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Techno-Economic and Environmental Analysis of an Off-grid Hybrid Renewable Energy System for Rural Electrification

[1]Adeleru Promise, and [2*]Adebayo Isaiah

[1]Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, P.M.B. 4000, Ogbomoso, Oyo State, Nigeria; ifeoluwa706@gmail.com
[2]Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, P.M.B. 4000, Ogbomoso, Oyo State, Nigeria; igadebayo@lautech.edu.ng
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Corresponding Author:
igadebayo@lautech.edu.ng
Tel: +2348060861354

ABSTRACT

Rural electrification is key to socio-economic development in developing countries like Nigeria. However, extending the national grid to remote rural areas is expensive and time-consuming. The traditional power supply method involves utilization of a standalone renewable energy source such as Solar and wind which have their associated drawbacks due to their unreliability in nature. Hence, this research carried out a techno-economic and environmental analysis of an off-grid hybrid renewable energy system for rural electrification using the Kepler Optimization Algorithm (KOA). Feasibility study on electricity and hourly load demand assessment of Alayin village was conducted and village load profile was estimated. Mathematical modeling of each hybrid RES was formulated. A KOA technique was employed to carry out optimal sizing and check the cost efficiency of BG/ PHES/ Battery, PV/PHES/Battery, and the hybrid RES (PV/BG/PHES/Battery). Simulation of the model was done using MATLAB R2021a. The value obtained was validated with Gravitational Search Algorithm (GSA) for performance evaluation using Levelized Cost of Energy (LCOE), Loss of Power Supply Probability (LPSP) and CO_2 reduction in manure management as performance metrics. The results of the analysis showed an appreciable reduction on the LCOE and CO_2 with high reliability using KOA-hybrid RES compared with GSA-hybrid RES.

INTRODUCTION

Electricity is a key driver of economic prosperity for any country. The electrification access rate in Urban and Rural areas in Nigeria was 83.9% and 24.6% respectively at the end of the year 2020 (Vendoti *et al*, 2020). Traditional power supply methods in remote areas typically involve grid extension and diesel generators and extending the grid faces numerous challenges, including long distances from existing electricity networks, difficult terrain, and the need for substantial investment. Alternatively, standalone energy conversion systems, for instance, diesel generators can be used, but considering the scarcity, environmental pollution and high transportation costs of fossil fuels, the use of local renewable energy sources has attracted significant global attention as a solution for providing electricity to remote regions (Liu *et al*, 2018).

Renewable energy sources, such as solar, wind, biomass, geothermal, and hydro are inexhaustible, locally accessible, free, and environmentally friendly, making them promising alternatives for power generation, particularly in remote rural areas (Luber and Jacobsson, 2016). The primary drawbacks of using single-source renewable energy sources are their unreliability and inability to work efficiently stemming from their intermittent and fluctuating nature. The main advantages of hybrid renewable energy systems over single-source systems include higher reliability, better efficiency, reduced energy storage capacity, and lower levelized life-cycle power cost. (Sinha and Chandel, 2014):

One of the main challenges confronting HRES is how to determine the optimal sizing of its components to achieve a design that is both technically and economically feasible. This process is much more complex by the presence of multiple components in the HRES and the unpredictable nature of available resources. Hybrid Optimization of Multiple Energy Resources (HOMER) software has been widely used by various researchers for sizing of HRES, however, a significant limitation of HOMER is that the mathematical modeling and the sizing process for optimization cannot be customized based on the user's constraints and modeling equations (Dirya and Ostergaard, 2009).

In this paper, a metaheuristics algorithm namely Kepler Optimization Algorithm (KOA) was used to obtain the techno-economic optimal design of a Photovoltaic (PV)/Biomass Generator (BG)/Pumped-Hydro Energy Storage (PHES)/Battery based HRES for powering Alayin Village in Oyo state, Nigeria. The hybrid systems utilize the complementarity of multiple resources to deliver affordable, reliable, and sustainable off-grid electricity access to support rural development.

