Optimal Operational Analysis of Off-Grid Hybrid Renewable Energy System with Multiple Storage Facilities

OludamilareB. Adewuyi, OlusolaA. Komolafe

Abstract— This paper discussed the benefits of integrating multiple storage facilities into hybrid renewable energy system(HRES) configuration.A scheduling algorithm was developed for a hybrid renewable energy system that consists of wind and solar energy sources, pumped-hydro and battery storage with diesel generator as backup, for a selected site. The sequential quadratic programming (SQP) approach for solving convex non–linear optimization problems was used to determine an adequate and cost-effective capacity for each of the incorporated energy systems. An algorithm for supervisory controller for optimal scheduling of the hybrid renewable energy system was developed and simulated on Matlab. The cost analysis of the hybrid renewable energy system was carried out using the cost per kW of each component for obtaining the total installation cost and the cost of consumed diesel for each of the considered scenarios. These costs were compared with the cost of grid extension and the cost of electricity using the current Nigerian electricity tariff. The results showed that an off-grid energy system that consists of renewable energy sources, with multiple storage facilities, is capable of meeting the energy requirement of the studied site with little or no contribution from the backup diesel generator in most of the considered scenarios. The simulation outcomes showed that renewable energy contribution varies between 17.26% of the total load demand, during weekdays of normal academic period in the dry season and 96.11% of the total load demand, during weekends of holiday periods inthe rainy season. The contribution from storage facilities to the energy contribution from the renewable energy sources was between 9.21% and 29.15% of the total load demand. In terms of the installation cost, supplying electricity from the grid was found to be more economical for a distance of up to 180 km, but the free relatively low or free running cost of the hybrid renewable energy system made it a better option in the long run.

Index Terms— Renewable energy technologies (RETs), hybrid renewable energy systems (HRES), pumped - hydro storage system (PHSS), cost of electricity per kW generation, optimtool, sequential quadratic programming (SQP), Supervisory control algorithm.

1 INTRODUCTION

Meeting the ever-increasing energy demand in a clean, neat and environmentally friendly manner is one of the major problems facing developing countries. Nigeria has one of the lowest population versus electricity supply profile in the world; a nation with a population of over 150 million people having a power generating capacity of about 4000 MW. Many of the rural areas of Nigeria have not benefited from the use of electricity in the same proportion as the more populated urban areas of the country [1] and a large percentage of the urban areas that are connected to the grid witness, on a daily basis, irregular and unreliable supply of electricity. One approach that has been identified as a means of overcoming this challenge is the adoption of renewable energy technologies.

However, solar energy system is not going to function at night; wind turbine will not generate electricity when the wind speed is not sufficient and the water level at the potential hydro sites changes with the season. Nevertheless, one suitable and cost effective way of obtaining the maximum benefits from these absolutely free but intermittent energy resources is through integrating them to produce hybrid energy systems.

Economic aspects of the Hybrid Renewable Energy System (HRES) technologies are becoming sufficiently promising for the development of power generation capacity for developing countries [32]. However, it is only recently that significant efforts are being made through research and development, to mobilize theavailable renewable energy resources in hybrid form towardsoptimizing theirbenefits [10], [12], [19]. In this study, the load demand data and the meteorological data for wind speed and solar radiation of the Obafemi Awolowo University main campus were used to optimally design an effective operational strategy for off-grid hybrid renewable energy system for the university community. The target of the design is to ensure efficient utilization of the available renewable resources through storage sufficiency.

2 LITERATURES REVIEW

Regions with difficult terrains and topography often have the highest potential for renewable energy technologies (RETs). Hence, countries have embarked on research and development programs that are targeted towards the proper utilization of RETs in either the off-grid or grid-tied

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mode and as either single-source or hybrid system [2], [7], [25], [27], [34], [35], [37]. Fluctuations in renewable resources availability often affect the output of renewable energy systems. These fluctuations consist of two overlapping parts; the macro-meteorological fluctuations and micro-meteorological fluctuations [30]. The macro-meteorological fluctuations are relatively slow and smooth while the micro-meteorological fluctuations are relatively fast and sharp. These observations indicate that, for optimum benefit, different storage systems can be used to accommodate each of the two fluctuation patterns.

For the macro-meteorological fluctuations, a storage facility with high energy capacity and a large power rating can be deployed, but its response speed may be slow. The micrometeorological fluctuations require that the storage system should have the capability of rapidly changing power, but a large capacity may not be necessary.

The hybrid optimization model for electric renewable sources (HOMER) and the Hybrid optimizations by genetic algorithms (HOGA) software have been extensively used for component sizing and performance analysis of hybrid renewable energy systems, in terms of feasibility, sensitivity, cost, and sustainability, for different load types [5], [6], [15]. The fact that most of these tools are developed based on experience and assumptions of their location of origin [14] and cannot be modified, makes most of these models to be insufficient for adaptability. In the study of [8], [17], [21], [24], [28], the heuristic approaches based on artificial intelligence were employed.

A fast convex programming approach for optimal design of a hybrid renewable energy system, for the University of the Witwatersrand community, was presented in [13]. The sizing algorithm employed was the sequential quadratic programming (SQP). The efficiency of the developed algorithm was compared with the output of the HOMER software. It was found to be very efficient, but it was limited to component sizing only. A supervisory control system that can be used to monitor and coordinate the operation of a properly sized hybrid energy system was presented in [4]. The approach was developed based on digital electronic logics. In this paper, a hybrid system of renewable energy converters and diesel generator, with multiple storage facilities, was designed and simulated using real data obtained over a period of five years (2011 to 2015) from the selected study area.

3 SOURCES OF RESEARCH DATA

The meteorological data were obtained from two sources namely: the Atmospheric Physics Research Laboratory (APRL) and Space Application and Environmental Science Laboratory (SPAEL). The feeder current data were obtained from the University Electrical section. The general assumption made was that the model developed for the university, as an off-grid community, can be easily deployed to actual off-grid communities when the needed data are available. The GIS map layout of the study area is shown in Fig. 1.

