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Optimisation of an On-grid Hybrid Energy System: A Case Study of the Main Campus of the University of Abuja, Nigeria

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Abstract: *The challenge of meeting the energy demands of institutions and organisations in an economically viable and environmentally friendly manner is becoming more and more complex especially in developing countries like Nigeria. This work presents a resilient hybrid renewable energy system to supply the electric power requirement of the main campus of the University of Abuja, Nigeria, estimated as 900 kW at a consumption rate of 6300 kWh/day. HOMER software was used as the modelling tool for simulations, optimizations, and sensitivity analyses carried out to explore the feasibility of utilizing Abuja's (MSW) in hybrid with the mini hydro power potential of River Wuye and solar PV resources to meet the load demand of the campus. The hybrid plant has the following component specifications: hydro resource nominal flow rate is 14.5 m^3/s; maximum head is 10 m and potential capacity is 885 kW; MSW plant specifications were determined to be 500 kW capacity, waste treatment of 2.3 ton/day; lower calorific value for MSW of 15.84 MJ/kg with the solar PV component having a capacity of 500 kW. Total installation cost for the hybrid plant for the 2 MW hybrid plant was determined to be ₦5.44 billion (US$7.225 million) with annual energy generation calculated to be 799,000 kWh/yr. The net present cost for the simulated system was found to be ₦ 9.37 billion ($12,486,120) with the corresponding LCOE being ₦55.2/kWh ($0.0736/kWh). The carbon emission was estimated to be 7.33 g per day which approximates to a net zero emission, demonstrating the environmental friendliness of renewable energy sources utilised. Sensitivity analysis performed on the system using project life span, inflation rate, solar irradiance, MSW's lower heating value (LHV), capacity shortage and the annual average volumetric flow rate of River Wuye showed that the net present cost increased with increasing plant life while the levelized cost of energy reduces with increasing life from ₦55.02/kWh for plant life of 25 years to ₦43.73/kWh for 30 years.*

Keywords: *Optimisation, Hybrid Energy System, System Architecture, Net Present Cost, Levelized Cost of Energy, Sensitivity Analysis.*

1. INTRODUCTION

Energy demand is on a persistent increase globally and with great reliance on fossil source which are non-renewable and impact the environment negatively due to greenhouse gas emission. To sustainably meet this demand attention is being paid to hybridisation of natural energy sources for power generation. A critical advantage inherent in the use of energy derived from natural sources is that they are replenished at a higher rate than they are consumed, within human time scale. Hence, energy from natural sources is known as renewable. This includes solar, hydro, geothermal, biomass and wind. The renewable energy resources have little negative impacts on the environment, such as emission of greenhouse gases. This is unlike energy from fossil fuel sources which are expendable without possibility of being replenished [1]. The formation process of fossil fuels takes millions of years and therefore fossil fuels are not regarded as replenishable nor renewable. Examples of fossil fuels include coal, oil and natural gas. They cause harmful greenhouse gas emissions to the environment when burnt to produce energy, in addition to other negative impacts.

Hybrid energy systems are described as power systems that produce electric energy from two or more sources, most often renewable, by sharing the same load connection point. Typical renewable energy technologies combined in most hybrid energy systems include biomass, especially waste-to-energy (WtE), solar photovoltaic (PV) and wind turbines. Other combinations of hybrid systems may be solar photovoltaic (PV)-diesel generator (DG)-battery energy storage (BES) system; PV-wind turbine – diesel system; WtE – PV – hydro turbine system, etc. Benefits of the hybrid energy system include: greater system flexibility, extended system longevity, improved system efficiency, improved reliability and versatility and improved cost reduction among other considerations.

In order to properly communicate the information obtained in this study, the manuscript has been structured as follows: The introduction which deals with the problem statement, motivation for the work and the general background of the study is presented in Section 1. Section 2 presents a brief review of literature concerning recent research works on the subject matter. The methodology and optimisation modelling applied in the study are given in Section 3 while Section 4 provides the results of the study and the appropriate discussions.

2. LITERATURE REVIEW

A very important and popular platform for design of hybrid energy systems is the HOMER software. The Hybrid Optimization Model for Multiple Energy Resources (HOMER) is a computer modelling software developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micro-power systems. The HOMER software has also been proved useful in the comparison of power generation technologies over a wide range of applications. The HOMER software has capacity to model a power system's functional behaviour and its life-cycle costs. HOMER allows the designer to evaluate and compare different design options on the basis of their technical and economic features. Optimization of the best hybrid configurations of different sources is also a useful capability of HOMER. The sensitivity analysis possible on HOMER also assists the designer in understanding and quantifying the effects of uncertainty or changes in the variable inputs. A micro power system designed to generate electricity to serve a nearby defined load may employ any combination of electric power generation and storage technologies. It may be grid-connected or stand-alone. Examples of micro power systems may include a solar PV–battery system serving a remote load; a wind turbine–diesel system serving an isolated village; a grid-connected WtE - mini hydro turbine providing electricity to a university community.

