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Investigation of solar-wind-biomass for water pumping application and wind shear determination across different locations in Nigeria

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Abstract

In this paper, nine different wind turbines (WTs) and ten different solar photovoltaic (SPV) modules from different manufacturers were employed in order to determine the best WT and SPV for water pumping applications across the six geopolitical regions of Nigeria. Capacity factor and unit cost of energy were employed as the technical and economic indices, respectively. The study also determined the wind shear across 37 locations in the country. Relevant results revealed that turbine DW 54 EWT (T_8) and Panasonic Solar module (M_2) produce the highest capacity factor across the sites considered in this study, with Turbine T_7 producing 40.08%, 32.17%, 3.72%, 9.55%, 43.85%, and 17.26% in sites S1 to S6, respectively, and module M_2 producing 18.76%, 17.38%, 15.08%, 17.43%, 18.33%, and 19.09% in sites S1 to S6, respectively. The cost of energy produced from wind ranges from \$1.84 (S2, Abakaliki) to \$8.58/kWh (S4, Abuja); the cost of energy obtained from biomass is between \$0.42 (S4) and \$1.11/kWh (S5), while the cost of energy produced from SPV ranges from \$0.21 (S2) to \$0.40/kWh (S4). Wind energy does not produce the best feasible solution for water pumping in any of the sites considered. The results also revealed that wind shear exponent values in Nigeria range from 0.10 (Calabar) to 0.48 (Asaba).

Keywords: Wind turbine, Solar photovoltaic, Cost of energy, Capacity factor, Nigeria

Highlights

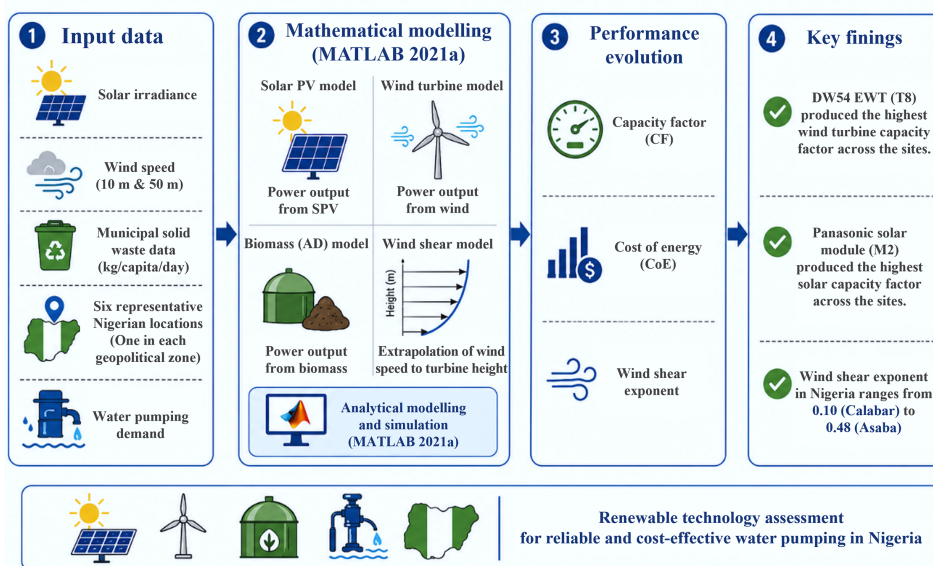
- Ten different solar photovoltaic (SPV) modules and nine different wind turbines (WTs) from different manufacturers were used to determine the best WT and SPV for water pumping applications.
- The study, which cut across the six geopolitical regions of Nigeria, used capacity factor and unit cost of energy as technical and economic indices respectively.
- Wind shear was determined across 37 locations in the country, and sensitivity analyses were performed.
- Turbine DW 54 EWT (T_8) and Panasonic solar module (M_2) produce the highest capacity factor across the sites considered in this study, with turbine T_7 producing 40.08%, 32.17%, 3.72%, 9.55%, 43.85%, and 17.26% in sites S1 to S6, respectively, and module M_2 producing 18.76%, 17.38%, 15.08%, 17.43%, 18.33%, and 19.09% in sites S1 to S6, respectively.
- Wind energy does not give the best feasible solution for water pumping in any of the sites considered, and wind shear exponent values in Nigeria range from 0.10 (Calabar)–0.48 (Asaba).

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Graphical abstract

Solar-Wind-Biomass investigation for water pumping application in Nigeria



Introduction

Water has applications for irrigation in farming, human intake and usage, and even in electric power generation; it is also germane to the growth of both living and non-living things. In fact, there is no living creature that does not use water. This has given the substance an indispensable feature. There exists a strong relationship between electric and water utility needs: water and wastewater utilities need to supply water to their customers or treat sewage before releasing it to water bodies; large quantities of electrical energy are required for the operation of these water and wastewater processes. Electric utilities also require water to generate steam, cool thermoelectric power plants, and transport fossil fuel^[1].

Several communities, institutions, and households in Nigeria are experiencing water poverty, whether as a result of the inability to extend national grid facilities to the communities or the high cost of renewable energy necessary for water pumping applications. Countries around the world are seriously looking for every means to abate the emission of greenhouse gases (GHGs) in their water pumping processes; hence, the employability of fossil fuels for water pumping or power generation is receiving less attention from researchers.

It is therefore of great importance to obtain a renewable option with a lower cost of energy and fewer emissions for water pumping in Nigeria. Wind shear is a useful factor in determining the wind speed of a location at a particular wind turbine height, given that the wind speed at an available height is known. The turbine height at which the wind speed is known and the height at which it is unknown must also be known.

Several researchers have attended to the subject of wind/solar/biomass as resources for electricity and water pumping applications. For instance, Olarewaju et al.^[2] used 13 different locations in Nigeria to obtain the economic assessment of some proposed grid-integrated solar photovoltaic systems. The study infers that the cost of energy across all the 13 locations varies from \$0.05 to \$0.06/kWh. However, the majority of the sites under study are located in the

northern part of the country. Solar, biomass, and wind energy are used in two different locations of South Africa for water pumping applications^[3]. The study infers that wind energy application is infeasible in the two locations; solar has a unit cost of energy of \$0.33 and \$0.66/kWh in locations L1 and L2, respectively, while biomass presents \$0.05/kWh. In the same vein, only two sites were used in the study. In order to perform the economic viability analysis of wind energy resources for power generation, Ayodele et al.^[4] employed a 10 kW wind turbine in Johannesburg and revealed that the cost of energy is between \$0.25 and \$0.33/kWh. However, the study was conducted with wind speed data obtained from 2005 and 2009, which may not reflect the current viability of the wind resource. In order to assess the wind energy resource potential in Sokoto, Argungu et al.^[5] used wind speed data measured at 10 m height logged for a period of three years. The findings of the study showed that electrical energy from wind in Sokoto has the capacity to compete with conventional energy sources, with a cost of energy and capacity factor of ₦17.12–18.65/kWh and 0.74–0.80, respectively, for the two turbines considered. The study considered only one location and did not take into consideration the environmental impact of the wind technology. Five different locations and four wind turbines were used in Ohunakin's study^[6], with the aim of investigating wind energy resources for electricity generation. The results of the wind speed, which were obtained at 10 m meteorological hub height, revealed that four locations (Ilorin, Makurdi, Minna, and Bida) are windier in the morning than in the afternoon periods, while Lokoja has a windy afternoon. The authors also discovered that all the locations considered will only be useful for non-connected mechanical and electrical applications with respect to their annual wind speeds. However, only the statistical and technical analysis of wind speed was of interest to the authors; the study did not consider the economic impact of the different turbines and locations. To obtain the most cost-effective system for water pumping, Tessemo et al.^[7] used photovoltaic (PV) and the organic Rankine cycle (ORC) for the rural areas of the Kanem oasis. The multi-criteria approach employed by the study revealed LCoE of \$0.31 and \$0.02/kWh, and an NPV of \$6,573.10 and \$12,068.00 for

