy of the business as usual (BAU) energy system (i.e. COE of GES), see Table A.1 for the COE of GES.

All the basic technical and economic calculations, Equs (13), (21), (22) through (24) are appended in the HOMER Software computational algorithm.

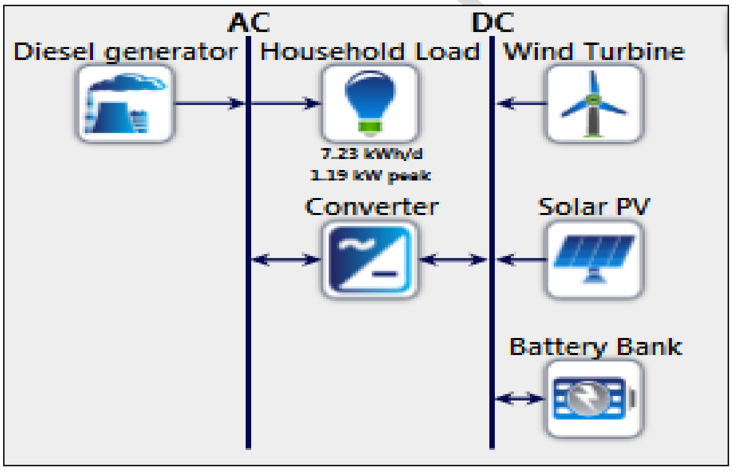

Figure 4 The hybrid system on HOMER schematic window

2.3 TOPSIS analysis

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the multi-criteria decision-making (MCDM) algorithms. TOPSIS offers some advantages over other MCDM algorithms in the form of: comprehensibility, simplicity, rationality, computational efficiency and simple mathematics that relate the relative performance of featured alternatives(Roszkowska 2011). These advantages have seen the adoption of TOPSIS in some of the decision making methods in the field of renewable energy research (Şengül et al. 2015; Cayir Ervural, Evren, and Delen 2018; Çolak and Kaya 2017; Sindhu, Nehra, and Luthra 2017; Kumar et al. 2017).

To deploy the TOPSIS method, the following algorithm applies.

Step 1: Specify the criteria (m) and the alternatives (n)

$i = 1,2,3,\dots, m$ and $j = 1,2,3, \dots, n$

Criteria come in: positive criteria (i.e. more is better) or negative criteria (i.e. less is better).

Step 2: Construct the decision matrix, X, and the weight of criteria, W,

Let $X = \{x_{ij}\}$, be the decision matrix and $W = [w_i]$ a weight vector, where $\sum_{i=1}^{m} w_i = 1$;

and x_{ij} is the element of the decision matrix that resides in the i-th column and j-th row.

Step 3: Obtain the normalised matrix R.

This is done by applying Equ (26) as follows:

$$R = \{(r_{ij})\} \equiv \frac{x_{ij}}{\left(\sum_{i=1}^{m} x_{ij}^2\right)^{1/2}} \tag{26}$$

where: r_{ij} is the element of the normalised matrix that resides in the i-th column and j-th row.

Step 4: Calculate the weighted normalised matrix, V.

This can be calculated according to Equ (27);

$$V = \{v_{ij}\} \equiv R \times W \tag{27}$$

where v_{ij} is the element of the weighted normalised matrix that resides in the i-th column and j-th row.

Step 5: Determine the positive and negative ideal solutions

Step 5.1: Positive ideal solution, A^+

$$A^+ = \left(v_1^+, \dots, v_i^+, \dots, v_m^+\right) = \left\{\left(\max_j v_{ij} \,\middle|\, i \epsilon P\right), \left(\min_j v_{ij} \,\middle|\, i \epsilon N\right)\right\} \tag{28a}$$

Step 5.2: Negative ideal solution, A^-

$$A^- = \left(v_1^-, \dots, v_i^-, \dots, v_m^-\right) = \left\{\left(\min_j v_{ij} \,\middle|\, i \epsilon P\right), \left(\min_j v_{ij} \,\middle|\, i \epsilon N\right)\right\} \tag{28b}$$

where P is associated with positive criteria and N with the negative criteria.

Step 6: Calculate the relative distance of each solution from the positive ideal solution and to the negative ideal solution

Step 6.1: Relative distance from the positive ideal solution using Euclidean metric, S_j^+

$$S_j^+ = \sqrt{\sum_{i=1}^{m} \left(v_i^+ - v_{ij}\right)^2}; j = 1,2,\dots,n \tag{29a}$$

Step 6.2: Relative distance from the negative ideal solution using Euclidean metric, S_j^-

$$S_j^- = \sqrt{\sum_{i=1}^{m} \left(v_i^- - v_{ij}\right)^2}; j = 1,2,\dots,n \tag{29b}$$

Step 7: Calculate the relative closeness of each alternative to the ideal solution; the ideal solution is 1.

$$C_j = \frac{S_j^-}{s_j^+ + S_j^-}; 0 \le C_j \le 1, j = 1,2,\ldots,n \qquad (30)$$

In this analysis, $j = [GES, GBES, PBES, WBES, GPBES, GWBES, PWBES, GPWBES] \equiv [1,2,3,4,5,6,7,8]$ represents the alternatives whereas the criteria are listed in Table 1. The table shows characteristics of the fifteen (15) criteria considered. The weights of the criteria are gotten from literature (Roszkowska 2011) and expert opinion as shown in Table 1 after normalisation. The scores for the criteria are gotten from the HOMER results, the analysis of the literature (Lozano-minguez, Kolios, and Brennan 2011), the questionnaire and the engineering expertise.

Table 1 Characteristics of the criteria

i	Criteria	Type	Weight
1	Initial capital cost, $	negative (-)	0.089202
2	Operation and maintenance cost, $	negative (-)	0.070423
3	Cost of energy, $/kWh	negative (-)	0.089202
4	Cost of fuel, $	negative (-)	0.061033
5	CO_2 emissions, kg/year	negative (-)	0.089202
6	Environmental impact, -	negative (-)	0.079812
7	Unmet load, kWh/year	negative (-)	0.032864
8	Net present cost, $	positive (+)	0.070423
9	Renewable fraction, %	positive (+)	0.042254
10	Sociocultural awareness, -	positive (+)	0.089202
11	Technology readiness, -	positive (+)	0.051643
12	Ease of installation, -	positive (+)	0.051643
13	Natural resources Availability/predictability/randomness (wind), -	positive (+)	0.070423
14	Natural resources availability/predictability/randomness (sun), -	positive (+)	0.070423
15	Life cycle assessment, -	positive (+)	0.042254

3 Results and Discussion

3.1 Energy Demand per Household in the Coastline Communities

The daily energy demand profile presented in Diemuodeke et al. (2017) for the future electrical energy demand in the coastline communities of the SS zone, as replicated in Figure 5, is adopted in the current analysis. The total daily electrical energy demand of the representative household is 7.23kWh/day as the future electrical energy demand (FEED) when the communities are well electrified (twenty-four hour access to electricity). About 9.5% (~0.68kWh/day) of the total daily electrical energy consumption represents electrical energy demand for lighting. It should be noted that the SS zone has affinity for modern electrical appliances because of the presence of oil exploration and production activities. Furthermore, the daily energy consumption of the representative household is about the average of the household energy demands presented in available papers in the open domain against the doubling effect of electricity demand every 12 years (Adeoti, Oyewole, and Adegboyega 2001; Ogbonna, Onazi, and Dantong 2011; Okoye, Taylan, and Baker 2016; Ajao, Oladosu, and Popoola 2011). It is proposed that the PV can serve medium (7.23 kWh/day) and low (under 1 kWh) consumers. The medium consumers would be incentivised to buy into PV because the grid is not reliable; and the low consumers would be driven by the SDG 7 access agenda.

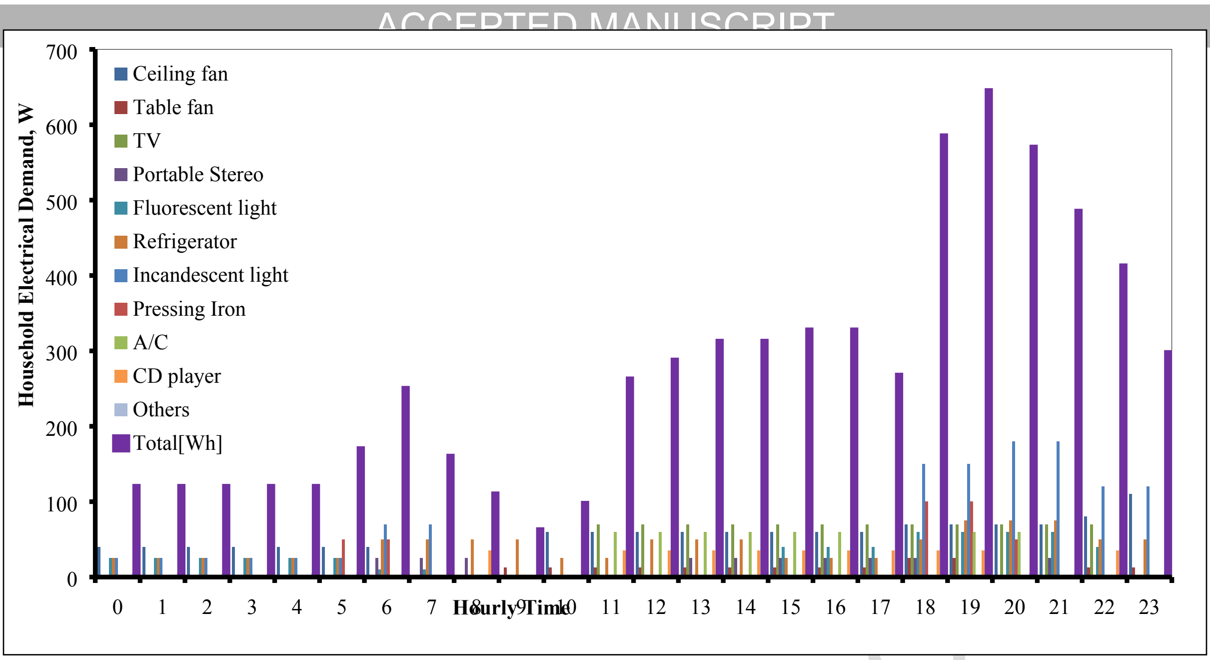

Figure 5 Typical household daily electrical energy demand (Diemuodeke et al. 2017)

3.2 Wind speed data

Measured monthly wind speed data at anemometer height of 10m from the Nigerian Meteorological Agency (NIMET) for the selected sites, as shown in Figure 6: Benin-city (Edo State), Warri (Delta State), Port Harcourt (Rivers State), Uyo (Akwa-Ibom State) and Calabar (Cross-River State) across the SS zone, for 7 year period (January 2007 – December 2013), were used for the current analysis. There are no available measured data for Yenagoa (Bayelsa State), however, the NASA SEE data (NASA 2015) monthly averaged anemological data for over a 22 year period (July 1983 – June 2005) was cross-plotted with the measured data from NIMET, to obtain appropriate correction factor to interpolate for the Yenagoa site.