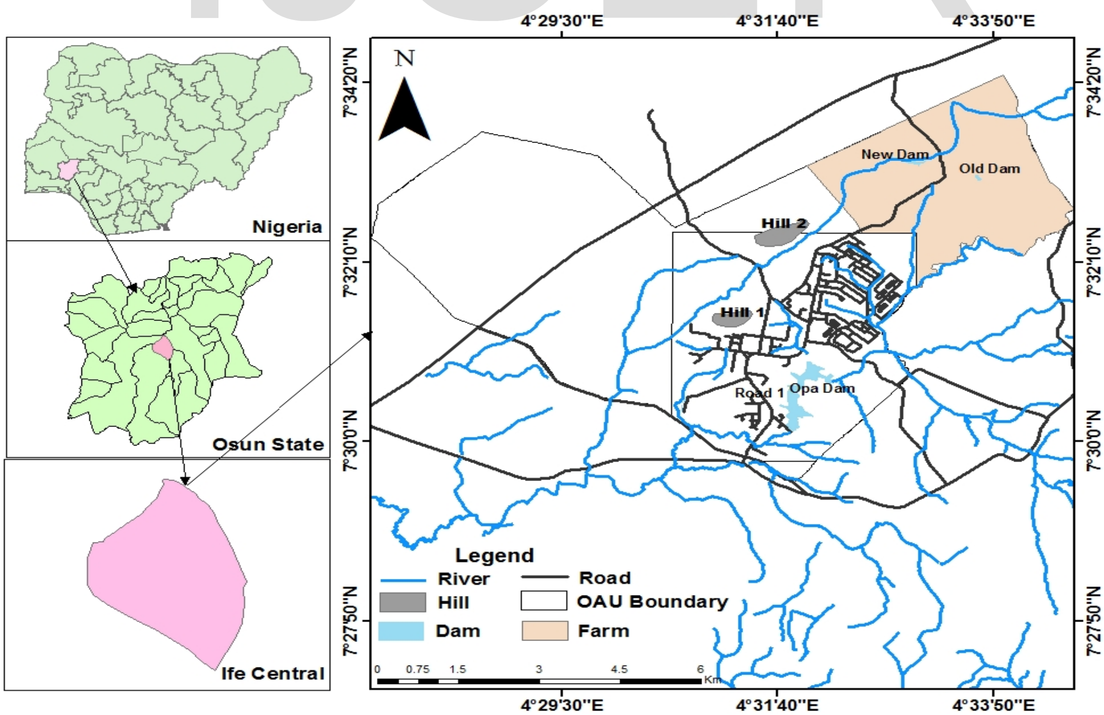


Fig. 1: GIS map of the study area showing important geographical features

Source: SPAEL, Institute of Ecology and Environmental Science, OAU, Ile – Ife

3.1 Renewable Resources Data

Solar and wind data for five years (2011 to 2015) were used to estimate the mean wind speed and mean solar radiation to be 4.21 m/s at height of 40 meters and 204.61 W/m2 respectively. The meteorological data for four geographical seasons recognized within the study area are obtained as follow: long rainy season (June), short dry season (August), short rainy season (October) and long dry season (December).

3.2 Load Demand Data

Based on the academic activities during the week, six distinct load demand profiles were considered in this study. In each time step, the real power consumed by the site was obtained using the following equation:

$$P(t) = \sqrt{3}V\cos\theta \times I(t) \qquad (1)$$

I(t) is the instantaneous load current and V is the supply voltage.

The daily energy consumption for each day was obtained according to equation (2)

$$E_{load} = \left(\sum_{n=1}^{n=48} P(t)\right)\mathrm{T} \qquad (2)$$

For a sampling time, T = 30 minutes over 24 hours scheduling horizon, there are 48-time steps.

The maximum and minimum energy consumptions obtained are 19.10 MWh and 7.71 MWh. The instantaneous peak load demand and average load demand recorded were 1.18 MW and 0.80 MW, respectively. This was obtained on weekdays during the normal academic period as shown in Fig. 2.

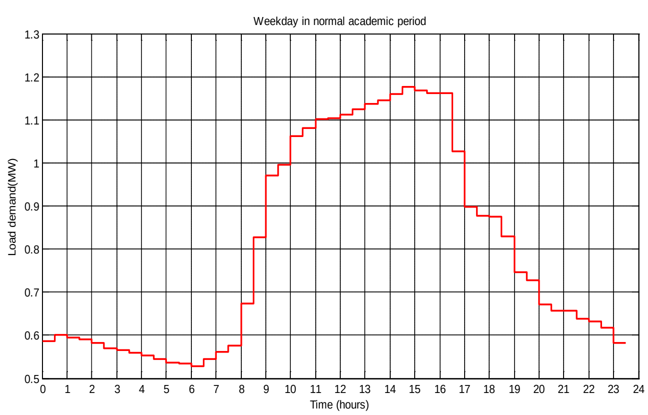


Fig. 2: Load demands data for weekday in normal academic period.

4 OPTIMAL COMPONENT SIZING

In this study, the net total cost of the hybrid renewable energy system to be optimized was expressed as the sum of the capital cost, C_c and running cost, R_c of the renewable energy sources and the backup generator. The net total cost was minimized subject to the power balance and system limits constraints as shown in Equations 3, 4, 5, 6 and 7:

Minimize

$$\left(C_c + R_c\right) = \left(K_w P_w + K_s P_s + K_{gen} P_{gen} + C_f\left(P_{gen}\right)\right) \qquad (3)$$

$$C_f(P_{gen}) = f_0 + f_1 P_{gen} + f_2 (P_{gen})^2 \qquad (4)$$

Subject to

$$(P_w + P_s + P_{gen}) = P_{load\,(\max)} \qquad (5)$$

$$P_w + P_s \geq P_{load\,(ave)} \qquad (6)$$

$$P_{gen}^{(\min)} \leq P_{gen} \leq P_{gen}^{(\max)} \qquad (7)$$

K_w, K_s *and* K_{gen} are the costs of electricity per kW of the wind, solar and diesel generator systems respectively. P_w, P_s and P_{gen} are the capacity ratings of each system respectively, f_0, f_1 and f_2 are the fuel consumption coefficients. The objective function satisfies the conditions for convexity and the minimization problem was solved using the quadratic programming approach. The size of the two storage facilities were systematically calculated from the size of the two renewable energy sources as explained later. The cost data used for the optimization and cost analysis are shown in Table 1. The procedure for system's component sizing was achieved using the Matlab optimization toolbox (Optimtool) and the flowchart is presented in Fig. 3.