PV and ORC systems, respectively. The authors strongly claim that ORC offers a strong alternative to PV systems and is suitable and versatile for applications like water pumping. The authors, in their efforts, did not consider wind turbines in order to consolidate the results. The Hybrid Optimization of Multiple Energy Resources (HOMER) was employed by El-Khozondar et al.^[8] to obtain the feasibility of integrating a high portion of renewable energy into Gaza's power system with the aid of a hybrid on-grid configuration. Among the numerous grid-connected scenarios that were assessed, 23.20% from wind, 48.50% from PV, 19.50% from hydropower, 8.44% from grid purchases, 0.34% from biogas, and 0.02% from geothermal produce the lowest cost of energy of \$0.03/kWh. In the future, the study aims to integrate a battery energy storage system (BESS) into the hybrid configuration and perform renewable resource variability. In order to investigate the operational strategies of wind turbines susceptible to variable wind conditions, Kadhim et al.^[9] utilize a maximum power point (MPPT) algorithm with the aim of maximizing energy capture during the periods of low to moderate wind speeds. The study underlines a hybrid economic-environmental strategy as a viable option in order to mitigate the unpredictability connected to wind energy. More efficient pitch control strategies for wind turbines in complex terrain are recognized as a future direction of study. The dynamic wind characteristics of the economic capital of Côte d'Ivoire were captured by Kouadio et al.^[10] using 1-m data. The study, which was targeted at estimating wind potential, revealed an annual energy production of 5,338 kWh/m²/day and also showed that the city harbours a moderate wind potential. The study only worked on energy potential, thereby leaving economic analysis unsolved. A 450 MW system in Xinjiang, China^[11] was used to obtain the capacity and economic configuration of an integrated solar-wind-thermal-storage power generation system. The inference from the study revealed that the net profit of the system first increases and then decreases with an increase in heat storage capacity and fixed capacity ratio. However, the environmental benefit of the hybrid model was not explicitly analysed. Six performance indicators were examined in the coastal region of Palestine^[12] to obtain the feasibility of wind turbines. The study, which used ten different turbines at three different hub heights, revealed that the Lagerway LW 58/750 turbine with a 20.50% capacity factor is the optimal choice for a wind power plant in the study location. However, the study is limited to only one study area. In terms of wind shear investigation, Gubadi in India was employed^[13] to analyse wind velocity fluctuations monthly, seasonally, and annually. The cogent results of the study revealed that no definite pattern could be observed for wind shear, and that the wind shear coefficient was found higher in winter. The Western Himalayas in India^[14] were used to carry out the Wind Atlas Analysis and Application Program (WAsP). The study, which carried out wind shear profile analysis, revealed that the percentage increase in wind speed at the 50 and 100 m heights is 15.30% and 27.00%, respectively. The authors assert that the model can be applied for low-wind speed regions worldwide. However, the study did not consider the economic and environmental potential of the site. Korabib & Warmbab in southern Namibia^[15] were employed in order to evaluate the surface roughness and wind shear coefficient. The results furnished by the authors revealed that the two parameters have mean values of 0.02–0.19 and 0.13–0.20, respectively. The authors also claim that energy yields and extrapolated hub height are dependent on the wind shear coefficient. However, the study is limited to the statistical, empirical, and energy models without considering the economic impact. Three sites in Iraq were employed^[16] to determine the atmospheric stability conditions (ASC) and wind shear coefficients (WSC). The study, which used

wind speeds taken at 10 and 50 m meteorological hub heights, revealed that the atmospheric stability conditions of the three sites were stable, stable, and strongly stable, and that the variation of 1 year WSC for the three locations is 0.23, 0.20, and 0.35, respectively. However, the study is only concerned with the daily and monthly WSC without any consideration for energy and economic impact at the three sites. As a means to determine the surface roughness parameter and wind shear coefficient, 10 and 13 m wind speed hub heights were employed in three locations of the Kisii region^[17]. The authors found that wind shear and roughness parameters in the locations of Kisii University, Ikobe, and Nyamecheo were 0.92, 0.41, and 0.54, and 3.75, 1.32, and 1.96, respectively. However, the study only deals with the wind shear coefficient and surface roughness parameter at four different turbine hub heights, leaving the energy investigation unattended. In Nigeria, several studies have been performed using renewable energy resources for water pumping. For instance, Ayodele et al.^[18] used 16-year daily average wind speed data for three selected communities in Oyo State to obtain the economic, technical, and environmental benefits of meeting the water requirements of the cities. The study found that wind power densities of the three selected cities, which range from 165.75 to 207.20 W/m², are sufficient to provide water requirements, which range from 1,987 to 2,333 m³/day. However, the study only used one renewable resource (wind energy) to carry out the study. Ibaa community in Rivers State was used^[19] to carry out the technical and cost-benefit analysis of a water pumping system directly coupled with Solar PV. The study reported that unit cost, in ₦/m³/day, reduced from ₦40.49 in the first year to ₦25.58 in the 10th year. This indicates that the proposed system is more cost-effective than the conventional public water corporation of the country. This study also engages one renewable energy source. Five 25 kW pitch-controlled wind turbines were used to carry out the techno-economic analysis of wind power generation for water pumping in Ikeja, Lagos^[20]. The relevant results of the study showed that WT5 has the highest CoE between \$0.11 and \$0.64/kWh, while WT3 has the lowest CoE between \$0.03 and \$0.13/kWh. Table 1 below reveals the research objective, methods, and evaluation metrics of some related studies.

The aforementioned literature showed that the technical and economic feasibility of renewable energy resources has been explored for different locations around the world; wind indices such as roughness parameters and wind shear have also been obtained for some locations, and only a few studies exist on renewable energy resources for water pumping applications. Table 1 also revealed that the analytical method is widely accepted by many authors, and diverse parameters are used as evaluation metrics depending on the resources employed for the study. However, this type of investigation is site-specific as there is no one resource best for all locations in a nation. To the best of the authors' knowledge, earlier studies conducted on renewable-energy-based water pumping systems in Nigeria employed only one renewable energy source, which does not allow for a side-by-side comparison with other renewable sources. Furthermore, wind speeds at a turbine hub height are needed to obtain accurate wind power of the turbine at a given site. However, wind speeds at the exact turbine height are seldom available from the meteorological station. In the event of downtime of one of the anemometers in a meteorological station or in the presence of only one anemometer, wind speeds at various hub heights can be obtained given knowledge of the wind shear exponent of the site. Therefore, this study seeks to perform a technical and economic investigation of three renewable resources (solar, wind, and biomass) for water pumping applications in six different locations and to obtain the wind shear exponent values

Table 1 Research objective, methods, and evaluation metrics in the literature

S/N	Research objective	Methods	Evaluation metrics
1	Wind energy potential in Yamoussoukro	Statistical and analytical method ^[10]	RMSE, MAE, COE, MAPE, R^2
2	Economic analysis and capacity configuration of integrated wind-solar-thermal-storage generation system	Net profit economic model based on adaptive weight particle swarm algorithm ^[11]	LCoE, Net profit
3	Techno-enviro-economic viability of wind farms in Palestine	Numerical and statistical method ^[12]	Power density and average wind speed, capacity factor, wind turbine output energy
4	Wind energy resource potential	Statistical and analytical method ^[14]	Wind speed characteristics, power density, Weibull parameters
5	Evaluation of wind shear, roughness coefficient	Statistical and analytical method ^[15]	Wind shear coefficients and roughness length
6	Determination of conditions of atmospheric stability and wind shear coefficient determination	Analytical method ^[16]	Wind shear coefficient, stability class
7	Surface roughness parameter and wind shear exponent determination	Analytical and statistical method ^[17]	Wind shear exponent, Weibull shape (k) and scale (c) parameters
8	Technical-economic analysis of hybrid solar-wind-biomass	Statistical and analytical ^[3]	Weibull parameters, LCoE, CO ₂ saved
9	Assessment of proposed grid-integrated solar	Analytical ^[2]	Y_r , Y_a , Y_p , CF, PR, PBp, LCoE
10	Techno-economic analysis of the viability of two standalone water pumping systems	Analytical ^[7]	Energy saving ratio, TLCC, NPV, LCoE, CO ₂ saving, CO ₂ cost saving

across the 36 state capitals and the Federal Capital of Nigeria. This paper therefore serves as a relevant source of scientific information for renewable energy operators, regulators, and researchers to obtain the technical and economic behaviour of the three resources considered and the knowledge of wind speed obtainable from wind shear at these locations.

