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Optimal Design And Cost Analysis of Hybrid Autonomous Distributed Generation System For a Critical Load

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Abstract

One of the universal targets of the United Nations Sustainable Development Goals is affordable and clean energy. It is on this premise that this study presents the integration of PV-wind distributed generation system into an existing diesel generator powered water treatment plant in a suburban town of Wudil, Nigeria. Inadequate and epileptic supply from the grid caused the dependence of the plant on the generator. The optimal design was determined using the Hybrid Optimization of Multiple Energy Resources (HOMER) software developed by the National Renewable Energy Laboratory. Simulation results produce an optimal hybrid system which includes photovoltaic (PV) panels, wind turbines, converter, batteries and a generator with a cost of energy of $0.26 at a renewable fraction of 95%. An analysis also demonstrates that implementing this design will result in low and fairly constant fuel price in the lifecycle of the project. This will, in turn, support sustainable economic development of communities served by the water treatment plant.

Keywords: Distributed Generation, Net Present Cost, Optimization, Renewable Energy, Sustainable Development.

1. INTRODUCTION

Adequate electricity is a panacea for sustainable human and economic development of any nation. However, increased socio-economic activities resulting from the growing population without commensurate increase in power generation has made provision of adequate electricity from conventional sources challenging; particularly for developing countries like Nigeria. Volatility in the price of oil and transmission line expansion cost [1] have further increased the pressure on conventional methods of power generation. Policy change proposed by governments and regulators of electricity industry to address the problem include diversification of generation mix to include large scale renewable energy and deregulation of the electricity market. Distributed generation (DG) or distributed energy resource (DER) is one of the fallout of the institutional change that characterizes the deregulation of the electric power sector. This has brought about improved security of supply and efficiency in the operations of electric power systems. In addition, environmental concerns have also made the adoption of this method of generation inevitable since some of the technologies are based on renewable energy.

For developing countries of the world with modest potentials for renewable energy, issues of inadequate power supply to meet the increasing load demand have decreased their dependence on conventional methods of power generation. This has lead to increased investment in power generation from renewable energy sources (RES). Amongst all renewable energy forms of DGs available today, solar photovoltaic (PV) and wind systems have proved to be the more acceptable [2]. While this is largely due to the technological advancements and reduced cost over the years, a major challenge still remains the intermittent nature of these resources.

The idea of DG is to generate electricity down stream of the traditional generating station in order to improve the security of supply for electricity to consumers and the idea of integration of renewable energy sources (RES) in DG is related to sustainability. The significance of sustainability received a boost recently with the signing of the Paris climate accord and the lunch of the Sustainable Development Goals (SDGs) by the United Nations Development Programme (UNDP). Part of these universal goals includes affordable and clean energy to meet the urgent environmental, political and economic challenges facing our world.

2. RELATED WORKS

A number of researchers have worked on the design and application of DGs for various locations using RES as demonstrated by [3]-[7]. The effect of environmental emissions was considered in the optimal design and operation of a RES based micro grid by [1]. A diesel-renewable mixed combination was the optimal design due to the low net present cost (NPC), however, small amount of carbon foot print was noticeable. [8] investigated the impact of the RES resources, load level and fuel prices on the optimal design of a distributed generation systems. [9] demonstrated the use of multiple DG technologies to determine the optimal size of a hybrid power system. The optimal design was a PV/Wind/Battery system and PV/Wind/Battery/Fuel Cell system based on the low net present cost (NPC) and levelized cost of energy (LCOE) when compared with other combinations of DGs. The integration of PV-wind system into an existing diesel generator for a site which is connected to the grid is discussed in [10]. The integration of various RES technologies in remote areas to improve the standard of living of rural communities especially for developing countries is presented in [11]-[14].

An optimal combination of hybrid RES for an off-grid remote village was proposed by [15]. Results obtained reveals that extending the grid to such location is a more expensive alternative to using RES generators that is sustainable and techno-economically viable. In this research, the application of multiple DG system is implemented while considering the SDG of UNDP.

3. ORIGINALITY

While quite a number of researchers have worked on the optimal design of different combination of DG technologies for residential, rural and commercial areas, few studies like [16] have examined the application of hybrid renewable energy on a critical load that could affect the sustainable development of the world and developing countries in particular. Hence, the need to understand how RES based DGs will perform in supporting an off grid water treatment plant.

