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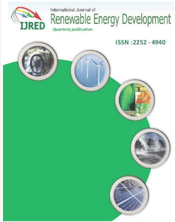

Research Article

Comparative Thermo-Economic and Advanced Exergy Performance Assessment of Wind Energy for Distributed Generation in Four Sites in Nigeria

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ABSTRACT. Electricity access and reliability in Nigeria is poor due to obsolete power distribution infrastructure. This could be improved by deploying wind energy resources. The present research assessed the thermo-economic, advanced and extended exergy analysis of deploying wind turbine for distributed generation in four Nigerian locations. The air temperature and wind speed of the sites was used together with Weibull statistical parameters to mathematically model the thermodynamic performance of selected wind turbine for the sites. The results show that the energy and standard exergy efficiency of the sites ranges from 0.16 – 0.44, 0.05 – 0.37, 0.23 –0.39, 0.26 – 0.37 and 0.12 –0.33, 0.04 – 0.25, 0.17 – 0.28, 0.18 – 0.28 respectively for Enugu, Kaduna, Katsina and Jos. The exergy efficiency based on the extended exergy analysis (EEA) approach was found to be much lower than the standard exergy efficiency for all the sites. Based on EEA, Enugu, Kaduna, Katsina and Jos has exergy efficiency of 1.05, 0.73, 2.52 and 3.22 % respectively. Economic performance results showed that Jos is the best site with least monthly average COE value of 0.15 $/kWh which compares closely with global average COE value of 0.14 $/kWh for households. Katsina and Enugu have a COE value of 0.19 and 0.84 $/kWh respectively while Kaduna is the worst in performance with highest COE value of 1.13 $/kWh. . ©2020. CBIORE-IJRED. All rights reserved

Keywords: Wind turbine, Exergy analysis, Advanced exergy, Extended exergy, Cost of electricity

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1. Introduction

Nigeria power infrastructure is made up of mostly centralized fossil-fuelled power plants (Ujam & Diyoke, 2013). Over the past years, there have been frequent power outages and insufficient supply owing to an archaic system of power distribution infrastructure with high losses.

To ameliorate the power situation, Nigeria government set up three ambitious targets for its electricity sector by the end of 2030 (Sambo, 2009), viz: electricity access for all with a 30% share of renewable energy target and a GHG emissions reduction target. To achieve this, a dramatic increase in capacity addition of up to 5,000 MW per year may be required. Centralized generation alone is not likely to meet this goal because of its shortcomings such as high network losses and costs, thus highlighting the need for more reliable local power sources. In this context, a distributed generation (DG) technology based on locally available energy resource is a paramount alternative for electrifying remote areas. This is because of its so many benefits such as improvement in tail-end voltages, reduction of distribution losses, improvement in system reliability and power quality and emission reductions (Diyoke, Idogwu, & Ngwaka, 2014).

Among the different types of DG technologies (internal combustion engines, small gas turbines, Stirling engines, fuel cells, photovoltaic, biogas and wind turbines) (Zhang et al., 2017), interest is now shifting to renewable-based DG technologies because of their sustainable and clean nature. The wind is one of the favorable RE sources and regional wind potential investigations by numerous researchers (Adaramola, Paul, & Oyedepo, 2011; Ayodele, Ogunjuyigbe, & Amusan, 2016, 2018; Effiom, Nwankwojike, & Abam, 2016; Mohammed, Mustafa, Bashir, & Mokhtar, 2013; Ohunakin, Ojolo, Ogunsina, & Dinrifo, 2012; Oyedepo, Adaramola, & Paul, 2012) suggest that exploitable wind resources for power generation is widespread in Nigeria. This represents an opportunity for Nigeria to diversify its power infrastructure and thus meet its target of increasing wind energy's contribution to 30% share of renewable energy target by 2030 and also do away with some of the pollution prone centralized fossil powered plants.

The erection and installation of wind power plants have been on a tremendous increase globally over the last decade (Diyoke, 2019). Since 2014, the annual installation has topped 50 GW each year with total installations in 2018 being 51.3 GW, bringing the global total to 591GW

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(GWEC, 2018). This makes wind power a highly important form of renewable energy resource for the future (Diyoke & Ngwaka, 2020). Optimal energy mix structure involving wind is opined as an effective measure to guarantee energy security in Nigeria (Effiom, Nwankwojike, & Abam, 2016). It is therefore of critical importance to evaluate the performance of a wind turbine for distributed generation in Nigeria accurately using realistic varying environmental conditions.

A lot of research work has been done on wind energy and its potential in Nigeria. Ohunakin & Akinnawonu (2012) carried out a technical and economic evaluation of using medium and large wind turbines for electricity generation in six selected high altitude sites across North-East and North-West Geopolitical zones. In another study, Oyedepo, Adaramola, & Paul. (2012) studied the wind speed characteristics and the energy potential in Enugu, Owerri and Onitsha respectively. They reported average annual wind speed of 5.4, 3.4 and 3.6 for Enugu, Owerri and Onitsha respectively. Adaramola, Paul & Oyedepo.(2011) assessed electricity production and energy cost of wind turbine systems in north central Nigeria. They reported that the cost of energy production varies from $ 0.04 to $1.67 per kWh for the sites. Ohunakin & Akinnawonu (2012) carried out an analysis of wind energy potential and economics of wind power production in Jos, Nigeria using 37-year (1971–2007) wind speed data measured at 10 m height. They reported that the site is suitable for wind power production. Salisu et al. (2019) carried out the viability of developing a standalone hybrid renewable energy (RE) system using solar and wind for Giri village in Nigeria. Their results indicated that optimal configuration has a cost of electricity (COE) of $0.110 per kWh and net present cost of $1.01million, with an operating cost of $4,723.

From the reviewed works of literature, it can be seen that although the characteristics and wind speed pattern across several locations in Nigeria has been studied, most attention has been devoted to wind resource assessment, capacity factor and power output determination and economic analysis under the assumption of constant air temperature and density.

Accurate assessment of wind resource is of paramount importance in the choice of a suitable and profitable location for harnessing wind power. Besides the technical and economic assessment of wind energy potential, thermo-economic and advanced exergy analysis is also very crucial in the planning of wind farms. Although, there are some studies related to exergy or second law analysis of wind turbines across the world in the past decades (Aghbashlo et al., 2018; Allouhi, 2019; Bascut, Omer; Ozgener, Onder; Ozgener, 2010; Baskut & Ozgener, 2012; Baskut, Ozgener, & Ozgener, 2011; Ehyaei, Ahmadi, & Rosen, 2019; Hu, Liu, & Tan, 2019; Khalilzadeh & Hossein Nezhad, 2018; Ozgener & Ozgener, 2007; Pope, Dincer, & Naterer, 2010; Redha, Dincer, & Gadalla, 2011; Şahin, Dincer, & Rosen, 2006), however, no research until this date has attempted to study the thermo-economic and extended exergy analysis of wind turbines for distributed generation in Nigeria; which is very important from investment and sustainability point of view, thus necessitating this present analysis.

Exergy is a valuable concept in the work towards the design and sustainability of engineering systems. Exergy analysis amalgamates the second law of thermodynamics with the conservation of energy and mass principles for the design, evaluation and optimization of numerous energy conversion systems (Diyoke & Wu, 2020). This approach could deliver better, accurate and meaningful insights into the sustainability and productivity issues because of its ability to reveal the source, magnitude, and exact location of the inefficiencies inherent in a thermodynamic system. Also, exergy analysis can help engineers to attain a more sustainable system by decreasing the exergy losses that occur during energy conversion processes. It has been suggested by many scholars that exergy analysis should be included in wind energy evaluations and assessments, to permit for more realistic modelling outcome (Aghbashlo et al., 2018; Bascut, Omer; Ozgener, Onder; Ozgener, 2010; Ehyaei, Ahmadi, & Rosen, 2019).

