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Modelling and optimisation of a hybrid PV-wind turbine-pumped hydro storage energy system for mini-grid application in coastline communities

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A B S T R A C T

This study proposes a clean, reliable and affordable hybrid energy conversion technology that is based on sunlight and wind, with a hydro based energy storage system. The proposed system comprises Photovoltaic arrays, wind turbine (WT) and Pumped Hydro Energy Storage (PHES). The study was focused on satisfying energy demand of a typical coastline community, Patani (Lat. 5.23° N and Long. 6.17° E) – a Local Government Area (LGA). Genetic algorithm was adopted to optimise the PHES of the proposed hybrid plant to minimise the difference between energy demand and energy generated. Economic models were developed to ascertain the economic feasibility of the hybrid plant. High fidelity software (HOMER®, MATLAB® and MS Excel® spreadsheet) were utilised for the analysis and optimisation. The peak rated power of PV and WT required to satisfy the energy demand of the LGA are 217 kW_p and 226050 kW, respectively. The minimum storage capacity of the PHES was estimated at about 3,930,615 kWh, with the upper reservoir volume of 43170.06 m^3. The value of 0.27 \$/kWh was obtained for the Levelised Cost of Energy (LCOE); while the loss of load probability of the proposed energy system was estimated at 0.1086. The proposed energy system supports the Sustainable Development Goal 7 – affordable and clean energy, with climate change mitigation potential.

1. Introduction

The sharp increase in energy demand, the adverse environmental effect of conventional energy resources (coal, natural gas, and crude oil) and the cost of generating energy have drawn attention to the utilisation of renewable energy conversion technologies. It has been demonstrated that affordable, clean and adequate energy supply is the bedrock of modern economic development (Herington et al., 2017). The implication is that nations and communities with shortage and no access to electricity, respectively, will suffer basic developmental services and economic development. Nigeria is currently facing a turbulent energy crisis as only about 36% of the rural populace have access to electrical energy, with less than average of 4 h per day availability. The current obtainable electricity generation capacity in the country was estimated at 4.662 GW, with more than 13% transmission and distribution losses due to weak and fragile transmission and distribution network (NERC, 2019).

The estimated yearly economic growth rate of the country is between 7% and 13% (The World Bank, 2019) and urbanisation rate of 3.9% (Farrell, 2018), therefore, the electricity demand could be projected to hit about 52 GW by the mid-2020. The implication is that about 91% of the electricity demand of the country would be unsatisfied at the current capacity of electricity generation. The huge unsatisfied demand by the national grid entails that low energy demand density potential customers that dwell in the rural communities in the remote and rugged terrains would continue to live without electricity since it is economically expensive to extend the national grid to these communities.

For the reason of lack of energy access, rural communities are socially backward with its economic prospects remain untapped. Whilst conventional energy conversion technologies will remain important for Nigeria's energy mix, renewable energy conversion technologies also offer new possibilities for areas where access is low and supply is unreliable. The country has the potentials for cleaner energy development – namely wind, solar, hydro etc. Wind and solar energy conversion technologies are adjudged as the fastest growing renewable energy technologies (RETs) according to

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data in the open domain (IRENA, 2019). However, wind and solar energy sources are highly intermittent in supply, which requires energy storage to guarantee continuous supply of energy. Nevertheless, it is a consensus agreement by literature in the unrestricted domain that renewable energy has a key role in energy access and transformation (Hansen et al., 2019), (Gielen et al., 2019). Renewable energy conversion technologies support distributed energy model, which guarantees low electrical energy losses because distribution network is minimal, which is well suited for mini-grid applications (ESMAP Mission, 2017), (Comello et al., 2017).

Ref. (Ren and Ren, 2018) presented a detailed analysis on sustainable ranking of energy storage technologies under uncertainty conditions of cost, performance, technological and environmental, with ten sub-criteria. The studies evaluated prominent energy storage technologies, namely compressed air, Pumped Hydro Energy Storage (PHES), Lead-Acid, Lithium-ion, and Flywheel. The pumped hydro system was identified as the most prominent sustainable energy storage technology for renewable energy penetration and reliability. In comparison, the capital cost and CO_2 intensity for Pumped hydro and battery range from 25 to 50 $/kWh and 165–1443 $/kWh and 8–16 kg/MJ and 5–50 kg/MJ, respectively. At this present time, the PHES is most-wide spread energy storage system that is independent on chemical conversion (Koko et al., 2017), and many researches have shown that PHES is the most suitable energy storage for hybrid energy systems adapted to autonomous island mini-grids, where round trip efficiency varies between 70% and 80%, long asset life (50–100 years) and minimal operation and maintenance cost (Rehman et al., 2015)– (Ma et al., 2014a). Furthermore, due to environmental hazards during shipment, installation and disposal of batteries, high initial investment cost for large-scale and high capacity systems coupled with short lifespan (1–8 years) of batteries, pumped hydro storage system is preferred (Ma et al., 2014a).

Ref. (Ghorbani et al., 2018) presented a GIS-based method to identify prospective sites for a PHES mini-grid system. Ref (Jurasz and Mikulik, 2017). introduced a plan for PV-PHES energy system; and formulated a mathematical relationship for simulating the workability of a PV-PHES energy system. A report on multi-objective robust scheduling optimisation model for multi-energy hybrid system integrated wind and sunlight energies was presented in (Zhang et al., 2017). Improved coordination framework and optimal energy management of hybrid energy systems with PHES are presented in (Ghasemi and Enayatzare, 2018), (Ghasemi, 2018).

The hybridisation of renewable energy sources is a key to reliable energy supply, but the problem is how to adequately combine the stochastic renewable energies to balance the energy demand-side. However, there are available many optimisation frameworks for optimal combination of energy systems, namely deterministic, stochastic (heuristic) and hybrid. The stochastic methods have played a prominent role in the optimisation of energy systems due to their obvious advantage over the deterministic approaches (Nazari-heris et al., 2017), (Haghrah, 2017). Ref (Lawan and Wei, 2019). presented a thorough literature review on optimisation framework for stand-alone hybrid energy systems. The Genetic Algorithm was tipped as one of the stochastic optimisation frameworks for optimally hybridising stochastic energy sources. Of particular, the GA method, which uses randomly generated variables, has the capacity to solve the problem of local optima entrapment that is inherent in the deterministic approaches, with high probable solution space to find the global optimum solution. The GA, which is drawn on the evolution theory of survival of the fittest, involves six basic steps, namely population generation, evaluation of fitness, optimality test, selection, cross-over and mutation (Britain, 1999). The selection paradigm typifies GA for the stochastic optimisation applications.