Various researchers have reported results on the use of HOMER for techno-economic evaluation of hybrid energy systems, especially for deciding the best system configuration in terms of specific technology applied that gives the least net present cost (NPC) while reliably satisfying the electricity demands. Dodo et al [2] used HOMER to assess two different configurations of a stand-alone diesel generator (DG) system and a hybrid solar photovoltaic (PV)-diesel generator (DG)-battery energy storage (BES) system for the supply of sustainable power to a university campus in Nigeria. From his results, the operating cost, levelized cost of energy, net present cost and carbon dioxide emission of the hybrid PV-DG-BES system were found to be lower by 30.93, 50 and 90% respectively, when compared to the stand-alone DG system.

Khan et al [3] carried out an evaluation of off-grid hybrid power systems (HPS) for a university campus. Rinaldi et al [4] determined the optimal configuration of hybrid PV-Wind-diesel systems for three small communities without access to the grid in remote Peruvian villages using HOMER. In the study the systems were modelled in seven different scenarios applying single component stand-alone systems and the hybrid component systems. The optimal sizing of the system was determined by HOMER software considering the lowest initial capital cost, total annual operating cost, lowest net present cost (NPC), cost of energy, the generation fractions and the resulting CO2 emissions. The results obtained revealed that the hybrid solar-wind-diesel system was the most sustainable configuration for all of the communities investigated.

Timilehin et al [5] examined the possibility of combining PV arrays, DG, and BES systems for efficient management of energy and to minimize dependence on CO_2 emitting diesel generators in a university campus. Jumare et al [6] utilised HOMER in carrying out a life cycle analysis of a grid-connected hybrid renewable energy systems in Northern Nigeria.

Ayamolowo et al worked on a hybrid distribution generation system for a typical Nigeria university where solution to intermittency of availability of solar energy resource was proffered by using solar PV- diesel generator - battery energy storage hybrid system [7]. Odoi-Yorke et al provided decision-making algorithms for optimisation of hybrid renewable energy systems in their recent work [8].

3. METHODOLOGY

The hybrid energy system (HES) is an integration of different renewable sources including municipal solid waste (MSW), micro-hydro and photovoltaic (PV) units. In general, an HES plant can be a combination of two or more renewable sources together with at least one nonrenewable energy source. A typical HES plant is depicted in Figure 1.

3.1 Modelling and Simulation of the Hybrid MSW-Solar PV-Wuye River Mini-Hydro Power Renewable Energy Resources

A simulation for this research work considers a proposal to supply the electric energy needs of the main campus of the University of Abuja, utilizing a hybrid renewable energy scheme incorporating MSW driven power generators with River Wuye mini hydroelectric power plant and photovoltaic modules. This is complemented with battery energy storage and converter systems. Grid electricity is presently supplied to the campus by the Abuja Electricity Distribution Company (AEDC) Plc on the L34 feeder from the 132/33 kV Gwagwalada substation. Despite the widely known strategic importance the university as a centre of excellence in teaching and research and its special need for electricity, the community has been contending with persistent power failures from the grid. Power failures usually last for hours and at times for days. This scenario has indeed been negatively impacting on the delivery of the university's mandate for cutting-edge research output and also effective administrative, teaching, and learning activities.

A correctly modelled hybrid energy system will be cost effective with high reliability in meeting the energy needs of the university community with the use of appropriate technology. The optimization is aimed at minimizing the cost variable in relation to demand and other potential constraints.

3.2. Description of University of Abuja's Electric Load

The main campus of the University of Abuja presently receives its electricity from the national grid through the distribution network managed by the AEDC. The campus has a load demand estimated at about 900 kW. The supply voltage is 33 kV. The campus' consumption consists mainly of illumination, power for mechanical equipment in the engineering workshops, laboratory equipment, photocopiers, computers and printers. Domestic appliances in student hostels also form part of the consumption. The average daily energy consumption of the university community was estimated to be 6300 kWh/day.

3.3. Model Development

The development of the proposed hybrid power system (HPS) consists of the major components such as solar PV arrays, the MSW power generator, dam civil structure, hydro turbines and generators with the relevant auxiliary equipment that make up the hydro power generating system. Excess power from the output of the hybrid system may be sold to AEDC based on a workable power purchase agreement (PPA). The three renewable energy sources are conceived to work together in hybrid as a single power plant, to be sited at the position of the Wuye River's optimal potential. Figure 1 shows a schematic diagram of a typical hybrid power plant.