Bascut, Omer; Ozgener, Onder & Ozgener, (2010) discussed the effects of several meteorological variables such as air density, pressure difference, humidity, and ambient temperature on exergy efficiency of a wind turbine and suggested that overlooking these meteorological variables when planning wind farms could lead to important errors in energy calculations and plans. Based on this, the objective of this research is to investigate and compare the performance of the use of a selected wind turbine for distributed generation in four Nigerian locations: Enugu & Kaduna with medium wind potential and Katsina & Jos with high wind potential using economic, energy, exergy, advanced exergy and extended exergy accounting approaches. The results of the study particularly that of the advanced and extended exergy accounting (EEA) analysis, could provide detailed and worthwhile performance information including average power generated, energy efficiency, exergy efficiency, avoidable and unavoidable destroyed exergy, cost of electricity produced and net present value cost for each location studied This information will be useful to government and interested individuals in planning and making informed decisions regarding investment in distributed generation using wind turbines in Nigeria. Besides, the computed performance results can be used to measure the sustainability of the system in the locations. For example, COE is usually considered in measuring sustainability since unfavorable economics is not sustainable. Moreover, efficiency values need to be known for meaningful sustainability measurement. Efficient processes will characteristically have lower process requirements, capital and operating costs (Evans, Strezov, & Evans, 2009). The main novelty of the current study include:

- Thermo-economic method is applied to comprehensively assess wind turbine for distributed generation in Nigeria.
- Based on the advanced and extended exergy accounting approach, a different exergy efficiency method that includes insurance, labour, maintenance and installation cost is applied to evaluate selected wind turbines for distributed generation based on climatic conditions of four Nigerian states

To the best of the author's knowledge, it is the first time that this kind of analysis is being carried out for any Nigerian location. Therefore, this work shall help in filling this gap. Such an inclusive analysis presented in the paper could be greatly beneficial for planning of wind farm as it enables a more realistic and accurate assessment of the performance of a wind plant for a given site.

2. Research Methodology

The methodology adopted in the research involves three key steps: site selection, selection of wind turbine for a specific site and mathematical modelling

2.1 Site selection

Based on exploitable wind potential, four sites were selected and analysed in this work: Enugu, Kaduna, Katsina, and Jos. Their geographical coordinates. (Latitude °**N**, Longitude °**E**, Elevation (m)) are 06.26/707.29/304.7, 10.36/06.42/463.9, 13.01/07.41/517.6, and 09.52/08.45/1217 respectively. The wind speed at the sites was captured at 10 m height using a cup-generator anemometer. The wind speed and statistical parameters of Enugu was obtained from Oyedepo, Adaramola, & Paul, (2012). That for Kaduna and Katsina were obtained from Ohunakin, (2011) while the one for Jos was obtained from Ohunakin & Akinnawonu, (2012). Table1 shows the wind speed and temperature data of the sites.

2.2. Selection of wind turbines for the sites

The technical and economic performance of a wind turbine (WT) in a site largely depends on the efficiency at which the installed WT interacts with the existing wind regime in the site. Thus, it is of paramount importance that the turbine characteristics should be properly matched to the wind regime in the site for optimum performance(Diyoke, 2019).

The capacity factor (CF) is one of the major indexes applied to determine how effective a WT matches the wind regime in a site. Thus, using the index of CF, a site matching study was carried out for each of the four locations using thirteen commercially existing turbines; to identify the best-matched turbines to each site. The considered turbine are Aircom/10kW (WT1), Siracco/6kW (T2), Wind Runner/25kW (T3), Eurowind /10.8kW (T4), Eurowind/30kW (T5), Alize/10kW (T6), Fuhrlander/30kW (T7), Fuhrlander/100kW (T8), Gazelle/20 kW (T9), Jonica Impianti/20 kW (T10), Polaris P17-50 (T11), Polaris P19-100 (T12), and Polaris P10-20 (T13).

Table 1
Wind speed and temperature distribution for the sites

Months	Enugu			Kaduna			Katsina			Jos		
	v (ms^{-1})	T (°C)	k	v (ms^{-1})	T (°C)	k	v (ms^{-1})	T (°C)	k	v (ms^{-1})	T (°C)	k
Jan	5.6	29.6	3.5	6.8	26.2	6.0	8.8	29.6	3.2	9.1	29.6	3.5
Feb	5.7	31.2	4.9	6.5	29.9	4.3	7.7	31.2	3.0	9.2	31.2	4.7
Mar	6.3	30.5	5.8	5.8	30.8	4.1	6.6	30.5	3.5	9.0	30.5	6.6
Apr	6.2	29.9	5.1	5.4	30.7	6.7	7.7	29.9	5.2	8.9	29.9	3.9
May	5.4	28.8	4.4	5.4	28.9	6.5	9.0	28.8	5.8	9.0	28.8	7.6
Jun	5.2	27.5	4.8	5.5	27.0	8.6	9.8	27.5	5.3	8.6	27.5	5.4
Jul	5.5	26.3	5.5	5.2	25.2	8.3	8.8	26.3	4.3	8.7	26.3	7.1
Aug	5.4	26.0	3.9	4.7	24.9	6.0	6.8	26.0	4.5	8.2	26.0	6.2
Sep	4.9	25.8	4.8	3.8	25.6	6.1	6.3	25.8	4.7	7.1	25.8	4.6
Oct	4.6	27.7	5.2	3.4	27.0	5.4	5.5	27.7	4.3	7.6	27.7	4.4
Nov	4.1	28.5	3.8	4.9	26.9	5.1	5.3	28.5	4.6	8.5	28.5	4.0
Dec	5.0	28.2	3.3	6.0	26.8	6.1	7.0	28.2	3.5	9.4	28.2	4.7

Table 2
Technical characteristics of wind turbines

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
P_r (kW)	10	6	25	10.8	30	10	30	100	20	20	50	100	20
H (m)	30	30	32	30	30	36	27	35	20	18	36.6	60	36.6
D (m)	7.1	5.6	10	6.3	10.3	7	13	21	11	8	16.5	19.1	10
v_i (ms^{-1})	2.5	4	3	3	3	3	2.5	25	4	3.5	2.7	2.5	2.5
v_r (ms^{-1})	11	13	12	12	12	12	12	13	13	12.5	11	12	10
v_o (ms^{-1})	32	12	12	28	28	12	25	25	20	37.5	25	25	25
A (m^2)	40	25	79	37	103	39	133	346	95	50.3	214	287	79
life (yrs.)	25	25	25	20	20	20	25	25	25	20	20	20	20

The technical characteristics of the turbines were obtained from Adaramola, Paul, & Oyedepo (2011) and Urbanwind (n.d) as summarized in Table 2 while Figure 1 shows the details of the computed CF of the thirteen turbines for the four sites. From the figure, it can be seen that Polaris P10-20 (T13) wind turbine has the highest CF of all the analysed turbines in each study location. It is therefore selected for further analysis using thermo-economic approach.

2.3. Mathematical modelling

2.3.1 Assumptions

- The flow of wind is steady, incompressible and one dimensional
- Heat transfer, chemical reactions, or phase changes are not present

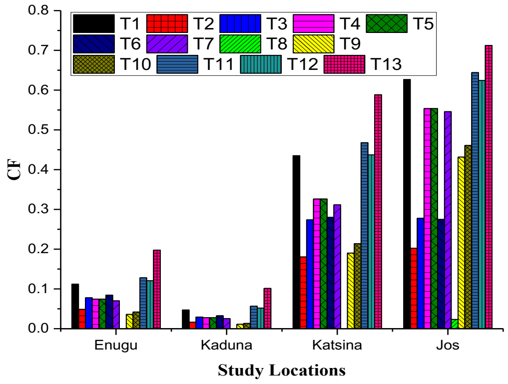

Fig. 1. Variation of CF at the sites for different turbines

2.3.2 Energy analysis

The diagrammatic representation of the wind turbine is as shown in Figure 2.