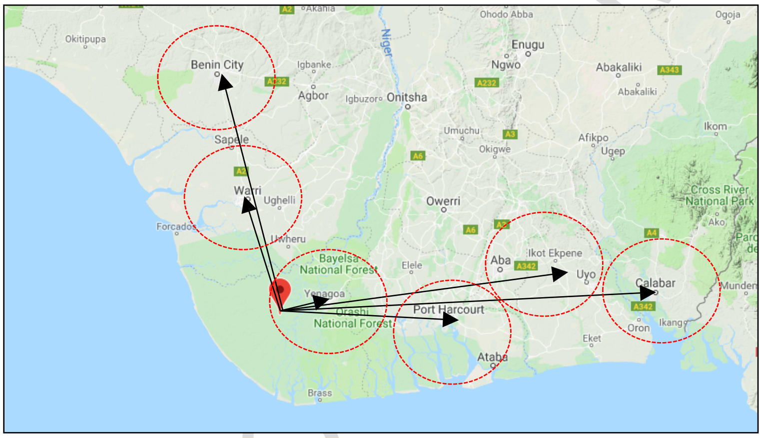

Figure 6 Selected sites for resource assessment

Figure 7 shows the monthly averaged wind speed of the selected sites within the six states of the SS zone at anemometer height of 10m. It could be inferred from the figure that the wind speeds within the SS zone have the same pattern, which is slightly different from the pattern recorded in (Okeniyi, Ohunakin, and Okeniyi 2015). The slight change in pattern may be attributed to climate change and the span of data acquired. On the average, the wind speed is lowest in the month of May and highest in the month of August. The months of June-October feature relatively high wind-speeds, which are associated with the rainy season. The months of December – April feature moderate wind speed, which are associated with the dry and harmattan of the tropical rain forest (or equatorial monsoon) that the SS zone belongs. The season-transition months, May and November, feature low wind speeds. Calabar and Warri anemological zones feature the highest and lowest wind-speeds, respectively. The SS zone wind-speed range between 2.837–4.495 m/s.

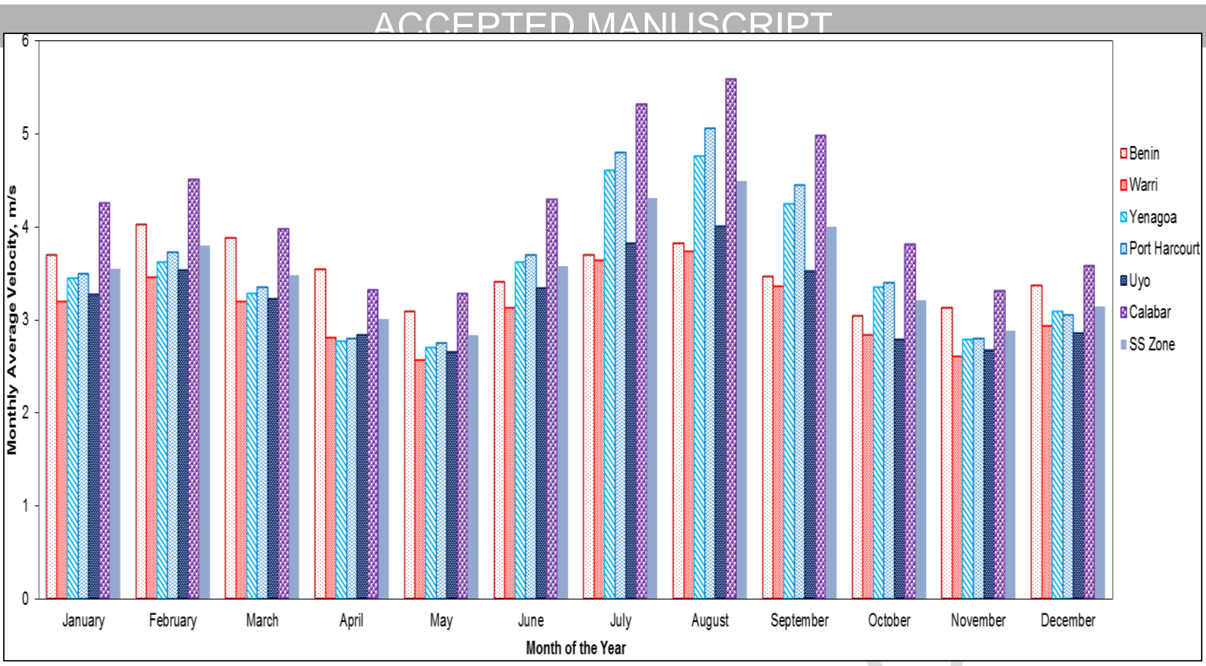

Figure 7 Monthly averaged wind-speed of selected sites in the SS Zone at hub height 10m

The Weibull shape factor, respectively, range between 3.038–4.022, 2.568–3.735, 2.703–4.753, 2.748–5.051, 2.676– 4.008, and 3.279–5.587 for Benin-city, Warri, Yenagoa, Port Harcourt, Uyo and Calabar; whereas the range of Weibull scale factors, are, respectively, 3.400 – 4.435 m/s, 2.892–4.137 m/s, 3.139–5.192 m/s, 3.088–5.490 m/s, 2.984–4.421 m/s, 3.657–6.046 m/s. Table 2 shows the mean wind-speed, optimum mean wind-speed, standard deviation, coefficient of variation, Weibull shape factor, Weibull scale factor and power density for the SS zone. The month of September has the lowest coefficient of variation, which indicates less mutability of wind-speeds in September; whereas May has the highest wind-speeds mutability. The Weibull shape factor range between 2.840–4.492 and the Weibull scale factor range between 3.184–4.926 m/s in the SS zone. The power density is highest in the month of August, which implies that the month of August has the highest potential of wind energy.

Table 2 Average monthly mean wind speed, standard deviation and Weibull factors for the SS zone at 10m

Month	$\bar{v}$ $[m/s]$	$\bar{v}_{op}$ $[m/s]$	σ	COV $[\%]$	k $[-]$	c $[m/s]$	$\bar{P}$ $[W/m^2]$
January	3.553	3.566	1.104	31.070	3.559	3.946	35.507
February	3.804	3.819	1.110	29.178	3.810	4.208	42.357
March	3.483	3.493	1.103	31.671	3.486	3.872	33.738
April	3.015	3.021	1.091	36.180	3.017	3.375	23.491
May	2.837	2.844	1.085	38.248	2.840	3.184	20.268
June	3.581	3.587	1.106	30.898	3.580	3.975	36.239
July	4.315	4.321	1.124	26.053	4.309	4.740	59.223
August	4.495	4.506	1.127	25.073	4.492	4.926	66.107
September	4.005	4.013	1.117	27.88	4.003	4.419	48.569
October	3.211	3.209	1.099	34.225	3.204	3.584	27.485
November	2.886	2.890	1.087	37.678	2.886	3.237	21.135
December	3.150	3.151	1.096	34.807	3.146	3.520	26.213

Figure 8 shows the theoretical probability density function and cumulative distribution function across the SS zone. Warri and Uyo anemological zones feature sharper peak of the Weibull probability density curves, which means that the wind-speeds in Warri and Uyo are more uniform than the other anemological zones. The cumulative distribution functions indicate that 61, 47, 60, 62, 51 and 78% of wind-speeds in Benin-City, Warri, Yenagoa, Port Harcourt, Uyo and Calabar anemological zones, respectively, belong to the wind-speed of 3.2 m/s. It shows that Calabar has the best wind energy potential within the SS zone. On the average, 61% of wind-speeds in the SS zone belong to wind-speed of 3.2 m/s, which indicates that a wind turbine with a cut-in wind-speed of 2.5m/s (e.g. Bergey Excel 1-R) is able to operate in the SS zone with reliable energy generation.