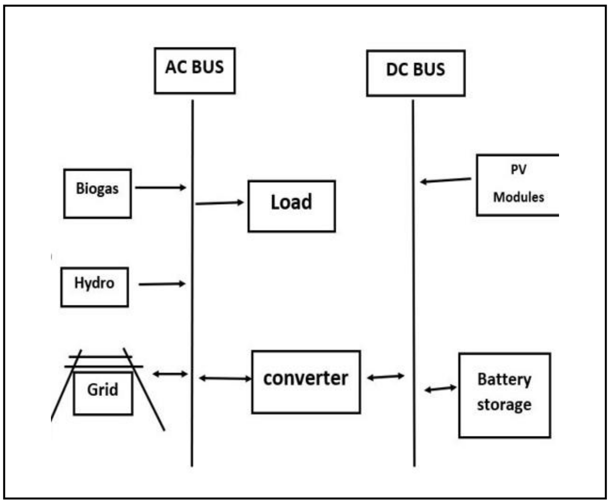


Figure 1: Schematic diagram of the hybrid energy system

The steps followed in designing the hybrid plant architecture includes obtaining the technical specifications for each component, obtaining installation and replacement costs for each component, determining the operation and maintenance (O&M) costs for the components, establishing minimum life span for the hybrid plant and the components. The resource details applicable to the MSW, solar PV and the Wuye hydro power potential were also obtained. All these specifications and resource details were then imputed into the HOMER software for the hybrid plant architecture, Figure 5, to be built. These relevant details are presented in the subsequent subsections.

3.3.1 Costs

The economic criteria most widely used for evaluating the effectiveness of various hybrid renewable energy system configurations are the net present cost (NPC) and the levelized cost of energy (LCOE). NPC represents the summation of all cost items incurred over the life of the project discounted to present value. As a result, the total NPC is the economic criterion considered in this study for ranking various configurations of components for the hybrid energy system in order of merit during optimization. Thus, the objective function will be to search for the hybrid power system architecture having the least NPC. Thelevelized cost of energy is the break-even cost of the energy charged to the consumers. The LCOE is the commonly accepted calculation of the total life-cycle cost (TLCC) for each unit of energy generated in the project's lifetime [9]. The formula for NPC is as given in Equation 1 [10].

$$NPC = \frac{C_{ann,\,tot}}{CRF(i,\,N)} \tag{1}$$

where $C_{ann,tot}$ is the total annualized operation and maintenance costs of the proposed hybrid energy system components in \$/year, CRF represents the capital recovery factor, i is the annual interest (%), and N represents the plant's lifetime (years). $C_{ann,tot}$ is given by Equation 2 [8].

$$C_{ann,\,tot} = \sum (C_{ann,\,cap} + C_{ann,\,rep} + C_{ann,\,O\&M}) \tag{2}$$

where $C_{ann,cap}$ is the annualized capital cost, $C_{ann,rep}$ is replacement cost annualised, and $C_{ann,\ O\,\&\,M}$ is the annualised operating and maintenance cost.CRF is given in Equation 3.

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

The interest rate i is as obtainable within an economy and is equal to the discount rate for the project.
The LCOE is given by Equation 4 [11]:

$$LCOE = \sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t} / \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{4}$$

Where: I is the total initial investment cost, M is the annual operation and maintenance cost, n = plant life; t = time period; r = discount rate and E is the energy generation per annum.

3.3.2 Technical specifications

For the hybridization to be feasible, relevant technical details for each energy source are as provided as shown below. Table 1 shows the WtE plant specifications.

Table 1: Abuja's WtE (MSW) power plant specifications:

Plant parameter	Value
Capacity (kW)	500
Daily operating hours	20
Energy generation per annum (kWh)	3,650,000kWh (13,140,000MJ)
Aggregate net calorific value of Abuja's MSW (MJ/kg)	15.84
Tonnage of MSW required per annum (tons)	829.55
Quantity of MSW required per day(tons)	2.27
Voltage level (kV)	33
Frequency (Hz)	50
Capital cost USD/kW	US$2,570 - 6,100

Source: [12]

The monthly MSW availability profile is shown in Figure 2.

Figure 2: Annual MSW availability profile

The hydropower component specifications are shown in Table 2.

Table 2: Hydro power plant specifications

Parameter	Value
River run-off (mm)	1,330
River flow rate (m^3/s)	14.5
Maximum head	10
Dam length (m)	120
Hydro power potential (kW)	885
Voltage level (kV)	33
Frequency (Hz)	50
Installation cost (US$/kW)	2,135 [13]
Replacement cost (US$/kW)	1,200

The monthly flow regime of River Wuye is shown in Figure 3.