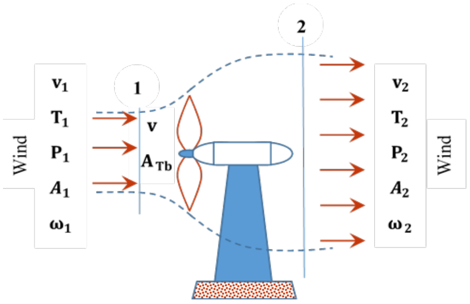

Fig. 2. Schematic of airflow around a wind turbine

Since air is incompressible, a mass balance can be written for WT control volume as follows:

$$\dot{m} = \rho A_1 v_1 = \rho A_{Tb} v = \rho A_2 v_2 \tag{1}$$

$$v = \frac{1}{2}(v_1 + v_2) \tag{2}$$

Where $\dot{m}$ is mass flow rate, ρ is the density of air, A_1 is the area of the wind approaching the WT, A_2 is the cross-sectional area of the air stream after the WT, A_{Tb} is the area of the turbine blade, v_1 is wind speed upstream the turbine, v is the wind velocity at the turbine blades, and v_2 is the downstream velocity after the turbine

The air density at the various sites is corrected for altitude using the following (Aghbashlo et al., 2018):

$$\rho = 1.225 \times \text{Exp}^{-\left(\frac{297 \times \text{altitude}}{3048}\right)} \tag{3}$$

The rate at which the kinetic energy (KE) of the wind is extracted by the blades is the average power ($P_{e,ave}$) and can be written as:

$$P_{e,ave} = \frac{\dot{m}}{2}(v_1^2 - v_2^2) \tag{4}$$

$$v_2 = \frac{v_1}{3} \tag{5}$$

The energy efficiency (η_{EN}) of a wind turbine can be estimated as the ratio of average power output ($P_{e,ave}$) to the total kinetic energy available as follows:

$$\eta_{EN} = \frac{P_{e,ave}}{{}^{1}\!/_{2}\, \rho A v_1^3} \tag{6}$$

The average electrical power of a wind turbine system can also be estimated using (Diyoke, 2019):

$$P_{e,ave} = \int_0^{\infty} P_e\, f(v) dv = P_r(CF) \tag{7}$$

Where f(v) is the Weibull probability density function of wind speed and (P_e) is electrical power.

The capacity factor (CF) is the ratio of the average power produced to the rated power (P_r) of the generator:

$$CF = \frac{P_{e,ave}}{P_r} \tag{8}$$

The rated electrical power can be calculated as follows:

$$P_r = \frac{1}{2} \rho A \eta_{actual} \eta_{mech} \eta_e v_r^3 \tag{9}$$

Where ρ is air density; A is the cross-sectional area of the blades; η_{actual} is the actual efficiency or power coefficient; η_{mech} is mechanical system efficiency; η_e is the alternator electrical efficiency. In this study, C_p, η_{mech} and η_e were assumed to be 0.4, 0.98 and 0.97 respectively.

Given that wind turbines operate between cut in (v_{in}), rated (v_r) and cut out (v_o) wind speeds, the CF can also be estimated as follows(Diyoke, 2019; Ehyaei et al., 2019):

$$CF = \frac{\exp\left[-\left({}^{v_{in}}\!/_{C}\right)^k\right] - \exp\left[-\left({}^{v_r}\!/_{C}\right)^k\right]}{\left({}^{v_r}\!/_{C}\right)^k - \left({}^{v_{in}}\!/_{C}\right)^k} - \exp\left[-\left(\frac{v_o}{C}\right)^k\right] \tag{10}$$

The terms C and k represent Weibull speed and shape parameters respectively. They can be estimated as follows:

$$c = \frac{\bar{v}}{\Gamma\left(\frac{1}{k} + 1\right)} \tag{11}$$

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{12}$$

The average wind speed at the anemometer height $(v(h))$ is extrapolated to the equivalent wind speed at the turbine hub height $(v(H))$ using the following (Ehyaei et al., 2019):

$$\left(v(H)\right) = v(h)\left[\frac{H}{h}\right]^{\beta} \tag{13}$$

$$\beta = x - y\log_{10}\dot{v}(h) \tag{14}$$

Where h and H represent anemometer and wind turbine mast heights respectively, while x and y are constant coefficients with average values of 0.25 and 0.14 respectively(Ehyaei, Ahmadi, & Rosen, 2019).

2.3.3 Conventional exergy analysis

Exergy analysis includes the flow irreversibilities associated with the WT system. The exergy balance equation can be expressed as:

$$\dot{m}_1\psi_{t,1} - P_{e,ave} = \dot{m}_2\psi_{t,2} + Ex_D \tag{15}$$

Where ψ signify specific exergy and subscript t denote total.

The exergy efficiency of a wind turbine can be expressed as the ratio of the average generated electrical energy by the plant to the net total exergy utilised for generating the power:

$$\eta_{Ex} = \frac{P_{e,ave}}{\dot{m}\Delta\psi_t} \tag{16}$$

The total specific exergy ((ψ_t) is the sum of the physical, chemical and kinetic exergy as follows (Diyoke & Wu, 2020):

$$\psi_t = \psi_{ph} + \psi_{ch} + \psi_k \tag{17}$$

The subscripts ph, ch and k denote physical, chemical and kinetic respectively.

The specific physical and chemical exergy of air flowing across a wind turbine blades can be expressed as follows respectively (Diyoke & Wu, 2020; Ehyaei, Ahmadi & Rosen., 2019):

$$\psi_{ph} = \left(C_{p,a} + \omega C_{p,wv}\right)\left[T_c - T_o - T_o\ln\frac{T_c}{T_o}\right] + (1 + 1.6078\omega)RT_o\ln\frac{P}{P_o} \tag{18}$$

$$\psi_{ch} = RT_o\left\{(1 + \omega 1.6078)\ln\frac{1 + 1.6078\omega_o}{1 + 1.6078\omega} + 1 + 1.6078\omega\ln\frac{\omega}{\omega_o}\right\} \tag{19}$$

Where $C_{p,a}$, $C_{p,wv}$, R, T, ω, and P denote air specific heat at constant pressure, specific heat for water vapour, characteristic gas constant for air, temperature, humidity ratio and pressure. The subscript c and o, denote wind chill and standard conditions of air taken as 298.15K and 1.015 bar respectively.

The specific humidity ratio ω is defined as ratio of mass of water vapour (m_v) to unit mass of dry air $(m_{d,a})$ as follows:

$$\omega = \frac{m_v}{m_{d,a}} = 0.62198\frac{p_{wv}}{p_a - p_{wv}} \tag{20}$$

Where p_w and p_a denote partial pressure of water vapour in moist air and atmospheric pressure of moist air (Pa) respectively.

The wind chill temperature at a given air temperature (T_a) in °C and speed (v) in m/s at the inlet or exit can be determined as follows (Nelson et al., 2000):

$$T_c = 13.12 + 0.6215T_a - 11.37(3.6v)^{0.16} + 0.3965T_a(3.6v)^{0.16} \tag{21}$$

The pressure at the inlet and exit of the wind turbine can be estimated as follows(Khalilzadeh & Hossein, 2018; Li, 2011; Pope, Dincer & Naterer (2010)):

$$p = p_o \pm \rho\frac{\bar{v}^2}{2} \tag{22}$$

The specific kinetic exergy at the inlet and exit can be obtained using:

$$\psi_k = \frac{v^2}{2} \tag{23}$$

The exergy destruction rate across the wind turbine can be expressed as follows:

$$Ex_D = \dot{m}_a\left\{\Delta\psi_{ph} + \Delta\psi_{ch} + \Delta\psi_k\right\} - P_{e,ave} \tag{24}$$

In the analysis, chemical exergy was neglected.

