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Multi-criteria assessment of hybrid renewable energy systems for Nigeria's coastline communities

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Abstract

Background: Nigeria's rural coastline communities have long suffered from the consequences of both poor rural electrification and environmental degradation. Therefore, there is an urgent need to provide an optimal sustainable and environment-friendly energy system for the coastline communities in Nigeria, which has the potential of ameliorating the climate change in this country.

Methods: The HOMER hybrid optimisation software and multi-criteria decision-making, based on the TOPSIS algorithm, were used to determine the best hybrid energy system. The decision is based on four alternatives as well as 15 different economic, social and environmental criteria. The NASA SEE data base with monthly averaged values for global horizontal radiation over a 22-year period (July 1983–June 2005) was considered in the current analysis.

Results: The results show that the most promising hybrid energy system, based on a multi-criteria decision analysis and prevailing economic data, is the diesel-PV-wind energy system, which has a relative closeness of 0.489226. The suggested best hybrid energy system has a cost of electricity of 0.787 $/kWh and potential to reduce gas emission by 48.5 %/year. The best energy system gives the best components with an appropriate operating strategy to provide an efficient, reliable, cost-effective and environment-friendly system. It is shown that both positive energy policies of the Federal Government of Nigeria towards renewable energy penetration and the support from the oil producing companies towards their operational areas would see the cost of electricity being significantly reduced.

Conclusions: It is envisaged that the implementation of the suggested energy system with other environmentally responsible interventions would support the Niger Delta coastline communities, whose livelihoods have been impaired by gas and oil exploration, to attain their full environmental, social and economic potentials. The suggested energy system could be useful in other coastline communities globally once there are available renewable energy sources.

Keywords: TOPSIS, HOMER, Hybrid system, Renewable energy

Background

Sub-Sahara Africa countries and other developing nations are facing challenges of development, which can be directly linked to the means and methods of energy generation and its use. The desire to have access to energy has created negative multiplier effects, namely climate change, non-equilibrium of the ecosystem, pollution of the environment and anxiety among nations. These challenges form the nucleus of the search for optimal socio-economic and environmental decisions to deploy clean and affordable energy solutions, as stipulated in No. 7 of the 17 Sustainable Development Goals (SDGs), which is due to replace the Millennium Development Goals (MDGs) [1]. This is evident from an avalanche of literature from intergovernmental organisations towards the policy of deploying a clean and creative energy supply, namely the Intergovernmental Panel on Climate Change (IPCC) [2]. All the intergovernmental organisations continue to stress the importance of drastic reductions in the use of climate impeding energy sources (especially fossil

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fuels) to minimise the dangerous impacts of climates change [3].

It has been reported that the global demand for primary energy is steadily increasing [4]; and that if the demand is maintained at a conservative average rate of 2 %, the total global energy demand will increase by 100 % in 30 years. Therefore, there is a need for a strong motivation to implement a more sustainable energy mix globally, driven by positive polices. More so, there is a concern for international development agencies—namely the United Nation Development Programme (UNDP), the Africa Development Bank (AfDB), the World Bank, the Global Environmental Facility (GEF), the Africa Renewable Energy Fund (ARDF), etc.—and regional and national governments to provide electricity to the about 16 % of the world population living without electricity in the rural communities [3]. A better solution to the energy starvation of the rural areas would be the deployment of a decentralised energy project, through the utilisation of renewable energy sources, as a majority of rural areas is dispersed settlements with relatively low energy demand.

In Nigeria, power generation and distribution is a major challenge. For example, the power per capital stood at about 31 (based on the December 2012 power generation data and 170 million people), which is far below the majority of countries like China (260 W/capita), Brazil (480 W/capita), South Africa (1047 W/capita), UK (1266 W/capita), etc. [5]. This challenge is closely tied to the use of conventionally centralised energy generation and the weak distribution network. Hence, there is a need for the generated energy to be transmitted over long distances by means of transmission lines. An expensive, congested and unstable transmission grid is often the result, as many lines have to be constructed to meet the ever growing demand for energy. The effect of the energy challenge is especially felt in the rural coastline communities, which are far from the point of power generation coupled with rugged terrains. Thus, connecting these dispersedly populated areas to the national grid further complicates the transmission problem. The grossly inadequate supply of electricity has left the communities underdeveloped—socially and economically. As the coastline areas have dispersed settlements located mainly in rugged terrain, and coupled with the privatisation of the power sector, this makes their electricity supply economically impossible (at least in the next decade)—in spite of the region's large daily production of oil and gas. Meanwhile, electricity is required for such basic developmental services such as pipe borne water, health care, telecommunications and quality education [2].

To satisfy these rural coastline communities' energy demand, the majority of the communities have resorted to use standalone diesel engines for power generation. These generators are known for high maintenance costs as well as high pollutant emissions, which have left a negative impression of the economy and environment of these communities. Moreover, the pump price of diesel fuel in the rural coastline areas is normally far above the regulated pump price. A better way to solve the rural community energy challenge would be the deployment of distributed renewable energy systems. Distributed energy systems are decentralised energy generation facilities that satisfy localised energy demands. These systems principally use renewable energy sources but may also have a fossil fuel element in the energy mix. The generated energy reaches the consumers through smaller transmission grids known as microgrids, which are cheaper and more easily maintained.