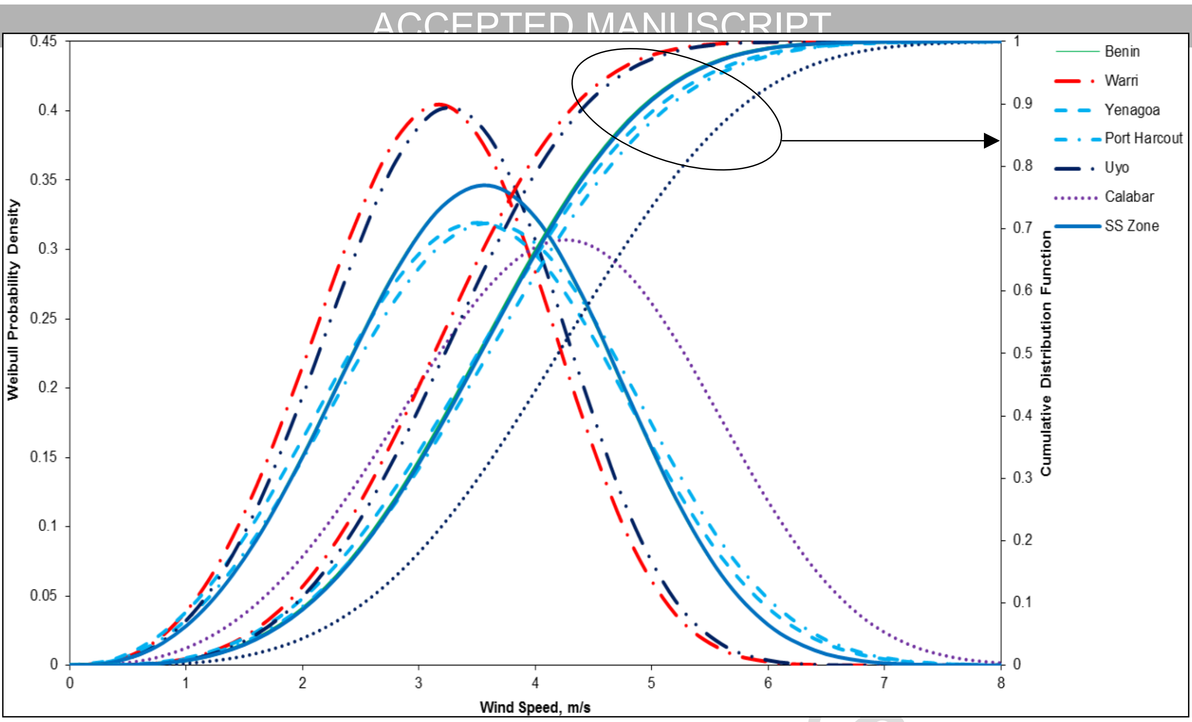

Figure 8 Weibull probability density and cumulative distribution function curves

The average wind speed characteristics and Weibull factors across the SS zone are presented in Table 3. It shows that Calabar zone has the best wind energy potential in the SS zone, with mean optimum wind speed and power density of 5.200m/s and 56.751W/m^2, respectively. Warri zone has the poorest wind energy potential, with optimum mean wind-speed and power density of 3.900m/s and 23.781W/m^2, respectively. The power density in Warri zone is about 42% of the power density in Calabar zone. The annual mean values of wind speed, optimum wind speed, standard deviation, coefficient of variation, Weibull shape factor, Weibull scale factor and power density, respectively, range between 3.122–4.185m/s, 3.900–5.20m/s, 0.947–1.249, 33.94–29.67%, 3.229–3.739,3.460–4.630m/s, and 23.781–56.751W/m^2 in the SS geopolitical zone. The whole SS zone belongs to the power class one, according to the wind power classification by Yu and Qu (2010), which is considered to be poor for direct wind power generation. However, the wind energy potential would be adequate for battery charging and water pumping, i.e. non-connected electrical and mechanical applications.

Table 3 Annual mean wind speed parameters across SS zone at 10m

Town	Geographical Location	Height above sea level (m)	$\bar{v}$ $[m/s]$	$\bar{v}_{op}$ $[m/s]$	σ	COV [%]	k $[-]$	c $[m/s]$	$\bar{P}$ $[W/m^2]$
Benin-city	6°20.1’N, 5°36.2’E	77.80	3.512	4.436	1.105	31.45	3.511	3.901	34.433
Warri	5°33.3’N, 5°47.6’E	6.10	**3.122**	**3.900**	**0.947**	30.33	3.651	**3.460**	**23.781**
Yenagoa	4°55.3’N, 6°16.5’E	17.20	3.523	4.557	1.196	**33.94**	**3.229**	3.925	36.001
Port Harcourt	4°89.9’N, 7°30.0’E	19.50	3.613	4.635	1.198	33.15	3.312	4.019	38.321
Uyo	5°20.3’N, 7°54.8’E	64.00	3.211	3.984	0.953	**29.67**	**3.739**	3.553	25.604
Calabar	4°58.5’N, 8°20.5’E	61.90	**4.185**	**5.200**	**1.249**	29.85	3.713	**4.630**	**56.751**

The wind speeds in all the locations were measured at 10m; therefore, Figures 9, 10 and 11 shows the extrapolated wind speed characteristics at hub heights of 30m and 50m across the SS zone. Figure 9 shows the extrapolated monthly averaged wind speeds at hub heights 30m and 50m.

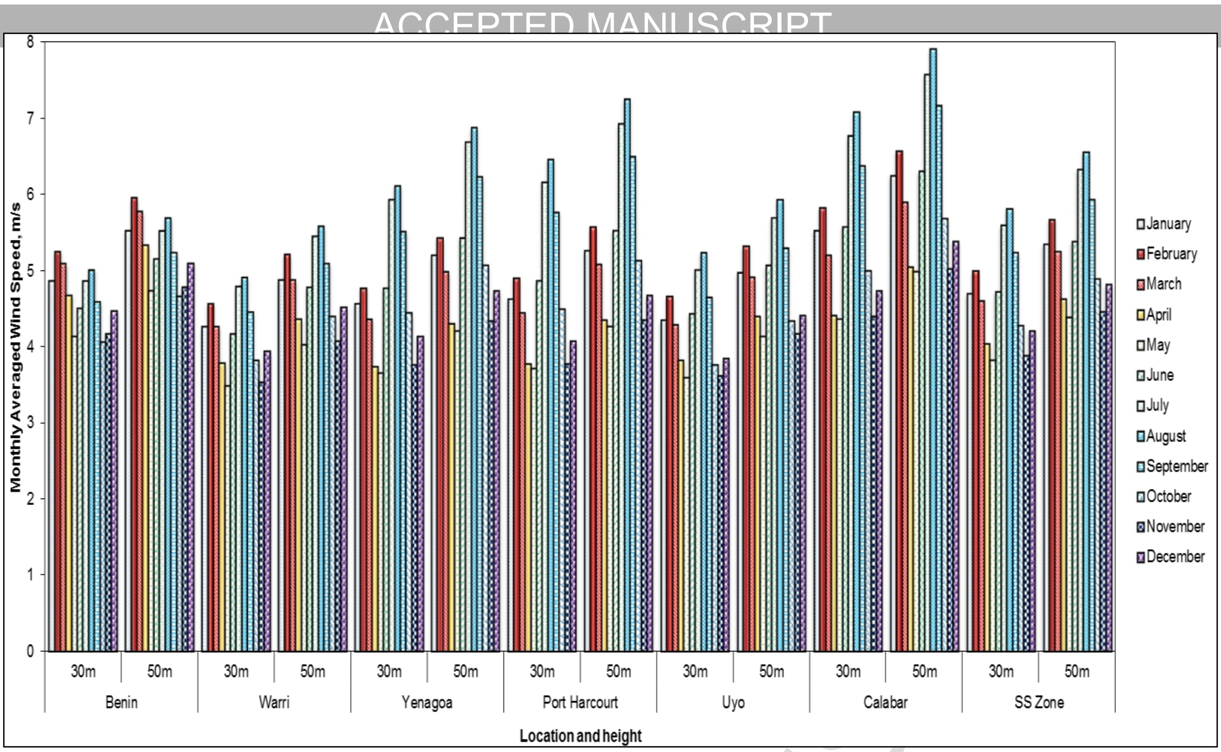

Figure 9 Variation of monthly averaged wind speed with hub height across the SS zone

Figure 10 shows the extrapolated monthly averaged Weibull factors for anemological zones; Benin-city, Warri, Yenagoa, Port Harcourt, Uyo, Calabar, and the average in the SS geopolitical zone at hub height of 30m.

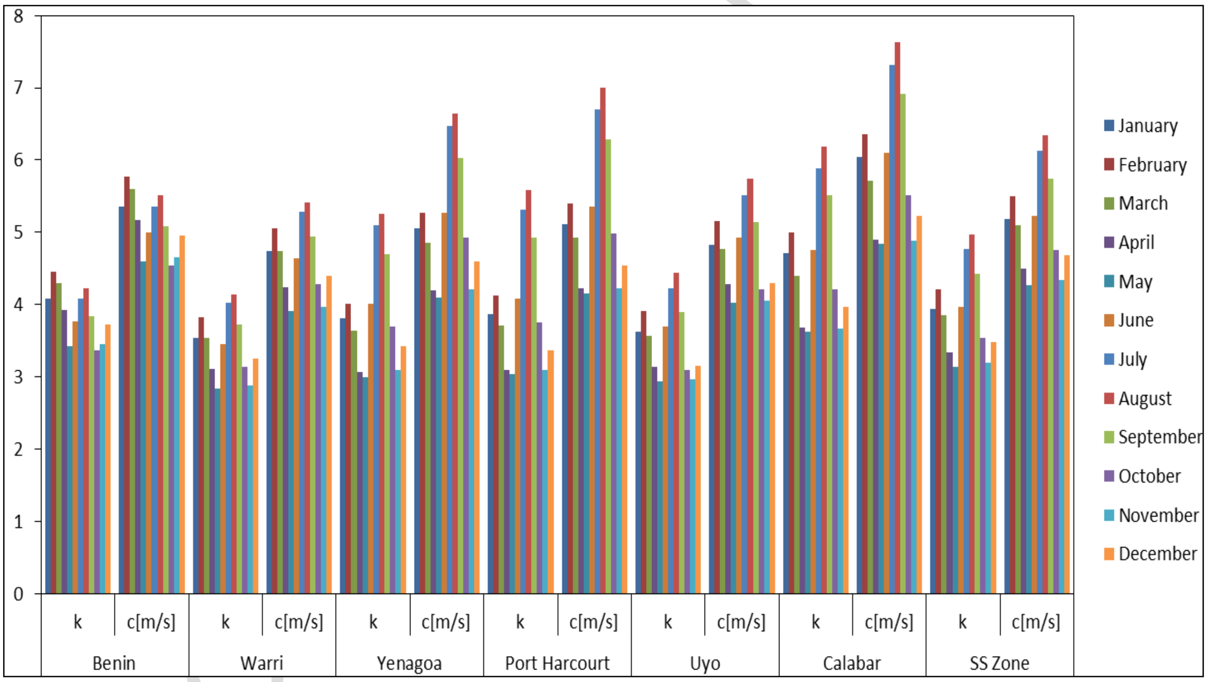

Figure 10 Extrapolated monthly averaged Weibull factors across the SS zone at 30m

Figure 11 shows the extrapolated monthly averaged Weibull factors for anemological zones Benin-city, Warri, Yenagoa, Port Harcourt, Uyo, Calabar, and the average in the SS geopolitical zone at hub height of 50m.