2.3.4 Advanced exergy analysis

Advanced exergy analysis significantly addresses some of the shortcomings of the conventional exergy analysis. The conventional exergy analysis cannot evaluate the effects of components interaction and technological limitations on the efficiency of the system neither can it reveal the actual potential for improvement in a component or system. But, this is possible with the advanced exergy analysis (Kelly, Tsatsaronis, & Morosuk, 2009), in which the total exergy destruction (Ex_D) in each component is split into two part to facilitate the subsequent optimization of the overall system:

- Avoidable (Ex_D^{AV}) and unavoidable (Ex_D^{UN}) exergy destruction:$Ex_D^{AV} + Ex_D^{UN}$

- Endogenous (EX_D^{EN}) and exogenous (EX_D^{EX}) exergy destruction: $Ex_D^{EN} + Ex_D^{EX}$

The total exergy destruction of a wind turbine can thus be expressed as follows:

$$Ex_D = Ex_D^{AV} + Ex_D^{UN} + Ex_D^{EX} + Ex_D^{EN} \qquad (25)$$

2.3.4.1 Avoidable and unavoidable exergy destruction

The avoidable exergy destruction is that part of the exergy destruction that can be eliminated or reduced by technologically feasible design modifications (Petrakopoulou et al., 2012). It enables the determination of the real exergy destruction that can be eliminated whereas the unavoidable exergy destruction is that part of the exergy destruction that is irreducible due to economic and physical constraints(Kelly, Tsatsaronis, & Morosuk, 2009).

The avoidable exergy destruction (EX_D^{AV}) of a wind turbine can be determined using:

$$Ex_D^{AV} = \dot{m}_a\left\{\Delta\psi_{ph} + \Delta\psi_{ch} + \Delta\psi_k\right\} - P_{e,ave-Betz} \qquad (26)$$

Where $P_{e,ave-Betz}$ is the maximum average power attainable in the site; calculated by assuming the wind plant operate at Betz's limit or maximum efficiency, η_{max} (which is 0.59).

$$P_{e,ave-Betz} = P_{e,ave} \times \frac{\eta_{max}}{\eta_{actual}} \qquad (27)$$
$$= CF \times \frac{1}{2}\rho A \eta_{max}\eta_{mech}\eta_e v_r^3$$

Once Ex_D^{AV} is determined, Ex_D^{UN} is determined by subtracting EX_D^{UN} from EX_D as follows (Ehyaei, Ahmadi, & Rosen, 2019):

$$Ex_D^{UN} = Ex_D - Ex_D^{AV} \qquad (28)$$

2.3.4.2 Endogenous and exogenous exergy destruction

In a system with k components, the endogenous exergy destruction is that part of the whole exergy destruction that is related to the operation of the component k itself (Petrakopoulou et al., 2012). It arises when the k component operates under real conditions and all the other components operate without irreversibilities theoretically (Petrakopoulou et al., 2012).

The exogenous exergy destruction (EX_D^{EX}) is the exergy destruction that arises in a component, k because of the operation of the k-1 components that make up the whole system (Petrakopoulou et al., 2012).

A wind turbine operates as an independent device, with no other components making up the system. In other words, other equipment do not affect them. Thus the endogenous and exogenous exergy parts $\left(EX_D^{EX} + EX_D^{EN}\right)$ are equal to zero(Ehyaei, Ahmadi, & Rosen, 2019).

2.3.5 Extended exergy analysis

Extended exergy analysis (EEA) is a detailed exergy accounting method that facilitates the improvement of system or component from the standpoint of thermodynamics, economics and environmental impact.

The exergy balance equation for a wind power plant based on the extended exergy analysis (EEA) method can be expressed as follows (Aghbashlo et al., 2018; Ehyaei, Ahmadi, & Rosen, 2019):

$$Ex_D = \dot{m}_a\left\{\Delta\psi_{ph} + \Delta\psi_{ch} + \Delta\psi_k\right\} + Ex_{TCC} + Ex_L - Ex_{gen} - Ex_D \qquad (29)$$

$$Ex_{TCC} = Ex_k + Ex_{O\&M} + Ex_{ins} \qquad (30)$$

Where $Ex_{TCC}, Ex_L, Ex_k, Ex_{O\&M}, Ex_{ins}$ represent the equivalent exergy content values for total capital cost, labour, capital cost, annual operation & maintenance and insurance costs (Aghbashlo et al., 2018; Ehyaei, Ahmadi, & Rosen, 2019).

For L working hours in one year, the value of Ex_L can be determined as follows(Aghbashlo et al., 2018):

$$Ex_L = w_h ee_L \qquad (31)$$

Where w_h is overall working hours of the wind power plant technical staff and $\mathbf{ee_L}$ is the extended exergy cost of labour (Ehyaei, Ahmadi, & Rosen, 2019)

In the work on sensitivity analysis of wind farm O&M cost and availability by Martin et al. (2016), it was established that the total number of technical staff (O&M base staff) required to keep a wind turbine operable varies directly as the size or number of turbines. Since information on actual data on total technical staff required to operate a wind turbine is non-existent for Nigeria, the overall working hours of the wind power plant technical staff in Nigeria is obtained by scaling an existing onshore wind turbine total technical staff working hours according to turbine size and weekly work hours as follows:

$${w_h}^{new} = {w_h}^{ref} \times \frac{N_{WT}^{new}}{N_{WT}^{ref}} \times \frac{wk_h^{new}}{wk_h^{ref}} \qquad (32)$$

In the above equation ${w_h}^{new}$ is the working hours for the new case, ${w_h}^{ref}$ is the working hours for the reference or existing wind farm in Iran which is 164354 $^{hours}/_{year}$, N_{WT}^{new} is the number of installed wind turbines for the new case which is 1, N_{WT}^{nref} is the number of installed wind turbines in the reference case (Iran) which is 4 (Aghbashlo et al., 2018), wk_h^{new} is the country weekly working hours for the new case which is 40 and and wk_h^{ref} is the country weekly working hours for the reference case (Iran) which is 44 (Aghbashlo et al., 2018).

The extended exergy cost of labour can be determined as follows (Aghbashlo et al., 2018):

$$ee_L = \frac{365 HDI Ex_{surv} N_h}{HDI_o N_{wh}} \qquad (33)$$

In the above equation, HDI is the human development index which is 0.774(Aghbashlo et al., 2018; Ehyaei et al., 2019), HDI_o is the human development index for a primitive society which is 0.055 (Aghbashlo et al., 2018), Ex_{surv} is the exergy consumption for survival which is $1.05\times10^7\left({}^{J}/_{PersonDay}\right)$, N_h is the number of inhabitants which is 190,000,000 for Nigeria.

The cumulative annual working hours of the power plant staff in Nigeria, N_{wh} will depend on the weekly work hours in the country and the capacity of the wind power plant. A mean value is estimated by scaling existing N_{wh} for Iran according to the official weekly working hours as follows:

$$N_{wh} = \frac{wk_h^{ref}}{wk_h^{new}}\times yr_h^{Iran} \tag{34}$$

Here, yr_h^{Iran} is cumulative annual staff working hours of an existing wind farm in Iran which is 54539487345 hours per year (Aghbashlo et al., 2018; Ehyaei, Ahmadi, & Rosen, 2019).

The exergetic equivalent of total capital cost can also be expressed as follows:

$$Ex_{TCC} = \left(TCC\times\frac{d_r(1+d)^n}{(1+d)^n-1}\right)\times ee_c \tag{35}$$

$$ee_c = \frac{365HDIEx_{surv}N_h}{HDI_oS} \tag{36}$$

Here, TCC is total capital cost, d is the real discount rate, n is years of operation, ee_c is extended exergy cost of capital while S represent the national monetary amount of wages and salaries$\left({}^{\$}/_{year}\right)$. TCC can be calculated as follows:

$$TCC = TIV_{WT} + C_{O\&M} + C_{ins} \tag{37}$$

Where TIV_{WT} is the total investment cost of WT, $C_{O\&M}$ is the cost of O&M and C_{ins} is the cost of insurance. The cost of O&M ($C_{O\&M}$) and insurance (C_{ins}) is taken as 5% of TCC respectively (Aghbashlo et al., 2018).

The exergy efficiency of the plant following the EEA method can be expressed as follows (Aghbashlo et al., 2018):

$$\eta_{Ex} = \frac{Ex_{gen}}{\dot{m}_a\{\Delta\psi_{ph}+\Delta\psi_{ch}+\Delta\psi_k\}+Ex_{TCC}+Ex_L} \tag{38}$$

2.3.6. Economic Analysis

The economic performance of the selected wind turbine in the four studied locations was assessed using the cost of electricity (COE) and post-tax net present value (NPV) as metrics.