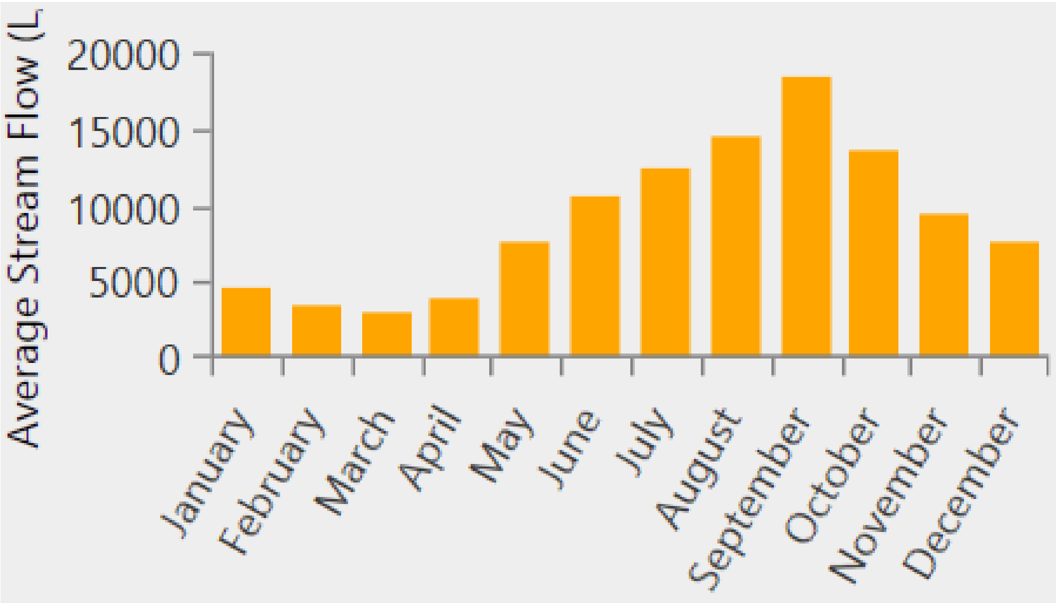


Figure 3: Wuye river monthly flow rate [14]

For proper utilization of solar energy to power using the PV modules, a location's average insolation will be required. Abuja's monthly insolation data are as shown in Figure 4.

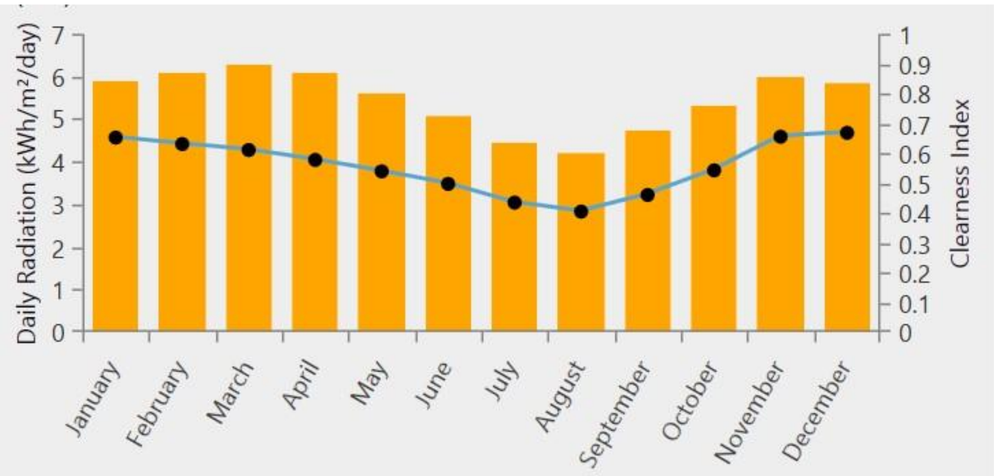


Figure 4: Abuja's monthly average solar irradiance (adapted from U.S. National Renewable Energy Laboratory, NREL)
The PV power lant specifications are as given in Table 3.

Table 3: Solar photovoltaic power plant specifications

Plant parameter	Value
Capacity (kW)	500
DC voltage output (V)	24
Battery capacity (kW)	1108
Converter capacity (kW)	1000
Step up transformer AC voltage (kV)	33
DC bus voltage (V)	24
AC bus voltage (kV)	33
Frequency (Hz)	50
PV power plant capital cost (US$)	857/kW [15]
Life span (Year)	21 [16]
Replacement cost (US $)	585.9 [13]
Lithium-ion battery life (Years)	10 [15]
Battery capital cost (US $)	262.5/kW [17]
Battery replacement cost (US $)	US $ 183.75/kW [17]
Converter life span (Years)	15 Years [18]
Converter capital cost (US$)	420/kW [19]
Replacement cost	199.5 /kW [19]

The relevant costs of the hybrid plant are summarized as in Table 4.

Table 4: Summary of hybrid power plant costs (25-year plant life)

Plant component	Component life (Year)	Capacity (kW)	Capex (US $) per kW	Replacement cost (US $) per kW	Operation & maintenance cost (US $) per kW
MSW power generator	25 [18]	1200	3000 [11]	0.00	75
PV power	21 [16]	500	857 [21]	857 [23]	15.75 [20]

generator					
Mini hydropower plant	50 [19]	855	2135 [21]	0.00	42.7 [22]
Lithium-ion battery storage	10 [15]	1108	262.5 [17]	183.75 [17]	8.0 [20]
Converter	15 [23]	1000	420 [20]	199.5 [20]	8.0 [20]

3.4 Sensitivity Analysis

Sensitivity analysis is a process through which the impacts of different values of an independent variable, known as sensitivity variable, on a particular dependent variable are determined under some stated assumptions. This is performed by imputing different values for a particular sensitivity variable into the HOMER software. The software then repeats the optimization process for each value of the variable and hence the effects on the simulation results are determined [24].