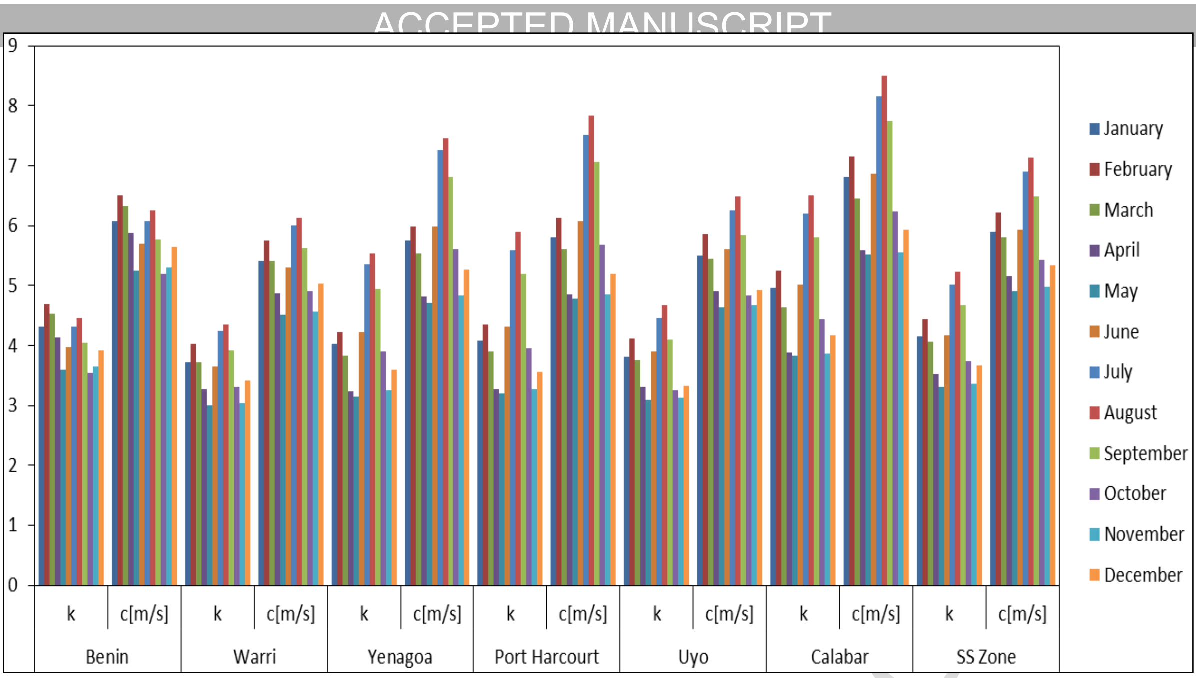

Figure 11 Extrapolated monthly averaged Weibull factors across the SS zone at 50m

Table 4 shows monthly mean wind-speed, optimum mean wind-speed, Weibull factors and power density at 30m and 50m hub heights for the SS zone. From Table 4, the power density progressively increases with increasing hub height.

Table 4 Monthly averaged wind-speed characteristics in the SS zone at 30m and 50m

Month	30m					50m				
	$\bar{v}$ $[m/s]$	$\bar{v}_{op}$ $[m/s]$	k $[-]$	c $[m/s]$	$\bar{P}_z$ $[W/m^2]$	$\bar{v}$ $[m/s]$	$\bar{v}_{op}$ $[m/s]$	k $[-]$	c $[m/s]$	$\bar{P}_z$ $[W/m^2]$
January	4.748	5.435	3.940	5.243	81.365	5.435	6.580	4.147	5.984	119.863
February	5.054	5.770	4.218	5.559	95.836	5.770	6.881	4.439	6.328	140.349
March	4.661	5.340	3.860	5.153	77.567	5.340	6.496	4.062	5.886	114.473
April	4.081	4.700	3.340	4.547	55.344	4.700	5.937	3.515	5.223	82.617
May	3.859	4.454	3.144	4.312	48.198	4.454	5.728	3.309	4.965	72.271
June	4.782	5.471	3.964	5.278	82.908	5.471	6.615	4.171	6.022	122.047
July	5.674	6.445	4.771	6.196	130.699	6.445	7.503	5.021	7.018	189.109
August	5.890	6.680	4.973	6.417	144.672	6.680	7.719	5.234	7.256	208.433
September	5.299	6.038	4.432	5.812	108.761	6.038	7.128	4.664	6.603	158.541
October	4.325	4.969	3.547	4.803	64.087	4.969	6.173	3.733	5.503	95.167
November	3.920	4.523	3.195	4.377	50.114	4.523	5.787	3.363	5.037	75.071
December	4.250	4.887	3.483	4.725	61.323	4.887	6.101	3.666	5.418	91.217

Table 5 shows annual mean wind speed, optimum mean wind speed, Weibull factors and power density at 30m and 50m hub heights for locations in the SS zone. It shows that Calabar zone has the best wind energy potential even at higher hub heights, with mean optimum wind speed and power density of 6.679m/s and 124.979W/m^2, and 7.507m/s and 180.685 W/m^2, at 30m and 50m, respectively. Warri zone has the poorest wind energy potential, however with significant improvement in wind energy potential at higher hub heights.

Table 5 Annual mean wind speed parameters across SS zone at 30m and 50m

Town	30m					50m				
	$\bar{v}$ $[m/s]$	$\bar{v}_{op}$ $[m/s]$	k $[-]$	c $[m/s]$	$\bar{P}_z$ $[W/m^2]$	$\bar{v}$ $[m/s]$	$\bar{v}_{op}$ $[m/s]$	k $[-]$	c $[m/s]$	$\bar{P}_z$ $[W/m^2]$
Benin	4.695	5.773	3.887	5.188	79.045	5.376	6.529	4.091	5.924	116.56
Warri	4.218	5.137	4.042	4.651	56.528	4.855	5.843	4.254	5.337	84.697
Yenagoa	4.700	5.909	3.575	5.218	82.004	5.380	6.671	3.762	5.956	120.444
Port Harcourt	4.809	6.003	3.667	5.331	86.887	5.500	6.775	3.859	6.08	127.418
Uyo	4.328	5.241	4.140	4.765	60.537	4.975	5.957	4.357	5.462	90.477
Calabar	5.506	6.679	4.111	6.065	124.979	6.261	7.507	4.326	6.876	180.685

3.3 Solar irradiance data

The solar resource assessment was based on the solar data retrieved from the Nigerian Meteorological Agency (NIMET) database and the Typical Meteorological Year (TMY2) data, which include solar irradiance and ambient temperature, from both the NASA Surface Meteorology database and US National Renewable Energy Laboratory (NREL) database. Onsite solar data acquired from meteorological stations presented in the literature confirms the reliability and applicability of both the NASA and NREL solar data for the Africa continent (Tesema 2014). The TMY solar resource assessment is adjudged adequate for long-term solar energy performance evaluation. The solar energy assessment was done for the entire SS zone.

Figure 12 represents the monthly averaged solar irradiance of the selected sites in the entire SS zone. The potential of PV is dependent on the solar irradiance. The monthly averaged of the available daily solar data of the sites were considered. The monthly and annual averaged solar irradiance range between 3.315 – 5.371 kWh/m^2/day and 4.211 – 4.710 kWh/m^2/day, see Figure 12, respectively, and varies along the SS zone, which can be validated by the Nigeria solar map presented in SOLARGIS website (SOLARGIS 2017).

On the average, the solar irradiance is low between the month of June and October, which is associated with the raining season. The solar irradiation is highest between the months of January and May, which is associated with the dry season. The months of November and December, which is associated with the Harmattan season, feature moderately high solar irradiance. The comprehensive data of the solar radiation data presented in Figure 12 serve as input data for the techno-economic analysis of the hybrid energy system on the HOMER platform.

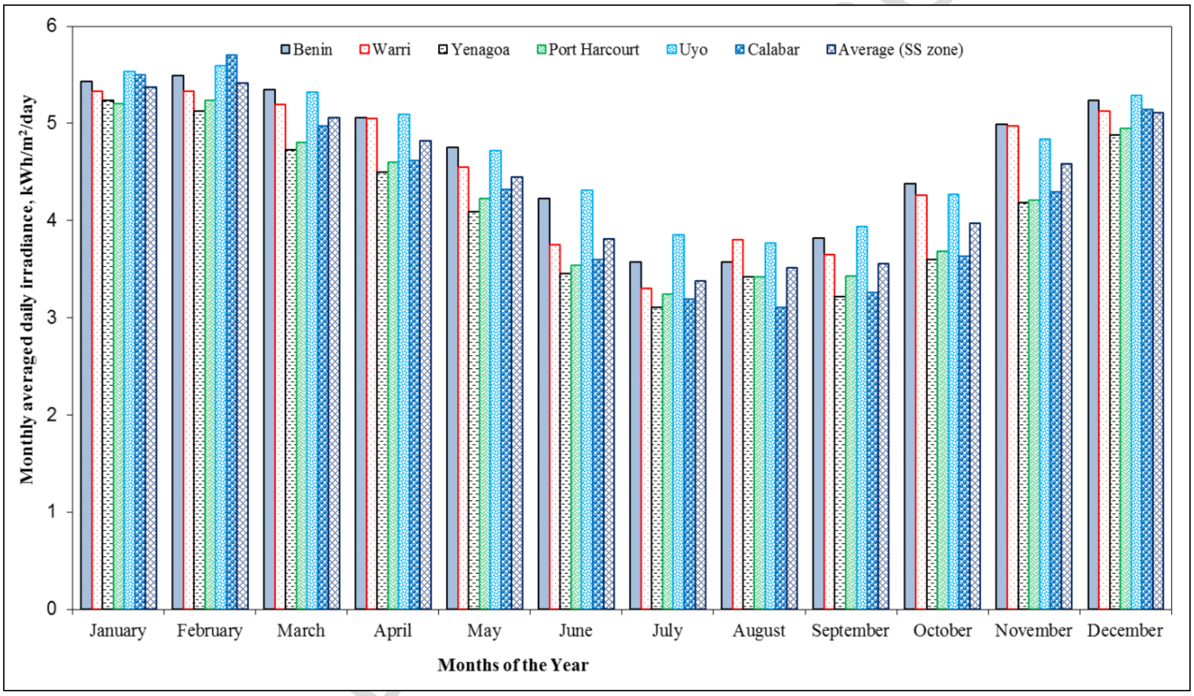

Figure 12 Monthly averaged solar irradiance

Table 6 shows the average solar irradiance, the average wind speed of the sites with the corresponding mean temperature. Uyo zone has the highest solar irradiance while Calabar zone has the highest wind speed. The implication is that the Uyo zone and the Calabar zone feature the best PV potential and wind potential, respectively, as both feature relatively low ambient temperatures over the other locations.

Table 6 Average solar irradiance and wind speed

Sites	Solar irradiance kWh/m^2/day	Wind speed at 50m m/s	Temperature ^{o}C
Benin-city	4.66	5.376	25.28
Warri	4.53	4.855	25.59
Yenagoa	4.13	5.380	25.49
Port Harcourt	4.21	5.500	25.33
Uyo	4.71	4.975	24.91
Calabar	4.28	6.261	24.67

3.4 Optimum system selection

The output data from the energy demand, resource and cost assessments serve as input data to the HOMER analysis, Figure 4 shows the system setup, which is used to size the energy system alternatives (GES, GBES, PBES, WBES, GPBES, GWBES, PWBES, GPWBES) for all the sites (Benin-city, Warri, Yenagoa, Port Harcourt, Uyo and Calabar). Wind speeds at hub height of 50 m are used for the HOMER analysis. The output data from the HOMER analysis are used to populate the criteria 1 to 9 in Table 1, while data from literature and experts are used to populate the criteria 10 to 15, for all the sites. The populated table forms the decision matrix for each of the six sites; see Tables A.1 to A.6 in Appendix A, which kick start the TOPSIS analysis.