Study location and data collection

The data employed for this study were obtained from six different sites in the six geopolitical regions of Nigeria. Each site is a federal university in each state capital, representing the region. The wind data used are daily average wind speeds obtained at 10 and 50 m anemometer hub heights. Both the wind speed and solar irradiation were obtained for a period of 11 years between 2014 and 2024 from the National Aeronautics and Space Administration (NASA). The waste generated, in kg/capital/day was obtained from Ogunjuyigbe et al.^[21] and Ayodele et al.^[22]. The geographical location of the sites and the waste generation expressed in kg/capital/day were furnished in Table 2. The electrical pumping requirement was obtained from Amusan et al.^[3], and this value was then used to extrapolate the energy demand for pumping requirements in each of the six sites in this study. The electrical pumping requirements for each of the sites are shown in Table 3. P_A and P_B represent the electrical pumping requirements of booster stations A and B, respectively. In Table 3, four units of 7.50 kW, two units of 5.50 kW, and four units of 3.00 kW vertical pumps are located in booster station A, while one unit of 2.32 kW and two units of 2.29 kW vertical pumps are located in booster station B. The wind turbine data were obtained from Ayodele et al., Aeolos, and EWT^[23–26], and the wind turbine parameters are presented in Table 4. The solar module parameters were obtained from Olarewaju et al.^[2] and the technical specifications of the best-performing module are furnished in Table 5.

Table 2 Location of study with their geographical location

S/N	Geographical region	Sites	Population	Waste (kg/capital/d)	Lat. (°N)	Long. (°E)
S1	Southwest	University of Ibadan	33,000	0.51	7.42	3.93
S2	Southeast	Alex Ekweme Federal University (Abakaliki)	12,230	0.53	8.29	8.62
S3	South-south	University of Benin	45,000	0.50	6.20	5.36
S4	North-central	University of Abuja	55,364	0.66	8.58	7.10
S5	Northeast	Abubakar Tafawa Balewa University (Bauchi)	18,685	0.22	9.39	10.04
S6	Northwest	Federal University, Dutse	4,532	1.00	11.42	9.22

Modelling and simulation

The methodology used in the solar-wind-biomass investigation for water pumping application is presented in this section. All modelling and simulation were performed using MATLAB 2021a.

Water pump power requirement

The overall power requirement^[3] estimated from two booster stations with power requirements P_A and P_B is given in Eq. (1):

$$P_{P1} = 1.3 \left(\sum P_A + \sum P_B \right) (kW) \quad (1)$$

The power required for pumping in station P_{P2} estimated from the population in P1 and the population in P2 is given by Eq. (2):

$$P_{P2} = 1.3 \times \left(\frac{1.77 P_{op2} \times P_{P1}}{P_{op1}} \right) (kW) \quad (2)$$

where P_{op1} is the population of location L1 with power requirement P_{p1} , P_{op2} is the population of location L2 with power requirement P_{p2} .

Solar power harvesting

The energy harvestable from solar photovoltaic (SPV)^[2] is represented by Eq. (3):

$$E_{sys(i)} = \left(1 - \frac{d_{mt}}{100} \right) * \left(1 - \frac{d_{tp(i)}}{100} \right) * \left(1 - \frac{d_{dt}}{100} \right) * G(i) * \eta_{pv,inv} * \eta_{inv} * \eta_{inv,sw} * P_{array} \quad (3)$$

In Eq. (3), $\eta_{pv,inv}$, η_{inv} , and $\eta_{inv,sw}$ denote the efficiency of the subsystem between the SPV and the inverter, the efficiency of the inverter, and the efficiency of the subsystem between the inverter and the switchboard, respectively. d_{mt} , d_{tp} and d_{dt} are the derivations due to manufacturers' tolerance, temperature, and dirt, respectively. $G(i)$ is the global horizontal irradiance of the prevailing site.

Table 3 Water pump requirements for each site

Pumps	Vertical pump rating (kW)	Unit	Total (kW)
Booster station A (P_A)	7.50	4	30.00
	5.50	2	11.00
	3.00	4	12.00
Booster station B (P_B)	2.32	1	2.32
	2.29	2	4.58
Submersible pump rating	5.00	2	10.00
Total Power ($P_A + P_B$)			69.90
Excess for future expansion			30% of ($P_A + P_B$)
Overall power requirement			91.00
Power requirement for site S1			165.00
Power requirement for site S2			61.00
Power requirement for site S3			226.00
Power requirement for site S4			278.00
Power requirement for site S5			93.00
Power requirement for site S6			23.00

Table 4 Wind turbine specifications from manufacturer data^[23–26]

Turbine index	Turbine manufacturers	Turbine operating speed range (m/s)			Rotor diameter (m)	Rated power (kW)	Hub height (m)
		V_{ci}	V_r	V_{co}			
T_1	MICON	4.0	14.0	25.0	30.0	200.0	30.0
T_2	MEPC-MICON	4.0	15.0	25.0	31.0	400.0	30.5
T_3	ENERCON E-40	2.5	13.0	25.0	44.0	600.0	46.0
T_4	VESTAS V-47	5.0	15.0	25.0	35.0	660.0	45.0
T_5	VESTAS V-52	4.0	17.0	25.0	52.0	850.0	55.0
T_6	mitsubishi MWT	4.5	14.4	24.0	29.0	300.0	30.0
T_7	DW 54 EWT	2.5	7.5	25.0	54.0	250.0	35.0
T_8	Aeolos-H 100	2.5	10.0	16.0	24.5	100.0	30.0
T_9	Aeolos-H 30	3.0	9.0	16.0	15.6	30.0	24.0

Wind power harvesting

The amount of wind power^[23] that can be obtained from wind is depicted in Eq. (4):

$$P_{e(v)} = \begin{cases} P_r \frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2}; (v_{ci} \leq v \leq v_r) \\ P_r = \frac{1}{2} \rho A C_p v_r^3; (v_{ci} \leq v \leq v_{co}) \\ 0; (v \leq v_{ci} \text{ and } v \geq v_{co}) \end{cases} \quad (4)$$

Here, v_{ci} , v_r , and v_{co} are the cut-in, rated, and cut-out wind speeds, respectively. v is the hourly, daily, or monthly average wind speed as the case may be; the daily average was used in this study. ρ denotes the air density, A is the turbine swept area, and C_p represents the coefficient of performance.

Waste generation modelling

The extrapolated population (P) of the people^[21] from which the waste is obtained is given in Eq. (5):

$$P = P_0 (1 + r)^t \quad (5)$$

where P_0 is the base population of each location, t represents the time of extrapolation interest, and r is the population rate. The total mass of waste generated (M_T) per year is represented in Eq. (6):

$$M_T = P \times w_c \times 365 \quad (6)$$

where w_c is the waste generated per capital per day.

The quantity of waste taken to dump site can be obtained as

$$M_F = 0.74 \times M_T \text{ (kg/year)} \quad (7)$$

Table 5 Technical specifications of the best (Panasonic solar) SPV module^[27]

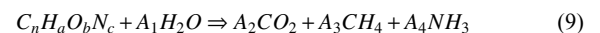
S/N	SPV module parameters	Rating
1	Nominal maximum power (P_{max})	335.00 Wp
2	Opt. operating voltage (V_{mp})	59.90 V
3	Opt. operating current (I_{mp})	5.60 A
4	Open-circuit voltage (V_{oc})	71.50 V
5	Short-circuit current (I_{sc})	6.05 A
6	Module efficiency ($M\%$)	20.00%
7	Operating temperature ($T_{op}(-), T_{op}(+)$)	$-40^\circ\text{C} \sim +85^\circ\text{C}$
8	Maximum system voltage (V_{ms})	1,000 V
9	Max. Series fuse rating (I_{msf})	15 A
10	Power tolerance (P_{tol})	$\pm 3.00\%$
11	Cell type	Monocrystalline silicon
12	Temperature coefficient (P_{max}) (γ)	$-0.26\%/^\circ\text{C}$
13	Temperature coefficient (V_{oc}) (β)	$-0.24\%/^\circ\text{C}$
14	Temperature coefficient (I_{sc}) (α)	$+0.06\%/^\circ\text{C}$
15	Model number (N_{md})	VBHN335KJ01
16	Degradation rate	3.00% (first year), 0.45%/year

Models of anaerobic digestion technology for energy generation from municipal solid waste (MSW)

Biogas is made up of a mixture of carbon dioxide (CO_2), methane (CH_4), and small traces of other gases. The mass of methane^[21] that is obtainable from any potential waste-to-energy project using anaerobic digestion technology is given in Eq. (8):

$$M_{CH_4} = \frac{16 * A_3}{(M_c * n) + (M_H * a) + (M_O * b) + (M_N * c)} * 1,000 \quad (8)$$

The model for determining the expected methane yield^[28] from anaerobic digestion of organic compounds having a composition of $C_n H_a O_b N_c$ is given in Eq. (9):



where A_1 , A_2 , A_3 , and A_4 are the coefficients of water, carbon dioxide, methane, and ammonia, respectively, in the anaerobic chemical equation.

n , a , b , and c are the mole ratios of carbon, hydrogen, oxygen, and nitrogen, respectively, and are furnished in Eq. (10a–d):

$$n = \frac{K_c}{M_c} \quad (10a)$$

$$a = \frac{K_H}{M_H} \quad (10b)$$

$$b = \frac{K_O}{M_O} \quad (10c)$$

$$c = \frac{K_N}{M_N} \quad (10d)$$

K_c , K_H , K_O , and K_N are the elemental compositions and M_c , M_H , M_O , and M_N are the molar masses of carbon, hydrogen, oxygen, and nitrogen, respectively.