3.4.1 Sensitivity variable

A sensitivity variable is an input variable for which different values can be used in the optimization process. For each specified value of the sensitivity variable, HOMER performs a separate optimization procedure. Sensitivity variables chosen for this study include plant life, MSW daily generation tonnage, MSW's higher heating value (HHV) and the gasification ratio of the MSW. The HOMER software has facility to receive multiple values of a sensitivity variable for the optimization procedures.

3.4.2 Sensitivity case

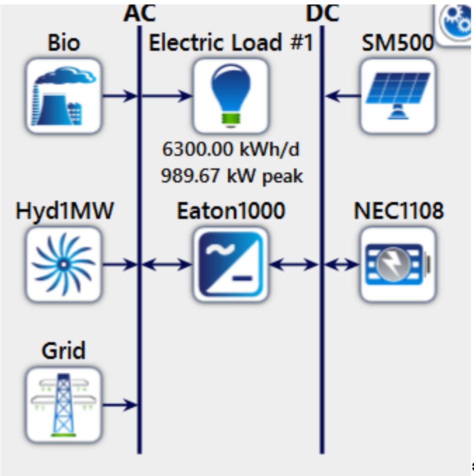
A specific combination of different values of a sensitivity variable is known as a sensitivity case. The total number of sensitivity cases is the product of the number of values specified for each sensitivity variable. For example, specifying three values for the average daily MSW generation rate and two values for HHV will lead to six sensitivity cases. Care is normally taken to ensure that the number of sensitivity cases do not become too large, thereby requiring very long computation time. A sensitivity link is applied to connect the sensitivity variables that vary similarly so as to reduce the number of optimizations performed by HOMER software. This is because multiple values for a sensitivity variable can be specified and HOMER will perform a separate optimization procedure for each possible combination of sensitivity variable values.

4. RESULTS AND DISCUSSION

4.1. Results

4.1.1 Hybrid system optimised architecture

The hybrid model is shown in Figure 5 while the configuration of the optimized system for the main campus of the University of Abuja is shown in Figure 6 below. The best configuration in terms of least net present cost is given by HOMER as shown in the first role for the optimized hybrid architecture.



***Bio stands for MSW**

Figure 5: Schematic diagram for on-grid hybrid power system

Figure 6: Optimized hybrid system architecture

4.1.2 Load profiles

The daily, seasonal and yearly load profiles of the campus are as shown in Figures 7 (a – c).

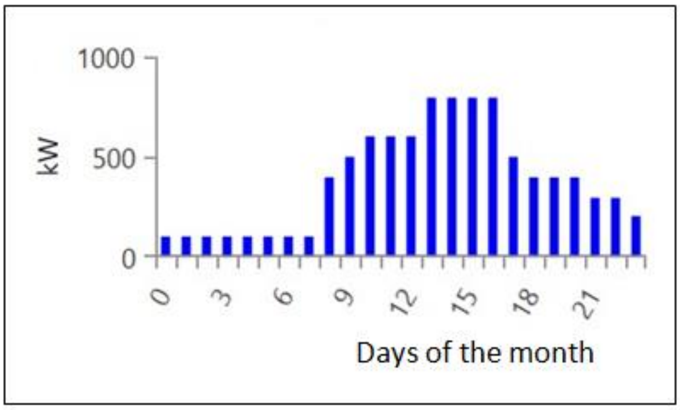


Figure 7(a): Univ. of Abuja's daily load profile

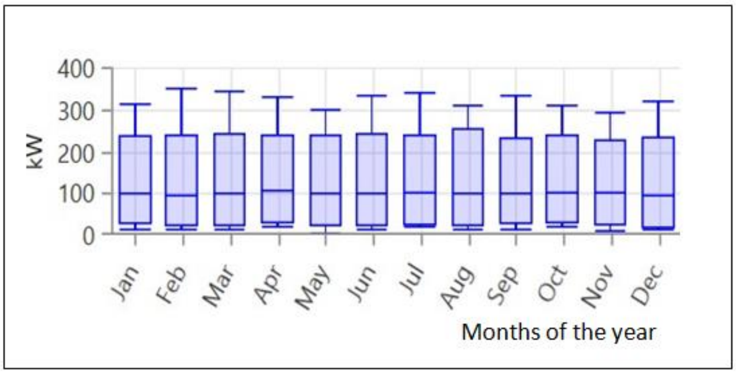


Figure 7 (b): Monthly load profile

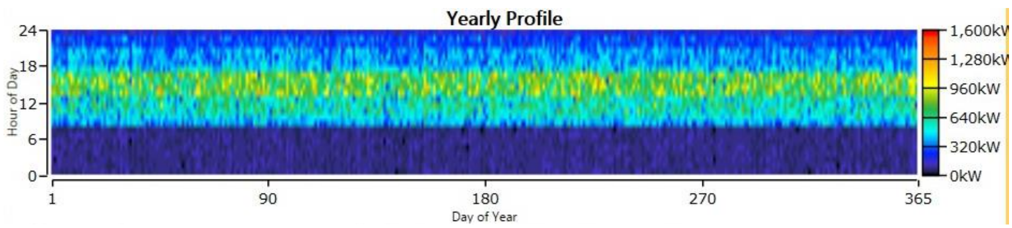


Figure 7 (c): Yearly load profile

The basic indices of the load profile are given in Table 5.