Several authors have worked on RES technologies and the application of various methodologies in solving them in almost every part of the globe, including Nigeria. In Ogheneruona *et al*., (2021), an analysis of solar PV systems in Nigeria for rural households was conducted. However, the Solar PV was not hybridized with other renewable energy source. A feasibility study and techno-economic analysis of a solar PV-Biomass/Battery Hybrid power system was developed in Ayodele *et al.*, (2022) for electrifying Kajola rural village in Nigeria; the analysis revealed that the proposed hybrid system could provide an average power supply. However, the cost is high, and no optimization technique is used. Chidozie and Suresh, (2023) worked on a feasibility study of integrating renewable energy systems to improve electricity access in rural areas, using the Choba community in Port Harcourt, Nigeria as a case study; the study concluded with a proposal for an on-grid hybrid PV/Wind turbine system which would address the frequent power outages currently experienced in Choba providing a more reliable energy solution. However, there was no storage device used.

The author in Donatus *et al.,* (2024) presented a hybrid power system for rural electrification in Cameroon incorporating hydroelectric, solar PV and battery storage components. However, the system was optimized using HOMER Pro. Based on the foregoing literature review, HOMER software was the most used simulation software, and no previous studies have hybridized PV and BG with two energy storage systems. Hence, this study filled the gap of carrying out a techno-economic and environmental analysis of an off-grid hybrid solar PV/BG/PHES/battery system for rural electrification especially for Alayin Village in Oyo state, using KOA.

MATERIALS AND METHODS

This paper focused on generating electrical energy through renewable energy resources with pumped hydro energy and battery banks as storage devices for off-grid uninterrupted power supply to Alayin village. The setups are known as a hybrid power system, and the components were optimized using KOA. To accomplish the objectives of this research, the demand for electrical energy at the study site was assessed based on a survey (questionnaire), taking into consideration the future needs of the village. Also, individual components of the renewable energy resources were modulated, and their combinations were evaluated to meet the energy demand.

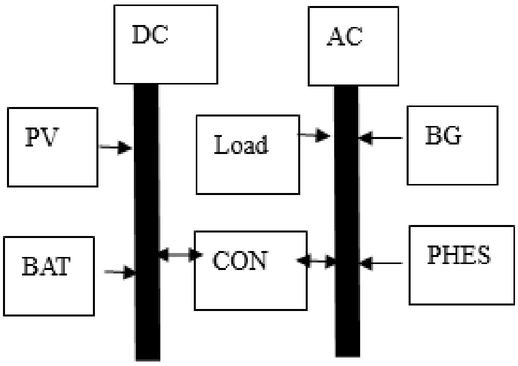

Figure 1: Solar PV-Biomass-PHES-battery system model

HES, which is considered in this approach, is shown in Figure 1. Complementary characteristics sources solar and biomass were considered as primary sources while PHES and batteries serve as backup systems on the non-availability of primary sources or lower energy received from primary sources. So, a defined energy management strategy for the HRES system is as follows:

The first case- when $[P_{RES}(t) > P_{LD}(t)/\eta_{inv}]$ there is a surplus of energy, then supply power to the Load and charge the battery. hence, update the battery's SOC and when $[SOC(t-1) \geq SOC_{max}]$, satisfy the load, stop charging the battery and pump the water from the lower reservoir to the upper reservoir but dump the excess load when $UR = UR_{max}$. Where the dump power is calculated as Equation (1)

$$P_{Dump}(t) = P_{RES}(t) - P_{LD}(t)/\eta_{inv} \qquad (1)$$

Second Case- When $P_{RES}(t) = P_{LD}(t)/\eta_{inv}$, supply power to the load only.

Third Case- a) When $[P_{RES}(t) < P_{LD}(t)/\eta_{inv}]$ then the electricity demand is high, check whether the deficit power can be served by the turbine power, if the turbine power satisfies the deficit load, then supply power to the load by discharging UR.

b) If $\left[P_{RES}(t) \leq \frac{P_{LD}(t)}{\eta_{inv}}\right]$ and $[UR(t) \geq UR_{max}]$, supply power to the load by discharging the battery. Set the constraints for SOC of battery and UR volume as $SOC_{min} \leq SOC(t) \leq SOC_{max}$ and $UR_{min} \leq UR(t) \leq UR$ respectively. If deficit power is not satisfied by the battery SOC, then the power shortage is calculated as Equation (2)

$$DP(t) = P_{actualLoad}(t) - (P_{PV}(t) + P_{BG}(t) + SOC(t) - SOC_{min} \qquad (2)$$

Then, subsequently, the LPSP is calculated.