The utilisation of renewable energy sources may prove to be the solution to the energy crisis in Nigeria, especially in the coastal areas where access to the national grid is lacking. The high penetration of renewable energy in Nigeria will increase access to generation of clean energy, and may encourage affordable energy in the rural communities. In order to achieve this, the adoption of hybrid energy system consisting of PV, wind and PHES system seems promising, judging from the abundant solar and wind energies in Nigeria (Shaaban and Petinrin, 2014). However, little research attention has been given to pumped hydro energy storage in Nigeria. Therefore, this paper is aimed at the optimal combination of solar and wind energy conversion technologies, with PHES, using the GA approach, for mini-grid application in Nigeria. The pumped hydro energy storage became imperative because the proposed energy system is for a location in the coastal region of the country, which has abundant water supply and a suitable topography for pumped hydro energy storage.

2. Materials and methods

Assessing the energy generation and economic potential of the proposed hybrid PV-WT-PHES plant for available, affordable and clean energy access requires the understanding of the interacting sub-systems, which can be analytically framed. Models with techno-economic parameters are developed and used to optimise the proposed hybrid energy system. Fig. 1 shows the structure of the proposed hybrid PV-WT-PHES plant with the functional components.

2.1. Description of system and location

The components of the proposed hybrid PV-WT-PHES plant are (see Fig. 1):

i. Photovoltaic (PV) modules panels
ii. Inverter converts.
iii. Horizontal axis wind turbines.
iv. Pumped hydro energy storage system, which comprises pump, hydro-turbine, upper and lower reservoirs.
v. Two reservoirs at different elevations. The Patani River serves as the Lower Reservoir (LR) while the Upper Reservoir (UR) is an artificial water storage unit.
vi. Power Control System (PCS)

The Photovoltaic (PV) panel converts sunlight to electrical energy, whereas the wind turbine converts wind energy to electricity. The PV produces Direct Current (DC), which is converted to

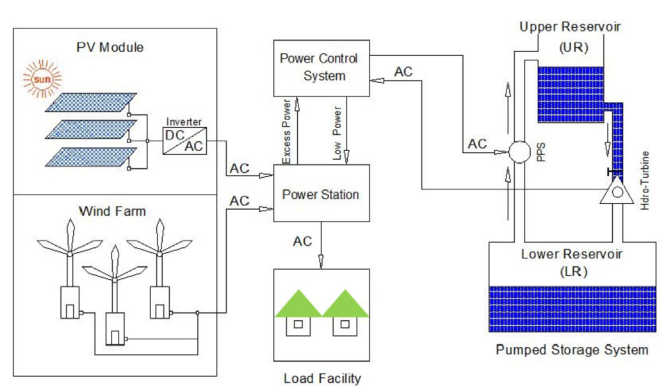

Fig. 1. Block diagram of the proposed plant.

Alternating Current (AC), before transmitting it to the Power Control System (PCS) – it regulates or controls the actions of the various electrical communications by the sub-systems. During the low demand period, the excess energy generated is used to pump water into the upper reservoir (UR) and stored as a potential energy. The water in the upper reservoir is allowed to flow to the lower reservoir (LR) through a hydro-turbine during capacity shortage. The hydro turbine produces electricity to serve the energy demand during the capacity shortage.

The location of the proposed hybrid PV-WT-PHES energy system is Patani Local Government Area of Delta State, Nigeria, as shown in Fig. 2. It is geographically located at 5.23° North Lat., 6.17° East Long., with 85 m elevation above the sea level. It covers an area of 217 km^2 and an estimated population of 89,722 in 2015. Patani LGA has 2 major towns and total of 12 major villages (Know Nigeria, 2019).

2.2. Power models of the proposed system

The hybrid plant is to operate in a manner that at any time, t, the power generated, (P_{Gen}), by the combined renewable energy technologies (RETs) and the power from the PHES P_{PHES}, must meet the power demand, P_{Dem}.

Mathematically,

$$P_{Gen}(t) = P_{PV}(t) + P_{WT}(t) \tag{1}$$

$$P_{Dem}(t) = P_{Gen}(t) \pm P_{PHES}(t) \tag{2}$$

where $P_{PV}(t)$, $P_{WT}(t)$ and $P_{PHES}(t)$ (MW) are the power generated by the: PV panels, WT and PHES, respectively.

It should be noted that:

- If $P_{Dem}(t) > P_{Gen}(t)$, the supplementary power from the hydro-turbine, $P_{PHES}(t) > 0$, compensates the shortfall in the power produced from the RETs.
- If $P_{Dem}(t) = P_{Gen}(t)$, $P_{PHES}(t) = 0$; the power produced by the RETs is just enough to meet the demand.
- If $P_{Dem}(t) < P_{Gen}(t)$, the power from the PHES $P_{PHES}(t) < 0$; the surplus power generated is stored by the PHES.

2.3. Modelling of system components

Assessing the energy generation of the proposed hybrid PV-WT-PHES plant requires the understanding of the interacting sub-systems. The sub-systems are analytically modelled in the following subsections.

2.3.1. PV module models

A PV panel is made up of solar cells which are joined in series and parallel so as to generate the required power – each cell is mainly a P–N diode. As sunlight strikes a solar cell, the incident energy is transformed directly into electricity.

The operating temperature, T_C (K), of a cell is given as (Engin, 2013):

$$T_C = T_{amb} + (0.03 \times G) \tag{3}$$

where T_{amb} (K) is the ambient temperature; G (W/m^2) is the irradiance or solar radiation.

The power output from PV panel is given as (Kumar and Biswas, 2017):

$$P_{PV}(t) = P_{rated} \times Y_{PV} \times \left(\frac{G}{G_{ref}}\right) \times \left[1 + K_T\left(T_C - T_{ref}\right)\right], \quad \text{or} \tag{4a}$$

$$P_{PV}(t) = P_{rated} \times Y_{PV} \times \eta_{PV} \times \eta_{INV} \times \left(\frac{G}{G_{ref}}\right) \tag{4b}$$

where $P_{PV}(kW)$ is the power yield of PV cell; $P_{rated}(kW)$ is PV rated power at reference condition; $G_{ref}(W/m^2)$ is solar irradiance at standard temperature conduction ($G_{ref} = 1000\ W/m^2$); $T_{ref}(°C)$ is cell temperature at reference conditions ($T_{ref} = 25°C$); $K_T(-)$ is the PV panel temperature coefficient; $K_T = 0.4 - 0.6\,\%$ (Hina and Palanisamy, 2015); and $Y_{PV}(-)$ is the PV derating factor.

The total number of modules that make up the PV panel can be estimated as:

$$N_{PV} = N_{PV_s} \times N_{PV_p} \tag{4c}$$

where N_{PV_s} and N_{PV_p} are number of PV module in series and number of PV module in parallel, respectively, which can be computed by

Fig. 2. Google earth of Patani (source: https://earth.app.goo.gl/?apn=com.google.earth&isi=293622097&ius=googleearth&link=https%3a%2f%2fearth.google.com%2fweb%2f%405.22793045,6.193285,8.4397481a,10289.02341054d,35y,0h,45t,0r%2fdata%3dChQaEgoKL20vMDgwcDZxZxgCIAEoAigC).

the knowledge of the bus and module voltage and current according to the methodology presented in ref. (Oko et al., 2012).