Equ.(26) is used to operate on the decision matrices (Tables A.1–A.6) to obtain the normalised decision matrices for all the sites. The combination of the normalised decision matrices and the weights, shown in Table 1, according to Equ.(27), give the weighted normalised decision matrices. Thereafter, Equs (28a) and (28b) are used to obtain the positive and negative ideal solutions, respectively, for the sites shown in Table 7.

Table 7 Positive and negative ideal solutions

Criteria	Type	Benin-city		Warri		Yenagoa		Port Harcourt		Uyo		Calabar	
		A+	A-	A+	A-	A+	A-	A+	A-	A+	A-	A+	A-
1	-	0.0032	0.0544	0.0029	0.0529	0.0029	0.0565	0.0029	0.0557	0.0030	0.0527	0.0032	0.0625
2	-	0.0076	0.0553	0.0088	0.0529	0.0078	0.0543	0.0080	0.0547	0.0089	0.0536	0.0051	0.0507
3	-	0.0257	0.0502	0.0265	0.0466	0.0253	0.0475	0.0249	0.0481	0.0265	0.0476	0.0232	0.0455
4	-	0.0000	0.0521	0.0000	0.0502	0.0000	0.0512	0.0000	0.0515	0.0000	0.0507	0.0000	0.0489
5	-	0.0000	0.0761	0.0000	0.0734	0.0000	0.0749	0.0000	0.0752	0.0000	0.0741	0.0000	0.0691
6	-	0.0162	0.0487	0.0162	0.0487	0.0162	0.0487	0.0162	0.0487	0.0162	0.0487	0.0152	0.0455
7	-	0.0000	0.0246	0.0000	0.0237	0.0000	0.0241	0.0000	0.0246	0.0000	0.0246	0.0000	0.0243
8	+	0.0401	0.0199	0.0373	0.0212	0.0380	0.0202	0.0385	0.0199	0.0380	0.0212	0.0475	0.0110
9	+	0.0209	0.0000	0.0225	0.0000	0.0215	0.0000	0.0214	0.0000	0.0223	0.0000	0.0207	0.000
10	+	0.0110	0.0069	0.0110	0.0069	0.0110	0.0069	0.0110	0.0069	0.0110	0.0069	0.0391	0.0244
11	+	0.0225	0.0169	0.0225	0.0169	0.0225	0.0169	0.0225	0.0169	0.0225	0.0169	0.0211	0.0158
12	+	0.0302	0.0134	0.0302	0.0134	0.0302	0.0134	0.0302	0.0134	0.0302	0.0134	0.0282	0.0125
13	+	0.0364	0.0045	0.0360	0.0051	0.0364	0.0045	0.0364	0.0045	0.0360	0.0051	0.0342	0.0038
14	+	0.0373	0.0053	0.0373	0.0053	0.0374	0.0047	0.0372	0.0062	0.0366	0.0041	0.0336	0.0048
15	+	0.0241	0.0107	0.0241	0.0107	0.0241	0.0107	0.0241	0.0107	0.0241	0.0107	0.0225	0.0100

Equs. (29a) and (29b) are used to operate on Table 7 to get the relative distance of each solution from the positive ideal solution and to the negative ideal solution, as shown in Table 8.

Table 8 Positive and negative ideal solutions

Location		Alternatives							
		GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
Benin-city	d+	0.122093	0.092289	0.063642	0.059696	0.057569	0.054401	0.048099	0.045007
	d-	0.064313	0.065589	0.11597	0.118452	0.093302	0.10665	0.12318	0.117238
Warri	d+	0.117448	0.089284	0.060902	0.064782	0.056218	0.055516	0.050191	0.043731
	d-	0.06186	0.063436	0.112498	0.112407	0.088971	0.093344	0.117314	0.101823
Yenagoa	d+	0.120408	0.091413	0.06554	0.062244	0.058656	0.053445	0.048768	0.041992
	d-	0.06547	0.06694	0.114259	0.115727	0.090187	0.10464	0.12112	0.112253
Port Harcourt	d+	0.120473	0.091103	0.065098	0.064708	0.058389	0.05244	0.048849	0.042172
	d-	0.065151	0.066631	0.114234	0.11508	0.090268	0.106088	0.121258	0.112987
Uyo	d+	0.118668	0.090104	0.05914	0.060712	0.055379	0.056133	0.049527	0.043662
	d-	0.062152	0.063764	0.113959	0.11417	0.091989	0.094553	0.119091	0.104718
Calabar	d+	0.113371	0.086935	0.074378	0.058505	0.059961	0.060559	0.05396	0.052247
	d-	0.078023	0.073688	0.107291	0.112939	0.096118	0.099158	0.117349	0.106226

Equ.(30) is used to operate on Table 8 to obtain the relative closeness of each alternative to the ideal solution, as shown in Table 9. The alternative (the hybrid system) with the highest relative closeness to the ideal solution, which is 1, is the most appropriate for that location. It implies, therefore, that locations around Benin-city, Yenagoa, and Port Harcourt should use diesel generator-PV-wind-Battery energy system (GPWBES) whereas locations around Warri, Uyo and Calabar require PV-Wind-Battery energy system (PWBES). The diesel generator energy system (GES) perform poorly in all the locations, this can be attributed to it severe adverse effect on climate change and huge operation and maintenance cost associated with GES. The PWBES is favoured by the uniformity in wind speeds in Warri and Uyo, and the high wind speed in Calabar.

Table 9 Relative closeness of each alternative to the ideal solution

Location	Alternatives							
	GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
Benin-city	0.345014	0.415439	0.64567	0.664908	0.618422	0.662213	0.719179	**0.7226**
Warri	0.344992	0.415377	0.648779	0.63439	0.612794	0.62706	**0.70036**	0.699555

Yenagoa	0.35222	0.422726	0.635483	0.650258	0.605923	0.661925	0.712941	**0.727759**
Port Harcourt	0.350985	0.422424	0.636997	0.640088	0.607224	0.669208	0.712835	**0.728202**
Uyo	0.343721	0.414409	0.658344	0.65284	0.624213	0.627484	**0.706276**	0.70574
Calabar	0.407656	0.458764	0.590584	0.658751	0.61583	0.620834	**0.685015**	0.670311

Table 10 shows the design parameters for the optima hybrid energy systems, with their corresponding useful electrical energy supplied to the facility. The hybrid energy systems in locations in Warri, Uyo and Calabar have capacity shortages of 3.45%, 3.37% and 2.95% respectively, which could be attributed to the variability associated with the availability of solar and wind resources.

Table 10 Pertinent design parameters

Location	Hybrid system	Diesel generator kW	PV kW	Wind kW	Battery kWh	Converter kW	Energy consumption kWh/year
Benin-city	GPWBES	1.40	0.250	2.00	5.00	0.900	2640
Warri	PWBES	-	1.030	2.00	9.00	3.100	2549
Yenagoa	GPWBES	1.40	0.250	2.00	3.00	1.070	2640
Port Harcourt	GPWBES	1.40	0.250	2.00	3.00	0.950	2640
Uyo	PWBES	-	1.120	2.00	8.00	1.240	2551
Calabar	PWBES	-	0.250	2.00	5.00	1.260	2562

Table 11 shows pertinent economic and environmental parameters of the mapped optima hybrid energy systems for the SS zone. Calabar has the lowest cost of energy (COE) of 0.459 US\$/kWh; whereas the location in Warri has the highest COE of 0.562 US\$/kWh. The optima hybrid energy systems for the locations in Benin-city, Yenagoa and Port Harcourt have small negative effect on the climate since they emit CO_2 during their operations; however, the CO_2 emission is very minimal as they respectively represent only 8.47%, 15.02% and 14.09% of the business as usual (i.e. the GES), as shown in Table A.1, A.3 and A.4. The Port Harcourt location requires the lowest initial capital cost of 8,421 US\$ to install the hybrid energy system capable of supplying 7.23 kWh/day of electrical energy; whereas the Warri location requires the highest initial capital of 12,194 US\$ for the same electrical energy capacity. The Warri location has the highest net present value follow by Uyo, Yenagoa, Benin-city, Port Harcourt and Calabar in that order. The COE of PWBES in the SS zone ranges between 0.459 – 0.562 US\$/kWh; it compares well with the 0.609 US\$/kWh presented in Al-Sharafi et al. (2017) for a coastal location, Yanbu (24°08’N, 38°03’E), with solar irradiance of 5.90kWh/m^2/h and 3.7 m/s wind speed. The difference in the COE may be attributed to the 14kWh/day electrical energy load and the different interest rate used in Al-Sharafi et al. (2017). The payback time ranges between 3.7 – 5.4 years, using the COE of the BAU (0.893 US\$/kWh of GES); with the SS zone average payback time being 4.2 years.

Table 11 Pertinent economic and environmental data

Location	Hybrid system	Initial capital cost, US\$	O&M, US\$	COE, US\$/kWh	CO_2 emission, kg/year	NPV, US\$	PBT Year
Benin-city	GPWBES	9,235	450.89	0.464	146	14621	3.9
Warri	PWBES	12194	412.62	0.562	0	17123	5.4
Yenagoa	GPWBES	8437	547.47	0.475	681	14977	3.6
Port Harcourt	GPWBES	8421	517.39	0.463	638	14602	3.6
Uyo	PWBES	11568	381.11	0.529	0	16121	5.1
Calabar	PWBES	8504	244.15	0.459	0	10733	3.7

The life cycle cost, which includes capital cost, replacement cost, O&M cost, fuel cost and salvage value, is shown in Figure 13. The wind turbine constitutes the highest cost and closely followed by battery cost. The implication is that the cost of energy obtained could be significantly reduced by favourable economic and cost data, namely the discount rate on capital investment, wind turbine cost, PV panel cost and lifespan, and the battery lifespan and cost, which have strong impact on the economic competitiveness of the hybrid energy systems, which has been demonstrated in Rezaei, Mostafaeipour, and Qolipour (2018).