Description of the study area

The community under study is Alayin village under Surulere Local Government Area (LGA) of Oyo State, Nigeria. Geographically, the village lies on latitude $8° \, 2' \, 49" N$ and longitude $4° \, 27' \, 53" E$ .About 150 houses are available in the village including primary healthcare and the average family of each household's number was taken as eight members with a total of 1200 people.

The village energy demand

The load profile summary is presented in Table 1. The average daily demand for the area is 658.22kWh and a daily average power of 54.5kW, while 50.3kW is the peak load.

Renewable energy resources assessment

The hybrid system components for this research consist of solar PV module, BG, PHES, and battery bank.

a. Mathematical model of Solar PV

The mathematical model of the PV output power is expressed by using the formula given in Equation (3) (Kumar and Biswas 2017).

$$P_{PV} = A_{PV} \times \left(P_r \frac{G}{G_{ref}}\right) + \left(1 - \propto (t_C - t_{c.STC})\right) \quad (3)$$

where; P_{PV} is the output power of PV arrays (W), P_r is the rated power under reference conditions, A_{PV} is the number of PV arrays, G is solar radiation in W/m^2, G_{ref} is 1000 W/m^2, $\propto$ is the temperature coefficient which is $3.7 \times 10^{-3}(1/°\text{C})$, $t_{c.STC}$ is the temperature in standard test conditions which is $25°\text{C}$, t_c is the cell temperature.

Table 1 Estimated Energy Demand for Alayin's Village

Categories	Load Type	Rated Power (W) (r)	Quantity (No) (q)	Operating (hr/day)	Usage (hr/day)	Load (kWh/day)	$r \times q$ (W)
Domestic	Lighting	15	300	16:00-06:00	14	63	4500
	Radio	12	150	05:00-07:00 17:00-22:00	7	12.6	1800
	Mobile Charger	5	150	05:00-07:00 19:00-22:00	5	3.75	750
	Fan	50	300	12:00-05:00	17	255	15000
	Refrigerator	700	1	00:00-24:00	24	16.8	700
	Television	230	80	16:00-23:00	7	128.8	18400
Commercial	Sewing machine	100	1	11:00-16:00	5	0.1	100
Shops	Compact Fluorescent Lamp	15	15	18:00-07:00	13	2.93	225
	Refrigerator	700	2	00:00-24:00	24	33.6	1400
Community	School	2700	1	08:00-16:00	8	21.6	2700
	Health Center	5400	1	06:00-12:00 19:00-06:00	17	91.8	5400
	Streetlight	100	20	18:00-06:00	12	24	2000
Agricultural	Electric grass-cutting machine	1400	1	15:00-17:00	2	2.8	1400
	Lighting	24	5	18:00-06:00	12	1.44	120
Estimated Total						658.22	54495
Approximated Load						700	

b. Mathematical Model of Biomass Power System

In this study, biomass is available in the form of manure. The manure production from the livestock of agricultural farms can be used for electricity production by using anaerobic digesters (Liliental *et al.*, 2004). Estimation of the total manure output from the farm's livestock throughout the year was calculated using Equation (4)

$$M = \sum_{n=1}^{x} N_x m_x \quad (4)$$

where, M is the total animal manure produced in one year in tons, n is the number of specified groups of animals, N_x is the total number of animals, and m_x is the manure per head.

c. Mathematical Model of Pumped Hydro Energy Storage System

In this study, lower reservoir sizing will not be considered as the natural lake in Alayin village was taken to be the lower reservoir.

For the turbine sizing, this was done based on the peak load demand. The expression for the nominal size of the turbine is given in Equation (5) (Ekoh *et al.*, 2016) as,

$$E_T = \frac{(1+SML)\times P}{\eta_{turbine}} \quad (5)$$

where, E_T is the installed turbine power, SML is the safety margin of the load, $\eta_{turbine}$ is the maximum turbine efficiency and P is the peak load.

d. Mathematical Model of Battery Bank

The state of charge and discharge of the battery is given by the available generated power from PV and biomass in addition to the load demand. The expression of their charging state is given in Equation (6). When the load demand exceeds the generated energy, a battery bank is discharged according to Equation (7). (Diaf *et al.*, 2007).