Table 1: Cost parameters

Components	**Cost/kW ($/kW)**
Wind ($/kW)	1,400
Solar ($/kW)	3,500
PHSS ($/kW)	350
Battery ($/kW)	625
Converter ($/kW)	140
Generator ($/kW)	850
f0($)	8.57
f1($/kW)	4.76
f2($/kW2)	0.15

Sources: [16], [20], [22], [23].

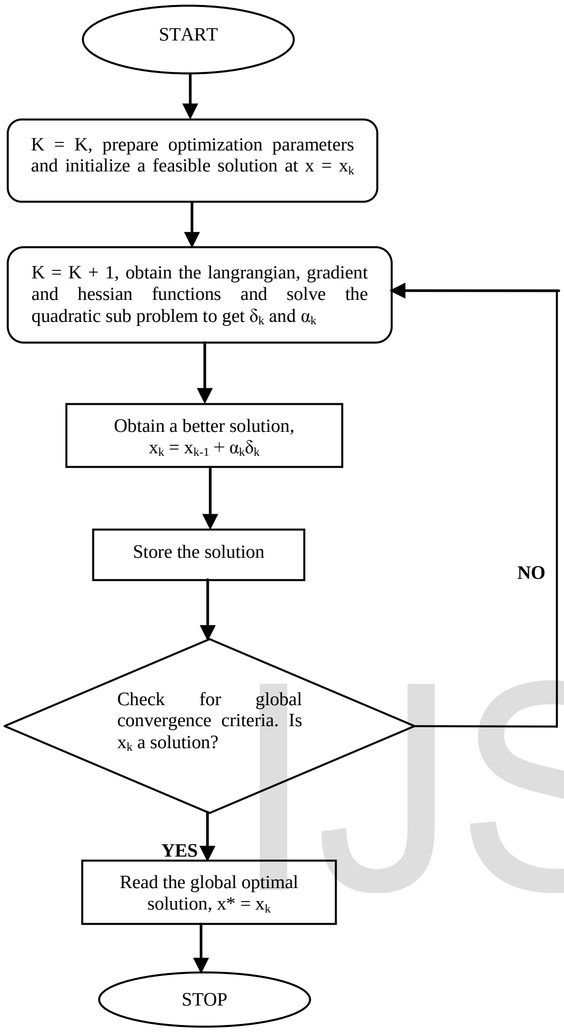


Fig. 3: Flow chart for optimal component sizing using SQP

5 HYBRID SYSTEM DESIGN

The supervisory control system described by [4] was modified with the inclusion of pumped-hydro storage system as shown in Fig. 4. Based on the peculiarity that is associated with each of the incorporated renewable energy systems, the pumped-hydro storage systems was incorporated to address macro-meteorological fluctuations that are often associated with wind energy systems, while the battery was incorporated to address short-term power fluctuations (turbulence) and micro-meteorological fluctuations which are common to the solar energy system. In another way, the presence of multiple storage facilities ensures a smooth transition of power supply to the load between the constituting energy sources, under varying load and climatic conditions.

6 MATHEMATICAL MODELS

6.1 The Wind Energy System

For the system design, the capacity of the wind energy system was calculated using equation 8:

$$P_w = 0.5 \times \eta_w \times \eta_g \times C_{p,\max} \times \rho_a \times A \times v_w^{\ 3} \quad (8)$$

The maximum power coefficient, $C_{p,max}$ of the wind energy conversion system is technically called the beltz limit and it is given as $C_{p,max}$= 0.599, η_w and η_g are the efficiencies of the wind turbine and the electromechanical system (generator) respectively. The overall efficiency of the wind turbine, which is the product of η_w and η_g was taken as 0.75. The swept area of the blade is A, the hub (tower) height of 40m above ground level was selected for better wind capacity. The density, ρ_a of air (onshore) is 1.25 kg/m³. During simulation, the actual output of the wind generator was calculated as a function of the instantaneous wind speed using the wind power generation equations given in [11], [31].

6.2 The Solar Energy System

The electrical power output of each PV panel, based on configuration of the PV cells, was calculated using equation 9.

$$P_s = \eta_{pv} \times N_{pvp} \times N_{pvs} \times V_{oc} \times I_{sc} \quad (9)$$

The common PV panels with high commercial availability, which are known to have practical efficiency value of about 23.1%, η_{pv} = 0.231 [9], were used for the design of the solar energy system. $V_{oc}$and I_{sc} are the open-circuit voltage and short-circuit current of the solar panel respectively, at a simulation temperature of 25^0C and the number of series and parallel connected solar cells are N_{pvs} = 36 and N_{pvp} = 6, respectively. For the simulation, the generated electrical power of the solar photovoltaic panel was taken to be a function of the instantaneous irradiation; Gt as in [24], [26].