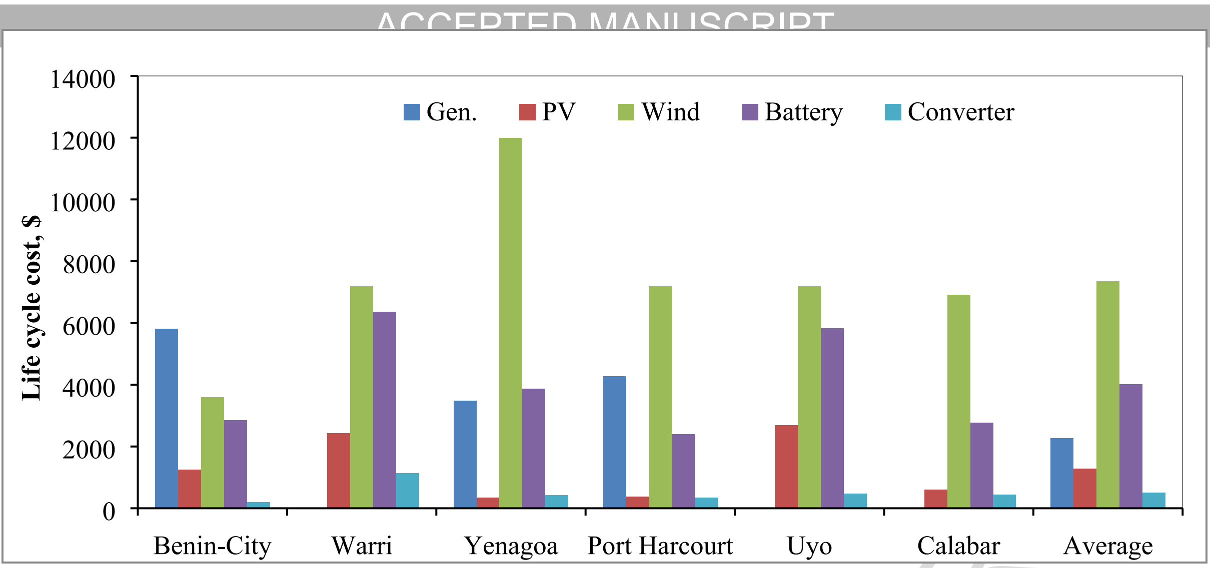

Figure 13 Life cycle cost (capital cost, replacement, O&M, fuel and salvage)

4 Conclusion

Out of the 1.3 billion people living without the electrical energy in the world, Nigeria accounts for 93 million people (about 15.5% of the sub-Saharan Africa); and has the second world's largest electricity access deficit, which has manifested in the poor development progress of Nigerians. Significant proportion of the South South geopolitical (SS) zone of Nigeria is domicile in rugged coastline terrains, with just 8.5% rural electrification and 17.7% electricity availability; the lowest, only after the South-East geopolitical zone (15.3% availability). Therefore, this paper presents the optimal mapping of hybrid energy systems, which are based on wind and PV, with the consideration of energy storage and backup diesel generator, for households in six locations in the SS zone of Nigeria: Benin-city, Warri, Yenagoa, Port Harcourt, Uyo and Calabar. The optima hybrid energy systems are able to meet 7.23 kWh/day of a household's electrical energy. The hybrid energy system for each of the locations was optimally chosen based on HOMER software computation and TOPSIS multi-criteria decision-making algorithm that considers technical, economic, environmental, and sociocultural criteria. Wind energy potential was conducted for the entire SS zone using the Weibull distribution function; the wind speed ranges between 3.21–4.19 m/s at 10m anemological height. The wind speeds and the wind characteristics were extrapolated for 30 m and 50 m hub heights. The solar resource potential across the six locations is also presented – ranges between 4.21 – 4.71 kWh/m^2/day. The best hybrid system for the locations in Benin-city, Yenagoa and Port Harcourt is Diesel generator-PV-Wind-Battery system; whereas the best hybrid system for the locations in Warri, Uyo and Calabar is PV-Wind-Battery system. The hybrid systems in Benin-city, Yenagoa and Port Harcourt emit CO_2; only 8.47%, 15.02% and 14.09% of the business as usual (the diesel generator). The payback time ranges between 3.7 – 5.4 years, using the business as usual cost of energy of 0.893 US$/kWh; whereas the cost of energy of the hybrid systems ranges between 0.459 – 0.562 US$/kWh, which compares well with available literature in the public domain. The design parameters of the optima hybrid energy systems are also presented.

The high cost of energy of the hybrid systems can be attributed to the unfavourable discount rate on capital investment, wind turbine cost, PV panel cost, and the battery lifespan and cost, which have strong impact on the economic competitiveness of hybrid energy systems as demonstrated in Rezaei, Mostafaeipour, and Qolipour (2018). Some of these are within the powers of the Federal Government of Nigeria such as making the financing of PV systems conducive for low-income households, but the more technical challenges such as battery lifespan and cost reside within the global R&D community. The recent breakthroughs in battery technology can become the real game changers in rural electrification programmes in South South geopolitical zone and elsewhere in Nigeria. The methodology presented will serve as a veritable tool for the optimal design of hybrid renewable energy systems under multi criteria conditions, especially in the global south where the quest for energy interventions is sacrosanct.

Acknowledgement

This work was supported under the CIRCLE Visiting Fellowship programme funded by the UK Department for International Development. Neither the findings nor the views expressed, however, necessarily reflect the policies of the UK Government.

References

Adeoti, O, B A Oyewole, and T D Adegboyega. 2001. "Solar Photovoltaic-Based Home Electrification System for Rural Development in Nigeria : Domestic Load Assessment" 24: 155–61.

Ajao, K R, O Oladosu, and O Popoola. 2011. "Using HOMER Power Optimization Software for Cost Benefit Analysis of Hybrid-Solar Power Generation Relative to Utility Cost in Nigeria." *International Journal of Research and Reviews in Applied Sciences* 7: 96–102.

Akuru, U B, I E Onukwube, O I Okoro, and E S Obe. 2017. "Towards 100% Renewable Energy in Nigeria." *Renewable and Sustainable Energy Reviews* 71 (January): 943–53. doi:10.1016/j.rser.2016.12.123.

Al-Sharafi, A., A.Z. Sahin, T. Ayar, and B.S. Yilbas. 2017. "Techno-Economic Analysis and Optimization of Solar and Wind Energy Systems for Power Generation and Hydrogen Production in Saudi Arabia." *Renewable and Sustainable Energy Reviews* 69 (September 2015): 33–49. doi:10.1016/j.rser.2016.11.157.

Aslani, Alireza, Petri Helo, and Marja Naaranoja. 2013. "Evaluation of Renewable Energy Development in Power Generation in Finland." *Journal of Renewable and Sustainable Energy* 5 (6): 63132. doi:10.1063/1.4855095.

Babatunde, Shakirat Adepeju, and Kabiru Isa Dandago. 2014. "Internal Control System Deficiency and Capital Project Mis-Management in the Nigerian Public Sector." *Procedia - Social and Behavioral Sciences* 164 (August): 208–21. doi:10.1016/j.sbspro.2014.11.069.

Babayani, D, M Khaleghi, S Tashakor, and M Hashemi-tilehnoee. 2016. "Evaluating Wind Energy Potential in Gorgan – Iran Using Two Methods of Weibull Distribution Function." *Int. Journal of Renewable Energy Development Journal of Renewable Energy Development* 5 (1): 43–48.

Baghdadi, Fazia, Kamal Mohammedi, Said Diaf, and Omar Behar. 2015. "Feasibility Study and Energy Conversion Analysis of Stand-Alone Hybrid Renewable Energy System." *Energy Conversion and Management* 105: 471–79. doi:10.1016/j.enconman.2015.07.051.

Bhandari, Binayak, Shiva Raj Poudel, Kyung-Tae Lee, and Sung-Hoon Ahn. 2014. "Mathematical Modeling of Hybrid Renewable Energy System: A Review on Small Hydro-Solar-Wind Power Generation." *International Journal of Precision Engineering and Manufacturing-Green Technology* 1 (2): 157–73. doi:10.1007/s40684-014-0021-4.

Bhattacharya, Tanima, Ajoy K Chakraborty, and Kaushik Pal. 2014. "Effects of Ambient Temperature and Wind Speed on Performance of Monocrystalline Solar Photovoltaic Module in Tripura , India." *Journal of Solar Energy* 2014: ID 817078.

Boait, P., V. Advani, and R. Gammon. 2015. "Estimation of Demand Diversity and Daily Demand Profile for off-Grid Electrification in Developing Countries." *Energy for Sustainable Development* 29: 135–41. doi:10.1016/j.esd.2015.10.009.

Cayir Ervural, Beyzanur, Ramazan Evren, and Dursun Delen. 2018. "A Multi-Objective Decision-Making Approach for Sustainable Energy Investment Planning." *Renewable Energy*. Elsevier Ltd. doi:10.1016/j.renene.2018.03.051.

Cloke, Jonathan, Alison Mohr, and Ed Brown. 2017. "Imagining Renewable Energy: Towards a Social Energy Systems Approach to Community Renewable Energy Projects in the Global South." *Energy Research and Social Science* 31 (June). Elsevier: 263–72. doi:10.1016/j.erss.2017.06.023.

Çolak, Murat, and İhsan Kaya. 2017. "Prioritization of Renewable Energy Alternatives by Using an Integrated Fuzzy MCDM Model: A Real Case Application for Turkey." *Renewable and Sustainable Energy Reviews* 80 (August 2016): 840–53. doi:10.1016/j.rser.2017.05.194.

Dawoud, Samir M., Xiangning Lin, and Merfat I. Okba. 2017. "Hybrid Renewable Microgrid Optimization Techniques: A Review." *Renewable and Sustainable Energy Reviews* 82 (May 2017): 2039–52. doi:10.1016/j.rser.2017.08.007.

de Christo, Tiago Malavazi, Jussara Farias Fardin, Domingos Sávio Lyrio Simonetti, Lucas Frizera Encarnação, and Cristina Engel de Alvarez. 2016. "Design and Analysis of Hybrid Energy Systems: The Brazilian Antarctic Station Case." *Renewable Energy* 88: 236–46.

doi:10.1016/j.renene.2015.11.014.

Diemuodeke, E. O., A. Addo, I. Dabipi-Kalio, C. O. C. Oko, and Y. Mulugetta. 2017. “Domestic Energy Demand Assessment of Coastline Rural Communities with Solar Electrification.” *Energy and Policy Research* 4 (1). Taylor & Francis: 1–9. doi:10.1080/23815639.2017.1280431.

Diemuodeke, E.O., S. Hamilton, and Ahmad Addo. 2016. “Multi-Criteria Assessment of Hybrid Renewable Energy Systems for Nigeria’s Coastline Communities.” *Energy, Sustainability and Society* 6 (26): 1–12. doi:10.1186/s13705-016-0092-x.