Table 5: Load profile metrics

Metric	Baseline	Scaled

Average daily energy consumption (kWh/day)	9191.4	6,300
Average load capacity (kW)	382.98	262.5
Peak load capacity (kW)	1443.8	989.67
Load factor	0.27	0.27

4.1.3 Component contribution to energy generation of the hybrid system

Individual component contribution to energy generation of the hybrid system is shown in Table 6.

Table 6: Energy generation by system components

Component	**Average utilized (kW)**	**Energy delivered to system (kWh/yr)**	**Percentage (%)**
Mini hydro	566	2,716,800	64.1
Solar PV	250	885,437	24.7
MSW	250	294,634	8.2
Total energy generated (kWh/yr.)		389,6871	97.0
Grid	999,999	108,216 (imported)	3.0
726,854 (exported)	18.7		

4.1.4 Economic analysis

The optimal architecture of the hybrid system has a net present cost of ₦ 9.37 billion ($12,486,120) with the corresponding LCOE being ₦55.2/kWh ($0.0736/kWh). The contribution of each component to total system's total net present cost is shown graphically in Fig. 8.

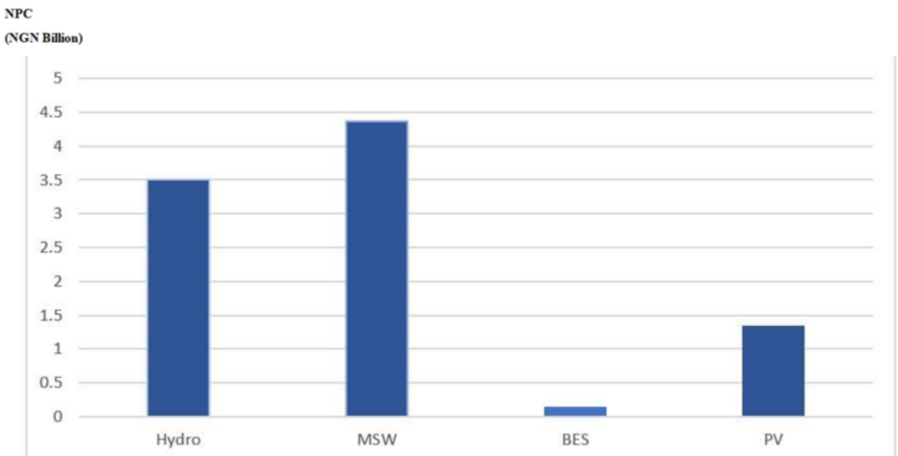


Figure 8: Component contribution to total net present cost (NPC)

Details for economic performance indicators for the optimized architecture and the next best alternative are given in Table 7.

Table 7: Economic performance indicators for the optimized architecture

Ranking	Initial capital (₦ x 10^9)	Operating & maintenance cost (₦ x 10^6/yr.)	NPC (₦ x 0^9)	LCOE ₦/kWh
Optimized architecture	5.44	66.14	9.38	55.20
Next best architecture	4.31	89.54	9.6	61.58

4.1.5 Sensitivity analysis

Sensitivity analysis was carried out on the optimal hybrid architecture to investigate effects of changes to the relevant variables in the operation of the hybrid energy system. The following parameters were used as sensitivity variables in this work: project life span, inflation rate, solar irradiance, MSW's lower heating value (LHV), capacity shortage and the annual average volumetric flow rate of River Wuye. Capacity shortage, in kWh, is the difference between operating capacity required and the actual amount of operating capacity that can be provided by the system.

Using project life as a sensitivity variable and considering 20, 22, 25, 28 and 30 years, HOMER simulated 87,780 solutions, out of which 71,592 were regarded by the system as feasible and 16,188 were considered infeasible due to capacity shortage constraints.

For solar irradiance as the sensitivity variable, HOMER calculated 8,832 simulations out of which 3,864 were feasible and the remaining 4,968 were non-feasible. When the hydro resource average volume flow rate was the sensitivity variable, HOMER performed 14,508 simulations with 11,709 solutions being feasible, while 2,451 were regarded as infeasible due to capacity shortage constraint.

Sensitivity analysis was also performed using inflation rate as the variable. Here, HOMER calculated 1,350 simulations out of which 540 solutions were feasible, while 810 were excluded as infeasible due to the constraint of capacity shortage. HOMER generated 2838 simulations when capacity shortage was used as a sensitivity variable, out of 2,301 were considered as feasible solutions.

4.1.6 Solar irradiance

With solar irradiance as the sensitivity variable, the optimal net present cost was ₦8.41 billion ($11,213,750) while the LCOE was NGN65.55/kWh($0.0874/kWh) for the hybrid system at average irradiance of 5.45 kWh/m^2/day as optimal for a plant life of 25 years as shown in Table 8.