The annual energy output of the solar PV panel, $E_{PV}(kWh)$, is determined as

$$E_{PV} = \sum_{t=1}^{8760} [P_{PV}(t)] \tag{5}$$

2.3.2. Wind turbine models

The wind energy is converted into mechanical power through a wind turbine. The mechanical power is, thereafter, converted into electrical power through an electrical generator. To model wind energy conversion system, it is vital to know the mean wind velocity, its distribution and wind power distribution for the location under study.

The mean wind power density is given (Diemuodeke et al., 2019):

$$P_D(t) = \frac{P(\nu)}{A} = \frac{1}{2}\rho \nu_m(t)^3 \tag{6a}$$

where P_D (kW/m^2) is mean wind power density; $P(\nu)$ (kW) is wind power; and A (m^2) is the rotor blades swept area; ρ (kg/m^3) is the air density ($\rho = 1.225$ kg/m^3); $\nu_m(t)$ (m/s) is mean wind velocity.

The mean wind speed can be related to the hub height according to Eq. (6b) (Shoaib et al., 2019):

$$\nu_m(t) = c_h \Gamma\left(1 + \frac{1}{k_h}\right) \tag{6b}$$

where k_h $(-)$ and, c_h (m/s) are hub height dependent shape factor and scale factor, respectively.

The wind turbine power output is given as:

$$P_{WT}(t) = P_D(t) \times C_P \tag{7a}$$

where $C_P(-)$ is the mechanical efficiency of the wind turbine.

The total number of wind turbine required to satisfy the facility load can be estimated as

$$N_{WT} = \frac{P_{WT}}{P_{rated}} \tag{7b}$$

where $P_{rated}(kW)$ is the rated power of a selected wind turbine.

The annual energy output of wind turbine, $E_{WT}(kWh)$, is determined as:

$$E_{WT} = \sum_{t=1}^{8760} [A_{ts} \times P_{WT}(t)] \tag{8a}$$

where the turbine swept area, A_{ts} (m^2), can be estimated as (Boukhezzar and Siguerdidjane, 2009):

$$A_{ts} = \frac{\pi}{4} D_{WTB}^2 \tag{8b}$$

2.3.3. Pumped hydro energy storage models

This is a mechanical energy storage system, which comprises two reservoirs at different elevations. The Patani River serves as the lower reservoir (LR), while the upper reservoir (UR) is an artificial structure sized to supply power during low demand.

The power demand of the pumping system, $P_{Dem,p}$ (MW), during pumping mode is given as:

$$P_{Dem,p} = \frac{\rho g H_{UR} Q_p}{\xi_p} \tag{9}$$

where ρ (kg/m^3) is the density of water; H_{UR} (m) is the altitude difference between the two reservoirs; g (m/s^2) is gravitational acceleration; Q_p (m^3/s) is volumetric flowrate of water in pumping mode and ξ_p is the conversion coefficient for pumping.

The power capable of being generated, P_{PHES} (MW), when PHES is in the generation status is given as (Padrón et al., 2011):

$$P_{PHES} = \rho g H_{UR} Q_g \xi_g \tag{10}$$

where Q_g (m^3/s) is flowrate in generation status and $\xi_g(-)$ is the conversion coefficient for generation.

The efficiency of micro turbine, generator and pipeline could be taken as 80%, 80% and 95% according to engineering practice and manufacturers' specifications. Thus, the overall efficiency of the PHES system, η_t (%), is estimated at 60.8 %, which include all losses in the system (turbine, pump and pipe).

Potential energy, E_{PHES} (kWh), released from upper reservoir is given as (Ma et al., 2014b):

$$E_{PHES} = \eta_t \times \rho \times V \times g \times H_{UR} \tag{11}$$

where $V(m^3)$ is the volume of UR.

2.4. Optimisation of the hybrid plant

The optimisation of the proposed hybrid plant is modelled by minimising the difference between energy generated and energy demanded to accurately size the hybrid plant configuration. The objective function of the optimisation model is the storage capacity of PHES, C_{PHES}.

Energy generated by the RETs, E_{RE}, is gives as:

$$E_{RE} = E_{PV} + E_{WT} \tag{13}$$

where E_{PV} (kWh) is the energy generated from PV module and E_{WT} (kWh) is the energy generated from wind turbine.

Excess energy generated by RETs is given as:

$$E_{excess} = Max[(E_{RE} - E_D),\ 0] \text{ if } E_{RE} > E_D \tag{14}$$

where E_D (kWh) is energy demanded (facility load).

Energy demanded is given as:

$$E_D = \begin{cases} E_{RE} + E_{PHES};\ if\ E_D > E_{RE} \\ E_{RE} - E_{PHES};\ if\ E_D < E_{RE} \end{cases} \tag{15}$$

where E_{PHES} (kWh) is energy generated from PHES.

Therefore, if $E_D = E_{RE}$, then $E_{PHES} = 0$. This explains that the energy generated from the renewable sources is enough for the energy demanded.

Energy shortage from RES is given as:

$$E_{shortage} = Max[(E_D - E_{RE}),\ 0] \text{ if } E_{RE} < E_D \tag{16}$$

The difference between excess energy generated and energy shortage from the RETs for one year is given as:

$$E_{diff} = \sum_{i=1}^{365} \left(E_{excess,i} - E_{shortage,i}\right) \tag{17}$$

Storage capacity, C_{PHES}, of the PHES to be minimised on daily basis is given as:

$$C_{PHES} = \frac{E_{diff} \times \eta_{PHES}}{365} \tag{18}$$

where η_{PHES}, estimated at 60.8%, is the PHES energy conversion efficiency.

The loss of load probability, *LLP*, which ranges from 0 to 1, indicates the capacity of the energy system to meet its demands; it can be computed as (Canales et al., 2016):

$$LLP = \frac{\sum_{i=1}^{365}\left(E_{shortage}\right)}{\sum_{i=1}^{365}(E_d)} \tag{19}$$

The constraints adopted in the software to size the renewable energy converters are:

$1 \le N_{PV},\ N_{WT} \le 1000$; $40 \le D_{WTB} \le 95$ and $5 \le H_{UR} \le 100$.

2.5. Economic model

The economic assessment is based on life cycle costs (LCC), which accounts for all the recurring and one-time costs over the service life of the proposed plant. The costs of the proposed plant include construction cost, replacement cost and operation & maintenance cost (O&M).