The mass of CO_2 that can be obtained using anaerobic digestion is represented in Eq. (11):

$$M_{CO_2} = \frac{44 * A_2}{(M_c * n) + (M_H * a) + (M_O * b) + (M_N * c)} * 1000 \quad (11)$$

where

$$A_1 = \frac{(4n - a - 2b + 3c)}{4} \quad (12a)$$

$$A_2 = \frac{(4n - a + 2b + 3c)}{8} \quad (12b)$$

$$A_3 = \frac{(4n + a - 2b - 3c)}{8} \quad (12c)$$

The volume of methane that can be obtained using anaerobic technology is represented in Eq. (13):

$$V_{CH_4} = \frac{M_{CH_4}}{\rho_{CH_4}} \quad (13)$$

The volume of CO₂ that can be obtained is given in Eq. (14):

$$V_{CO_2} = \frac{M_{CO_2}}{\rho_{CO_2}} \quad (14)$$

where ρ_{CH_4} and ρ_{CO_2} represent the density of methane and carbon dioxide, respectively.

Equation (15) gives the total volume of biogas available using anaerobic digestion technology:

$$V_{bio} = (V_{CO_2} + V_{CH_4}) \quad (15)$$

The electrical energy that can be obtained from the biogas generator is given in Eq. (16):

$$E_{P(AD)} = \frac{(0.85 * \eta * LHV * M_{F(AD)})}{C_o} \quad (16)$$

The lower heating value (LHV) of methane^[29] and higher heating value (HHV)^[30] can be represented as given in Eqs (17) and (18), respectively:

$$LHV = HHV - (9 * \%H + \%H_2O) * 2.44 \quad (17)$$

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.015N - 0.0211A \quad (18)$$

where C, H, O, N, S, and A are the carbon, hydrogen, oxygen, nitrogen, sulphur, and ash content of the material.

Equation (19) represents the size of the generator with respect to the estimated biogas, and is given by

$$G_{P(AD)} = \frac{E_{P(AD)}}{8760 * CF} \quad (19)$$

where CF is the capacity factor of the digester.

Economic modelling of solar-wind-biomass technology

This section discusses the economic models of solar-wind-biomass employed in this study.

Economic models for SPV

The unit cost of energy is the aggregate cost of installation and operation of the system measured in \$/kWh.

The overall cost/watt (C_{ok}) of a commercial ground-mounted PV is \$1.74/W^[31] as given in Eq. (20a):

$$C_{ok} = 1.74P_i \quad (20a)$$

$$C_{i(pv)} = 1.16C_{ok} \quad (20b)$$

$$C_{om(pv)} = 0.64C_{ok} \quad (20c)$$

$$C_{ib(pv)} = 0.07C_{ok} \quad (20d)$$

$$C_{m(pv)} = 0.39C_{ok} \quad (20e)$$

where $P_{i=1:k}$ is the electrical power requirement of each site, k is the number of sites in this study, $C_{i(pv)}$ represents the installation cost given in Eq. (20b), $C_{om(pv)}$ is the operation and maintenance cost represented in Eq. (20c), $C_{ib(pv)}$ is the cost of inverter and battery in the PV system furnished in Eq. (20d), and $C_{m(pv)}$ is the miscellaneous cost as given in Eq. (20e). i denotes the interest rate while f is the inflation rate.

Equation (21) represents the total cost incurred throughout the lifetime of the system:

$$C_{TO(pv)} = C_{ok} + C_{om(pv)} \left(\frac{1+f}{i+1} \right) \left[1 - \left(\frac{1+f}{1+i} \right)^n \right] + C_{i(pv)} + C_{m(pv)} + C_{ib(pv)} \quad (21)$$

The unit cost of energy $C_{uc(pv)}$ obtained from SPV is given by Eq. (22):

$$C_{uc(pv)} = \frac{C_{TO(pv)}}{P_{pv} * t} \quad (22)$$

Economic models for wind

The unit cost of wind energy in a location provides foreknowledge of the economic feasibility of the system at that location. The unit cost is represented as given in Eq. (23):

$$C_{TO(w)} = I + C_{om(w)} \left(\frac{1+f}{i+1} \right) \left[1 - \left(\frac{1+f}{1+i} \right)^n \right] - s_c \left(\frac{1+f}{1+i} \right)^n + C_{ci(w)} + C_{m(w)} + C_{ib(w)} \quad (23)$$

where $I = C_{asp} * P_r$, n is the lifetime of the system taken as 25 years, s_c represents the salvage value, I denotes the investment and installation cost, $C_{ib(w)}$ is the cost of the inverter and the battery in the wind energy system, and $C_{m(w)}$ is the miscellaneous cost. $C_{ci(w)}$ denotes the cost of installation and civil work while f is the inflation rate. P_r is the turbine rated power and C_{asp} showed the average specific cost per kW.

Hence, the unit cost of energy $C_{uc(wind)}$ obtainable from the wind turbine is depicted as given in Eq. (24):

$$C_{uc(w)} = \left(\frac{C_{TO(w)}}{P_{avg(w)} * t} \right) \quad (24)$$

Economic models for biomass system

The unit cost of energy for a biomass system is furnished as given in Eq. (25)^[32]:

$$C_{uc(Bio)} = \left(\frac{LCC}{E_{p(AD)}} \right) * CRF \quad (25)$$

where LCC represents the life cycle cost as given in Eq. (26), CRF denotes capital recovery factor furnished in Eq. (27), and $E_{p(AD)}$ is the electrical energy obtained from anaerobic digestion.

$$LCC = C_{inv(i)} + \sum_{n=1}^N \frac{C_{O\&M(i)}}{(1+d_n)^n} \quad (26)$$

$$CRF = \frac{d_n(1+d_n)^N}{(1+d_n)^N - 1} \quad (27)$$

where

$$C_{inv(AD)} = (51827.082 * M_{F(AD)}^{0.55}) \quad (28)$$

$$C_{O\&M(AD)} = (25340.71553 * M_{F(AD)}^{-0.61}) \quad (29)$$

d_n is the nominal discount rate and $M_{F(AD)}$ represents the capacity of the biomass system in tons per year. $C_{inv(AD)}$ and $C_{O\&M(AD)}$ given in Eqs (28) and (29) are the investment and operation and maintenance costs for anaerobic digestion.

The economic parameters used in this study are furnished in Table 6 below. Annual operation and maintenance cost (O&M) for solar power systems is taken as 1%–2% of the investment cost^[33] over the 25-year lifecycle. The operation and maintenance cost of a biomass^[21] system is given in Eq. (29).