The net present value is estimated as follows(Diyoke et al., 2018; Short, Packey, & Holt, 1995):

$$NPV = \sum_{n=0}^{N}\frac{NCF_n}{(1+d)^n} = -TIC + \sum_{1}^{N}\frac{(1-Tax)\times(R-c_{O\&M}-c_{ins})+Tax\times(D_d)}{(1+d)^n} \tag{39}$$

Where NCF is net cash flow in year n, N is the analysis period, d is the annual nominal discount rate. R is revenue from electricity sale and D_d is discounted depreciation.

The COE is the minimum price at which energy must be sold for an energy project to break even (Diyoke et al., 2018). It can be calculated as follows:

$$COE = \frac{TLCC}{AEO}\times\frac{d_r(1+d)^n}{(1+d)^n-1} \tag{40}$$

Where AEO and TLCC denote annual energy output and total life cycle cost respectively. The total life cycle cost (TLCC) is estimated as follows (Diyoke et al., 2018; Short, Packey, & Holt, 1995):

$$TLCC = \left[TIC - Tax\times(c_D)_{PV} + (1-Tax)\times\left\{(c_{O\&M,})_{PV}+(c_{En})_{PV}\right\}\right] \tag{41}$$

In the above, c_D is the cost of depreciation and subscript pv means present value. The input parameters in the model include Electricity tariff of N25 per kWh (0.07 $/kW), a tax rate of 34% (Diyoke, Idogwu, & Ngwaka,. 2014; Ujam & Diyoke, 2013), the economic life of 20 years, an inflation rate of 11%, a real discount rate of 14% , wind turbine specific cost of 3110 $/kW, and yearly depreciation rate of 5%.

3 Results and Discussions

3.1 Result validation

Average power is the product of CF and rated power. Since the rated power is constant for every wind turbine, the fidelity of the results presented in this research depends on the accuracy of the computed capacity factor (CF). For validation of the results, the CF computed using the described methodology in the paper is compared against a representative real wind farm annual capacity factor of Kappadagudda wind power station (KWPS), Karnataka State in India (Jangamshetti & Rau, 1999). The technical parameters of the wind turbine installed in the site are shown in Table 3. Based on annual average wind speed, the annual CF obtained with the model is 0.3612 while the annual CF reported for the wind farm is 0.3600, representing an error of just 0.33%. Thus the results presented in the paper can be said to be reasonably accurate.

Table 3
Technical parameters of wind farm

Wind turbine		
Manufacturer	:	Vestas
Capacity	:	225.0 kW
Wind farm		
capacity	:	2.0 MW
no of turbines	:	9.0
Characteristic speed of turbine		
Cut in speed (v_{in})	:	3.5 m/s
Rated speed (v_r)	:	13.5 m/s
Cut-out speed (v_o)	:	25.0 m/s
Hub height	:	30.0m
Site wind speed		
Yearly average	:	7.09 m/s
Maximum wind speed	:	15.0 m/s
Standard deviation	:	3.62

3.2 Energy and conventional exergy analysis

The average monthly power output for the selected 20 kW Polaris P10-20 wind turbine at 36.6 m height in the four studied locations is 3.79, 2.67, 9.92 and 12.97 kW corresponding to meteorological height average wind speeds of 5.32, 5.27, 7.45 and 8.61 m/s respectively for Enugu, Kaduna, Katsina and Jos. Jos has the highest average monthly power because it has the highest average wind speed among the locations as can be seen in Table 1. Kaduna has the least average power output because its average velocity is the least among the sites. The average power fluctuates monthly according to the prevailing wind speed in the month. Figure 3 shows the monthly breakdown of the average power for the sites. As expected, the trends followed closely that of the monthly wind speeds at the sites.

The effectiveness of conversion of the kinetic energy of the wind into power by the wind turbine blades can be revealed by the energy and exergy efficiency of the system. The average monthly energy efficiency computed for Enugu, Kaduna, Katsina and Jos are 0.29, 0.17, 0.31 and 0.30 respectively. Figures 4-7 shows the monthly breakdown of both the energy and exergy efficiency for the four locations to highlight the difference between them.

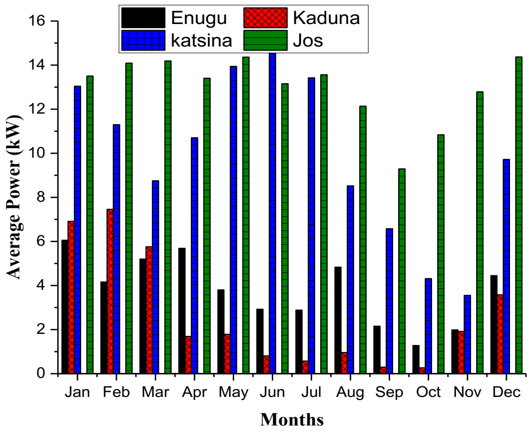

Fig. 3 Monthly variation of average power

As can be seen, the energy efficiency followed the same trend with the average power. It can be seen that although the exergy efficiency displayed almost the same trend as the energy efficiency, its magnitude is however always lower than the corresponding energy efficiency. This suggests that the exergy efficiency can describe the performance of a wind turbine more precisely than energy efficiency (Redha, Dincer, & Gadalla, 2011). The difference between energy and exergy efficiency arises as a result of irreversibility in the system that could not be accounted for in energy efficiency. Also, it could be seen that there is a fluctuation in energy and exergy efficiency across the months in all the locations with low exergy efficiency occurring in some months. This probably because of the daily variation of wind speed and temperature. In the months with low energy and exergy efficiency, the convenient environmental conditions were not good enough to come up with enough and desired output.

The exergy destruction rate of the wind turbine in the four studied locations using the selected wind turbine is shown in Figure 8. Observe that the exergy destruction is in a complete inverse relationship with the exergy efficiency. This is because, the higher the exergy efficiency, the lesser the losses which result to lower exergy destruction and vice versa. Average exergy destruction rate of 14.10, 15.0, 36.49 and 47.62 kW is calculated for Enugu, Kaduna, Katsina, and Jos respectively. Jos has the highest average monthly exergy destruction rate because it has the highest annual wind speed of the study locations and locations with high wind speed tend to have more exergy destruction (Ehyaei, Ahmadi, & Rosen, 2019).