The total LCC for the proposed hybrid plant can be estimated as (Oko et al., 2012):

$$LCC_T = \sum_{j=1}^{5} LCC_j; \quad j = \{1,\ 2,\ 3,\ 4,\ 5\} \equiv \{PV,\ WT,\ PHES,\ INV,\ PS\} \tag{20}$$

where

$$LCC_j = \sum_{q=1}^{3} C_q; \qquad q = \{1,\ 2,\ 3\} \equiv \{CC,\ O\&M,\ RC\} \tag{21}$$

where LCC_j ($) is the life cycle cost of different parts; C_q ($) is the present value of different cost component; and the indices CC, O&M and RC are Construction Cost, Operation & Maintenance and Replacement Cost, respectively.

Annual interest rate, *i*, converts one-time costs into annualised costs (Kumar and Biswas, 2017):

$$i = \frac{i' - f}{1 + f} \tag{22}$$

where i' is nominal interest rate, and f is inflation rate.

The total replacement cost (RC) of the main components can be estimated as (Kumar and Biswas, 2017)

$$RC = \sum_{j}^{N}\left[C_{rep_j} \times f_{rep_j} \times SFF_j - S_j \times SFF\right] \tag{23}$$

where f_{rep_i} is a factor due to component's lifetime and project's lifetime; *SFF* is the reducing fund factors; *S* is the salvage value.

$$f_{rep_j} = \frac{CRF}{CRF_j} \tag{24}$$

$$SFF = \frac{i}{(1+i)^{N-1}} \tag{25}$$

$$S_j = C_{rep\,j} \times \frac{L_{rem}}{L_{comp}} \tag{26}$$

where L_{rem} is the residual life of components; L_{comp} is total life of components and C_{rep} is the RC factor.

The Levelised Cost of Energy, LCOE ($/kWh), for a system having energy generated over the project lifetime can be expressed as (Oko et al., 2012):

$$\text{LCOE} = \frac{LCC_T}{E_{RE}} \times \frac{d(1+d)^N}{(1+d)^N - 1} \tag{27}$$

$$d = \frac{i' - f}{1 + f} \tag{28}$$

where i' is nominal interest rate, f is inflation rate, E_{RE} (kWh) is the energy generated by RETs, and $N = 25$ *years*.

The optimisation model is implemented in MATLAB's Genetic Algorithm (GA) optimisation tool, which is well suited for multi-modal and multi-objective optimisation problems (i.e. power and economic). The GA procedure, which is based on the genetics and natural selection theory of evolution, involves six basic steps as shown in Fig. 3a (Haupt and Haupt, 2004) (Britain, 1999). The GA procedure starts with the generation of population (representations of the solution vectors), with the capacity to procreate; the children from the population are subjected to survival of the fittest. The survived children are genetically uttered by crossover together with occasional random change of offspring structures (called mutation) and follow by selection of viable spring for the next generation. This process is repeated until the optimality condition is met; interested readers should consult refs. (Britain, 1999), (Haupt and Haupt, 2004) for details. The general algorithm (flow-chart) of the optimisation procedure, which incorporates the GA procedure, is shown in Fig. 3b.

The decision variables in the optimisation process are: Number of PV panel (N_{PV}); Diameter of wind turbine blade (D_{WTB}); Number of wind turbine (N_{WT}); and Head of the UR (H_{UR}).

2.6. Energy demand profile in Patani

An hourly energy demand investigation of a given facility is very vital when determining the optimal size of a hybrid system (Diemuodeke et al., 2017). The determination of energy demand in Patani was focused on: design of appropriate questionnaires, community visitations and quick interviews were conducted to assess the existing energy needs of the communities.

The energy demand profile in this study was estimated based on categories of energy demands:

Category A: This group consists of domestic household demand, which features: fluorescent light, incandescent light, portable stereo, CD player, television, radio, pressing iron, A/C, refrigerator, ceiling fan, table fan and others.

Category B: This category comprises of energy demand for social purposes, which was further grouped into:

i. *Primary Health Centre:* The loads here include fluorescent light, incandescent light, refrigerator, television, ceiling fan and table fan.
ii. *Public Schools:* The load here includes: fluorescent light, incandescent light, ceiling fan and table fan.

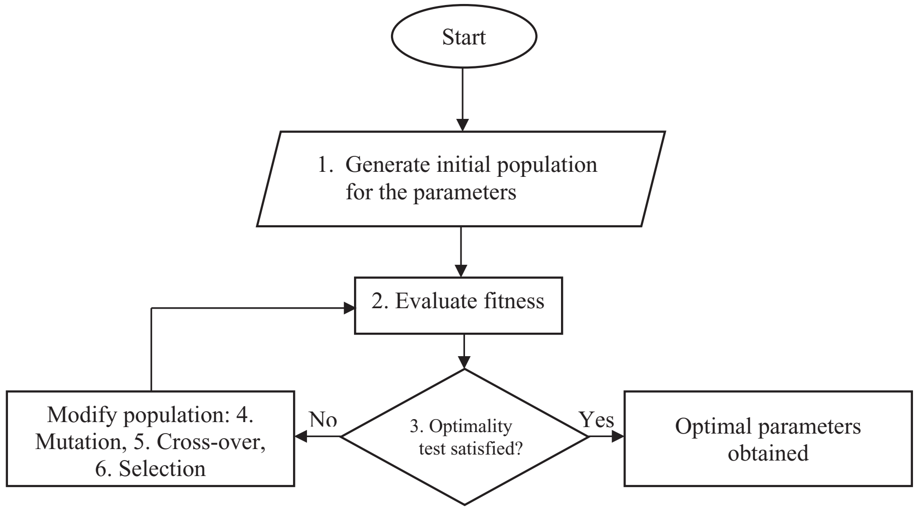

Fig. 3a. GA procedure.

The average daily energy demand $E_{kj}(Wh/facility/day)$ of the facilities was estimated by using Equ. (29) according to (Diemuodeke et al., 2017):

$$E_{kj} = \frac{\sum_{i}^{N_F} P_{ij}^{k}}{N_H}; j = 1,\ 2, 3, 4,\ \ldots,\ 24 \tag{29}$$