Therefore, the object of this study is to combine the SDG goals 6 (clean water and sanitation) and 7 (affordable and clean energy) by investigating an optimized hybrid (PV-Wind) renewable power generation system for a water treatment plant. The Hybrid Optimization of Multiple Energy Resources (HOMER) software [17]-[22] is used to design and analyze which of the hybrid system configurations could be the most economical and sustainable to power the plant. This research is unique because it captures the need to meet the UNDP sustainable developments goals in a developing country like Nigeria.

4. SYSTEM DESIGN

4.1 Study System

The case study is a critical water treatment plant (WTP) located in the semi-urban town of Wudil, Kano state; in northern Nigeria. This WTP is critical because it supplies a population of about 200,000 (mostly rural) people spread across 4 local councils with portable water for domestic use in homes, small scale commercial enterprises and public institution (schools and health centres). It has however been established by [23] that a major contributory factor to the sub-optimal performance of Wudil WTP (WWTP) is the inadequate and inconsistent power supply from the national grid. For this reason, the plant been disconnected from the grid, with a total reliance on a backup diesel generator which is operational for a maximum of 15 hours daily. Even at that, WWTP continues to suffer from various challenges ranging from the high cost of diesel, unscheduled downtime due to maintenance of the generator, maintenance of damaged pumps etc. All these have resulted in the inefficient operation of the plant and hence the high operating cost. WWTP is located at about 45km from the city of Kano on the banks of river Hadejia as seen from the location map of figure 1. It has a total of 15 tube wells (9 operational) of 250mm in diameter along with the associated collector piping.

The key energy users within the facility are the water pumping systems e.g. submersible pumps in the tube wells, chlorine pump and high lift pumps for consumer supply. Table 1 provides a summary of major equipment and estimated daily operational hours.

Figure 1. Map showing the location of WWTP

Table 1. Equipment details of WWTP

S/No	Equipment Description	Equipment Load (kW)	Est. Operational Hours (Hrs/day)
1	High lift pumps (4 Units):		
	Kano line	110	10
	Wudil line	90	10
	Gaya line	200	8
	Indabo/Dagumawa/Utai/Lajuwa line	132	8
2	Chlorine pump	1.5	15
3	Submersible pumps for tube wells (15 units):		
	11 kW (9 nos)	99	15
	7.5 kW (6 nos)	67.5	15
4	Estimated lighting load	6	-
5	Estimated small power load	15	-
Total (Peak)		**721**	

4.2 Renewable Energy Resource Potential at Wudil

The foundation necessary for the hybrid RES based DG system is the availability of the required resources that will cause the PV-Wind system to supply the load at the WTP. These resources include the wind speed variation and the average solar isolation. For the WWTP with geographical coordinates of 11.7942° N, 8.8390° E at an elevation of 419 m above sea level, the wind speed and solar isolation data were obtained from NASA surface meteorology and solar energy website. The average monthly solar radiation is shown in Figure 2. It varies from minimum of 5.219kWh/m^2/day to a maximum of 6.365kWh/m^2/day with an annual average radiation of 5.901kWh/m^2/day. Figure 3 represents the monthly wind speed variation with an annual average of 5.861m/s.