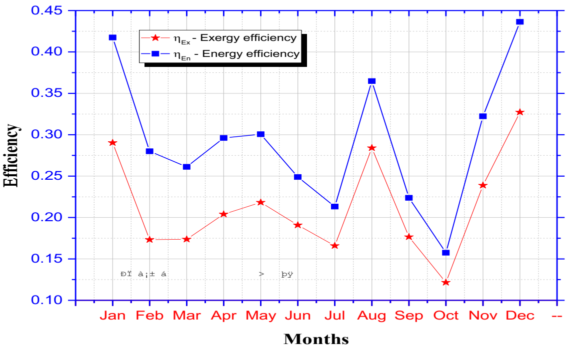

Fig. 4. Variation of energy and exergy efficiency for Enugu

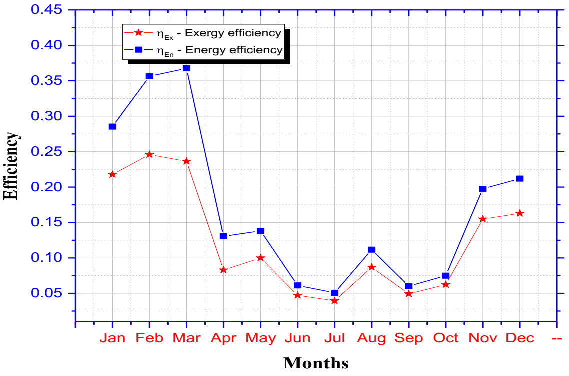

Fig. 5. Variation of energy and exergy efficiency for Kaduna

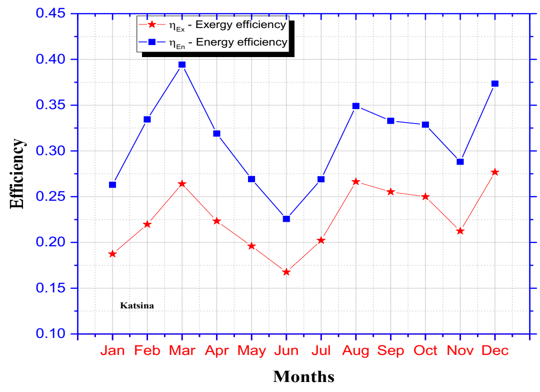

Fig. 6. Variation of energy and exergy efficiency for Katsina

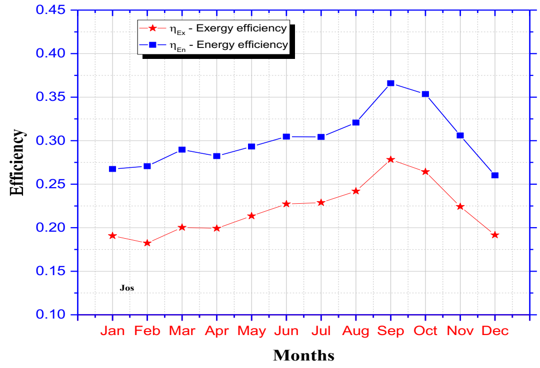

Fig. 7. Variation of energy and exergy efficiency for Jo

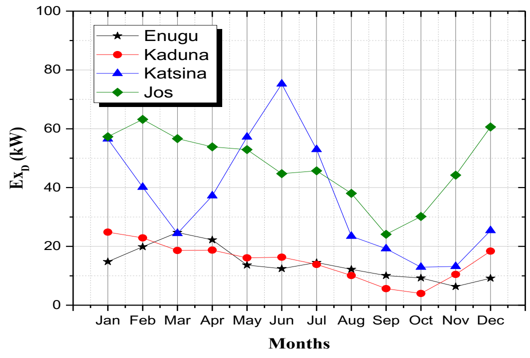

Fig. 8. Conventional exergy destruction rate of the sites

3.2 Advanced exergy analysis

The average exergy destruction rates following the EEA approach using the selected Polaris wind turbine for the four sites analysed in this study are 354.72, 354.70, 377.41, and 389.13 kW for Enugu, Kaduna, Katsina, and Jos respectively. The breakdown of the exergy destruction on a monthly basis for the selected wind turbine is shown in Figure 9.

The exergy destruction rate fluctuates in a direct relationship with monthly wind speed across the studied location. Observe that the trend of the plot is the same with the **Ex_D** obtained by the conventional method, with Jos remaining the state with the highest exergy destruction rate, followed by Katsina. Kaduna has the least average exergy destruction rate. However, the exergy destruction based on EEA method is found to be higher than that obtained through the conventional exergy analysis method. This is due mainly to the inclusion of the exegetic equivalent of labour, influx of capital, insurance and O&M costs in the EEA calculation.

Maximum exergy destruction of 374.76, 369.86, 408.80 and 427.36 kW occurs in Feb, March, June and February for Enugu, Kaduna, Katsina and Jos respectively. High exergy destruction suggests there is high inefficiency in the system that may be improved depending on what fraction of it is avoidable.

When a plant is being evaluated, the focus should be on the avoidable exergy destruction because it represents the improvement potential present in the system. Table 4 shows the breakdown of the monthly avoidable and unavoidable exergy destruction across the analysed locations.

The avoidable exergy destruction across the sites is seen to be higher than the unavoidable part. This is because the prevailing wind speed and other environmental conditions in the sites do not make it possible for the wind turbine to produce enough and desired output, thus making the avoidable part of the exergy destruction high.

In Enugu, approximately 87.5% of the exergy destruction is avoidable. In Kaduna, Katsina and Jos, it is 91.4, 86.9 and 86.9 % respectively. Since this exergy destruction is made up of entirely endogenous exergy destruction, it means that interaction of the component as represented by exogenous exergy destruction does not play a prominent role. Therefore the focus should be on reducing the internal irreversibilities in the wind turbine.

It is observed that maximum avoidable exergy destruction of 22.2, 21.5, 67.9 and 56.4 occurred in March, January, June and February for Enugu, Kaduna, Katsina and Jos respectively corresponding to the months with maximum wind speed in the study locations. This is expected since it has been determined that avoidable exergy destruction varies directly as the wind speed (Ehyaei, Ahmadi, & Rosen, 2019). The avoidable exergy destruction of all the sites can be reduced by reducing the internal irreversibilities in the system.

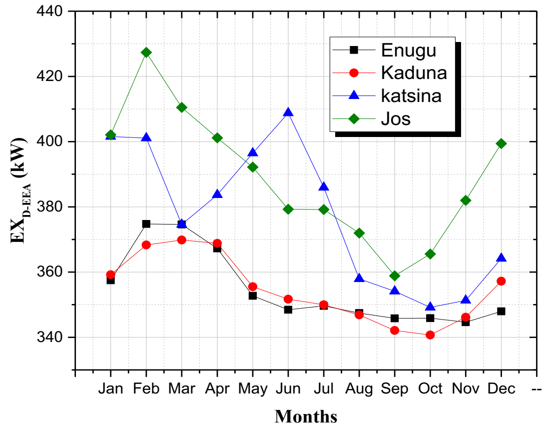

Fig. 9. Advanced exergy destruction rates across the sites

Table 4
Avoidable and unavoidable exergy destruction in KW

Months	Enugu		Kaduna		Katsina		Jos	
	Ex_D^{AV}	Ex_D^{UN}	Ex_D^{AV}	Ex_D^{UN}	Ex_D^{AV}	Ex_D^{UN}	Ex_D^{AV}	Ex_D^{UN}
Jan	11.9	2.9	21.5	3.3	50.3	6.3	50.8	6.5
Feb	17.9	2.0	19.3	3.6	34.7	5.4	56.4	6.8
Mar	22.2	2.5	15.8	2.8	20.2	4.2	49.8	6.8
Apr	19.5	2.7	17.9	0.8	32.1	5.2	47.4	6.5
May	11.8	1.8	15.2	0.9	50.5	6.7	46.0	6.9
Jun	11.0	1.4	15.9	0.4	67.9	7.3	38.4	6.3
Jul	13.1	1.4	13.6	0.3	46.5	6.5	39.2	6.5
Aug	9.9	2.3	9.6	0.5	19.4	4.1	32.2	5.8
Sep	9.0	1.0	5.5	0.1	16.0	3.2	19.6	4.5
Oct	8.6	0.6	3.9	0.1	10.9	2.1	25.0	5.2
Nov	5.4	1.0	9.5	0.9	11.5	1.7	38.1	6.2
Dec	7.0	2.1	16.7	1.7	20.7	4.7	53.7	6.9
Sum	147.3	21.9	164.6	15.4	380.5	57.3	496.5	75.0
Sum (%)	87.1	12.9	91.4	8.6	86.9	13.1	86.9	13.1

Similar to exergy efficiency under the conventional exergy analysis, the exergy efficiency under the EEA method varies inversely as the exergy destruction.as can be seen in Figure 10. Jos has the highest monthly average exergy efficiency of 3.22% followed by Katsina with a value of 2.52%. Kaduna remained the site with the lowest exergy efficiency with a value of 0.73% while Enugu has 1.05%. Dissimilar to the exergy destruction, the exergy efficiency obtained under the EEA approach for the different months of the year in the studied location is far lower than those obtained through the conventional exergy analyses. This is made possible because of the integration of the exegetic equivalent of labour, capital cost, insurance and O&M in the total exergy entering the system which consequently resulted to a lowered exergy efficiency under the EEA approach. Such observed large deviation between the exergy efficiency obtained using both the conventional exergy and advanced (EEA) approach highlights the paramount importance of deploying EEA method in the assessment of power production potential of a particular wind site. The EEA approach should be used for wind energy evaluations and assessments, to allow for a more flexible, and realistic modelling.