where $P(kW)$ is the power consumed by an appliance in a given

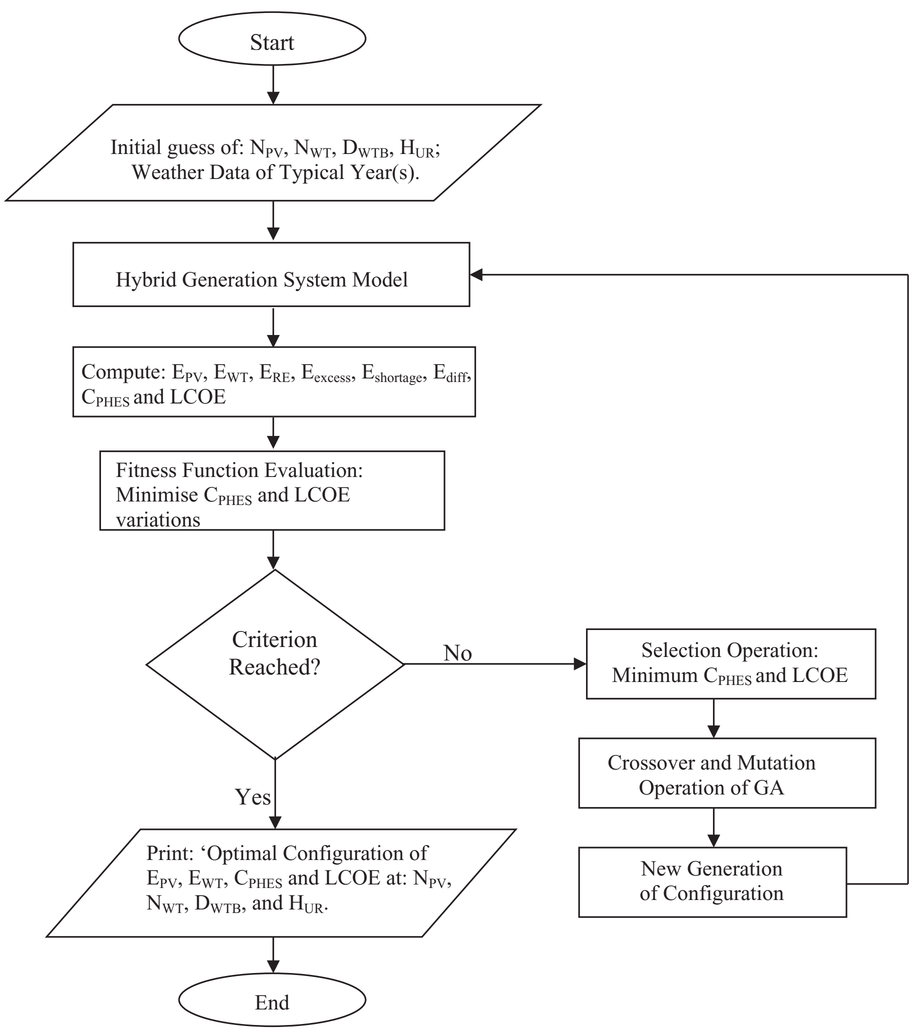

Fig. 3b. Flowchart of the GA incorporated optimisation procedure.

hour; N_F is the number of facilities (namely households, primary health centres and public schools); k represents individual appliance; i is the current households, primary health centres, public schools and j is the hour of the day.

The average hourly energy demands per facility per day, E_{kj} $(Wh/facility/day)$, can be obtained as:

$$E_j = \sum_{k}^{N_A} E_{kj}; j = 1, 2, \ldots, 24 \tag{30}$$

where N_A is the entire number of appliances.

The daily energy required, E_{DER} $(Wh/facility/day)$, is computed according to Equ. (31).

$$E_{DER} = \sum_{j=1}^{24} E_j \tag{31}$$

2.7. Analysis

The proposed hybrid PV-WT-PHES plant was designed and analysed by implementing the developed models in the following computer software: Microsoft Excel®, MATLAB® and HOMER Pro software. Microsoft excel was used for the energy assessment; a template was developed and the cells coded to execute the required task.

The optimisation of the hybrid PV-WT-PHES plant was conducted on MATLAB® platform. In this light, a computer program was developed using MATLAB® to perform the optimisation task. The MATLAB® optimisation tool, the genetic algorithm toolbox, was utilised to optimise the size of the storage system so as to minimise difference between energy demand and energy generated from the hybrid plant. This was implemented by specifying the objective function and boundaries of the decision variables.

Economic assessment was executed utilising HOMER Pro software. The hybrid PV-WT-PHES plant was modelled in HOMER Pro environment. The economic analysis was implemented by supplying the optimised data and the following data: solar radiations, wind speeds, energy demand, wind turbine specifications, PV module specifications, PHES specifications and economic specifications.

3. Results and discussion

The results obtained based on the modelled systems are displayed and discussed.

3.1. Input data

3.1.1. System specifications

Table 1 shows the wind turbine, PV module and PHES specifications, which serve as input data.

3.1.2. Meteorological data

The yearly mean meteorological data (solar irradiance and wind speed) are presented in Table 2, which are in agreement with data presented in (Diemuodeke et al., 2019). The data were retrieved from both the NASA Surface Meteorology database and the US National Renewable Energy Laboratory (NREL) database that are embedded in the HOMER Pro Software®. The wind data were recorded for over 10 year period and extrapolated to 50 m above the earth's surface for terrain similar to airports. The solar irradiance is highest in the months of January and March due to less rainfall within these months. The wind speed is highest between the months of July and August, which may be attributed to the heavy rainy period. The solar resource assessment was based on the solar data.

3.1.3. Energy demand assessment

Fig. 4 shows Patani's hourly energy demand profile based on the energy demand assessment using Equs. (29) through (31), with the consideration of the appliances and power rating presented in Table 3. The figure shows that between 1:00–5:00 the energy demand was low and stable because people are at sleep, whereas between 6:00–8:00 the energy demand increased because people are awake and preparing to go out for daily activities. Energy demand is lowest at 10:00 because people are at their different work places since about 65% of the populace in Patani works outside the location. The energy demand is highest at 20:00 because people are back from work and 95% of appliances in domestic household, health centres and schools (lighting) are on. Thereafter, the energy demand drops as people retire to bed. The total daily energy demand of Patani is estimated at 119959.37 kWh/day. It is expected that the demand would increase in the future but the increase would be offset by vigorous campaign for energy efficiency.

3.1.4. Economic specifications

The economic specifications of the system components consist of construction cost (capital cost), operation and maintenance (O&M) cost and replacement cost of the individual sub-system as shown in Table 4. The project life span is 25 years. The inflation rate and interest rate are, respectively, estimated at 9% and 9.5% (Diemuodeke and Oko, 2016). Import tariff of 10% was added to the cost of components not produced in Nigeria, namely wind turbine and balance of system.

3.2. Output data

3.2.1. Optimal technical parameter of the PV-WT-PHES plant

Table 5 shows the result obtained from the optimisation of the PHES. The decision variables considered are number of PV, number of wind turbine, diameter of turbine blade and head elevation of PHES. To satisfy the energy demand of the facilities, the following are required 217 kW_P PV peak rated power and 226,050 kW rated

Table 1
Input data.