A typical distributed energy system is a diesel-photovoltaic-wind-battery hybrid energy system. Such a system can be used in a coastline community because of the availability of renewable energy sources [6]. Many research works have covered the deployment of hybrid energy systems like a PV-diesel-battery system [7] and a PV-diesel-wind-battery system [8] for locations within Nigeria. In the literature, [9] is reported that there is an increase in the use of renewable energy sources for power generation in remote areas, due to the continuous decrease in the cost of renewable technologies. The author reviewed the current state of the design and operation of stand-alone PV-diesel hybrid energy systems and highlighted the possible future developments of such systems that would increase their socio-economic and environmental acceptance. Others [10] used the HOMER software to analyse the techno-economic viability of using hybrid PV-diesel-battery systems to meet the load requirement of a typical commercial building. The optimised system could offer 0.149 $/kWh as the cost of energy. Other scientists [11] carried out an energy optimization for two data centres in Nigeria, at Abuja (Northern Nigeria) and Nkanu west (Southern Nigeria), in order to determine the least cost pathway in power generation. The possible options were different combinations of grid supply, diesel generator, wind turbines and PV panels. The authors found that the best economic choice is the grid supply, which is, however, highly unreliable. On the premises of reliability and environment, the overall best is a hybrid grid tied solar power, since the hybrid system could reduce CO_2 emission by 973 and 853 kg/year in Abuja and Nkanu west, respectively.

However, the majority of the research works has not properly addressed the energy challenges facing the coastline communities in the light of techno-economic, social and environmental consideration. Therefore, this work employs a multi-criteria decision towards the deployment of green and sustainable energy systems for the coastline communities in Nigeria. This becomes necessary as the move by the FGN to a radically increase in the nation's power capacity to 25000 MW by 2025 [12], if realised, may not even favour the extension of the national grid to the coastline communities due to both the rugged terrain and the privatisation of the power sector that is profit driven.

Methods

System description

Four energy system alternatives are considered for the multi-criteria optimal energy system, namely a diesel-solar PV-wind energy system (DPWES), a diesel-PV energy system (DPES), a diesel-wind energy system (DWES) and a diesel-battery energy system (DBES). An absolute renewable energy technology, a wind-solar PV hybrid energy system (WPES), is not considered as one of the alternatives, as the majority of the coastline communities have already installed diesel generators and matured expertise in diesel engine maintenance. Moreover, a background study on the WPES, based on the current prevailing economic and technical parameters, shows that its choice for the coastline communities is not economically feasible.

The diesel-PV-wind energy system

The hybrid DPWES is shown in Fig. 1. This hybrid system comprises diesel, wind and solar energy sources. The electrical power from the diesel engine (within a scheduled period) goes directly to the facility load; the PV electrical power is supplied directly to the battery bank; and the wind turbine power (AC type) is partly supplied to the battery and the facility load is depending on the level of charge and facility energy demand. The stored energy in the battery is used through the converter (inverter/rectifier) during capacity shortage.

The diesel-PV energy system

The hybrid DPES is shown in Fig. 2. This hybrid system comprises diesel and solar energy sources. The electrical power from the diesel engine (within a scheduled period) partly goes to the facility load and the battery bank, depending on the level of charge and facility energy demand; whereas the PV electrical power is supplied directly to the battery bank. The stored energy in the battery is used through the converter (inverter/rectifier) during capacity shortage.

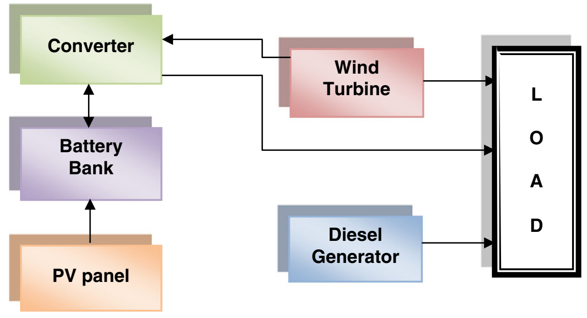

Fig. 1 Diesel-PV-wind-battery hybrid energy system description

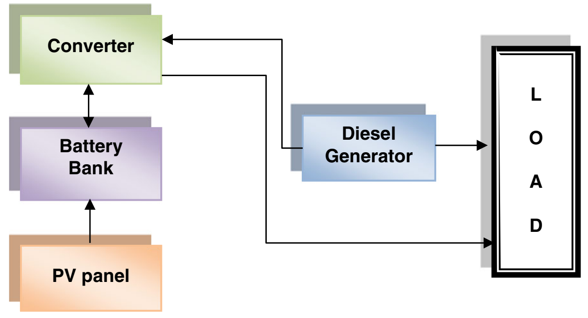

Fig. 2 Hybrid diesel-PV-battery energy system

The diesel-wind-battery energy system

The hybrid DWES is shown in Fig. 3. This hybrid system comprises diesel and wind energy sources. The electrical power from the diesel engine (within a scheduled period) and wind turbine partly goes to the facility load and the battery bank, depending on the level of charge and facility energy demand. The stored energy in the battery is used through the converter (inverter/rectifier) during capacity shortage.

The diesel-battery energy system

The DBES is shown in Fig. 4. The electrical power from the diesel engine partly goes to the facility load and the battery bank. The stored energy in the battery is used through the converter (inverter/rectifier) during capacity shortage. The capacity shortage is expected to occur during the night.