Table 8: Performance of hybrid PV/MSW/Hydro system with varying average solar irradiance

Solar irradiance (kWh/m^2/day)	4.97	5.45	5.50	5.80	6.15
MSW (% energy contribution	11.3	10.5	10.4	9.9	9.45
Photovoltaic array (% energy contribution	22.5	24.2	24.4	25.4	26.4
Hydro (% energy contribution)	66.1	65.3	65.2	64.7	64.1
Battery storage (strings)	5	5	5	5	3
Converter (kW)	97.2	102	103	105	101
Initial capital(₦ X 10^9)	5.44	5.44	5.44	5.44	5.43
Net present cost (₦ X 10^9)	8.4	7.53	9.03	7.98	6.93
Energy generated (kWh x 10^6/Yr.)	3.61	3.66	3.67	3.69	3.73
Levelized cost of energy (LCOE) (₦)	74.33	83.25	58.28	59.33	75.00

4.1.7 Emission to environment

Apart from nuclear fission, every electricity generation technology emits greenhouse gases at some point in their life-cycle. However, energy generation from fossil fuels is responsible for most of the emission of the GHG in the energy sector. Table 9 shows various components of negligible emission to the atmosphere from the simulated HES.

Table 9: Components of emission to the atmosphere from the hybrid plant

Quantity	Value
Carbon dioxide	2,677
Carbon monoxide	3.4
Unburnt hydrocarbons	0
Particulate matter	0
Sulphur dioxide	3.85
Nitrogen oxides	4.22
Total emission	2,688.47

4.2. Discussion

The optimized system architecture for the main campus of the University of Abuja is shown in Fig. 6 with the least net present cost (NPC) of NGN9.38 billion (US$12.5 million) and with the LCOE as NGN55.2/kWh (US$0.0736/kWh). It is also seen from Fig. 6 that the next best option excludes the solar PV modules from the configuration but its NPC is higher than for the optimal architecture at NGN9.6 billion (US$12.8 million) with the LCOE higher at NGN61.58/kWh ($0.0821/kWh), Table 7, and will therefore be uncompetitive in the energy market. Table 10 gives a comparison of performance indicators for the optimal and alternative architectures.

Table 10: Summary of hybrid system comparative performance

Optimization	Initial capital (US$million)	NPC (US$ million)	LCOE ($/kWh)	Emission (Kg/yr.)
Optimal architecture	7.25	12.51	0.0736	2,688.47
Alternative	5.75	12.80	0.0821	20,156.34

As may also be observed from Table 10, the optimized architecture has negligible total emission to atmosphere of only 2,688.47 kg/yr. compared to the other alternative configuration with greatly higher total emissions of 20,156.34 kg/yr.

The daily load profile of the campus as shown in Fig. 7a follows a slightly binomial distribution. From the period 0:00 – 8:00 hrs, the load is about 100 kW, and then increasing from about 100 kW at 8:00 am to about 500 kW at 9:00 and then to a peak of about 900 kW during the period 13:00 – 16:00 hrs and then falling gradually to a value of about 250 kW at around 23:00 hrs. This distribution corresponds to energy supply and consumption pattern in other educational institutions operating within the daily periods of 8:00 - 17:00 hrs [10]. The load capacity factor is also correspondingly low at 0.27, Table 5. The seasonal and yearly profiles show relatively flat distribution curves, as shown in Fig. 7 (b) and 7 (c), respectively.

Individual component contribution to energy generation of the hybrid system is shown in Table 6 with the mini hydro plant contributing the highest at 64.1%, while contribution from the MSW plant is least at 8.2 %. The results of costs of the optimized hybrid system are shown in Table 11 below, using plant lifespan as the sensitivity variable.

Table 11: Hybrid system plant life cost profile

Plant life (yr.)	Initial capital cost (₦ Billion)	O & M cost (₦ Million)	Net present cost (₦ Billion)	LCOE (₦/kWh)
25	5.44	66.14	9.38	55.2
28	5.44	62.68	10.13	47.55
30	5.44	61.72	10.73	43.73

The NPC is least for the optimal architecture for a plant lifespan of 25 years at NGN9.38 billion (US$12.51 million) and highest for a plant life of 30 years. The contribution of each component to total system net present cost is also shown graphically in Fig. 8 for the optimal plant life of 25 years. Operating costs fall within range at about NGN60 Million per annum (US$ 80,000/yr.) for all years of plant life considered in the simulation.

From Table 8, it may be observed that at solar irradiance of 5.45kW/m^2/day gives optimal NPC of ₦ 7.53 billion (US$10.04 million), ignoring average irradiance value of 6.15 kW/m^2/day which is not realizable in Abuja. Individual contribution to energy generation of the hybrid system reduces for all components except the PV power generator which increase with increasing average irradiance.