6.3 Pumped-Hydro Storage System

The efficiency, η_h of the pumped-hydro storage, in both generation and pumping mode, was taken to be 75% [33]. During simulation, the energy available to be stored into the pumped-hydro storage, under different system conditions during pumping mode, was estimated from the available wind energy as presented in equations 10, 11, 12:

For $P_{w(t)}>P_{load(t)}$;

$$E_h^+(t) = \sum^{N_t} \eta_h \left(P_w(t) - P_{load}(t)\right) \mathrm{T} \quad (10)$$

For $P_{w(t)}<P_{load(t)}$;

$$E_h^+(t) = \sum^{N_t} \left(\eta_h P_w(t)\right) \mathrm{T} \quad (11)$$

For $P_{w(t)}=P_{load(t)}$;

$$E_h^+(t)=0 \tag{12}$$

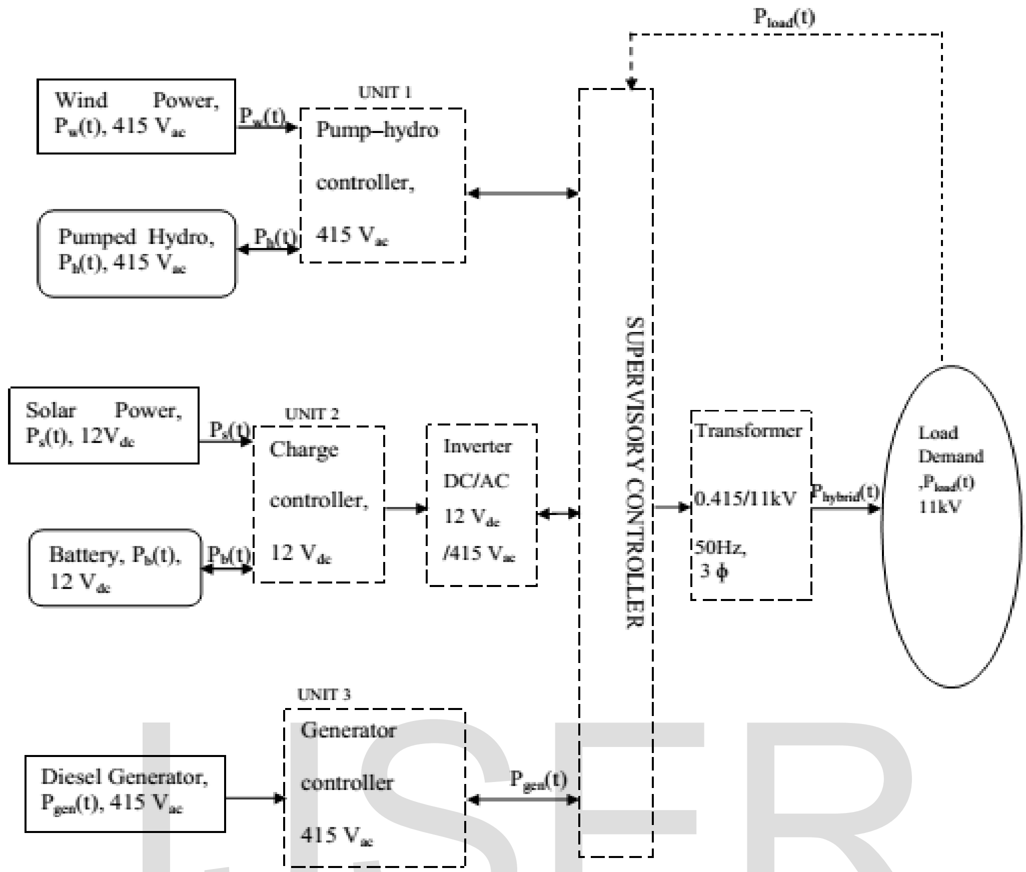


Fig. 4: Implementation strategy for the hybrid renewable energy system

At each time instance, the total energy remaining in the PHSS after pumping was estimated as:

$$E_h(t)=E_h(t-1)+E_h^+(t) \tag{13}$$

The energy output expected from the pumped-hydro storage at any given time during generation was estimated from Equation 14:

$$E_h^-(t)=\frac{\sum^{N_t}\left(P_{load}(t)\right)\mathrm{T}}{\eta_h} \tag{14}$$

At each time instance, the total energy remaining in the PHSS after generation was estimated as:

$$E_h(t)=E_h(t-1)-E_h^-(t) \tag{15}$$

N_t is the time interval (number of time steps) at which the device is in operation (either pumping or generation mode) and each time step, T = 30 minutes.

6.4 Battery

The battery is expected to absorb the surplus energy from the solar energy system. Hence, the capacity of the energy available for storage in the battery was estimated from Equation 16:

$$E_s=\mathrm{T}\times\sum_{n=1}^{N_t}P_s(t) \tag{16}$$

In this study, energy interactions and the state of charge of the battery, via the inverter and the charge controller, at any time instance are estimated from the solar PV system according to the battery charging and discharging equations obtained from [9], [20]. The efficiencies of battery and inverter are taken to be n_b = 78% (during charging only) and n_i = 90% (for both charging and discharging mode), respectively. The depth of discharge, DoD = 80% and charge controller efficiency was taken to be 98% [9].

6.5 Diesel Generator

For round-the-clock reliability, due to a need for planned outages of renewable energy sources and storage devices either for maintenance or when the system experiences bad climatic conditions, the rated power, P_{gen} of the diesel generator system should be selected to be slightly above maximum load demand. However, this approach has a negative economic impact on the system; this is because this kind of situation does not occur frequently. The output power limit of the diesel engine is a critical constraint that was considered in this study. The real power output of the diesel generating unit is constrained between the upper and the lower limits as $P_{gen}(min)$ = 30% of rated power and $P_{gen}(max)$ = 95% of rated power, respectively.