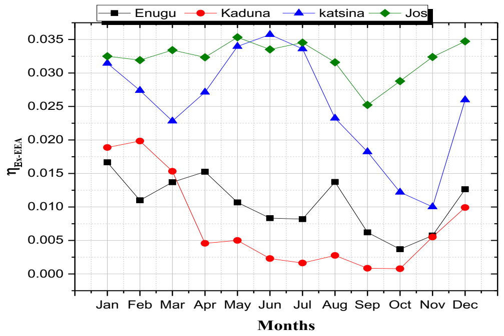

Fig. 10. Advanced exergy efficiency across the sites

3.3 Economic analysis

The total investment cost of the wind turbine is estimated as $62,200. The NPV and COE results of the financial analysis are summarized in Figures 11 & 12 respectively. The study of these figures reveals that locations with higher wind potential generally give a better financial performance. As can be observed from the plot of average NPV across the sites as shown in Figure 11, all the studied sites returned a negative NPV. This means that it is not financially viable to deploy the selected wind turbine in the locations for commercial power generation at the prevailing very low electricity tariff rate in Nigeria. With government incentives in the form of a feed-in tariff, renewable credit and tax waivers, wind power will become more competitive. The COE followed an inverse trend with the NPV as can be seen from the average COE plot for the sites as shown in Figure 12.

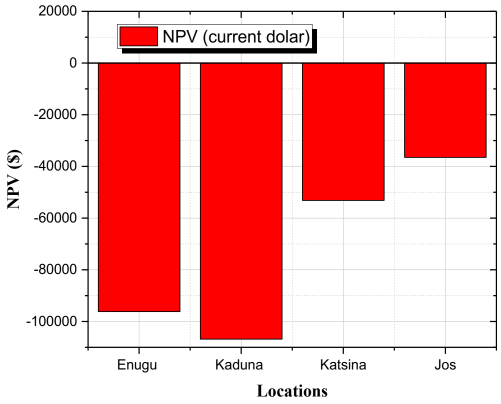

Fig. 11. Average NPV across the sites

It is observed from the figure that sites with higher wind potential tend to have a lower COE and vice versa. Again, Jos is the best site with least monthly average COE value of 0.15 \$/kWh, Katsina has a COE value of 0.19 \$/kWh while Kaduna remains the worst in performance with highest COE value of 1.13 \$/kWh. The COE for Jos compares fairly with the average electricity tariff in the world as at June 2019 which is 0.14 \$/kWh for households (Nigeria electricity prices, 2020.).

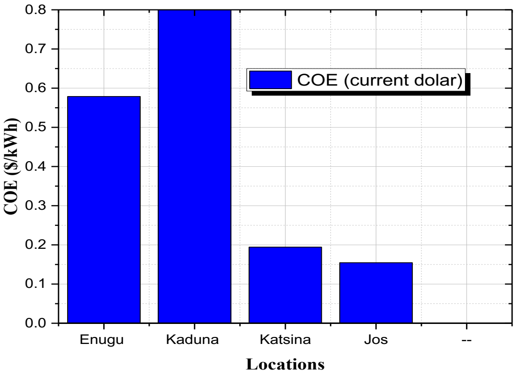

Fig. 12. Average COE across the sites

4. Conclusions

In this study, comparative performance assessment of wind turbines for distributed generation in Nigeria was carried out using thermo-economic, advanced and extended exergy analysis approaches.

The thermodynamic performance result demonstrated that the energy and exergy efficiency varies directly with the wind potential, with energy efficiency being always greater than the exergy efficiency. Among the sites considered in this study, Jos is found to be the best site for distributed generation wind energy deployment, followed by Katsina. Kaduna is the least in performance. The exergy efficiency obtained under the extended exergy analysis (EEA) approach for the different months of the year followed the same trend as the conventional exergy analysis but are far lower than those obtained through the conventional exergy analyses.

Also, Jos is the best site with least monthly average COE which compares closely with global average COE value of 0.14 \$/kWh for households. From a commercial investment perspective, it is not financially viable without government incentives, to deploy the selected wind turbine in the locations for commercial power generation at the prevailing very low electricity tariff (0.07 \$/kWh) in Nigeria.

Nomenclature

Abbreviations		**Greek Letters**	
A	Area (m^2)	η_e	Electrical efficiency
AEO	Annual energy output (kWh)	η_{max}	Maximum efficiency
C	Cost (\$)	η_{En}	Energy efficiency
c	Weibull parameter (m/s)	η_{Ex}	Exergy efficiency
Cp	Specific heat (kJ/kg K)	ρ	Air density (kg/m^3)
CF	Capacity factor	ψ	Specific exergy (kJ/kg)
Ex_D	Exergy destruction (kW)	Γ	Gamma
Ex_{gen}	Exergy of generation (kW)	Δ	Change
ee_L	Extended exergy cost of labour (kJ/hr)	ω	Humidity ratio (kg/kg of air)
Ex_{TCC}	Exergy of total capital cost (kw)		
Ex_L	Exergy of labour costs (kW)	Subscripts and superscripts	
$Ex_{O\&M}$	Exergy of O & M costs (kW)	a	air
Ex_{ins}	Exergy of insurance costs (kW)	AV	avoidable
Ex_{surv}	exergy for survival ($^J/_{Person\ Day}$)	ave	average
Ex_k	Exergy content values for capital cost (kW)	B	Betz's limit
HDI	Human development index	ch	Chemical
HDI_o	HDI for a primitive society	EN	Endogenous
k	Shape parameter	EX	Exogenous
N_{wh}	Cumulative annual working hours (hr)	k	Kinetic
O&M	Operation and maintenance	o	Reference state
P	Power (kW)	ph	physical
p	Pressure (bar)	r	Rated
R	Gas constant (kJ/kg K)	ref	Reference
T	Temperature (℃)	Tb	Turbine blade
TCC	Total capital cost (\$)	t	Total
v	Velocity (m/s)	UN	Unavoidable
m_v	Mass of water vapour (kg)	w_h	Overall working hours (hrs)
$\dot{m}$	Mass flow rate (kg/s)	WT	Wind turbine
$m_{d,a}$	Mass of dry air (kg)	wv	Water vapour
v_{in}	Cut in velocity (m/s)		
v_o	Cut out velocity (m/s)		
v_r	Rated velocity (m/s)		
W_h	Working hours (hr)		

References

Adaramola, M. S., Paul, S. S., & Oyedepo, S. O. (2011). Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria. *Energy Conversion and Management*. https://doi.org/10.1016/j.enconman.2011.07.007

Aghbashlo, M., Tabatabaei, M., Hosseini, S. S., B. Dashti, B., & Mojarab Soufiyan, M. (2018). Performance assessment of a wind power plant using standard exergy and extended exergy accounting (EEA) approaches. *Journal of Cleaner Production*, *171*, 127–136. https://doi.org/10.1016/j.jclepro.2017.09.263

Allouhi, A. (2019). Energetic, exergetic, economic and environmental (4 E) assessment process of wind power generation. *Journal of Cleaner Production*, *235*, 123–137. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.06.299

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Amusan, T. O. (2016). Wind power utilization assessment and economic analysis of wind turbines across fifteen locations in the six geographical zones of Nigeria. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.04.060

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Amusan, T. O. (2018). Techno-economic analysis of utilizing wind energy for water pumping in some selected communities of Oyo State, Nigeria. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2018.03.026

Bascut, Omer; Ozgener, Onder; Ozgener, L. (2010). Effects of meteorological variables on exergetic efficiency of wind turbine power plants. *Renewable and Sustainable Energy Reviews*, *14*(9), 3237–3241.