Sensitivity analysis shows that the hybrid plant gives optimal results when the capacity shortage factor allowed is 0% at the NPC of ₦ 9.55 billion (US$12.73 million). At 10% capacity shortage, HOMER excludes the MSW power generator from the optimized architecture. It was also seen that capacity shortage had no impact on individual component contribution to energy generation by the hybrid system. A capacity shortage factor of 1.5% leads to higher NPC of ₦ 13.92 billion (US$18.57 million), while energy generation remains fairly same for all capacity shortage factors considered.

The hydro component contribution to energy generated by the hybrid system increases with increasing average flow rate of the river being used to harness the energy. However, average flow rate of 8500 lit./s gives the optimal NPC of ₦ 9.18 billion ($12.24 million) with corresponding LCOE of ₦58.43/kWh ($0.0779/kWh).

Sensitivity analysis revealed that inflation rates do not affect individual component performance. However, 20.5% inflation rate in Nigeria gives optimal results for the hybrid energy system, with NPC being ₦ 9.11 billion (US$12.15 million). Sensitivity analysis revealed that LCOE decreases with increasing inflation rate as depicted in Fig. 9. This compares well with results obtained by Xing et al, 2021 [25].

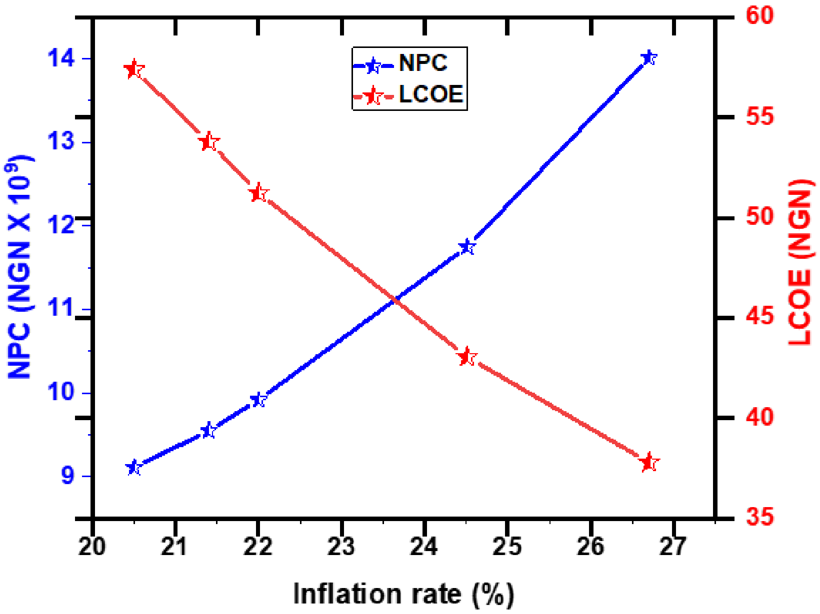


Figure 9: Variation of hybrid plant NPC and LCOE with inflation rate

All parameters taken together indicate that LCOE of ₦55.20/kWh ($0.0736/kWh) for the optimal hybrid system architecture developed is much lower than values obtained by other researchers in HES. In an optimization work on PV/Biomass/Wind turbine hybrid system, Tabak et al, 2019, obtained LCOE of $0.2551/kWh as optimal [26]. Another study by Zebra et al achieved an LCOE of $0.77/kWh [27].

4.2.1 Emission from the optimized hybrid system

Considering CO_2 as the main component of emission, 2,677 kg CO_2/annum obtained for the 2 MW HES plant simulated with a daily energy generation of 10,676.34 kWh translates to 250.66 kg CO_2/MWh. An equivalent gas turbine has an average emission of CO_2 is 644.9 kg/MWh [28], while a 3 MW steam power plant emits about 3,677.27 kg CO_2/MWh when running on natural gas and 6,624.26 kg CO_2/MWh when coal fired [29]. Carbon dioxide emission rate of 2,677 kg/annum gives a daily emission of 7.33 kgCO_2/day. It is therefore seen that the hybrid energy system has almost net zero emission to the atmosphere and is therefore very environmentally friendly.

5. CONCLUSION

The 2 MW capacity simulated and optimized hybrid waste-to-electricity/photovoltaic/hydro system, aimed at reducing carbon emission from the use of Abuja's MSW for electricity generation revealed that the optimised hybrid architecture has potential to generate 3,896,871 kWh per annum while emitting only 7.33 kgCO_2/day which is close to net zero carbon emission. The hybrid plant with initial investment cost of ₦5.44 billion (US$ 7.25 million) and a net present cost (NPC) of ₦9.38 billion (US$12.51 million).The levelized cost of energy(LCOE) of the project was determined to be₦55.20/kWh (US$0.0736/kWh) indicates that energy from hybrid system is much cheaper than electric energy from the Nigerian grid which was sold at about N82/kWh in 2023, in addition to it being more environmentally friendly. Sensitivity analysis showed that the hybrid system will give optimal performance at the average annual flow rate of 8500 lit/s for Wuye River, average irradiance of 5.45 kWh/m^2 per day and the average annual inflation rate of 21.4%.

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