7 SCHEDULING STRATEGIES FOR THE HRES

The order of priority for the system's coordination, based on cost and sufficiency, is wind - solar- storage devices (pumped-hydro and battery) – diesel generator. Depending on the instantaneous available renewable energy resources and load demand, the scheduling operation of the HRES involved two modes (storage and generation modes) as shown in Fig. 5. A simulation program was developed for the coordination of the hybrid renewable energy system based on the flow chart of Fig 5. At each time step, the total power in the hybrid renewable energy system was estimated by using equations 17 and 18.

$$P_{hybrid}(t) = P_{load}(t) = P_w(t) + P_s(t) + P_{sto}(t) + P_{gen}(t) \quad (17)$$

$$P_{sto}(t) = P_h(t) + P_b(t) \quad (18)$$

$P_{sto}(t)$ is the power from both storage facilities. The total power from the wind and solar PV systems that are available within the hybrid renewable energy system at a particular time was estimated as given by Equation 19:

$$P'_{ren}(t) = P_w(t) + P_s(t) \quad (19)$$

The actual contribution of the renewable energy systems (with the storage) to meeting the load was estimated using Equation 20:

$$P_{ren}(t) = P'_{ren}(t) + (P_h(t) + P_b(t)) = P_{load}(t) - P_{gen}(t) \quad (20)$$

where $P_w(t)$, $P_s(t)$, $P_h(t)$, $P_b(t)$ and $P_{gen}(t)$ are, respectively, the instantaneous power from the wind, solar, pumped-hydro, battery and the generator, respectively. $P_{load}(t)$ is the load demand at a time, t. A graphical user interface was developed, as shown on Fig.6, for collection of result data and direct analysis.

The total daily percentage energy contribution from the renewable systems was obtained from Equations 21 and 22:

$$E_{ren} = \left(\sum_{n=1}^{48} P_{ren}(t) \right) T \quad (21)$$

$$E_{ren}(\%) = \frac{E_{ren}}{E_{load}} \times 100\% \quad (22)$$

8 COST ANALYSES FOR THE ENERGY SYSTEM

The fixed installation cost, which is the net capital cost of the designed HRES, was compared to the cost of grid extension. Also, the variable cost, which is the cost of diesel in the hybrid renewable energy system and the cost of grid electricity for the grid extension option, were compared under different scenarios. The net capital cost of the hybrid system was obtained by using equation 23:

$$C_k = K_w P_w + K_s P_s + K_h P_h + K_b P_b + K_{gen} P_{gen} \quad (23)$$

Where K_i is the respective cost coefficient for each unit indicated. The capital cost for extending the grid was estimated at $20,000 per km [35]. The annual operations and maintenance (O&M) costs were estimated to be 2% of the capital costs [29]. The variable costs, which are the cost of diesel, C_f in HRES and cost of grid electricity, C_u are calculated from equations 24 and 25, respectively.

$$C_f = C_{f/kwh} \times E_{gen} \quad (24)$$

$$C_u = C_{u/kwh} \times E_{load} \quad (25)$$

$C_{f/kWh}$ and $C_{u/kWh}$ are the variable costs of electricity per kWh from HRES and grid respectively. E_{gen} is energy contribution from the diesel generator in kWh and E_{load} is the total load demand in kWh.

9 DISCUSSIONS OF RESULTS

9.1 Optimal Size of The Hybrid Renewable Energy System's Components

The sequential quadratic algorithm was initialized on Matlab for optimal sizing of the three primary energysources. The result of the optimal ratings of the incorporated energy generating systems was obtained after two iterations as shown in Table 2:

Table 2: Components size

Systems	Ratings (kW)
Wind	400
Solar	400
Diesel Generator	500

9.2 Output Power of the Wind and Solar System under Different Geographical Seasons

In Fig. 7, the real power generated by the wind system and the solar system, at an average temperature of 25.50C and average humidity of 94.5%, under each of the geographical seasons were shown. The power generated by the wind energy system is clearly higher than the power generated

ISSN 2229-5518

by the solar energy system in the long rainy season.

However, in the short dry season, the rain has reduced drastically and there is a considerable increase in the solar potential.