Data collection

A typical coastline community (Abonnema, Rivers State), which has all the prevailing attributes of coastline communities in Nigeria, is chosen as a case study. It has the following geographical description: location coordinates 4.7231° N and 6.7788° E and elevation of 276 m. There are, normally, three basic approaches are available for the estimation of solar radiance on flat surfaces—estimation

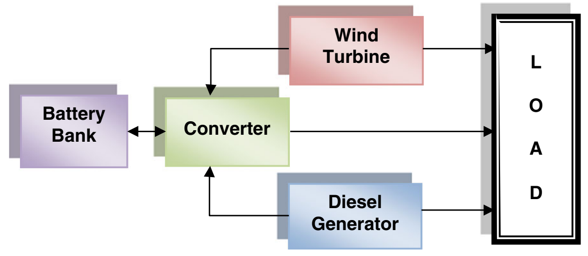

Fig. 3 Diesel-wind-battery energy system

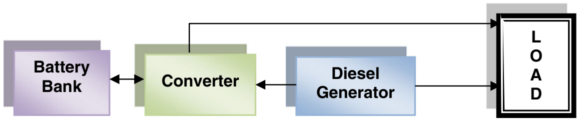

Fig. 4 Diesel-battery energy system

based on in situ data, estimation based on satellite data and combination of in situ data and satellite data. Estimation based on geostationary satellite data have been deployed in many applications [13, 14]. Specifically, experimental data presented in [15] confirms the applicability of the NASA Surface Meteorology and Solar Energy (SSE) data for the Africa continent. Therefore, the NASA SEE data base about global horizontal radiation that monthly averaged values over a 22-year period (July 1983–June 2005) was considered in the current analysis. Figures 5 and 6 show the monthly averaged solar insolation and the monthly averaged wind speed of the community, respectively, as retrieved from NASA surface meteorology [16].

The NASA Surface Meteorology and Solar Energy (SSE) database has a global coverage, and the available data can be used for both solar and wind energy resources, as verified by experimental data of [15]. The wind speeds presented in Fig. 6 are extrapolated at a 50-m hub height, as wind speeds at lesser heights are not feasible for electrical energy generation for the site considered. The location considered belongs to the power class one, according to wind power classification by [17, 18], which is considered to be poor for direct wind power generation. However, the wind energy potential would be adequate for battery charging and water pumping, i.e. non-connected electrical and mechanical applications [8].

The load profile of a typical coastline household is presented in Fig. 7. The typical coastline household has a 24-h supply of electricity from an oil-producing field logistic base. The profile was recorded on a day-to-day basis to compute the average daily energy requirement of the household. The typical household has no energy management scheme and no use of low energy demand appliances (e.g. low energy bulbs); therefore, the load profile is not optimised. However, it is expected that the current energy demand would increase across the coastline communities with the availability of a constant electricity supply, which would be balanced with proper energy management. Therefore, the use of the current household load profile of Fig. 7 is adequate for the current analysis.

It is observed from Fig. 7 that between the hours of 12:00 midnight and 6:00 AM, the demand is considerably low since the members of the household are asleep and electricity is only needed to power a few light bulbs and fans; however, there is a sharp rise in the energy demand within the hours of 6:00 AM and 8:00 AM period, which is associated to morning activities in preparation for work and school. It is also observed that the demand is lowest within the hours of 9:00 AM to 1:00 PM, and this can be explained by the fact that most people are out of the house for their daily activities during this period. Furthermore, between 1:00 PM and 6:00 PM, the demand starts to increase since those who were out during the day begin to return home. Finally, between 7:00 PM and 11:00 PM, the electricity demand is high because virtually all the members of the household are back home and make use of electricity for various domestic loads specified in Fig. 7.

System specification and modelling

System specification

The technical and economic specifications used in the HOMER analysis are presented in Table 1.

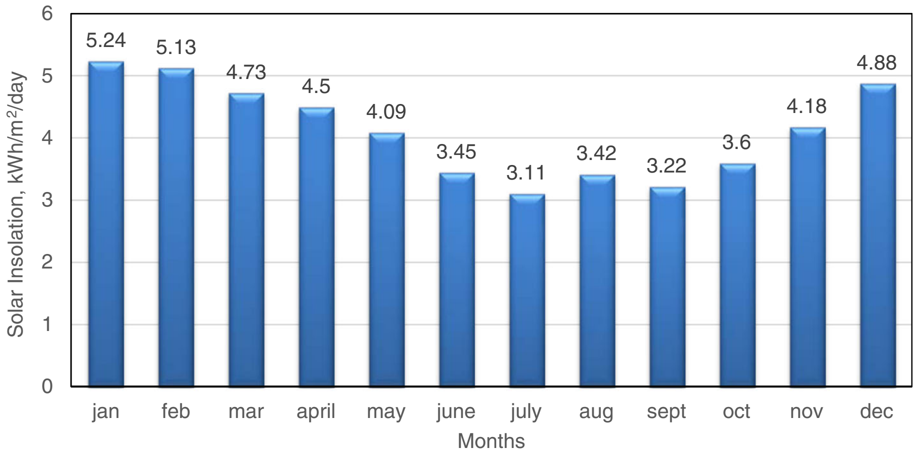

Fig. 5 Monthly averaged solar insolation of a typical coastline community in Nigeria