$$SOC(t) = SOC(t-1).(1-\sigma) + \left[P_{Gen}(t) - \frac{P_L(t)}{\eta_{inv}}\right] \times \eta_{Batt} \quad (6)$$

$$SOC(t) = SOC(t-1).(1-\sigma) + \left[\frac{P_L(t)}{\eta_{inv}} - P_{Gen}(t)\right] / \eta_{Batt} \quad (7)$$

where; $SOC(t-1)$ is the State of battery capacity at hour $(t-1)$, $PL\ (t)$ is the load demand, $P_{Gen}\ (t)$ is the total power generated by the renewable energy sources in the hybrid system at time t, σ is the battery hourly self-discharging rate, η_{inv} and η_{Batt} are the charging/discharging efficiency of the inverter and battery respectively.

e. Green House Gas (GHG) Emission Reduction from Biogas System

The GHG emission reduction effect of biogas production primarily stems from the emission reduction by manure management (ERMM). Animal manure, typically stored as liquid slurry storage or in open ponds, produces methane under anaerobic conditions (in the absence of oxygen) during storage.

$$ERMM_{CO_2} = CH_{4Manure} \times 25 \quad (8)$$

where, $ERMM_{CO_2}$ is the CO_2 emission reduction from manure management (kg), 25 is the coefficient of the CO_2 equivalent of CH_4 (The Global Warming Potential (GWP) of CH_4 in CO_2 equivalent over a 100 years' time-horizon).

Problem Formulation

The problem was modelled according to the Loss of Power Supply Probability (LPSP) and the system capital cost. The main decision variables include photovoltaic PV panels, biomass power, number of batteries, upper reservoir volume and converter capacity.

Objective function

The main objective optimization approach is based on the Levelized Cost of Electricity (LCOE), to determine the optimum configuration of the hybrid energy system model that guarantees a reliable and 100% continuous supply of power to load for any point of time. Hence, the cost objective function to be minimized can thus be expressed as;

$$f = min(LCOE) \quad (9)$$

$$LCOE = \frac{CC\times CRF+OMC+FC+RC}{CF} \quad (10)$$

Where;CRF is the capital recovery factor, OMC is the total operational and maintenance costs, CF is the Capacity Factor, FC is the Fuel cost, RC is the Replacement cost.

Constraints

Constraints are conditions that system configuration must satisfy. The optimal design of a hybrid system needs to satisfy all the operational constraints. Thus, the objective function is subjected to the constraints from Equations (11) to (15)

$$0 \leq A_{PV} \leq A_{PV,Max} \tag{11}$$

$$0 \leq P_{BG} \leq P_{BG,Max} \tag{12}$$

$$0 \leq N_{Batt} \leq N_{Batt,Max} \tag{13}$$

$$0 \leq UR \leq UR_{Max} \tag{14}$$

$$0 \leq LPSP \leq LPSP_{Max} \tag{15}$$

Where, A_{PV}, P_{BG}, N_{Batt} are the number of PV panels, biomass generator power, number of batteries respectively and UR is the upper reservoir volume. The system reliability is the Load Power Supply Probability (LPSP).

Kepler Optimization Algorithm

Kepler optimization algorithm (KOA) is a physics-based metaheuristic algorithm inspired by Kepler's law of planetary motion, used to predict the position and velocity of planets at any given time. In KOA, each planet represents a candidate solution, with its position being randomly updated throughout the optimization process relative to the best-so-far solution (the sun). KOA was used for its effective exploration and exploitation (Mohamed and Reda, 2023). The following is the algorithm for the KOA model.

Step 1: Input all the system parameters and data.

Step 2: Initialize the object population with random position, orbital eccentricities, and orbital periods.

Step 3: Evaluate fitness values for RES and Determine the global best solution.

Step 4: Calculate the Euclidian distance, gravitational force between RES and the velocity of all the Objects.

Step 5: Generate two random numbers r, r_1 between 0 and 1.

Step 6: If $r \geq r_1$, Update the new position of the object and if not, Update the distance between the objects.

Step 7: Apply the Elitist strategy and evaluate the fitness value for all the parameters.

Step 8: Determine the global best solution.

Step 9: Is termination criteria satisfied? If No, go to step 4

Step 10: Print optimization results.

RESULT AND DISCUSSION

To design a hybrid renewable power system with techno-economic benefits, the practical system component configuration and environmental assessment of the hybrid renewable energy must be accomplished. This was done considering three cases: BG/PHES/Battery, PV/PHES/Battery, and hybrid RES (PV/BG/PHES/Battery) using KOA and the most efficient value was compared with hybrid renewable energy using GSA.