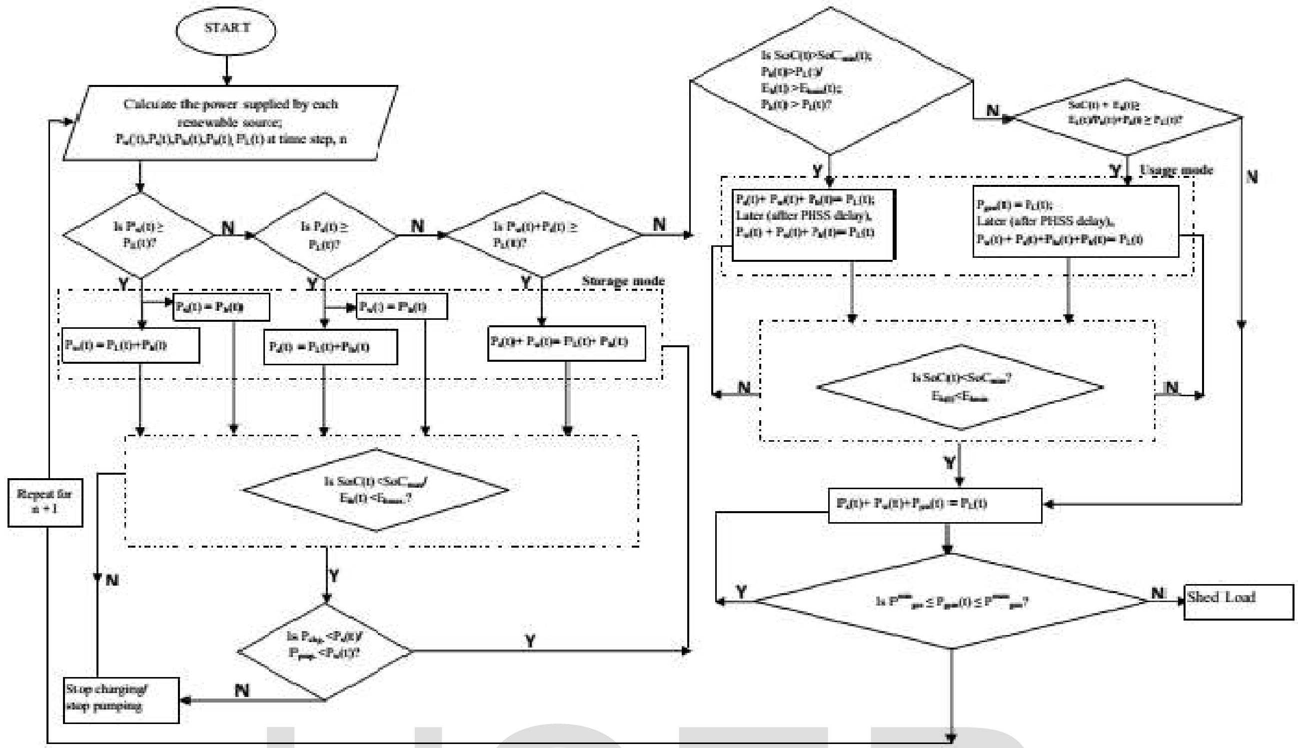


Fig. 5: Flowchart for the hybrid renewable energy system'sscheduling

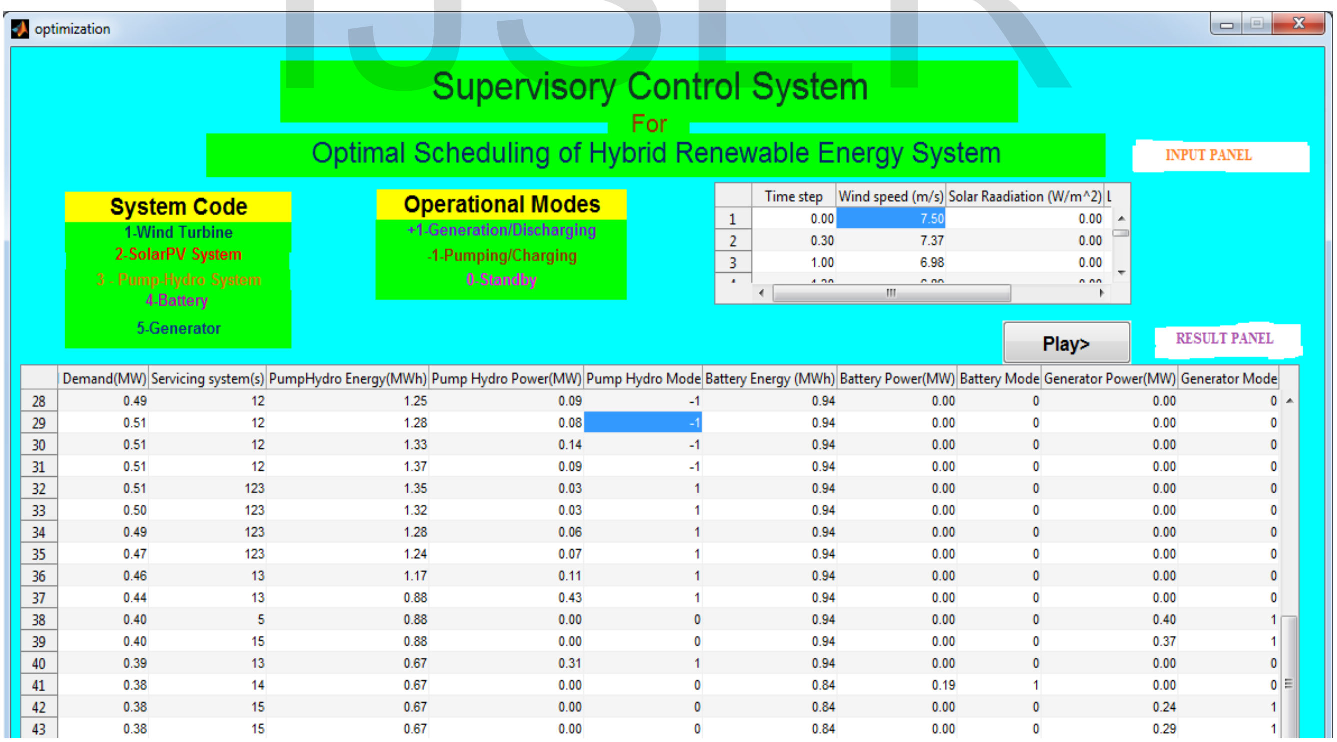
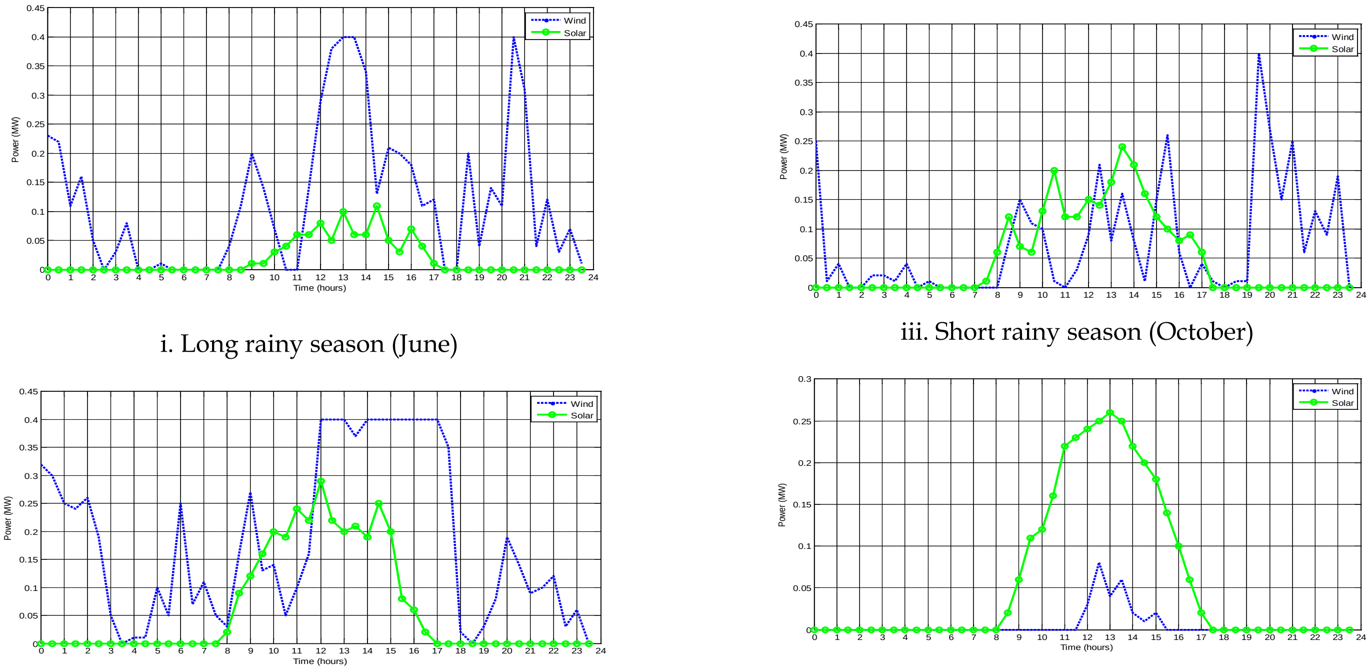