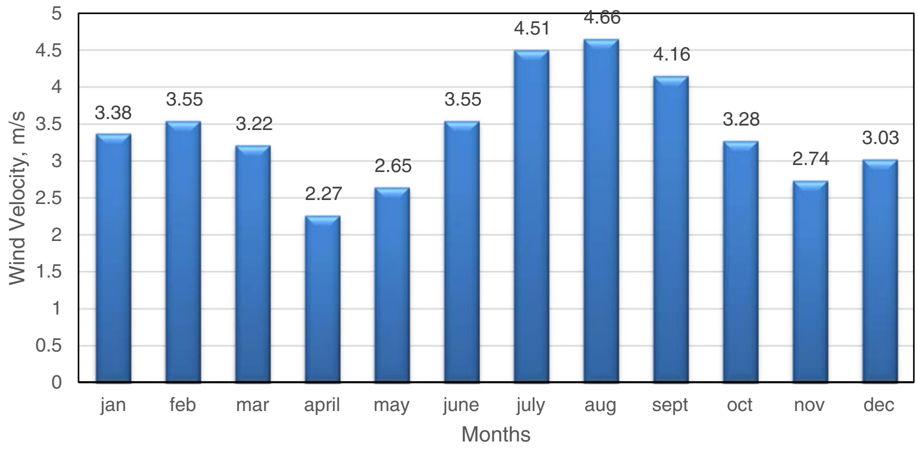

Fig. 6 Monthly averaged wind speed of a typical coastline community in Nigeria

From Table 1, the capital and replacement costs of the PV panel and wind turbine are \$3,975/kW and \$3,378.75/kW and \$3,560/kW and \$3,026/kW, respectively. The cost of replacing these components are 15 % lesser than the initial cost [6]. The costs of the other items listed in the specification table are derived from the cost and performance data for power generation technologies of the National Renewable Energy Laboratory (NREL) as reported by [19]. The project life span is taken as 25 years. Economic specification is at a discount rate of 13 %, and an inflation rate of 9.4 % as used in [20].

System modelling with HOMER

HOMER is an acronym for a Hybrid Optimisation Model for Electric Renewable. The NREL of the USA developed HOMER for both grid-tied and stand-alone applications. HOMER's computational algorithm is based on the life-cycle cost. Optimisation and sensitivity computational algorithms allowed rapid and robust techno-economic evaluations of various renewable energy technology (RET) options by accounting for the cost of RET alternatives and the availability of renewable energy resources. HOMER uses the load demand, the resources, the components details (with costs), the constraints, the systems control and the emission data as an input to simulate various feasible configurations and ranked by the net present cost (NPC). Normally, HOMER simulations cover 8,760 h of a typical year. Possible outputs from HOMER simulation are optimal sizing, NPC, cost of energy, capital cost, capacity shortage, excess energy generation, renewable energy fraction and fuel consumption [21].

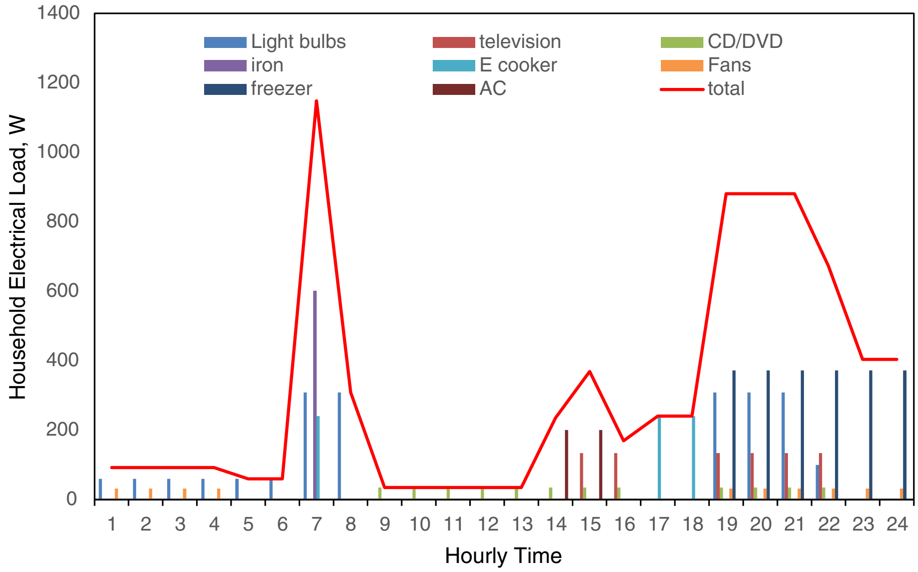

Fig. 7 Load profile of a typical coastline household

Table 1 Technical and economic specifications

No.	Description	Specification
1	Generic flat plate PV panel	
	Capital cost [$/kW]	3,975.00
	Replacement cost [$/kW]	3,378.75
	Maintenance cost [$/kW/year]	0[a]
	Lifetime [years]	20
2	Generic wind turbine	
	Capital cost [$/kW]	3,560.00 [26]
	Replacement cost [$/turbine]	3,026.00
	Maintenance cost [$/turbine/year]	10.00
	Lifetime [year]	20
3	Auto size genset	
	Fuel	Diesel
	Capital cost [$/kW]	500.00
	Replacement cost [$/kW]	500.00
	Maintenance cost [$/kW/hr]	0.030
	Lifetime [hours]	15,000
4	System converter	
	Capital cost [$/kW]	300.00
	Replacement cost [$/kW]	300.00
	Maintenance cost [$/kW/year]	100.00
	Lifetime [years]	15
5	Generic 1 kWh lead acid battery	
	Capital cost [$/battery]	300.00
	Replacement cost [$/battery]	300.00
	Maintenance cost [$/kW/year]	10.00
	Lifetime [years]	5

[a] This value is based on the assumption that the operating and maintenance cost is negligible for a localised distributed energy systems [24, 27]

The input data that were used in this analysis are a daily load profile obtained from Fig. 7, the monthly averaged solar insolation and wind speed, as shown in Figs. 5 and 6 and the technical and economic data presented in Table 1. The load profile presented in Fig. 7 is presented for a typical household. However, the coastline community considered has a projected population of about 68,591 people, with an average of 6 persons per household [22]; therefore, in the HOMER optimisation, the load profile is scaled up by 11,432 households for the entire community.