Parameter	Symbol	Unit	Value
Wind Turbine Specifications for Vestas V82 (1.65 MW): HOMER Pro Software			
Rated capacity	P_{rated}	kW	1650
Rotor diameter	D_{WTB}	M	82
Hub height	h	M	59–80
Cut-in wind speed	V_{CI}	m/s	2.5
Cut-off wind speed	V_{CO}	m/s	32.0
Rate wind speed	V_{rated}	m/s	13.0
PV Module Input Data for Peimar SG310MBF Module (Flat Plate) (Oko et al., 2012)			
Rated Capacity	P_{rated}	kW	0.25
Temperature Coefficient	T_C	–	−0.4
Operating Temperature	T	K	298
Efficiency	η_{PV}	–	0.191
Area	A_{PV}	m^2	1.627
Derating Factor	Y_{PV}	–	0.85
Temperature correction factor	T_{CF}	–	0.97
Inverter efficiency	η_{INV}	–	0.95
Safety factor	SF	–	1.20
Pumped Hydro Energy Storage System Input Data (Canales et al., 2016)			
Flow rate (turbines)	Q_t	m^3/s	0.10–0.50
Flow rate (pumps)	Q_p	m^3/s	0.2
Efficiency of pump	η_p	–	0.95
Efficiency of turbine	η_t	–	0.70

Table 2
Monthly meteorological data at Patani.

Month	Clearness Index	Daily Radiation (kWh/m^2/day)	Average Wind Speed (m/s)
January	0.52	4.998	4.425
February	0.491	4.907	4.770
March	0.483	5.023	4.395
April	0.463	4.813	3.870
May	0.442	4.460	3.570
June	0.430	4.236	4.425
July	0.351	3.483	5.100
August	0.379	3.868	5.280
September	0.413	4.274	4.710
October	0.453	4.561	3.855
November	0.518	4.952	3.615
December	0.528	4.899	3.960

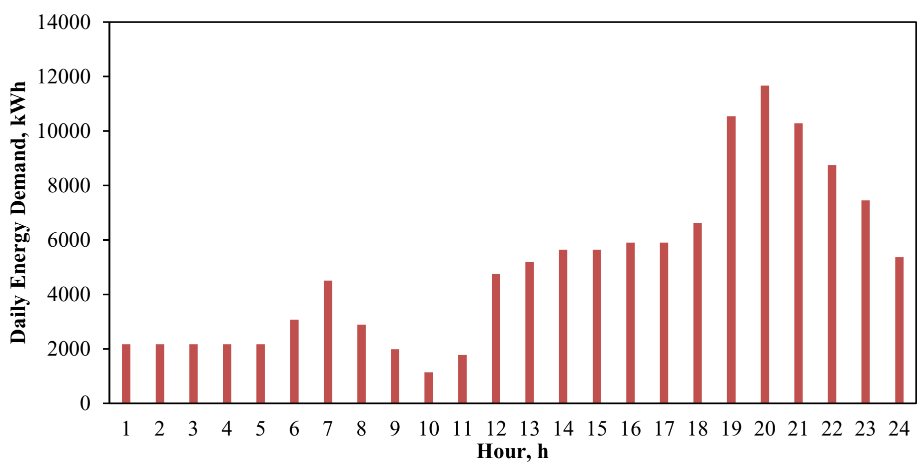

Fig. 4. Patani's hourly energy demand profile.

Table 3
Power rating of appliances.

Appliances	Power Rating (W)
Fluorescent Light	23
Incandescent Light	100
Portable Stereo	20
CD Player	35
Television	150
Radio	10
Pressing Iron	1000
Refrigerator	600
Ceiling Fan	40
Table Fan	20
Air Conditioner	1000

power of wind turbine., which implies that 868 PV modules and 137 wind turbines are required. Furthermore, the optimum storage capacity of the PHES was established as 3,930,614.73 kWh, which requires upper reservoir volume of 43170.06 m^3. The head of the upper reservoir obtained is 17.27 m, which is within the efficient range of pump-as-turbine according to (Ajibola et al., 2018).

Fig. 5 shows the various energy contributions in the hybrid system, with excess energy generation and energy shortage. The LLP was estimated at 0.1086, which agrees with (Canales et al., 2016). This implies that about 90% of the energy demand in Patani can be met all-year round by the proposed hybrid PV-WT-PHES plant.

3.2.2. Economic data of the hybrid plant

Table 6 shows pertinent economic data regarding the hybrid plant. The levelised Cost of Energy (LCOE) was obtained as 0.27 $/kWh, which is within the range of LCOE reported for renewable energy technology by IRENA (IRENA, 2018) and is well below the 0.95 $/kWh for diesel powered electricity generator (Olatomiwa, 2016). However, the obtained LCOE is well above the cost of electricity from the national grid, average of 0.19 $/kWh, without

Table 4
Cost specifications.

Description ($/kW)	Specifications				
	PV Module[a]	Wind Turbine[b]	PHES[c]	Inverter[d]	Power Station[e]
Construction Cost	3518.60	4197.42	4694.48	301.25	$602.50
Operation and Maintenance Cost	70.37	209.87	234.72	100.42	$12.05
Replacement Cost	3518.60	4197.42	4694.48	301.25	$602.50
Lifetime (years)	25	20	40	15	25

Source: a,eOkoye et al. (Canales et al., 2016), bGonzalez et al. (González et al., 2015); cBarbour et al. (2016), dDiemuodeke et al. (2016).

Table 5
Optimisation result of the hybrid plant.

Parameter	Symbol	Unit	Value
Peak Rated Power of PV Required	P_{rated}	kW_P	217
Rated Power of WT Required	P_{rated}	MW	226.05
Number of Photovoltaic Module	N_{PV}	–	217
Number of Wind Turbine	N_{WT}	–	137
Diameter of the wind turbine	D_{WTB}	m	54.88
Head elevation of Upper Reservoir	H_{UR}	m	17.27
Total energy generated	E_{RE}	MWh	2847.00
Minimum Storage Capacity of PHES	C_{PHES}	MWh	3930.61
Volume of the Upper Reservoir	V_{UR}	m^3	43170.06
Loss of Load Probability	LLP	–	0.1086

Table 6
Economics analysis of the hybrid plant.

Parameter	Symbol	Unit	Value
Life cycle cost of photovoltaic module	LCC_{PV}	\$	1,210,458
Life cycle cost of wind turbine	LCC_{WT}	\$	1,071,677
Life cycle cost of inverter	LCC_{INV}	\$	502.08
Life cycle cost of PHES system	LCC_{PHES}	\$	8748.80
Life cycle cost of control station	LCC_{PC}	\$	1217.05
Total life cycle cost	LCC_T	\$	2,292,602
Capital recovery factor	CRF	\$	0.11
Uniform capital recovery factor	$UCRF$	\$	0.10
Annualise life cycle cost	$ALCC$	\$/year	242,922.80
Levelised cost of energy	$LCOE$	\$/kWh	0.27

the consideration of the cost of grid extension and end-to-end cost analysis of grid electricity. The implication is that combined effect of government action and appropriate finance mechanism will guarantee the general acceptance of the proposed system.