Fig. 6: Screenshot of the hybrid renewable energy system GUI



i. Long rainy season (June)

iii. Short rainy season (October)

ii. Short dry season (August)

iv. Long dry season (December)

Fig.7: Real power produced by the wind and solar energy systems at different seasons

The long dry season comes with less rain and there is an increase in the number of hours with sufficient radiant energy from the sun (i.e. better output from the solar system). The short rainy season can be said to produce substantial power from both the wind and solar photovoltaic system.

Table 3: Contributions from energy sources

	Scenarios	E_{load} (MWh	E_{ren} (MW	E_{ren} (%)	E_{gen} (MW	E_{gen} (%)
1	June – WD - NAP	19.12	5.44	28.45	13.68	71.55
2	June - SAT – NAP	8.33	5.49	65.91	2.84	34.09
3	June - SUN – NAP	8.01	5.33	66.54	2.68	33.46
4	June - SAT - HP	7.86	5.48	69.72	2.39	30.41
5	June - SUN – HP	7.72	5.45	70.60	2.28	29.53
6	June - WD – HP	9.22	5.58	60.52	3.64	39.48
7	August- WD – NAP	19.12	7.99	41.79	11.13	58.21
8	August - SAT – NAP	8.33	7.52	90.28	0.81	9.72
9	August - SUN – NAP	8.01	7.35	91.76	0.66	8.24
10	August - SAT – HP	7.86	7.38	93.89	0.49	6.23
11	August - SUN – HP	7.72	7.42	96.11	0.30	3.89
12	August - WD – HP	9.22	7.69	83.41	1.53	16.59
13	October- WD – NAP	19.12	5.03	26.31	14.09	73.69
14	October – SAT – NAP	8.33	5.20	62.42	3.13	37.58
15	October - SUN– NAP	8.01	5.13	64.04	2.89	36.08
16	October - SAT – HP	7.86	5.17	65.78	2.70	34.35
17	October - SUN – HP	7.72	5.23	67.75	2.49	32.25
18	October - WD – HP	9.22	5.20	56.40	4.02	43.60
19	December -WD– NAP	19.12	3.30	17.26	15.82	82.74
20	December-SAT– NAP	8.33	3.77	45.26	4.56	54.74
21	December-SUN–	8.01	3.67	45.82	4.34	54.18
22	December - SAT – HP	7.86	3.77	47.96	4.09	52.04
23	December - SUN –	7.72	3.80	49.22	3.93	50.91
24	December - WD – HP	9.22	3.70	40.13	5.52	59.87

9.3 Contribution of Renewable Energy System to the Load Demand

In this study, the effectiveness of the coordination strategy was evaluated for 24 scenarios, using the percentage energy contribution from the renewable energy systems. The outcomes of the 24 scenarios were summarized in Table 3.
In Table 3, 19 out of the 24 scenarios showed that the renewable energy systems have a significant degree of participation in meeting the load demand of the site under study over the 24 hours scheduling horizon. For five out of the six load conditions that are been considered, the short dry season showed remarkable between 83.41% and 96.11% for meeting the load demand of the site under study. The participation of the diesel generator in supplying the load is greatly reduced; this can be seen in scenarios 8, 9, 10, 11 and 12. The long rainy season and short rainy season show good renewable energy generation potential of about 56.40% and 70.60% for five out of the six load conditions as seen in scenarios 2, 3, 4, 5, 6, 14, 15, 16, 17 and 18. Also, as seen in scenarios 20, 21, 22, 23 and 24; the long dry season showed an average energy contribution from the renewable system that is between 40.13% and 49.22%. However, the weekday in normal academic session, under each of the seasons, requires more energy from the diesel generator as seen in scenarios 1, 7, 13 and 19. Under this load condition, the contribution of the renewable energy systems was between 17.26% and 41.79%.

9.4 Contribution of Storage Devices to Meeting the Load Demand

Table 4 shows the percentage contribution of the storage devices towards meeting the load demand at different scenario. The storage devices contributed 9.21% to 29.15% of the total energy demand of the site being studied at different conditions; with values that range from 1.43 MWh to 2.25 MWh. These are huge energy values that the battery alone may not be able to manage technically and economically [18, 33]. Hence, the pumped-hydro storage allows for optimal utilization of the energy from renewable sources, especially for a hybrid renewable energy system with a high penetration of wind energy. With the pumped–hydro storage, there is a large capacity for storing the surplus energy which can be used up later when it is needed.