Wind shear model

The wind shear exponent of a given site^[34] can be obtained as given in Eq. (30):

Table 6 Economic parameters of the renewable resources

Parameter	SPV	Wind	Biomass
Interest rate (i)	0.27	0.27	
Inflation rate (f)	0.22	0.22	0.22
Discount rate (d_n)			0.30
O&M cost (C_{om})	0.02 C_{ok} (annually)	0.25 I	Eq. (29)
Lifetime (n)	25	25	15
Installation and civil work (C_{ci})		0.04 I	
Battery and inverter (C_{ib})		0.13 I	

I shows that operation and maintenance cost of a wind turbine system is 25% of the investment and installation cost.

$$p = \frac{\log\left(\frac{v_1}{v_2}\right)}{\log\left(\frac{h_1}{h_2}\right)} \quad (30)$$

where v_1 and v_2 are known wind speeds at corresponding heights h_1 and h_2 , respectively. Equation (31) is thereafter used for extrapolation to obtain the unknown wind speed:

$$v_i = v \left(\frac{h_d}{h} \right)^p \quad (31)$$

where h_d is the desired turbine hub height, h depicts the hub height of the available wind, v represents the velocity of the available wind, and v_i is the velocity of the wind at the desired hub height.

Capacity factor (CF)

The capacity factor of an SPV system is the average output power obtained from an SPV over a defined period of time to the power produced when operated at rated capacity over the same defined period of time^[34]. In the same vein, the CF of a wind turbine (WT) system is the average power output obtained from the WT system over a definite period of time to the power produced when operated at rated capacity over the same definite period of time. The CF of solar photovoltaic and wind turbine system are furnished in Eqs (32) and (33), respectively:

$$Cf_w = \frac{P_{a,w}}{P_{r,w}} \quad (32)$$

$$Cf_{spv} = \frac{P_{a,spv}}{P_{r,spv}} \quad (33)$$

where $P_{a,w}$ is the average output power of the wind turbine, $P_{r,w}$ represents the rated power of the wind turbine. $P_{a,spv}$ and $P_{r,spv}$ are the average output power and rated power of the SPV system, respectively. Cf_w and Cf_{spv} denote the wind turbine and solar photovoltaic capacity factors, respectively.

Table 7 Solar PV capacity factor for different modules and sites under study

Sites	Parameters	Solar module performance									
		M ₁	M ₂	M ₃	M ₄	M ₅	M ₆	M ₇	M ₈	M ₉	M ₁₀
S1	Cf (%)	18.18	18.76	18.50	18.20	18.30	18.22	18.25	18.06	18.20	18.15
S2	Cf (%)	16.83	17.38	17.06	16.81	16.92	16.81	16.86	16.61	16.82	16.76
S3	Cf (%)	14.63	15.08	14.85	14.59	14.68	14.63	14.65	14.48	14.61	14.58
S4	Cf (%)	14.09	17.43	17.15	16.86	14.17	16.90	16.91	16.71	16.87	16.83
S5	Cf (%)	17.75	18.33	18.02	17.76	17.86	17.75	17.80	17.56	17.76	17.70
S6	Cf (%)	18.43	19.09	18.72	18.40	18.72	18.44	18.81	18.25	18.25	18.53

The bolded data shows that Solar module M2 gives the highest capacity factor in all the sites.

Environmental models

The environmental impact is modelled such that the quantity of coal needed^[3] for the complete life cycle of a biomass plant for the generation of electrical power is given in Eq. (34):

$$Q = \frac{8760 \times E_p \times H_{ie} \times l_c}{1000 \times \eta_{bc} \times \eta_{sc} \times HHV} \text{ (tonnes)} \quad (34)$$

where E_p represents the electrical power generated (kW) at each site p , H_{ie} denotes the heat required to produce a unit kW of electricity, l_c is the life cycle of biomass plant, η_{bc} , η_{sc} are the efficiencies of the boiler and combustion unit, and efficiency of the steam cycle, respectively. HHV represents the high heating value or gross calorific value which describes the energy content in coal. The carbon (IV) oxide equivalent of a tonne of coal is 2.86 tonnes CO_{2eq}^[35]. This value was used to obtain the CO_{2eq} of coal in the six locations considered for environmental analysis.

Results and discussion

This section unveils the results of the solar-wind-biomass for water pumping application and wind shear across different locations in Nigeria. The study was performed using a Federal University site in each of the six geopolitical zones in Nigeria. The wind shear determination was performed using 37 sites, and MATLAB 2021a was employed for simulations in this study.

Panasonic solar module and the EWT DW 54 (T₇) wind turbine have the highest capacity factors in all the sites under study, as furnished in Tables 7 and 8, respectively. The site in Dutse possesses the highest SPV capacity factor among all the sites. Even though turbine (T₇) has the highest capacity factor among all the sites, its rated power is much higher than some of the applications in this study. Based on the load demand requirements, this study employs turbine (T₁) with a rated power of 200 kW for site 1, turbine (T₈) with a rated power of 100 kW for site 2, turbine (T₇) with a rated power of 250 kW for site 3, turbine (T₃) with a rated power of 600 kW for site 4, turbine (T₈) with a rated power of 100 kW for site 5, turbine (T₉) with a rated power of 30 kW for site 6.

Figure 1 shows that at site S1(Ibadan), SPV produces the least cost of energy (\$0.26/kWh) while wind is associated with the highest cost of energy (\$5.95/kWh); in site S2 (Abakaliki), the cost of energy ranges from \$0.21 (SPV) to \$1.84/kWh (wind); in site S3 (Benin), SPV gives the least cost of energy (\$0.35/kWh) while wind is associated with the highest cost of energy (\$8.58/kWh); in site S4 (Abuja), the cost of energy ranges from \$0.40 (SPV) to \$4.11/kWh (wind); in site S5 (Bauchi), SPV produces the least cost of energy (\$0.30/kWh) while wind is associated with the highest cost of energy (\$2.05/kWh); in site S6 (Dutse), the cost of energy ranges from \$0.24 (SPV) to \$4.67/kWh (wind). In all, the cost of energy obtained from SPV is between \$0.21 (Abakaliki) and \$0.40/kWh (Abuja); the cost of energy obtained from biomass ranges from \$0.42 (Abuja) to

Table 8 Capacity factor of different turbines

Sites	Parameters	Wind turbine performance								
		T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉
S1	Cf/%	7.56	6.51	17.19	4.44	4.98	5.94	40.08	22.72	25.88
S2	Cf/%	5.42	4.66	13.88	2.99	3.57	4.11	32.17	18.10	20.00
S3	Cf/%	0.01	0.01	2.39	0.00	0.01	0.00	3.72	1.98	0.99
S4	Cf/%	0.38	0.33	4.41	0.05	0.25	0.14	9.55	5.09	4.09
S5	Cf/%	8.58	7.39	17.77	5.13	5.65	6.84	43.85	24.42	28.62
S6	Cf/%	1.33	1.14	8.25	0.20	0.87	0.58	17.26	9.21	8.94

The bolded data shows that Wind turbine T7 gives the highest capacity factor in all the sites.