HOMER output

HOMER simulates thousands of system configurations for the four energy system alternatives considered. It picks out the optimum configuration for each of the alternatives based on the lowest net present value (NPV). A summary of HOMER optimised system configurations for the four energy alternatives are presented in Table 2.

Table 2 shows that the diesel-PV-Wind-energy system showing the highest renewable fraction of 38 % and the least fuel cost ($3.87 million) and CO_2 emission (13,967,743 kg/year). However, it features the highest capital cost, net present cost and cost of energy of all the four alternatives. On the other hand, the diesel-battery energy system has the least capital cost and cost of energy, but it has the highest CO_2 emission of 27,121,554 kg/year, which is almost double that of the diesel-PV-Wind-energy system, highest cost of fuel ($7.52 million) and no renewable fraction. The results obtained need further analysis to obtain the best alternatives, as they all have substantial merits and demerits. The multi-criteria decision analysis is, therefore, considered for the further analysis.

Multi-criteria decision analysis

The multi-criteria decision analysis is employed when a decision on the best alternative must be made based on several attributes [23]. The results from HOMER provide the optimum configuration of four hybrid energy systems. A decision on which system best suits the coastline community must be made. This decision is based on technical, economic, environmental and social factors, which make up the different attributes for the coastline energy system.

TOPSIS method

A good multi-criteria decision analysis method is the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). The basic idea of TOPSIS is that the best alternative should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution [23]. To deploy the TOPSIS method, the following steps are sequentially followed.

Step 1—Definition of the attributes

Step 2—Formulation of the decision matrix, *X*, which has *m* alternatives and *n* criteria with scores for every attribute of each alternative. The scores make up the elements of the matrix x_{ij}.

Step 3—Obtaining the normalised matrix *R*. This is done by applying Eq. 1.

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

where:

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

$$i = 1, 2, \dots, m \,;\, j = 1, 2, \dots, n$$

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

Step 4—Calculate the weighted normalised matrix. This can be calculated according to Eq. 2.

Table 2 Optimised system data

Components	Alternatives			
	DPWES	DWES	DPES	DBES
Diesel generator [kW]	25,000	25,000	25,000	25,000
Solar panel [kW]	25,000	0	20,000	0
Wind turbine [kW]	25,000	25,000	0	0
Battery [KWh]	40,000	20,000	30,000	15,000
Converter [kW]	15,000	4,000	10,000	3,000
Capital cost ($)	217,000,000	109,000,000	104,000,000	17,900,000
Operation and maintenance cost ($)	3,500,000	2,520,000	3,150,000	3,300,000
Net present cost($)	415,000,000	310,000,000	311,000,000	282,000,000
Cost of energy($/kWh)	0.787	0.588	0.589	0.554
Cost of fuel ($)	3,870,000	5,240,000	5,390,000	7,520,000
Renewable fraction (%)	38	18	14	0
CO_2 emissions (kg/year)	13,967,743	18,887,588	19,454,924	27,121,554

$$v_{ij} = w_{ij} \times w_j \tag{2}$$

where;

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

Step 5—Determination of the positive and negative ideal solutions by means of the Eqs. 3 and 4.

$$\begin{aligned} A^+ &= \left(v_1^+, \dots, v_j^+, \dots, v_n^+\right) \\ &= \left\{\left(\max_j v_{ij} | j = 1, \dots, n\right) i = 1, \dots, m\right\} \end{aligned} \tag{3}$$

$$\begin{aligned} A^- &= \left(v_1^-, \dots, v_j^-, \dots, v_n^-\right) \\ &= \left\{\left(\min_j v_{ij} | j = 1, \dots, n\right) i = 1, \dots, m\right\} \end{aligned} \tag{4}$$

Step 6—Calculation of the relative distance of each solution from the positive ideal solution and to the negative ideal solution by Eq. 5 and Eq. 6, respectively.

$$S_i^+ = \sqrt{\sum\nolimits_{j=1}^{n}} \left(v_j^+ - v_{ij}\right)2 \tag{5}$$

$$S_i^- = \sqrt{\sum\nolimits_{j=1}^{n}} \left(v_j^- - v_{ij}\right)2 \tag{6}$$

Step 7— Calculation of the relative closeness of each alternative to the ideal solution. This can be computed by Eq. 7.

$$C_i = \frac{S_i^-}{s_i^+ + S_i^-} \tag{7}$$

Analysis of attributes

The attributes considered which are based on the technical, economic, environmental and social factors in the presented analysis are discussed as follows.

Capital cost: This is the initial cost required to start the project. It is a negative factor, thus, it is expected to be low as possible.

Operation and maintenance cost: This is the sum of money spent on operating and maintaining the system during its lifetime. It is also a negative factor; it should be as low as possible.

Net present cost: This is the sum of present value of incoming and outgoing cash flow during the project lifetime. It is a negative factor and, thus, it should be as low as possible.

Cost of energy: This is also a negative factor, since the cost of producing electricity should be as low as possible.

Cost of fuel: This is the total sum spent on fuel during the life time of the project. Our aim is also to keep this as low as possible.

Type of technology used: It is a positive attribute and should be as high as possible.

Renewable fraction: This is the percentage of the energy generated that comes from renewable sources. It is a positive factor, in regard to the environment, so it should be as high as possible.

CO_2emissions: This is the total mass of CO_2 that is emitted due to the combustion of diesel per year. It is a negative factor so it should be reduced.

Socio-cultural awareness: It shows that the communities are aware of the benefits of using any of the alternatives. It is a positive factor so it should be as high as possible.