Duffie, J A, and W A Beckman. 1991. *Solar Engineering of Thermal Processes*. 2nd ed. New York.

Engin, Mustafa. 2013. “Sizing and Simulation of PV-Wind Hybrid Power System.” *International Journal of Photoenergy* 2013: 1–10. doi:10.1155/2013/217526.

Federal Ministry of Power. 2015. “National Renewable Energy and Energy Efficiency Policy.” http://www.power.gov.ng/download/NREEE POLICY 2015- FEC APPROVED COPY.pdf.

Gan, Leong Kit, Jonathan K H Shek, and Markus A. Mueller. 2015. “Hybrid Wind-Photovoltaic-Diesel-Battery System Sizing Tool Development Using Empirical Approach, Life-Cycle Cost and Performance Analysis: A Case Study in Scotland.” *Energy Conversion and Management* 106: 479–94. doi:10.1016/j.enconman.2015.09.029.

Genchi, Sibila A, Alejandro J Vitale, M Cintia Piccolo, and Gerardo M E Perillo. 2016. “Wind Energy Potential Assessment and Techno-Economic Performance of Wind Turbines in Coastal Sites of Buenos Aires Province, Argentina.” *International Journal of Green Energy* 13 (4): 352–65. doi:10.1080/15435075.2014.952426.

GIZ. 2015. “The Nigerian Energy Sector: An Overview with a Special Emphasis on Renewable Energy, Energy Efficiency and Rural Electrification.” https://www.giz.de/en/downloads/giz2015-en-nigerian-energy-sector.pdf.

Gujba, H., Y. Mulugetta, and A. Azapagic. 2010. “Environmental and Economic Appraisal of Power Generation Capacity Expansion Plan in Nigeria.” *Energy Policy* 38 (10). Elsevier: 5636–52. doi:10.1016/j.enpol.2010.05.011.

IRENA. 2016. “Renewable Electricity Capacity.” http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=16.

———. 2017. *Power Generation Costs in 2017*.

Kaldellis, John K, Marina Kapsali, and Kosmas A Kavadias. 2014. “Temperature and Wind Speed Impact on the Efficiency of PV Installations . Experience Obtained from Outdoor Measurements in Greece.” *Renewable Energy* 66: 612–24.

Karakaya, Emrah, and Pranpreya Sriwannawit. 2015. “Barriers to the Adoption of Photovoltaic Systems: The State of the Art.” *Renewable and Sustainable Energy Reviews* 49: 60–66. doi:10.1016/j.rser.2015.04.058.

Khan, Mohammad Junaid, Amit Kumar Yadav, and Lini Mathew. 2017. “Techno Economic Feasibility Analysis of Different Combinations of PV-Wind- Diesel-Battery Hybrid System for Telecommunication Applications in Different Cities of Punjab, India.” *Renewable and Sustainable Energy Reviews* 76 (January): 577–607. doi:10.1016/j.rser.2017.03.076.

Khare, Vikas, Savita Nema, and Prashant Baredar. 2016. “Solar-Wind Hybrid Renewable Energy System: A Review.” *Renewable and Sustainable Energy Reviews* 58: 23–33. doi:10.1016/j.rser.2015.12.223.

Kumar, Abhishek, Bikash Sah, Arvind R. Singh, Yan Deng, Xiangning He, Praveen Kumar, and R. C. Bansal. 2017. “A Review of Multi Criteria Decision Making (MCDM) towards Sustainable Renewable Energy Development.” *Renewable and Sustainable Energy Reviews* 69 (June 2016). Elsevier: 596–609. doi:10.1016/j.rser.2016.11.191.

Lal, Deepak Kumar, Bibhuti Bhusan Dash, and a K Akella. 2011. “Optimization of PV / Wind / Micro-Hydro / Diesel Hybrid Power System in HOMER for the Study Area.” *International Journal on Electrical Engineering and Informatics* 3 (3): 307–25.

Lambert, Tom, Paul Gilman, and Peter Lilienthal. 2006a. “Micropower System Modeling with HOMER.” *Integrated Alternative Sources Energy* 1: 379–85. doi:10.1002/0471755621.ch15

Leonforte, Fabrizio, and Claudio Del Pero. 2015. “Modeling and Performance Monitoring of a Photovoltaic – Thermal (PVT) Water Collector.” *Solar Energy* 112: 85–99. doi:10.1016/j.solener.2014.11.025.

Lozano-minguez, E, A J Kolios, and F P Brennan. 2011. “Multi-Criteria Assessment of Offshore Wind Turbine Support Structures.” *Renewable Energy* 36 (11). Elsevier Ltd: 2831–37. doi:10.1016/j.renene.2011.04.020.

Mahmoud, M, and I Ibrik. 2006. “Techno-Economic Feasibility of Energy Supply of Remote Villages in Palestine by PV-Systems, Diesel Generators and Electric Grid.” *Renewable and Sustainable Energy Reviews* 10 (2): 128–38. doi:10.1016/j.rser.2004.09.001.

Mohammadi, Kasra, and Ali Mostafaeipour. 2013. “Using Different Methods for Comprehensive Study of Wind Turbine Utilization in Zarrineh, Iran.” *Global Conference on Renewable Energy and Energy Efficiency for Desert Regions 2011 “GCREEDER 2011”* 65 (0): 463–70. doi:http://dx.doi.org/10.1016/j.enconman.2012.09.004.

Mulugetta, Yacob, Alison Doig, Simon Dunnett, Tim JACKSON, Smail Khennas, and Kavita Rai. 2005. *Energy for Rural Livelihoods*. Warwickshire.

NASA. 2015. “NASA Surface Meteorology and Solar Energy.”

Ogbonna, A C, O Onazi, and J S Dantong. 2011. “Domestic Energy Consumption Patterns in a Sub Sahara Africa City: The Study of Jos-Nigeria.” *Journal of Environmental Science Management* 3: 48–62.

Okeniyi, Joshua Olusegun, Olayinka Soledayo Ohunakin, and Elizabeth Toyin Okeniyi. 2015. “Assessments of Wind-Energy Potential in Selected Sites from Three Geopolitical Zones in Nigeria : Implications for Renewable / Sustainable Rural Electrification.” *The Scientific World Journal* 2015. Hindawi Publishing Corporation: 581679. doi:10.1155/2015/581679.

Oko, C. O. C, E. O Diemuodeke, N. F Omunakwe, and E Nnamdi. 2012. “Design and Economic Analysis of a Photovoltaic System : A Case Study.” *International Journal of Renewable Energy Developmemt* 1 (3): 65–73.

Okoye, Chiemeka Onyeka, Onur Taylan, and Derek K. Baker. 2016. “Solar Energy Potentials in Strategically Located Cities in Nigeria: Review, Resource Assessment and PV System Design.” *Renewable and Sustainable Energy Reviews* 55: 550–66. doi:10.1016/j.rser.2015.10.154.

Olatomiwa, Lanre. 2016. “Optimal Configuration Assessments of Hybrid Renewable Power Supply for Rural Healthcare Facilities.” *Energy Reports* 2: 141–46.

Ouedraogo, Bachir I., S. Kouame, Y. Azoumah, and D. Yamegueu. 2015. “Incentives for Rural off Grid Electrification in Burkina Faso Using LCOE.” *Renewable Energy* 78: 573–82. doi:10.1016/j.renene.2015.01.044.

Paul, S S, S O Oyedepo, and M S Adaramola. 2012. “Economic Assessment of Water Pumping Systems Using Wind Energy Conversion Systems in the Southern Part of Nigeria.” *Energy Exploration & Exploitation* 30 (1): 1–18.

Quan, Pharm, and Leephakpereeda. 2015. “Assessment of Wind Energy Potential for Selecting Wind Turbines: An Application to Thailand.” *Sustainable Energy Technologies and Assessment* 11: 17–26.

Ramli, Makbul A.M., H.R.E.H. Bouchekara, and Abdulsalam S. Alghamdi. 2018. “Optimal Sizing of PV/wind/diesel Hybrid Microgrid System Using Multi-Objective Self-Adaptive Differential Evolution Algorithm.” *Renewable Energy* 121: 400–411. doi:10.1016/j.renene.2018.01.058.

Rezaei, Mostafa, Ali Mostafaeipour, and Mojtaba Qolipour. 2018. “Investigation of the Optimal Location Design of a Hybrid Wind-Solar Plant: A Case Study.” *Hydrogen Energy* 43: 100–114. doi:10.1016/j.ijhydene.2017.10.147.

Roszkowska, Ewa. 2011. “Multi-Criteria Decision Making Models by Applying the TOPSIS Method to Crisp and Interval Data.” *Multi Criteria Decision Making* 6: 200–230.

Şengül, Ümran, Miraç Eren, Seyedhadi Eslamian Shiraz, Volkan Gezder, and Ahmet Bilal Sengül. 2015. “Fuzzy TOPSIS Method for Ranking Renewable Energy Supply Systems in Turkey.” *Renewable Energy* 75: 617–25. doi:10.1016/j.renene.2014.10.045.

Shahzad, M Kashif, Adeem Zahid, Tanzeel Rashid, Mirza Abdullah Rehan, Muzaffar Ali, and Mueen Ahmad. 2017. “Techno-Economic Feasibility Analysis of a Solar-Biomass off Grid System for the Electri Fi Cation of Remote Rural Areas in Pakistan Using HOMER Software.” *Renewable Energy* 106: 264–73.

Siddaiah, Rajanna, and R.P. Saini. 2016. “A Review on Planning, Configurations, Modeling and Optimization Techniques of Hybrid Renewable Energy Systems for off Grid Applications.” *Renewable and Sustainable Energy Reviews* 58. Elsevier: 376–96. doi:10.1016/j.rser.2015.12.281.

Sindhu, Sonal, Vijay Nehra, and Sunil Luthra. 2017. “Investigation of Feasibility Study of Solar Farms Deployment Using Hybrid AHP-TOPSIS Analysis: Case Study of India.” *Renewable and Sustainable Energy Reviews* 73 (February). Elsevier Ltd: 496–511. doi:10.1016/j.rser.2017.01.135.

Singh, Sarangthem Sanajaoba, and Eugene Fernandez. 2017. "Modeling, Size Optimization and Sensitivity Analysis of a Remote Hybrid Renewable Energy System." *Energy* 143 (2018): 719–39. doi:10.1016/j.energy.2017.11.053.

Sokona, Youba, Yacob Mulugetta, and Haruna Gujba. 2012. "Widening Energy Access in Africa: Towards Energy Transition." *Energy Policy* 47 (SUPPL.1): 3–10. doi:10.1016/j.enpol.2012.03.040.