In Case 1, BG/PHES/Battery was analyzed. From the result in Table 2, the BG size to carry the total peak load of 50.295kW was 23.79kW. The LCOE was \$88.81 while LPSP was 0.90 meaning the system is 10% reliable.

In Case 2, PV/PHES/Battery was carried out and PV required for the load is presented as 75.44kW, the LCOE obtained was \$3.54. No emission was needed due to natural resources from sun for PV. The value of LPSP obtained was 0.54 which implies that the system is 46% reliable.

In Case 3, the renewable energy system was hybridized Solar PV/BG/PHES/Battery. The PV needed for the system was 75.11kW, the BG size was 23.37kW. Results of both LCOE and LPSP obtained were \$2.48 and 0.42, respectively.

From the results of Table 2, It could be observed that case 3 which is PV/BG/PHES/battery is the most efficient among them since the LCOE was \$2.48, and the system reliability is 58% compared to others, and it has the lowest deficit energy value.

Table 2: Optimal Result for Case 1, Case 2, and Case 3

	BG/PHES/Battery	PV/PHES/ Battery	PV/BG/PHES/ Battery
PV modules (kW)	0	75.44	75.11
No of Battery	21	21	26
Capacity of the UR (m^3)	2083.1	2018	1252
BG (kW)	17.79	0	23.37
LCOE (US\$)	88.81	3.54	2.48
CO_2 reduction (kg)	8853435.86	0	11631051.31
LPSP	0.90	0.54	0.42
Deficit Energy (Watt)	5423210.18	3216190.84	2549064.87
Processing time (sec)	4.023	3.92	4.62

In Table 3, the hybrid renewable energy system (PV/BG/PHES/Battery) result using GSA was presented. The PV modules was found to be 74.69kW while BG required was 23.41kW. Results of the system reliability (LPSP), LCOE and deficit energy obtained were 55%, \$2.68, and 2586566.35W, respectively.

Table 3: Optimal Result for PV/ BG/ PHES/ Battery Using GSA

	Values
PV modules (kW)	74.69
No of Battery Modules	39
Capacity of the upper reservoir (m^3)	2081.5
Biogas Generator (kW)	23.41
Capacity of Converter (kVA)	51.85
LCOE (US\$)	2.68
CO_2 emission reduction (kg)	11600004.36
LPSP	0.45
Deficit Energy (Watt)	2586566.35
Processing time (sec)	97.48

The comparison of the optimal sizing of the PV/BG/PHES/Battery using KOA and PV/BG/PHES/Battery using GSA is made to check for the feasibility of the system configuration. Table 4 shows the detailed optimization results for both algorithms. From the result, it was observed that the LCOE and the Deficit energy of the hybrid renewable energy using KOA were US\$2.48 and 2549064.87, respectively. This is much lesser when compared with that of GSA with LCOE and Deficit energy of US$2.68 and 2586566.35, respectively.

Similarly, it was observed that KOA hybrid system is more reliable than GSA. The reliability result from LPSP for KOA was 0.42 which means the system is 58% reliable and for GSA hybrid system the LPSP was 0.45 that is the system 55% reliable.

Finally, the results also show that the CO_2 reduction from manure management of KOA is much lower than that of GSA.

Table 4: Comparison of Hybrid System PV/BG/PHES/Battery using KOA and GSA

	KOA	GSA
LCOE (US$)	2.48	2.68
CO_2 emission reduction (kg)	11631051.31	11600004.36
LPSP	0.42	0.45
Deficit Energy (Watt)	2549064.87	2586566.35
Processing time (sec)	4.62	97.48

CONCLUSION

In this paper, optimization of hybrid power system for techno economic and environmental benefit was carried out. Energy sources of HRES are Solar energy (for PV), Biomass (for BG), water (for PHES) as well as chemical energy (for battery) were hybridized optimally using KOA with reduction in LCOE, System reliability (LPSP), as well as the reduction in GHG CO_2 manure management. The results justify the economic benefit of hybrid power system (PV/BG/PHES/Battery) was most efficient when compared to conventional power system where only BG/PHES/Battery and PV/PHES/Battery were used.