Technology availability: It shows the effect of the availability of the technology when it needs to be replaced to alter the whole system. It is a negative criteria hence it should be as low as possible.

Ease of installation: It quantifies how easily the components of the energy system could be installed. It is a positive criterion and is expected to be increased.
Environmental impact: It shows the impact of the energy system on the environment. It is a negative factor, and it should be as low as possible.
Natural resources availability/predictability/randomness (wind, sun): It is a positive factor that should be as high as possible, since the more the renewable resources, the cleaner the energy produced.
Life cycle assessment: This too is a positive attribute and should be increased.

Analysis

Table 3 shows the initial decision matrix which has 4 alternatives and 15 attributes. The scores for the attributes are gotten from the HOMER results, the analysis of the literature [23], the questionnaire and the engineering expertise.

Table 4 shows the normalised matrix based on Eq. 1 and the corresponding criteria weights.

Table 5 shows the weighted normalised matrix based on Eq. 2.

Table 6 shows the positive and negative ideal solutions based on Eqs. 3 and 4.

Table 7 shows the relative distance of each solution from the positive ideal solution and to the negative ideal solution based on Eq. 5 and Eq. 6 for each of the alternatives.

The alternative with relative closeness value closest to 1 is the best alternative, whereas the alternative with the value farthest from 1 is the worst alternative.

Results and discussion

The results show that the most promising alternative, based on the multi-criteria decision analysis, is the DPWES, which has a relative closeness of 0.489226; followed by the DWES, with a relative closeness of 0.477244. In the third place is DPES, with a relative closeness of 0.46917; and the DBES, with a relative closeness of 0.34451, is ranked fourth and the worst. The energy systems with renewable energy contribution are in fair competition with the diesel-battery combination. This is attributed to the negative exertion the DBES has on the environment and the high fuel cost required in running the DBES.

The best alternative has a cost of electricity of 0.787 \$/kWh. The proposed system compared fairly well with a similar system (hybrid diesel-solar PV energy system) under a Malaysian's condition, which gives a COE of 0.796 US\$/kWh for a solar irradiance and a cost of fuel of 5.5 kWh/m^2/h and 2.03 US\$/L, respectively [24]. Also, the COE compared well with a similar study in the Niger Delta region that gives 0.673 US\$/kWh for an average solar irradiance and a cost of fuel of 3.75 kWh/m^2/day and 1.02 US\$/L, respectively [6]. The net present value of the best energy alternative is \$415,000,000. The cash flow, which details the movement of money into and out of the project during the project's life span, for the best alternative energy system (DPWES) is presented in Fig. 8.

Figure 8 shows that the maximum negative cash flow of \$217 million occurred at the start of the project. This is expected as all the components of the energy system

Table 3 Initial decision matrix

Components	Alternatives			
	DPWES	DWES	DPES	DBES
Capital cost [\$]	217,000,000	109,000,000	104,000,000	17,900,000
Operation and maintenance cost [\$]	3,500,000	2,520,000	3,150,000	3,300,000
Net present cost [\$]	415,000,000	310,000,000	31,100,000	282,000,000
Cost of energy [\$/kWh]	0.787	0.588	0.589	0.554
Cost of fuel [\$]	3,870,000	5,240,000	5,390,000	7,520,000
Renewable fraction [%]	38	18	14	0
CO_2 emissions [kg/year]	13,967,743	18,887,588	19,454,924	27,121,554
Cultural awareness	6	6	6	6
Technology availability	6	7	5	2
Ease of installation	5	5	6	3
Environmental impact	4	5	6	9
Natural resources Availability/predictability/randomness (wind)	6	7	4	1
Natural resources availability/predictability/randomness (sun)	7	4	7	1
Life cycle assessment	4	5	5	8
Type of technology used	6	6	6	6

1—slightly affected, 10—highly affected

Table 4 Normalised matrix

Alternatives				Criteria weights
DPWES	DWES	DPES	DBES	
0.81956	0.411668	0.392785	0.067604	1
0.557505	0.401404	0.501755	0.525648	0.5
0.622412	0.464934	0.466434	0.42294	1
0.618526	0.462126	0.462912	0.435405	1
0.342013	0.463088	0.476344	0.664584	0.53
0.857458	0.406164	0.315906	0	1
0.342216	0.462754	0.476654	0.66449	0.5
0.609994	0.457496	0.457496	0.457496	0.91
0.561951	0.65561	0.468293	0.187317	0.79
0.512989	0.512989	0.615587	0.307794	0.6
0.318223	0.397779	0.477334	0.716002	0.8
0.652753	0.652753	0.373002	0.09325	0.5
0.594089	0.396059	0.693103	0.099015	0.5
0.350823	0.438529	0.438529	0.701646	0.78
0.5	0.5	0.5	0.5	0.6

Table 6 Positive and negative ideal solution

	Ideal solution	
Factor	A+	A−
Negative	0.0676	0.81956
Negative	0.2007	0.27875
Negative	0.00527	0.70363
Negative	0.4354	0.61853
Negative	0.18127	0.35223
Positive	0.85746	0
Negative	0.17111	0.33225
Positive	0.455	0.455
Negative	0.14798	0.51793
Positive	0.36935	0.18468
Negative	0.25458	0.5728
Positive	0.32638	0.04663
Positive	0.34655	0.04951
Positive	0.54728	0.27364
Positive	0.3	0.3

are purchased at the start of the project. At year 20, $136 million is spent replacing the solar panels and wind turbines whose life spans are 20 years each. At the end of the project life span of 25 years, the components of the system can be sold and a salvage of $135 million is recovered.