Baskut, O., & Ozgener, L. (2012). Exergoeconomic assessment of a wind turbine power plant (WTTP): Cesme, Izmir, example. *Energy*, *47*(1), 577–581. https://doi.org/https://doi.org/10.1016/j.energy.2012.09.014

Baskut, O., Ozgener, O., & Ozgener, L. (2011). Second law analysis of wind turbine power plants: Cesme, Izmir example. *Energy*. https://doi.org/10.1016/j.energy.2011.01.047

Diyoke, C, Idogwu, S., & Ngwaka, U. C. (2014). An Economic assessment of biomass gasification for rural electrification in Nigeria. *International Journal of Renewable Energy Technology Research*, *3 (1)*, 1–17.

Diyoke, Chidiebere. (2019). A new approximate capacity factor method for matching wind turbines to a site: case study of Humber region, UK. *International Journal of Energy and Environmental Engineering*, 1–12. https://doi.org/10.1007/s40095-019-00320-5

Diyoke, Chidiebere, Aneke, M., Wang, M., & Wu, C. (2018). Techno-economic analysis of wind power integrated with both compressed air energy storage (CAES) and biomass gasification energy storage (BGES) for power generation. *RSC Adv.*, *8*, 22004–22022.

Diyoke, Chidiebere, & Wu, C. (2020). Thermodynamic analysis of hybrid adiabatic compressed air energy storage system and biomass gasification storage (A-CAES + BMGS) power system. *Fuel*, *271*, 117572. https://doi.org/https://doi.org/10.1016/j.fuel.2020.117572

Diyoke, C., & Ngwaka, U. (2020). Numerical comparison of two operating modes of thermal energy storage tank for compression heat storage in adiabatic compressed air energy storage. Journal of Energy Storage, 30, 101558. https://doi.org/10.1016/j.est.2020.101558

Effiom, S. O., Nwankwojike, B. N., & Abam, F. I. (2016). Economic cost evaluation on the viability of offshore wind turbine farms in Nigeria. *Energy Reports*. https://doi.org/10.1016/j.egyr.2016.03.001

Ehyaei, M. A., Ahmadi, A., & Rosen, M. A. (2019). Energy, exergy, economic and advanced and extended exergy analyses of a wind turbine. *Energy Conversion and Management*. https://doi.org/10.1016/j.enconman.2019.01.008

Evans, A., Strezov, V., & Evans, T. J. (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *13*(5), 1082–1088. https://doi.org/https://doi.org/10.1016/j.rser.2008.03.008

GWEC. (2018). Global Status of Wind Power. Retrieved from Global Wind Energy Council website: http://gwec.net/global-figures/wind-energy-global-status/

Hu, W., Liu, Z., & Tan, J. (2019). Thermodynamic Analysis of Wind Energy Systems. In *Wind Solar Hybrid Renewable Energy System [Working Title]*. https://doi.org/10.5772/intechopen.85067

Jangamshetti, S. H., & Rau, G. V. (1999). Site matching of Wind Turbine generators: A case study. IEEE Transactions on Energy Conversion, 14 No. 4, 1537–1543.

Kelly, S., Tsatsaronis, G., & Morosuk, T. (2009). Advanced exergetic analysis: Approaches for splitting the exergy destruction into endogenous and exogenous parts. *Energy*. https://doi.org/10.1016/j.energy.2008.12.007

Khalilzadeh, S., & Hossein Nezhad, A. (2018). Utilization of waste heat of a high-capacity wind turbine in multi effect distillation desalination: Energy, exergy and thermoeconomic analysis. *Desalination*. https://doi.org/10.1016/j.desal.2018.04.010

Li, X. (2011). *Green energy : basic concepts and fundamentals*.

Martin, R., Lazakis, I., Barbouchi, S., & Johanning, L. (2016). Sensitivity analysis of offshore wind farm operation and maintenance cost and availability. *Renewable Energy*, *85*, 1226–1236. https://doi.org/https://doi.org/10.1016/j.renene.2015.07.078

Mohammed, Y. S., Mustafa, M. W., Bashir, N., & Mokhtar, A. S. (2013). Renewable energy resources for distributed power generation in Nigeria: A review of the potential. *Renewable and Sustainable Energy Reviews*, *22*, 257–268. https://doi.org/http://dx.doi.org/10.1016/j.rser.2013.01.020

Nelson, C. A., Tew, M., Phetteplace, G., Schwerdt, R., Maarouf, A., Osczevski, R., … Oceanic, N. (2000). *Review of the Federal Interagency Process Used To Select the New Wind Chill Temperature (Wct) Index*. 2000–2002.

Nigeria electricity prices, (2020). GlobalPetrolPrices.com. (n.d.). Retrieved March 18, 2020, from https://www.globalpetrolprices.com/Nigeria/electricity_prices/

Ohunakin, O. S. (2011). Wind resource evaluation in six selected high altitude locations in Nigeria. *Renewable Energy*. https://doi.org/10.1016/j.renene.2011.04.026

Ohunakin, O. S., & Akinnawonu, O. O. (2012). Assessment of wind energy potential and the economics of wind power generation in Jos, Plateau State, Nigeria. *Energy for Sustainable Development*, *16*(1), 78–83. https://doi.org/http://dx.doi.org/10.1016/j.esd.2011.10.004

Ohunakin, S. O., Ojolo, S. J., Ogunsina, S. B., & Dinrifo, R. R. (2012). Analysis of cost estimation and wind energy evaluation using wind energy conversion systems (WECS) for electricity generation in six selected high altitude locations in Nigeria. *Energy Policy*. https://doi.org/10.1016/j.enpol.2012.05.064

Oyedepo, Sunday O, Adaramola, M. S., & Paul, S. S. (2012). *Analysis of wind speed data and wind energy potential in three selected locations in south-east Nigeria*. Retrieved from http://www.journal-ijeee.com/content/3/1/7

Ozgener, O., & Ozgener, L. (2007). Exergy and reliability analysis of wind turbine systems: A case study. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2006.03.004

Petrakopoulou, F., Tsatsaronis, G., Morosuk, T., & Carassai, A. (2012). Conventional and advanced exergetic analyses applied to a combined cycle power plant. *Energy*, *41*(1), 146–152. https://doi.org/https://doi.org/10.1016/j.energy.2011.05.028

Pope, K., Dincer, I., & Naterer, G. F. (2010). Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines. *Renewable Energy*, *35*(9), 2102–2113. https://doi.org/https://doi.org/10.1016/j.renene.2010.02.013

Redha, A. M., Dincer, I., & Gadalla, M. (2011). Thermodynamic performance assessment of wind energy systems: An application. *Energy*. https://doi.org/10.1016/j.energy.2011.05.001

Şahin, A. D., Dincer, I., & Rosen, M. A. (2006). Thermodynamic analysis of wind energy. *International Journal of Energy Research*, *30*(8), 553–566. https://doi.org/10.1002/er.1163

Salisu, S., Mustafa, M. W., Olatomiwa, L., & Mohammed, O. O. (2019). Assessment of technical and economic feasibility for a hybrid PV-wind-diesel-battery energy system in a remote community of north central Nigeria. *Alexandria Engineering Journal*, *58*(4), 1103–1118. https://doi.org/https://doi.org/10.1016/j.aej.2019.09.013

Sambo, A. S. (2009). Renewable energy master plan of Nigeria. *World Future Council Workshop on Renewable Energy Policies*, 1–18. Abuja, Nigeria.

Short, W., Packey, D. J., & Holt, T. (1995). *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies- National Renewable Energy Laboratory (NREL)* . Retrieved from http://www.nrel.gov/docs/legosti/old/5173.pdf

Urbanwind (n.d). Catalogue of European Urban Wind Turbine Manufacturers . (n.d.). Retrieved from http://www.urbanwind.net/pdf/CATALOGUE_V2.pdf

Ujam, A. J., & Diyoke, C. (2013). Economic viability of coal based power generation for Nigeria. *American Journal of Engineering Research (AJER)*, *2(11)*, 14–24.

Zhang, X., Chen, H., Xu, Y., Li, W., He, F., Guo, H., & Huang, Y. (2017). Distributed generation with energy storage systems: A case study. *Applied Energy*. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.05.063