SOLARGIS. 2017. "Solar Resource Map." *SOLARGIS*. http://solargis.com/products/maps-and-gis-data/free/download/nigeria.

Tesema, Samuel. 2014. "Resource Assessment and Optimization Study of Efficient Type Hybrid Power System for Electrification of Rural District in Ethiopia." *International Journal of Energy and Power Engineering* 3 (6): 331. doi:10.11648/j.ijepe.20140306.16.

The World Bank. 2017. "State O F Electricity Access."

———. 2018. "Nigeria- General Household Survey, Panel2015-2016, Wave 3." *The World Bank*. http://microdata.worldbank.org/index.php/catalog/2734.

Thiam, D R. 2011. "Renewable Energy, Poverty Alleviation and Developing Nations: Evidence from Senegal." *Journal of Energy in Southern Africa* 22 (3): 23–34.

Trading Economics. 2017. "Interest Rate in Nigeria." https://tradingeconomics.com/nigeria/deposit-interest-rate.

Yu, X, and H Qu. 2010. "Wind Power in China: Opportunity Goes with Challenges." *Journal of Renewable and Sustainable Energy* 14: 2232–39.

Zhou, Sheng, Yu Wang, Yuyu Zhou, Leon E Clarke, and James A Edmonds. 2018. "Roles of Wind and Solar Energy in China's Power Sector: Implications of Intermittency Constraints." *Applied Energy* 213 (January): 22–30.

Appendix A
Decision Matrices

Table A.1 Decision matrix for Benin-city

S/N	Criteria	Type	Alternatives							
			GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
1	Initial capital cost, $	-	840	2221	14175	11064	6433	8010	9996	9235
2	Operation and maintenance cost, $	-	2287	1674	484.74	314.17	852.85	558.01	335.28	450.89
3	Cost of energy, $/kWh	-	0.893	0.705	0.661	0.484	0.527	0.465	0.458	0.464
4	Cost of fuel, $	-	1722	1153	0	0	530	261	0	146
5	CO_2 emissions, kg/year	-	4535	3037	0	0	1397	688	0	386
6	Environmental impact, -	-	9	8	3	3	6	5	3	4
7	Unmet load, kWh/year	-	0	0	110.37	77.33	0	0	82.21	0
8	Net present cost, $	+	28,165	22,222	19,966	14,817	16,621	14,676	14,001	14,621
9	Renewable fraction, %	+	0	0	100	100	52	79	100	88
10	Sociocultural awareness, -	+	8	6	8	5	8	5	5.5	5
11	Technology readiness, -	+	8	7	8	6	8	6	6	6
12	Ease of installation, -	+	9	6	6	5	6	4	5	4
13	Natural resources Availability/predictability/randomness (wind), -	+	1	1	4	8	1	8	8	8
14	Natural resources availability/predictability/randomness (sun), -	+	1	1	7	1	7	1	7	7
15	Life cycle assessment, -	+	9	8	5	5	5	5	5	4

Table A.2 Decision matrix for Warri

S/N	Criteria	Type	Alternatives							
			GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
1	Initial capital cost, $	-	840	2221	15106	14688	6077	7674	12194	7034
2	Operation and maintenance cost, $	-	2287	1674	514.76	379.35	915.49	782.52	412.62	749.35
3	Cost of energy, $/kWh	-	0.893	0.705	0.703	0.629	0.54	0.54	0.562	0.507
4	Cost of fuel, $	-	1722	1153	0	0	577	453	0	433
5	CO_2 emissions, kg/year	-	4535	3037	0	0	1518	1193	0	1141
6	Environmental impact, -	-	9	8	3	3	6	5	3	4
7	Unmet load, kWh/year	-	0	0	110.54	80.55	0	0	90.61	0
8	Net present cost, $	+	28165	22,222	21255	19220	17014	17022	17123	15986
9	Renewable fraction, %	+	0	0	100	100	49	63	100	63
10	Sociocultural awareness, -	+	8	6	8	5	8	5	5.5	5
11	Technology readiness, -	+	8	7	8	6	8	6	6	6
12	Ease of installation, -	+	9	6	6	5	6	4	5	4
13	Natural resources Availability/predictability/randomness (wind), -	+	1	1	4	7	1	7	7	7
14	Natural resources availability/predictability/randomness (sun), -	+	1	1	7	1	7	1	7	7
15	Life cycle assessment, -	+	9	8	5	5	5	5	5	4

Table A.3 Decision matrix for Yenagoa

S/N	Criteria	Type	Alternatives							
			GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
1	Initial capital cost, $	-	840	2221	16534	13788	6242	8032	11685	8437
2	Operation and maintenance cost, $	-	2287	1674	510.41	326.38	948.83	590.22	346.07	547.47
3	Cost of energy, $/kWh	-	0.893	0.705	0.75	0.578	0.557	0.478	0.52	0.475
4	Cost of fuel, $	-	1722	1153	0	0	609	298	0	259
5	CO_2 emissions, kg/year	-	4535	3037	0	0	1605	773	0	681
6	Environmental impact, -	-	9	8	3	3	6	5	3	4
7	Unmet load, kWh/year	-	0	0	113.58	77.52	0	0	92.01	0
8	Net present cost, $	+	28165	22,222	22631	17687	17577	15082	15819	14977
9	Renewable fraction, %	+	0	0	100	100	46	76	100	79
10	Sociocultural awareness, -	+	8	6	8	5	8	5	5.5	5
11	Technology readiness, -	+	8	7	8	6	8	6	6	6
12	Ease of installation, -	+	9	6	6	5	6	4	5	4
13	Natural resources Availability/predictability/randomness (wind), -	+	1	1	4	8	1	8	8	8
14	Natural resources availability/predictability/randomness (sun), -	+	1	1	8	1	8	1	8	8
15	Life cycle assessment, -	+	9	8	5	5	5	5	5	4

Table A.4 Decision matrix for Port Harcourt

S/N	Criteria	Type	Alternatives							
			GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
1	Initial capital cost, $	-	840	2221	16019	13497	6440	8043	11518	8421
2	Operation and maintenance cost, $	-	2287	1674	512.08	311.7	924.28	556.09	332.9	517.39
3	Cost of energy, $/kWh	-	0.893	0.705	0.734	0.562	0.554	0.466	0.508	0.463
4	Cost of fuel, $	-	1722	1153	0	0	589	275	0	242
5	CO$_2$ emissions, kg/year	-	4535	3037	0	0	1552	723	0	638
6	Environmental impact, -	-	9	8	3	3	6	5	3	4
7	Unmet load, kWh/year	-	0	0	114.45	75.68	0	0	88.66	0
8	Net present cost, $	+	28165	22,222	22136	17219	17481	14686	15495	14602
9	Renewable fraction, %	+	0	0	100	100	47	78	100	80
10	Sociocultural awareness, -	+	8	6	8	5	8	5	5.5	5
11	Technology readiness, -	+	8	7	8	6	8	6	6	6
12	Ease of installation, -	+	9	6	6	5	6	4	5	4
13	Natural resources Availability/predictability/randomness (wind), -	+	1	1	4	8	1	8	8	8
14	Natural resources availability/predictability/randomness (sun), -	+	1	1	6	1	6	1	6	6
15	Life cycle assessment, -	+	9	8	5	5	5	5	5	4

Table A.5 Decision matrix for Uyo

S/N	Criteria	Type	Alternatives							
			GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
1	Initial capital cost, $	-	840	2221	14015	14681	6429	7679	11568	7527
2	Operation and maintenance cost, $	-	2287	1674	492.37	379.22	848.54	765.08	381.11	680.93
3	Cost of energy, $/kWh	-	0.893	0.705	0.66	0.627	0.525	0.533	0.529	0.497
4	Cost of fuel, $	-	1722	1153	0	0	525	446	0	383
5	CO$_2$ emissions, kg/year	-	4535	3037	0	0	1383	1175	0	1009
6	Environmental impact, -	-	9	8	3	3	6	5	3	4
7	Unmet load, kWh/year	-	0	0	114.56	76.47	0	0	89.25	0
8	Net present cost, $	+	28165	22,222	19897	19211	16566	16819	16121	15662
9	Renewable fraction, %	+	0	0	100	100	52	64	100	66
10	Sociocultural awareness, -	+	8	6	8	5	8	5	5.5	5
11	Technology readiness, -	+	8	7	8	6	8	6	6	6
12	Ease of installation, -	+	9	6	6	5	6	4	5	4
13	Natural resources Availability/predictability/randomness (wind), -	+	1	1	4	7	1	7	7	7
14	Natural resources availability/predictability/randomness (sun), -	+	1	1	9	4	9	1	9	9
15	Life cycle assessment, -	+	9	8	5	5	5	5	5	4

Table A.6 Decision matrix for Calabar

S/N	Criteria	Type	Alternatives							
			GES	GBES	PBES	WBES	GPBES	GWBES	PWBES	GPWBES
1	Initial capital cost, $	-	840	2237	16308	10134	6679	4663	8504	5289
2	Operation and maintenance cost, $	-	2280	1679	508.99	228.26	900.97	693.57	244.15	602.87
3	Cost of energy, $/kWh	-	0.88	0.678	0.74	0.52	0.553	0.456	0.459	0.448
4	Cost of fuel, $	-	1722	1152	0	0	0	436	0	371
5	CO$_2$ emissions, kg/year	-	4535	3034	0	0	1483	1147	0	977
6	Environmental impact, -	-	9	8	3	3	6	5	3	4
7	Unmet load, kWh/year	-	0	0	112.73	66.74	0	0	77.67	0
8	Net present cost, $	+	46441	35,821	22382	12218	17442	10995	10733	10793
9	Renewable fraction, %	+	0	0	100	100	50	65	100	70
10	Sociocultural awareness, -	+	8	6	8	5	8	5	5.5	5
11	Technology readiness, -	+	8	7	8	6	8	6	6	6
12	Ease of installation, -	+	9	6	6	5	6	4	5	4
13	Natural resources Availability/predictability/randomness (wind), -	+	1	1	4	9	1	9	9	9
14	Natural resources availability/predictability/randomness (sun), -	+	1	1	7	4	7	1	7	7
15	Life cycle assessment, -	+	9	8	5	5	5	5	5	4

The highlights are:

i. Wind energy potential in the South-South geopolitical region of Nigerias

ii. Multi-criteria decision making algorithm in renewable energy selection.

iii. Optimal hybrid energy system for location under multi-criteria conditions.

iv. Pertinent design parameters for the hybrid systems and cost distributions.