Figure 9 shows the monthly average amount of electricity generated by each component of the DPWES— XL1R is wind turbine, auto denotes the diesel generator and PV the solar-PV in the figure. Critical observation of Fig. 9 shows that the trend of electricity generation by the solar-PV and wind turbine follow the trend of the monthly averaged solar insolation and wind speed of Figs. 5 and 6, respectively. Therefore, it is expected that if the wind speed is extrapolated for a 100-m hub height, the DPWES would have more renewable energy penetration, which would see the diesel engine's size being reduced, and by implication a reduction in exhaust emissions.

Table 5 Normalised weighted matrix

DPWES	DWES	DPES	DBES
0.81956	0.411668	0.392785	0.067604
0.278753	0.200702	0.250877	0.262824
0.622412	0.464934	0.466434	0.42294
0.618526	0.462126	0.462912	0.435405
0.181267	0.245437	0.252463	0.35223
0.857458	0.406164	0.315906	0
0.171108	0.231377	0.238327	0.332245
0.555095	0.416321	0.416321	0.416321
0.443942	0.517932	0.369951	0.147981
0.307794	0.307794	0.369352	0.184676
0.254578	0.318223	0.381867	0.572801
0.326377	0.326377	0.186501	0.046625
0.297044	0.19803	0.346552	0.049507
0.273642	0.342053	0.342053	0.547284
0.3	0.3	0.3	0.3

The DPWES generates 13,967,743 kg/year of CO_2 into the atmosphere, whereas the DBES generates 27,121,554 kg/year of CO_2. The DPWES is able to reduce CO_2 emissions by 48.5 %/year (which culminates in a reduction of the Global Warming Potential) of the DBES and an equivalent fuel cost by 48.5 %/year. This emission reduction is a significant achievement as it will reduce the cost imposed on CO_2 emission by environmental legislations, which is the normal practice in most developed nations [9]. Although there are currently no such environmental legislations in Nigeria, but it has been emphasised in the new energy policy [25]. However, even in the absence of a carbon penalty cost, the 48.5 % carbon reduction would make the environment friendlier. It is expected that the reduction in GWP due to the reduction in CO_2 would equally manifest in the reduction of other environmental impacts, namely abiotic depletion, ozone depletion potential, human toxicity,

Table 7 Relative distance

s1+	1.079197	s1−	1.033669
s2+	0.867285	s2−	0.791779
s3+	0.867879	s3−	0.767069
s4+	1.127874	s4−	0.592783