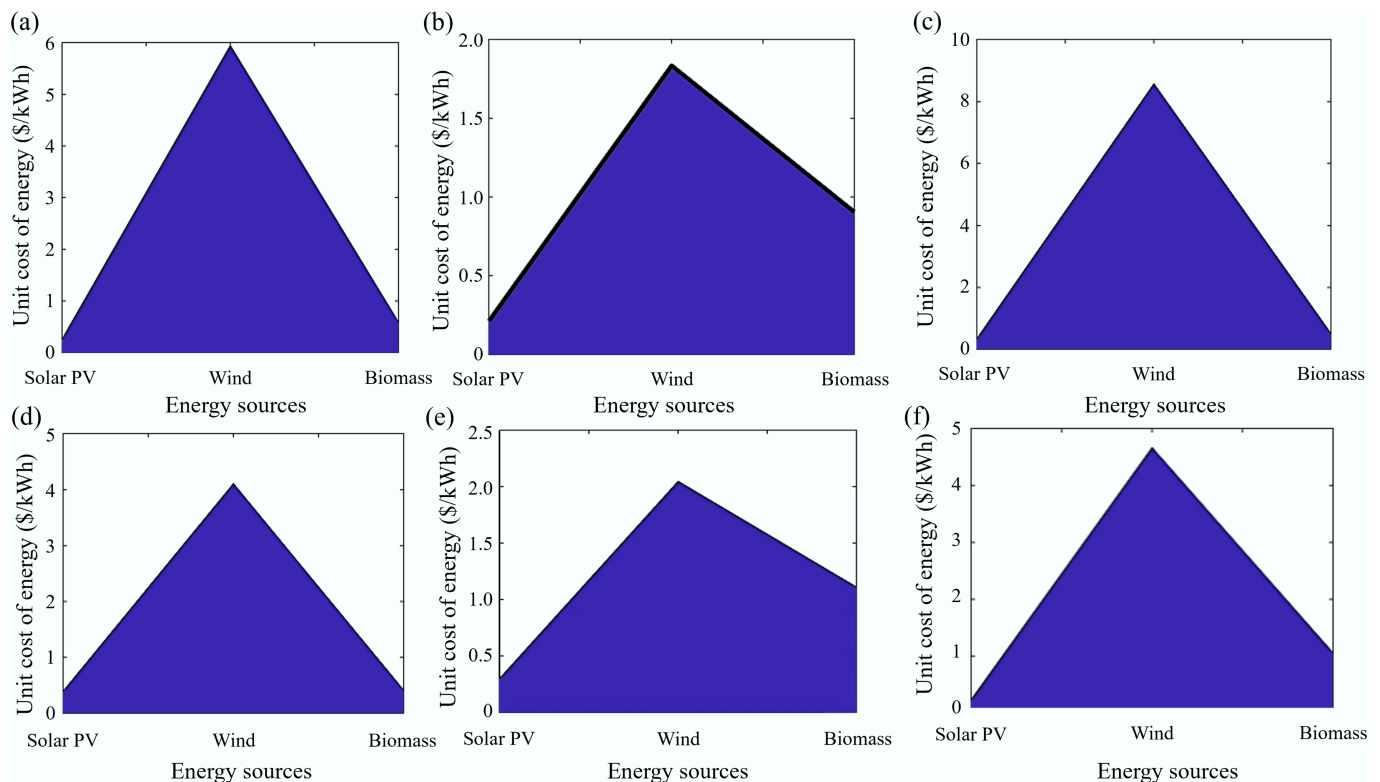
\$1.11/kWh (Bauchi), while that obtained from wind is between \$1.84 (Abakaliki) and \$8.58/kWh (Benin). In order to validate the results obtained in this study, the results obtained are compared with those in earlier studies and are furnished in Table 9. The table shows that wind energy is not feasible for water pumping

applications in the two sites under consideration in South Africa^[3], with LCoE of \$26,943 and \$50,915/kWh, respectively. Other results in the literature indicate that the results obtained in this study are comparable to those obtained by earlier researchers. In order to get more insights into the cost of energy of wind resources, this study obtained the relationship between the average wind speed and the cost of energy across all the sites considered in this study, and the results are furnished in Fig. 2. The figure shows that site S3 (Benin), which has the minimum wind speed of 1.85 m/s, also possesses the maximum cost of energy (\$8.58/kWh). This is due to the low wind speed in the Benin region. Site S5 (Bauchi) produces the maximum wind speed of 4.03 m/s. The cost of energy is between \$1.84 (Abakaliki) and \$8.58/kWh (Benin). Site S2 gives the lowest cost of energy of \$1.84/kWh as a result of a lower load requirement when compared to site S5, in which the turbine employed has the same cut-in wind speed.

The same turbine (turbine 8), with a cut-in wind speed of 2.50 m/s, was used to size site S5 (Bauchi) and was also used to size site S2 (Abakaliki); however, the rated load at Bauchi (93.00 kW) is higher than that at Abakaliki (61.00 kW); therefore, site S2 presents

Table 9 Cost of energy in the literature compared with this study

Country/location		LCoE
South Africa ^[3]	Wind	\$26,943/kWh (University of Johannesburg), \$50,915/kWh (Zuikerbosh pumping station)
	SPV	\$0.33/kWh (L1), \$0.66/kWh (L2)
	Biomass	\$0.05/kWh (L1), \$0.05/kWh (L2)
Nigeria	Biomass (AD) ^[22]	\$0.03–0.07/kWh
	Biomass (LFG)	\$0.04–0.05/kWh
	Wind ^[36]	\$0.03–0.71/kWh
	SPV ^[2]	\$0.05–0.06/kWh
Chad ^[7]	ORC	\$0.02/kWh
	SPV	\$0.03/kWh

**Fig. 1** Unit cost of energy for solar, wind, and biomass in sites S1 to S6.

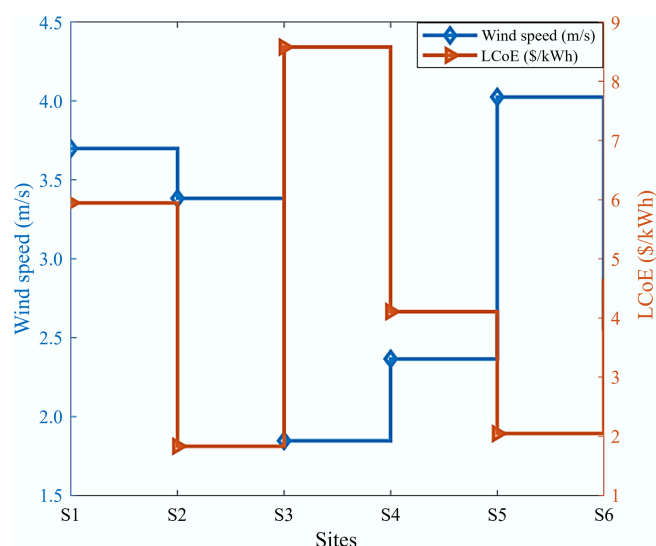


Fig. 2 Relationship between wind speed and LCoE.

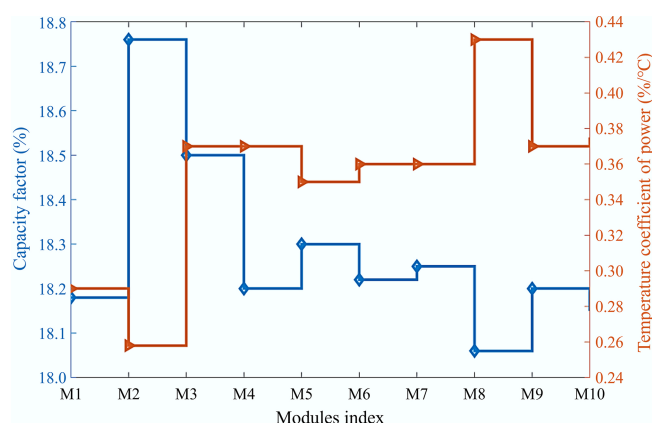


Fig. 3 Relationship between modules temperature coefficient of power and capacity factor.

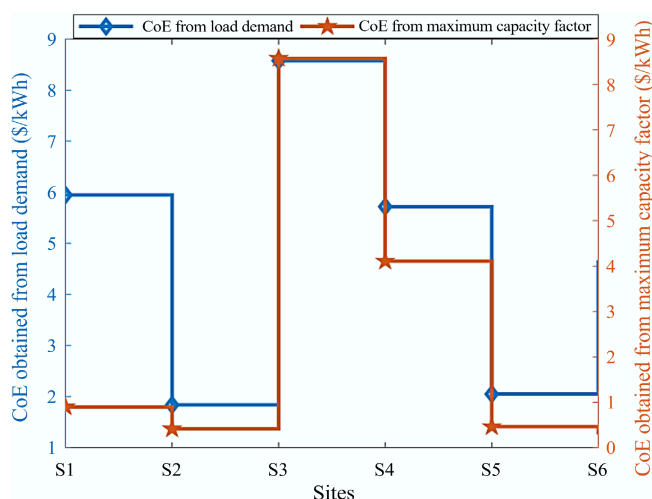


Fig. 4 Cost of energy (CoE) with maximum load demand and CoE with maximum capacity factor at different sites under study.

the lowest cost of energy. This depicts that the wind speed of the site, appropriate sizing and selection of the wind turbine, and the load demand are factors that affect the cost of energy of a wind turbine. It is also worthy of note that turbine DW 54 EWT produces the highest capacity factor in all the sites because it has the lowest cut-in wind speed of 2.50 m/s and also produces its rated power at the rated speed of 7.50 m/s (which is the lowest among the turbines considered in this study). Hence, turbines that are characterized by low cut-in wind speed and produce their rated power at a lower wind speed are better candidates to obtain a high capacity factor. To investigate the relationship between the capacity factor and temperature coefficient of power, the site in Ibadan (S1) was used for the study, and the result is furnished in Fig. 3. The figure shows that module M2 (Panasonic solar), which has the lowest temperature coefficient of power (0.26 %/°C), also possesses the highest capacity factor, while module M8 (0.43 %/°C), which has the highest temperature coefficient of power, has the lowest capacity factor. Hence, module M2 was able to produce a higher capacity factor as a result of its lower temperature coefficient of power. Consideration should be given to modules with lower temperature coefficients of power in order to obtain a higher capacity factor.