Also, from the results, it is revealed that the performance of KOA outweighs that of GSA in terms of accuracy and computational time. The optimal configuration of the system that led to highest reduction was achieved when KOA is employed. It can therefore be concluded that the rural electrification problem as a result of distance from the grid can be solved using hybrid power system whose components were optimally configured using KOA.

REFERENCES

Owolabi, B.U., (2022). Feasibility Study and Techno-Economic Analysis of Solar PV-Biomass Hybrid Power System for Rural Village—Kajola, Nigeria. *Journal of Ecological Engineering*, **23**(6).

Chidozie, C. V., & Suresh, M. (2023). Feasibility study of integrating the renewable energy system for increased electricity access. *Case Studies in Thermal Engineering*, 101079.

Diaf, S., Diaf, D., Belhamel, M., Haddadi, M. and Louche, A., (2007). A Methodology for Optimal Sizing of Autonomous Hybrid PV/Wind System. *Energy policy*, **35**(11): 5708-5718.

Dirya, E. and Qstergaard, J., (2009). Reviewing Optimization Criteria for Energy Systems Analyses of Renewable Energy Integration. *Energy*, **34**(9): 1236-1245.

Donatus Chu I., Guy Clarence S., and Roger H.A. (2024). Optimization of a Hybrid Off-grid Solar PV-Hydro Power System for Rural Electrification in Cameroon. *Journal off Electrical and Computer Engineering httpss://doi.org/10.1155/2024/4199455*

Ekoh, J., Akarakiri, J. and Nwankwojike, B.N. (2016). Design of a Hybrid Photovoltaic-Hydroelectric Pumped Storage System. *International Journal of Engineering Research in Africa*, **19**: 8-10.

Kashif I., Awais A., and Muhammad U. S., (2017). Techno-Economic Feasibility Analysis of a Solar-Biomass Off Grid System for The Electrification of Remote Rural Areas in Pakistan Using HOMER Software. *Renewable Energy*.

Kumar, R. and Biswas, A. (2017). Optimal Sizing Of PV/Wind/Battery Hybrid System for RuralvElectrification In Uttarakhand State, India. *Journal of Cleaner Production*, **143**: 286-303.

Liliental, P., Lambert, T. and Gilman, P., (2004). Computer Modeling of Renewable Power Systems. *Chapter 6: Internal Combustion Generators. Homer Energy LLC. Encyclopedia of Energ*y: 633-647

Liu, X., Wang, S. and Liu, P., (2018). Techno-Economic Feasibility Study of Autonomous Hybrid Wind/PV/Battery Power System for A Household in Urumqi, China. *Energy*, **135**: 545-555.

Luber, D. and Jacobsson, S., (2016). The Politics and Economics of Constructing, Contesting, and Restricting Socio-Political Space for Renewables – *The German Renewable Energy Act. Environmental Innovation and Societal Transitions*, **18**: 147-163.

Meena, N.K., Swarnkar, A. and Grewal, N.S., (2014). Optimization And Sensitivity Analysis of Biomass-Based Gasifier-SOFC integrated CHP systems. *International Journal of Hydrogen Energy*, **39**(36): 21222-21234.

Mohamed, A., Reda M., Shaimaa A., Mohammed J., and Mohamed A., (2023). Kepler Optimization Algorithm: A New Metaheuristic Algorithm Inspired by Laws of Planetary Motion. *Expert Systems with Applications*, **119**: 1-21.

Monotosh D., Maisanam A., and Agnimitra B. (2019). Techno-economic optimization of an off-grid Renewable energy system using metaheuristic optimization approaches. Energy Conversion and Management. **185**: 339-352

Norlina, M.S., Mazidah P., and Mohamad R.M., (2013). A Review of Gravitational Search Algorithm. International Journal of Advances in Soft Computing and Its Applications. **5**(3): 2-40.

Ogheneruona E.D., Yacob M., and Henry I.N. (2021). Solar PV Electrification in Nigeria: Current Status and Affordability Analysis. *Journal of Power and Energy Engineering*. **5**(9): 1-13

Sinha, S. and Chandel, S.S. (2014). Review Of Software Tools for Hybrid Renewable Energy Systems. *Renewable And Sustainable Energy Reviews*, **32**: 192-205.

Vendoti Suresh, Muralidhar M., and Kiranmayi (2020). Modelling and Optimization of an off-grid hybrid renewable energy system for electrification in rural areas. Energy Reports, **6**: 594-604