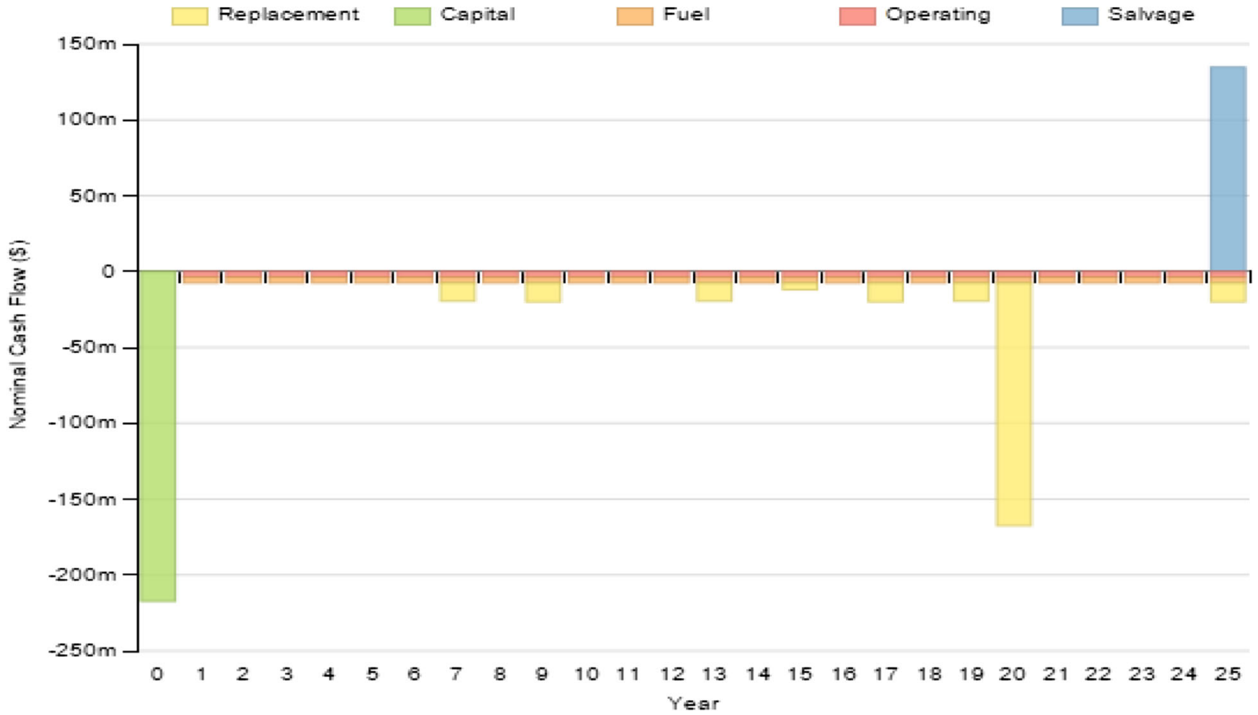

Fig. 8 Cash flow for the DPWES

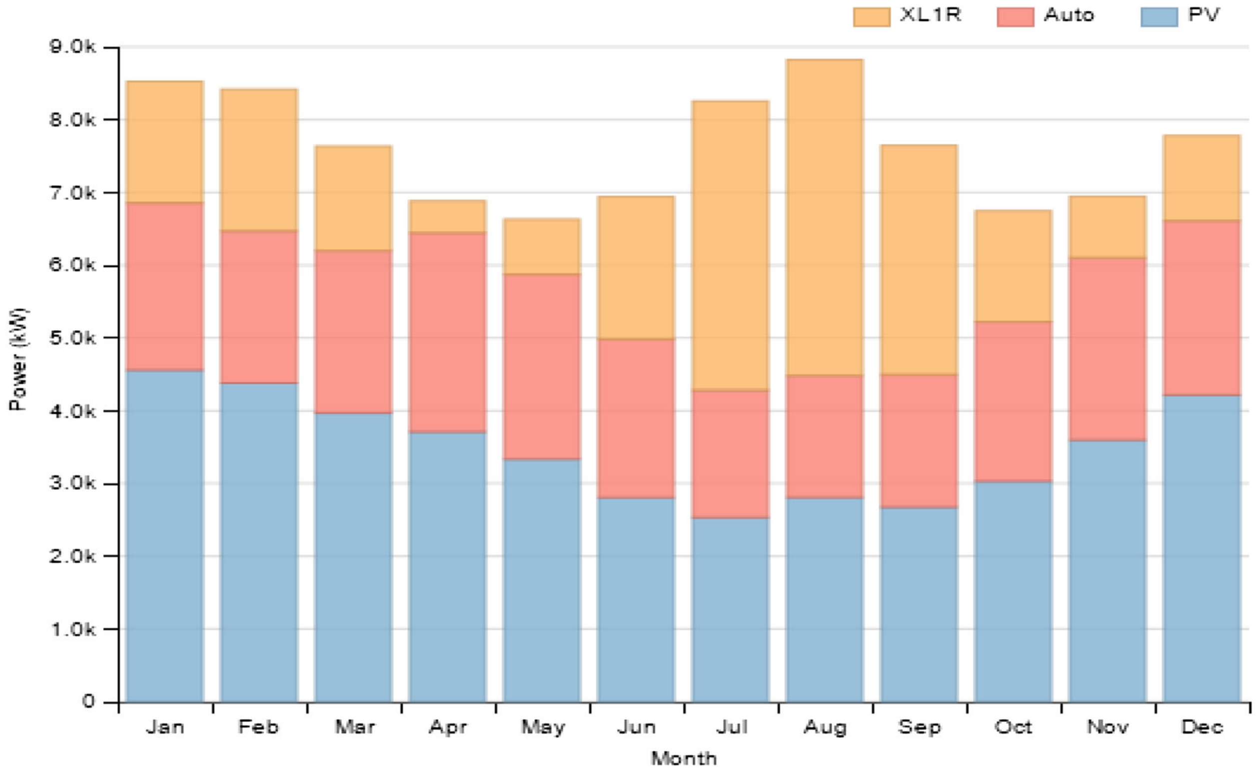

Fig. 9 Monthly average energy generations for the DPWES

freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication.

Conclusions

A significant number of Nigeria's coastline communities, which are mainly concentrated in the Niger Delta, absolutely depend on diesel generators and firewood to the meet energy demand; which implies that the combined effect of stringent Government's policy against indiscriminate deforestation and global hike in fuel prices would have undesirable impact on the social-economic position of the communities. This paper, therefore, suggests the best hybrid energy system (diesel-PV-wind), which has a potential of ameliorating climate change, for the coastline communities in Nigeria. The best energy system provides the best components with an appropriate operating strategy to provide an efficient, reliable, cost-effective and environment-friendly system. The HOMER hybrid optimisation software and the multi-criteria decision-making, based on the TOPSIS algorithm, were used to arrive at the best hybrid energy system. The decision is based on four alternatives and 15 different economic, social and environmental criteria. The best hybrid energy system has a cost of electricity of 0.787 $/kWh, which compares well with other hybrid energy systems presented in the literature. However, the COE of 0.787 US$/kWh is not competitive with the current average COE of 0.091$/kWh from the national utility grid. However, with positive FGN policies towards renewable energy penetration and the support from the oil-producing companies towards their operational areas would see the COE being significantly reduced. The suggested best energy system is able to reduce CO_2 emissions by 48.5 %/year compared to a diesel-battery energy system. This emission reduction is a significant achievement as it will reduce the cost imposed on CO_2 emission by environmental legislations, which is the normal practice in the developed nations. Reducing fossil-fuel-fired energy sources in the coastline communities, which are mainly concentrated in the Niger Delta region of Nigeria, would not only reduce the environmental impacts but also contribute to the socio-economic advancement of the disadvantaged coastline communities.

The move by the FGN to radically increase the grid capacity to 25,000 MW by 2025 [19], if realised, it may not even favour the extension of the national grid to the coastline communities due to rugged terrains and the privatisation of the power sector that is profit driven. It is envisaged that the implementation of the suggested energy system with other environmentally responsible interventions would support the Niger Delta coastline communities, whose livelihoods have been impaired by gas and oil exploration, to attain their fully environmental, social and economic potentials. Their potential would be driven by the availability of electricity, as electricity is required for such basic developmental services such as pipe borne water, health care, telecommunications and quality education. However, the suggested energy system is not absolutely environment-friendly, though it suggests having appreciable positive impact on the environment. Continuous research in this area would deploy absolutely environment-friendly energy system, namely a solar thermal/PV-wind-hydro pump-organic Rankine cycle energy system, which has a minimal exertion on the environment.

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Authors' contributions
The article was jointly prepared by all authors. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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