Effect of wind turbine selection based on maximum capacity factor on the unit cost of energy

To investigate the impact of wind turbine selection based on maximum capacity factor on the unit cost of energy, this study employed turbine (T_7), which has the maximum capacity factor across all the sites, and used the energy output of the turbine to obtain the cost of energy. The cost of energy obtained is then compared with that obtained when the wind turbine with rated power close to the load demand was used, and the result is furnished in Fig. 4. The figure shows that the cost of energy when the turbine with maximum capacity factor was used is between \$0.29 (site S6) and \$8.58/kWh (site S3), while that obtained when wind power close to the load demand was used ranges from \$1.84 (site S2) to \$8.58/kWh (site S3). It can be observed that the cost of energy obtained from the turbine with maximum capacity factor is lower than that obtained from load demand by 84.92%, 77.50%, 0.00%, 28.18%, 77.45%, and 93.78% in sites S1, S2, S3, S4, S5, and S6, respectively. If the producer is

interested in a lower cost of energy, excess energy generated when the wind turbine with the maximum capacity factor is used can be used for other energy applications. It should be noted that there is no reduction in the cost of energy at site S3 because the same turbine (T_7) that produces the maximum capacity factor is the turbine that matches the site from the load demand perspective.

Environmental analysis

The carbon (IV) oxide that was abated by using solar photovoltaic generation instead of coal generation in the six locations under study is furnished in Table 10. The table shows that the amount of carbon (IV) oxide that was abated by using SPV instead of a coal-fired power plant in the six sites is between 7,678.5 tonnes (site 6) and 93,802.0 tonnes (site S4). This shows that solar photovoltaic technology played a key role in abating carbon emissions in the process of electricity generation.

Table 10 Environmental effect of replacing coal with SPV

Parameters	Sites					
	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
CO ₂ saved (tonnes)	55,911.0	20,721.0	76,243.0	93,802.0	31,658.0	7,678.5

Impact of yearly variation of wind speed on the shear exponent

To investigate the impact of yearly variation of the wind shear exponent, 11-year data from 2014 to 2024 was employed at a representative site of the six geopolitical regions of Nigeria, and the results are presented in Fig. 5. The figure shows that wind shear in Asaba is between 0.48 and 0.51, corresponding to 2015 and 2021, respectively. Wind shear in Abeokuta ranges from 0.29 in 2016 to 0.31 in 2021; Awka wind shear logged 0.28 and 0.30 as the minimum and maximum, corresponding to 2024 and 2021, respectively. Wind shear in Dutse is between 0.33 and 0.35, corresponding to 2023 and 2022, respectively. Wind shear in Bauchi ranges from 0.21 in 2024 to 0.23 in 2022; wind shear in Abuja logged 0.24 and 0.26 as the minimum and maximum, corresponding to 2019 and 2023, respectively. Hence, the operating region of wind shear for the six locations throughout the 11-year horizon is furnished in Eq. (35):

$$W_{sh} = \begin{cases} 0.49 \pm 0.01 & \text{Asaba} \\ 0.30 \pm 0.01 & \text{Abeokuta} \\ 0.29 \pm 0.01 & \text{Awka} \\ 0.33 \pm 0.01 & \text{Dutse} \\ 0.22 \pm 0.01 & \text{Bauchi} \\ 0.25 \pm 0.01 & \text{Abuja} \end{cases} \quad (35)$$

where W_{sh} is the wind shear of the location under study.

Sensitivity of the discount rate on the cost of energy and seasonal variability of variable renewable resources

To investigate the impact of the sensitivity of the discount rate on the cost of energy, site S1 (Ibadan) and the biomass model were employed for the analysis, and the results are furnished in Fig. 6. The discount rate was increased from 30.29% (base case) in steps of 10% to 50.29% and was also reduced in steps of 10% to 10.29%. The study obtained the cost of energy between \$0.32 and \$0.92/kWh when the discount rate was increased from 10.20% to 50.29%. This revealed that the cost of energy of an anaerobic biomass plant increases with an increasing discount rate. In order to investigate the variability of renewable energy resources, this study grouped the locations in the northern and southern regions of the country separately and studied the GHI (global horizontal irradiance) and WS (wind speed) as furnished in Figs 7–10, respectively. In Nigeria, two seasons are prevalent: the dry season (November–March) and rainy season (April–October). Figure 7 shows that in the north-central region (Abuja), wind speed ranges from 1.74 (October) to 3.00 m/s (April); in the northeast region (Bauchi), wind speed is between 2.16 (September) and 6.04 m/s (December); in the northwest region (Dutse), wind speed is between 1.73 (September) and 3.10 m/s (January). In the southwest region (Ibadan), Fig. 8 shows that wind speed ranges from 2.36 (September) to 5.58 m/s (December); wind speed is between 4.06 (August) and 6.31 m/s (November) in the

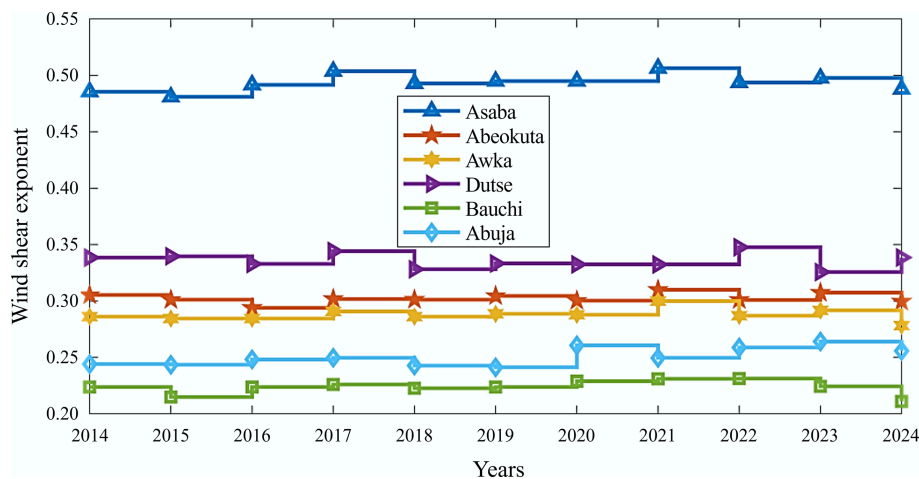


Fig. 5 Yearly variation in wind shear exponent.

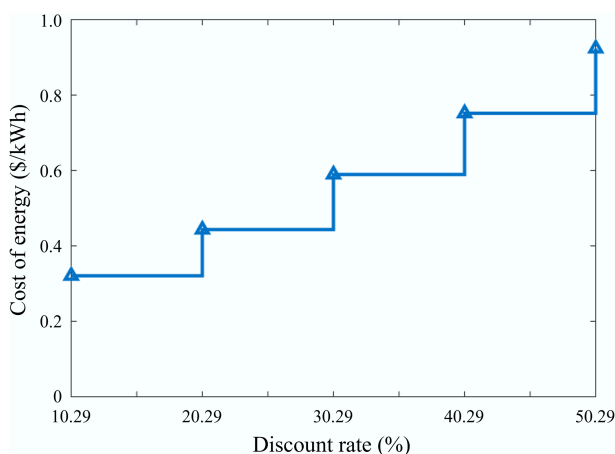


Fig. 6 Influence of increase in discount rate on the cost of energy.