3.2.3. Simulations

The proposed hybrid plant was subjected to ranges of pertinent parameters and simulated for sensitivity analysis. The effects of the wind turbine (WT) blade diameter on energy generated and PHES capacity are shown in Figs. 6 and 7, respectively. Fig. 6 shows that increasing the WT blade diameter increases the energy generation. This is expected because increase in the diameter means increase in swept area vis-à-vis wind energy conversion. The increase in the WT blade will increase the system's cost, but may manifest in reduced specific cost (cost/kWh energy generated) of the entire system.

Fig. 7 shows the influence of WT blade diameter on the storage capacity of the PHES. It is observed that the storage capacity decreases with increasing WT blade diameter up to a minimum point after which it increases with increasing WT blade diameter. This observation can be attributed to shortage of energy generation from the hybrid plant at lower diameter and excess energy generation at higher diameter. That is, at high diameter value, excess energy generation at higher diameter cancelled out the energy deficit to upturn the storage capacity of the PHES.

Fig. 8 shows that increasing the storage capacity of the PHES increases the volume of the upper reservoir (UR), which can be translated to increase in cost. This observation shows that the excess energy generated should be optimally matched with energy demand in order not to oversize the storage capacity (the upper reservoir).

The effect of head elevation of the upper reservoir on the volume of the upper reservoir is demonstrated in Fig. 9. The head elevation has an impact on the volume of UR at the minimised storage capacity. As such, increasing the head elevation translates to decline in the volume of the UR. This confirms why the optimum head elevation of the UR at the optimised storage capacity of the PHES in this study is 17.26 m and volume is 43170.06 m^3. The implication is that seasonal variation of the water depth in the lower reservoir has significant effect on the storage capacity of the PHES vis-à-vis meeting energy demand of the facility.

Fig. 10 shows the variation of the levelised cost of energy (LCOE) with interest rate and overall system efficiency. It can be observed from the figure that interest rate has a significant influence on the affordability of the energy generated. That is, an increase in interest rate increases the unit cost of energy generated. This observation calls for proper finance mechanism and government interventions in the development of mini-grids for coastline communities. In the

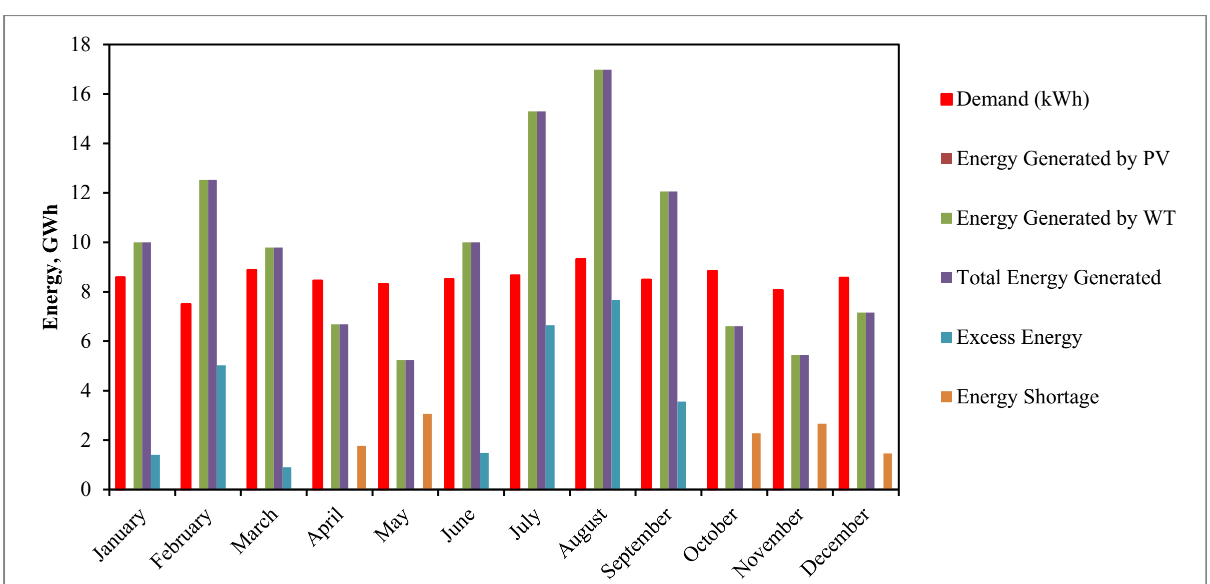

Fig. 5. Energy contribution.

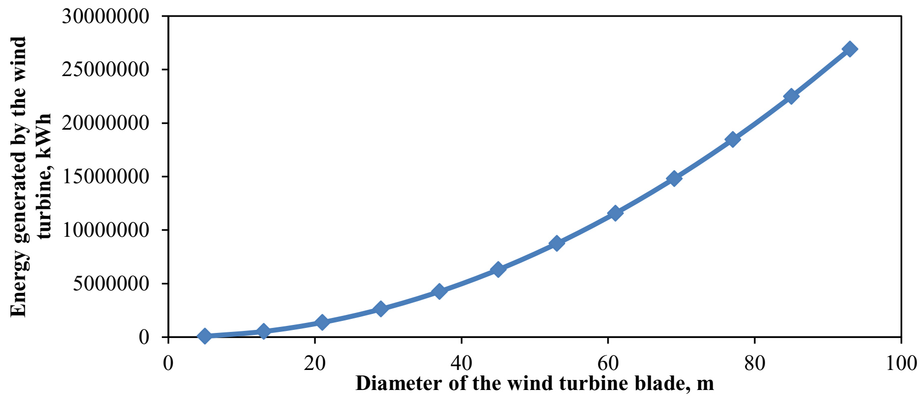

Fig. 6. Effect of WT blade diameter on the energy generated.

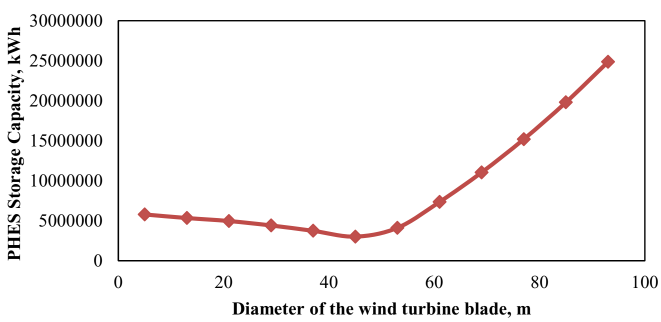

Fig. 7. Effect of diameter of the turbine blade on the capacity storage of the PHES.