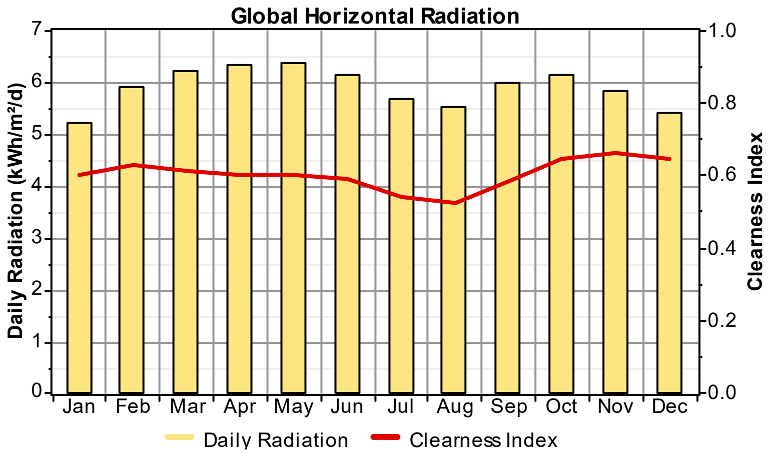

Figure 2. Average monthly solar radiation for Wudil

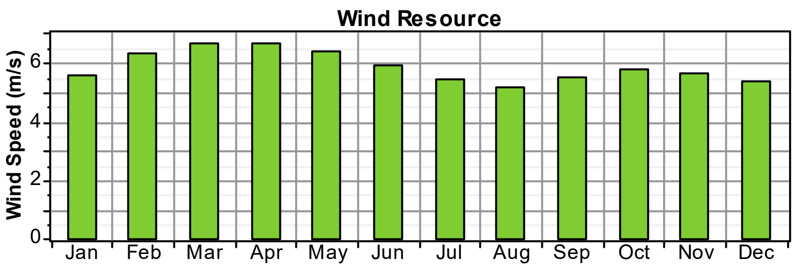

Figure 3. Average monthly wind speed for Wudil

4.3 Hybrid System Component Design

The DG technologies considered in this autonomous hybrid system design are solar PV array, battery-converter system, wind turbines and generator. Figure 4 illustrates the schematic of the system setup in HOMER.

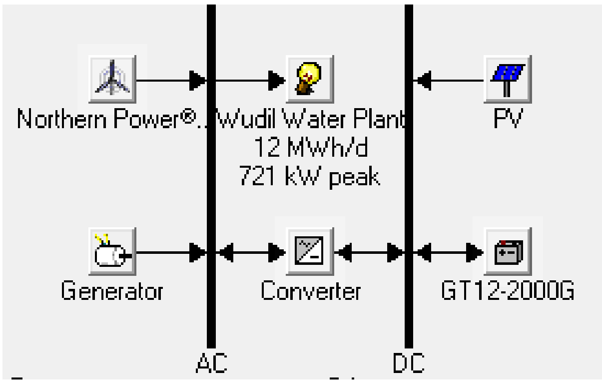

Figure 4. Autonomous Hybrid system in HOMER

4.3.1 PV System

Taking into consideration the average temperature of the site of about 40°C, a polycrystalline silicon PV module manufactured by Yingli solar is chosen. Some of the specifications of the PV module include a peak power of 250Wp at a voltage of 29.8V and a short circuit current of 8.92A with module efficiency of 15.3% at standard test conditions. The PV panels used cost $1400/kW including the cost of charge controller since HOMER does not model charge controller separately. The PV module have 80% power output by a lifetime of 25 years, showing that they will almost certainly last longer than that. For the battery bank, Gaston GT12-2000G (2V, 2000AH) with gel electrolyte technologies was chosen for this design.

4.3.2 Wind Turbine

A wind turbine is integrated in the design to ensure a possibility of continuous energy production during cloudy condition and at some point in the night when energy output from PV system is zero/low. Based on the wind data obtained for the location, a wind turbine whose output characteristic would match the wind data was chosen. Hence, a Northern Power®, 100C-24, 100kW AC, wind turbine is chosen. With a rotor diameter of 21.5m and hub height of 35m, the cut-in speed for this wind turbine is about 3m/s as illustrated by the power curve shown in Figure 5.

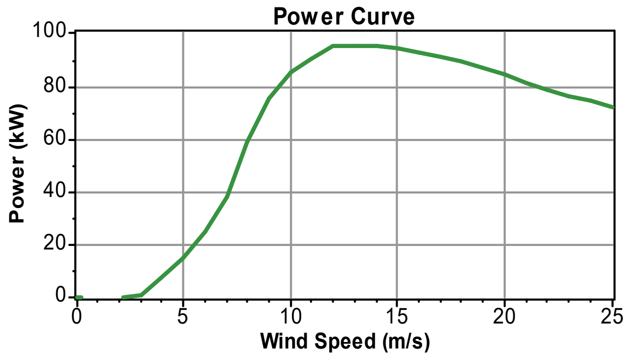

Figure 5. Power curve for Northern Power® 100C-24 wind turbine.

4.3.3 Generator

Primarily, this study is trying to eliminate/reduce the use of the existing 1320kW generator at the plant to ensure system sustainability by using RES. The diesel generator at WWTP is used as a backup system to compliment the supply from the grid. However, due to poor and inadequate supply from the grid it has become the norm for the WWTP to be powered solely by the diesel generator. This has resulted in the high cost of running the plant due to the increasing price of diesel fuel and high number of maintenance routine. However, the intermittent nature of PV and wind energy means that the generator will be necessary in periods with low renewable energy output or schedule downtime of the hybrid RES DG system.