Table 4: Contributions from storage systems

scen-arios	E_{load} (MWh)	E_w (MWh)	E_s (MWh)	E'_{ren} (MWh)	E_{gen} (MWh)	E_{sto} (MWh)	E_{sto} (%)
1	19.12	2.92	0.42	3.34	13.68	2.10	10.98
2	8.33	2.92	0.42	3.34	2.84	2.15	25.81
3	8.01	2.92	0.42	3.34	2.68	1.99	24.84
4	7.86	2.92	0.42	3.34	2.39	2.13	27.10
5	7.72	2.92	0.42	3.34	2.28	2.10	27.20
6	9.22	2.92	0.42	3.34	3.64	2.24	24.30
7	19.12	4.43	1.49	5.92	11.13	2.07	10.83
8	8.33	4.43	1.49	5.92	0.81	1.60	19.21
9	8.01	4.43	1.49	5.92	0.66	1.43	17.85
10	7.86	4.43	1.49	5.92	0.49	1.45	18.45
11	7.72	4.43	1.49	5.92	0.30	1.50	19.43
12	9.22	4.43	1.49	5.92	1.53	1.77	19.20
13	19.12	1.79	1.21	3.00	14.09	2.03	10.62
14	8.33	1.79	1.21	3.00	3.13	2.20	26.41
15	8.01	1.79	1.21	3.00	2.89	2.12	26.47
16	7.86	1.79	1.21	3.00	2.70	2.16	27.48
17	7.72	1.79	1.21	3.00	2.49	2.23	28.89
18	9.22	1.79	1.21	3.00	4.02	2.20	23.86
19	19.12	0.13	1.41	1.54	15.82	1.76	9.21
20	8.33	0.13	1.41	1.54	4.56	2.23	26.77
21	8.01	0.13	1.41	1.54	4.34	2.13	26.59
22	7.86	0.13	1.41	1.54	4.09	2.23	28.37
23	7.72	0.13	1.41	1.54	3.93	2.25	29.15
24	9.22	0.13	1.41	1.54	5.52	2.16	23.43

9.5 Cost Analysis for the Energy Systems

i. Fixed costs

Total installation cost of the HRES was estimated to be $3,692,152.50. Installation of grid electricity seems to be the cheaper option for a distance of up to 180 km at $20,000 per km [35] as shown in Fig. 8.

However, the benefits of HRES over the grid extension option are seen in cases when the topography of the region is difficult for grid extension and when the available grid system is inadequate and unreliable.

ii. Variable costs

The cost of grid electricity (per kWh) was compared with the cost of diesel (per kWh) for the HRES as shown in Table 5.

The almost free nature of the energy generated from the renewable sources has a huge influence on the economic parameters of the HRES. It provides an offset for the huge cost involved in installing the HRES, since the electricity from the grid cost more than the cost of electricity generated from the HRES under all the considered scenarios. In most of the cases, the cost of grid electricity is twice that of the HRES.

10 CONCLUSIONS

In this study, the performance evaluation and cost analysis of a hybrid renewable energy system was conducted using Matlab programming and simulation tool. The study demonstrated that the design and implementation of off–grid hybrid renewable energy system with multiple storage facilities (using the pumped – hydro storage system and battery) will help in maximizing the use of energy from the renewable energy sources and also help in ensuring smooth transition of power between the energy sources and the load in the face of fluctuations.

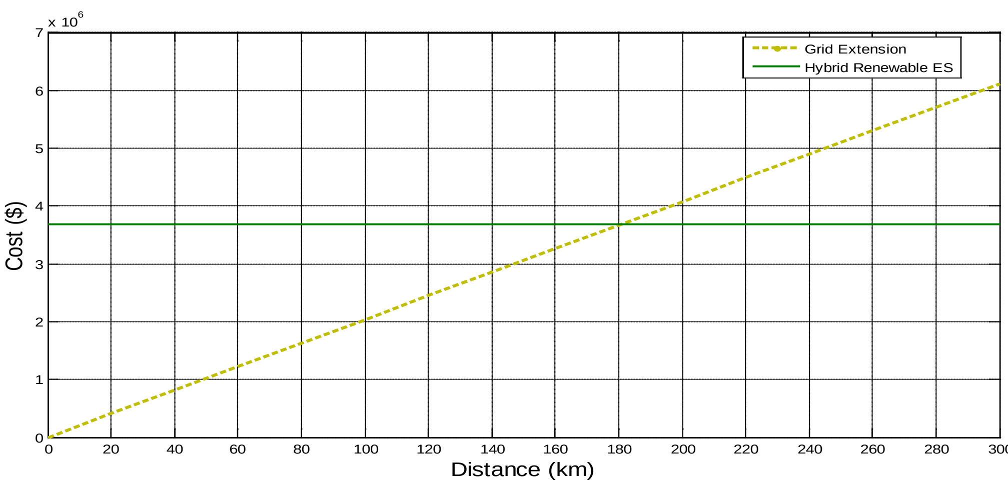


Fig. 8: Comparison of installation cost

Table 5: Variable costs comparison

	Hybrid – RES		Grid Electricity	
Scenarios	E_{gen} (MWh)	C_f (₦)	E_{load} (MWh)	C_u (₦)
1	13.68	487.008	19.12	570,541
2	2.84	101,104	8.33	248,567
3	2.68	95,408	8.01	239,018
4	2.39	85,084	7.86	234,542
5	2.28	81,168	7.72	230,365
6	3.64	129,584	9.22	275,125
7	11.13	396,228	19.12	570,541
8	0.81	28,836	8.33	248,567
9	0.66	23,496	8.01	239,018
10	0.49	17,444	7.86	234,542
11	0.30	10,680	7.72	230,365
12	1.53	54,468	9.22	275,125
13	14.09	501,604	19.12	570,541
14	3.13	111,428	8.33	248,567
15	2.89	102,884	8.01	239,018
16	2.70	96,120	7.86	234,542
17	2.49	88,644	7.72	230,365
18	4.02	143,112	9.22	275,125
19	15.82	563,192	19.12	570,541
20	4.56	162,336	8.33	248,567
21	4.34	154,504	8.01	239,018
22	4.09	145,604	7.86	234,542
23	3.93	139,908	7.72	230,365
24	5.52	196,512	9.22	275,125

The outcome of this study showed that, if properly planned and designed, hybrid renewable energy system, HRES can provide grid quality and reliable electricity for small industries and rural communities that are yet to be connected to the grid. The system can be designed to be 100% renewable by substituting the diesel (fossil fuel) generator with a biodiesel (renewable) generator. In a case where PHSS is not feasible, other storage facilities with high energy, such as flywheel, density can be used instead.

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