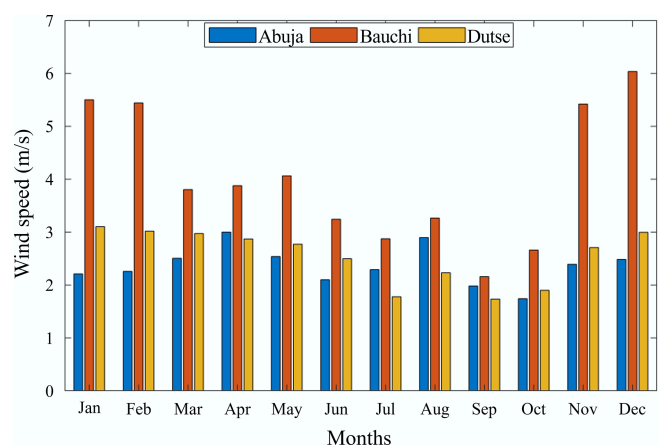


Fig. 7 Wind speed resource variability in the northern regions.

southeast region (Abakaliki); while wind speed is between 3.45 (July) and 5.55 m/s (November) in the south-south region (Benin). This revealed that wind speed is generally low in the rainy season while high wind speeds are experienced in the dry season, except in the north-central region (Abuja), which has its upper boundary wind speed in April, equivalent to some lower boundary wind speeds in other regions. In the same vein, Fig. 9 shows that GHI in the north-central region (Abuja) is between 4.11 (August) and 6.27 kWh/m²/d (November); in the northeast region (Bauchi), GHI ranges from 4.25 (August) to 6.29 kWh/m²/d (November), while GHI is between 4.68 (August) and 6.29 kWh/m²/d (March) in the northwest region. Figure 10 also shows that GHI is between 4.19 (August) and 6.39 kWh/m²/d (March) in the southwest region; GHI ranges from 4.05 (August) to 6.31 kWh/m²/d (November) in the southeast region (Abakaliki), while GHI is between 3.45 (July) and 5.55 kWh/m²/d (November) in the south-south region (Benin). This shows that solar GHI is low in the rainy season, while high irradiation is experienced in the dry season. Hence, wind speed and solar GHI are low in the rainy season and high during the dry season in Nigeria.

Determination of wind shear exponent

To determine the wind shear exponents of different locations in Nigeria, daily average wind data for 1 year (2024) was employed for 37 locations which are the capitals of each state in the country, together

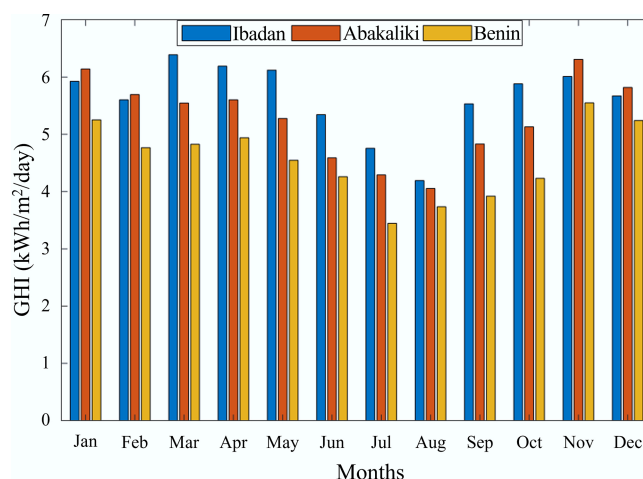


Fig. 10 GHI resource variability in the southern regions.

with the Federal Capital Territory (FCT), were used for the investigation, and the results were furnished in Table 11. The table shows that annual wind shear exponent values range from 0.10 (Calabar) to 0.48 (Asaba) in Nigeria.

Conclusions

Solar, wind, and biomass resources have been investigated for water pumping applications in the six geopolitical regions of Nigeria, and wind shear has also been determined for 37 locations in the country. Unit cost of energy and capacity factor were employed as economic and technical indices, respectively. The effect of appropriate wind turbine capacity factor on unit cost of energy, impact of yearly variation of wind speed on shear exponent, influence of increase in installed capacity of wind on capacity factor, the determination of wind shear exponent across 37 locations, and seasonal variability of variable renewable resource (VRR) were performed. The outcome of the study shows that wind turbine DW 54 EWT (T₇) and Panasonic solar module (M₂) produce the highest capacity factors across the sites. SPV is the best candidate for water pumping applications from the cost of energy point of view. The range of wind shear exponent in Nigeria is between 0.10 (Calabar) and 0.48 (Asaba) for a typical year, and yearly variation in wind shear for Asaba, Abeokuta, Awka, Dutse, Bauchi, and Abuja are 0.49 ± 0.01 , 0.30 ± 0.01 , 0.29 ± 0.01 , 0.33 ± 0.01 , 0.22 ± 0.01 , and 0.25 ± 0.01 , respectively. Seasonal variability of wind speed and solar GHI is low in the rainy season and high during the dry season in Nigeria.

Ethical statements

During the preparation of this study, the authors did not use any AI tools for language refinement, data analysis, figure enhancement, or any other purpose. The authors take full responsibility for the integrity and originality of the final manuscript.

Author contributions

The authors confirm their contributions to the paper as follows: all authors contributed to the study conception and design. Richard Oladayo Olarewaju: writing – first and final draft. Ayodeji Samson Olatunji Ogunjuyigbe and Temitope Raphael Ayodele: supervision, editorial work, review and writing. Samson Oladayo Ayanlade:

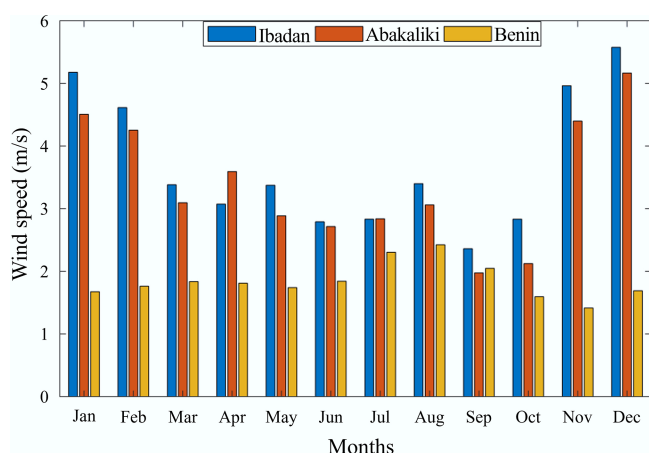


Fig. 8 Wind speed resource variability in the southern regions.

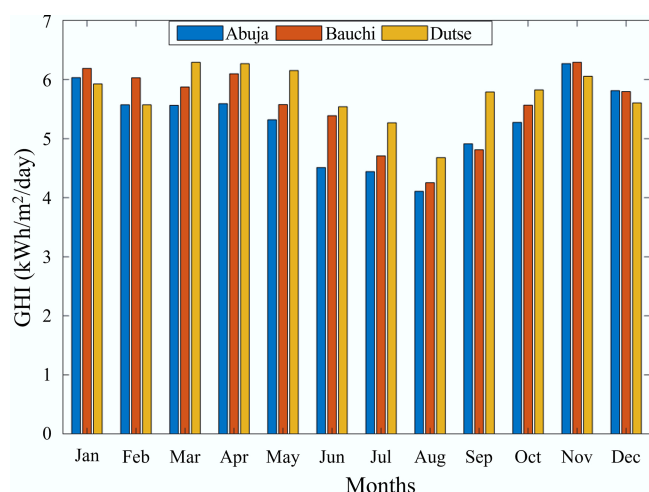


Fig. 9 GHI resource variability in the northern regions.

Table 11 Wind shear exponent for different regions

Region	Wind shear exponent	
(a) North-central region	Minna	0.24
	Lokoja	0.24
	Makurdi	0.26
	Jos	0.23
	Lafia	0.25
	Ilorin	0.24
(b) Northeast region	Abuja	0.25
	Bauchi	0.21
	Maiduguri	0.25
	Jalingo	0.25
	Yola	0.22
	Gombe	0.22
(c) Northwest region	Damaturu	0.25
	Gusau	0.23
	Sokoto	0.23
	Kaduna	0.27
	Birnin kebbi	0.27
	Katsina	0.30
(d) Southeast region	Kano	0.24
	Dutse	0.33
	Enugu	0.24
	Owerri	0.30
	Abakaliki	0.26
	Umuahia	0.30
(e) South-south region	Awka	0.27
	Yenagoa	0.38
	Uyo	0.36
	Benin City	0.33
	Port Harcourt	0.28
	Calabar	0.10
(f) Southwest region	Asaba	0.48
	Ibadan	0.28
	Ado Ekiti	0.29
	Oshogbo	0.35
	Akure	0.41
	Ikeja	0.18
	Abeokuta	0.30

literature review, editorial work, review and writing. Ignatius Kema Okakwu: literature review and editorial work. Olusola Kunle Akinde: editorial work, review and writing. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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