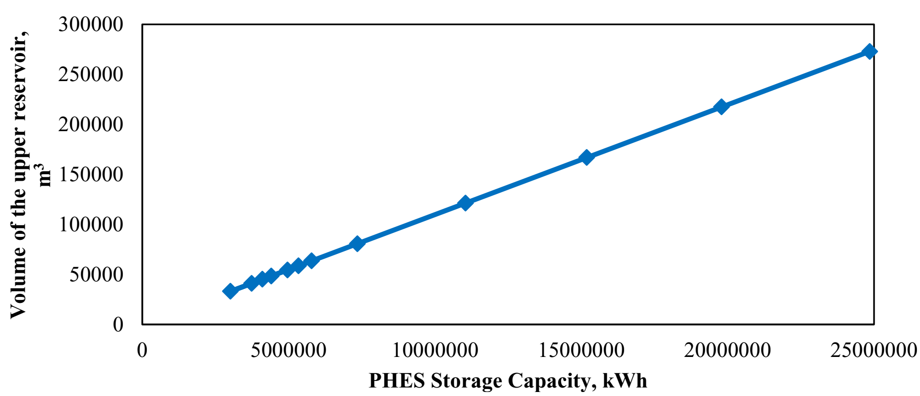

Fig. 8. Effect of capacity storage of the PHES on the volume of the upper reservoir.

same light, an increase in system efficiency increases affordability (decrease in unit cost of energy generated). The figure shows that system efficiency improvement from the 60.8%–80% (as shown in some of the literature (Ren and Ren, 2018)) has the potential of reducing the cost of energy generated by about 28%.

4. Conclusion

This study focused on satisfying energy demand of a typical coastline community, Patani (Lat. 5.23° N and Long. 6.17° E), in Nigeria. In the current study, a hybrid energy conversion system that is based on sunlight energy and wind energy is proposed. The proposed mini-grid hybrid energy system has the potential of meeting all the energy demand of the community throughout the year, with 0.1088 loss of load probability. The reliability of the proposed system was enhanced by the utilisation of a pumped

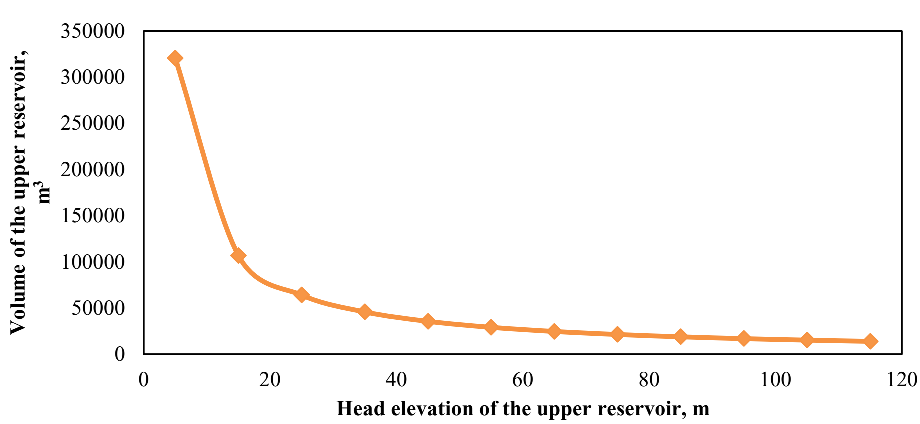

Fig. 9. Effect of head elevation on volume of the upper reservoir.

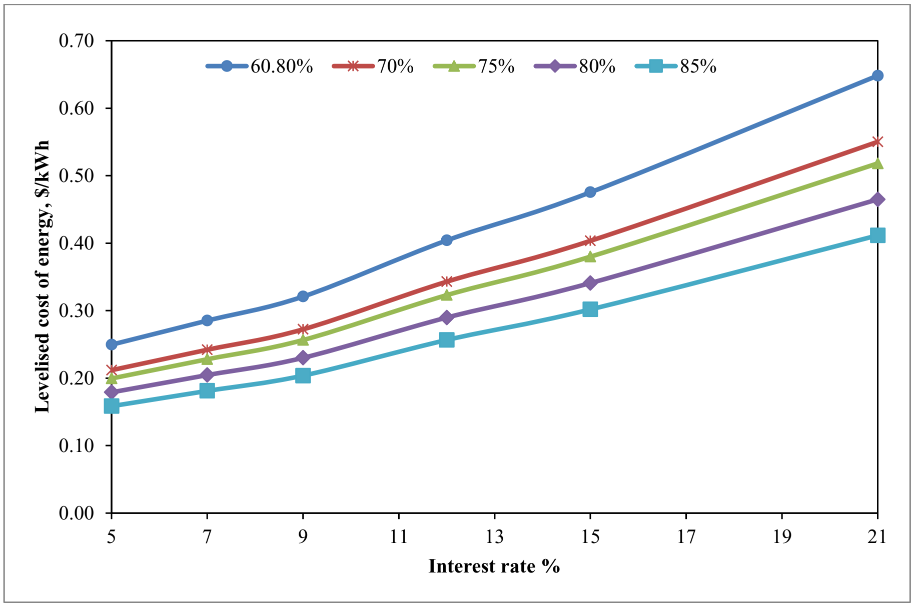

Fig. 10. Effects of interest rate and overall system efficiency on levelised cost of energy (LCOE).

hydro energy storage system. The proposed system is made of photovoltaic array, wind turbines, power regulators and pumped hydro energy storage system.

The proposed system was modelled and implemented in the Microsoft Excel®, HOMER Pro® and MATLAB® software environments. The modelled system was optimised using capacity shortage and cost as the objective functions. The Microsoft excel® software was utilised for the location's energy demand assessment. The genetic algorithm in MATLAB® was used to minimise the capacity shortage. The outputs from the energy assessment and the optimal parameters serve as input data to the HOMER Pro® platform for the cost optimisation. The levelised Cost of Energy (LCOE) was obtained as 0.27 $/kWh, which is within the range of LCOE reported for renewable energy technology in IRENA (IRENA, 2018) and is well below the 0.95 $/kWh for diesel powered electricity generator (Olatomiwa, 2016). However, the obtained LCOE is well above the cost of electricity from the national grid, average of 0.19 $/kWh, without the consideration of the cost of grid extension and end-to-end cost analysis of grid electricity. The implication is that combined effect of government action and appropriate finance mechanism will guarantee the general acceptance of the proposed system. In this regard, appropriate finance mechanism that consider the house level energy innovation and business profitability are essential to induce rapid penetration of renewable energy in the coastal communities (Yujia and Finenko, 2016), (Islam, 2014).

Author contribution

Dr. E.O. Diemuodeke: Conceived the research question, developed the methodology, analysed the preliminary data, supervise the implementation of the methodology and finalised the paper manuscript.

Mr. E. N. Nyeche: Implemented the methodology, analysed data and drafted the first order draft of the manuscript.

Declaration of competing interest

We hereby declare that there are no known conflicts of interest associated with this publication as the research receives no funding from any organization that could have influenced the outcomes of the research.

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