4.3.4 Load Estimation

Due to the poor power supply from the national grid leading to the disconnection of the WTP from the grid, a 24hr load profile for the plant was not available. However, the operational schedule of the plant shows that it currently operates for a maximum of 15hrs daily with some equipments working for less. A 24hr load profile was developed from the data obtained from Table 1 by applying load factors to the equipment and scaling the hourly load demand on the maximum demand. The resulting profile gives energy consumption of 12,000 kWh/day with 721 kW peak demand. Figure 6 illustrates the load profile used in this study. Water demand is higher during the dry season from November to March with considerable drop at the peak of the rainy season between May and September.

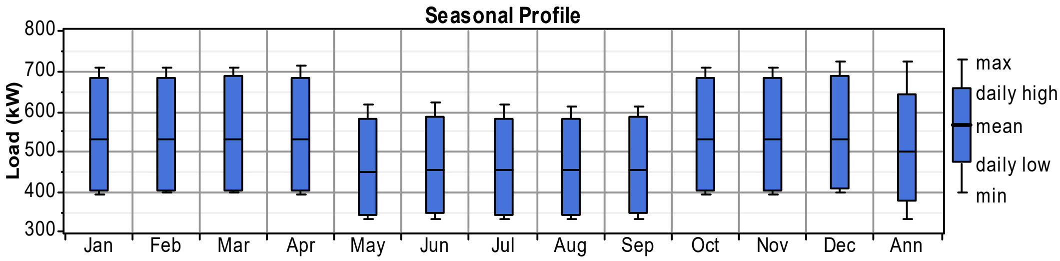

Figure 6. Average monthly load profile

4.4 System Simulations and Optimization

This system design is implemented using the HOMER software. HOMER is a micro-power optimization tool used to evaluate designs options for DG units, grid connected and autonomous power systems. It accepts techno-economic parameters such as sizes of PV panels, wind turbines, converters/batteries system, solar irradiation, wind speed, load demand, fuel price/cost of renewable energy components, etc as input. The optimization process follows an economic algorithm which use these input parameters in its search space to determine the optimal system design by minimizing the net present cost (NPC). NPC is made up of system life-cycle cost and the present value of all the accruable revenue which includes capital cost, replacement cost, operation and maintenance cost, fuel cost, and salvage value using a discounted rate to calculate future cash-flows. In addition, the optimal solution ensures that the energy demand of the system is satisfied with the least possible NPC. The optimization results also provide a list of different system configuration arranged in increasing order of Cost of Energy (COE) for every optimized system. The COE is the average cost of a unit of energy generated by the system. The NPC and COE is calculated in HOMER as follows:

$$C_{NPC}=\frac{C_{ann,\,tot}}{CRF(i,R_{proj})} \quad (1)$$

$$COE=\frac{C_{ann,\,tot}}{E_{served}} \quad (2)$$

Where E_{served} is the total energy served by the system, R_{proj} is the project lifetime in years. $C_{ann,tot}$ is the total annualized cost and CRF is the capital recovery factor given by

$$C_{ann,\,tot}=C_{cap}+C_{rep}+C_{O\$M}+C_{fuel} \quad (3)$$

$$CRF(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \qquad (4)$$

Where C_{cap}, C_{rep}, $C_{O\&M}$, *and* C_{fuel}, is the capital cost, replacement cost, operation and maintenance cost and fuel cost in \$/yr respectively, *i* is the interest rate, and *N* is the number of years.

The technical input parameters for this study are presented in Table 2. In addition, input constraints for the system include a maximum annual capacity shortage of 2%, 10% operating reserve for the hourly load along with a 50% of the solar and wind power output. For the economic parameter, the annual interest rate of 14% provided by the Central Bank of Nigeria was applied. Table 3 shows the cost input parameters.

Table 2. Technical parameters for the DG units

System Components	Components Size/Number of units to consider	Lifetime
PV Array (kW)	600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2100, 2200, 2300, 2400	25yrs
Wind (Nos.)	1, 2, 3, 4	20yrs
Generator (kW)	1320	15000hrs
Battery (Strings)	10, 14, 18, 22, 26, 30, 32, 34, 36, 38, 40	15yrs
Converter (kW)	400, 600, 800, 1200, 1400, 1600	15yrs

Table 3. Economic parameters for the DG units

System Components	PV Array	Wind	Generator	Battery	Converter
Size (kW)	1	100	1,320	4	100
Capital (\$)	1,400	350,00	0	575	30,500
Replacement (\$)	1,400	350,000	32,000	575	30,500
O&M	\$0/yr	\$10,000/yr	\$0.5/h	\$5/yr	\$0/yr

HOMER takes into consideration all the input parameters and a set of defined constraints to arrive at the optimal solution. Figure 7 Illustrate this process.

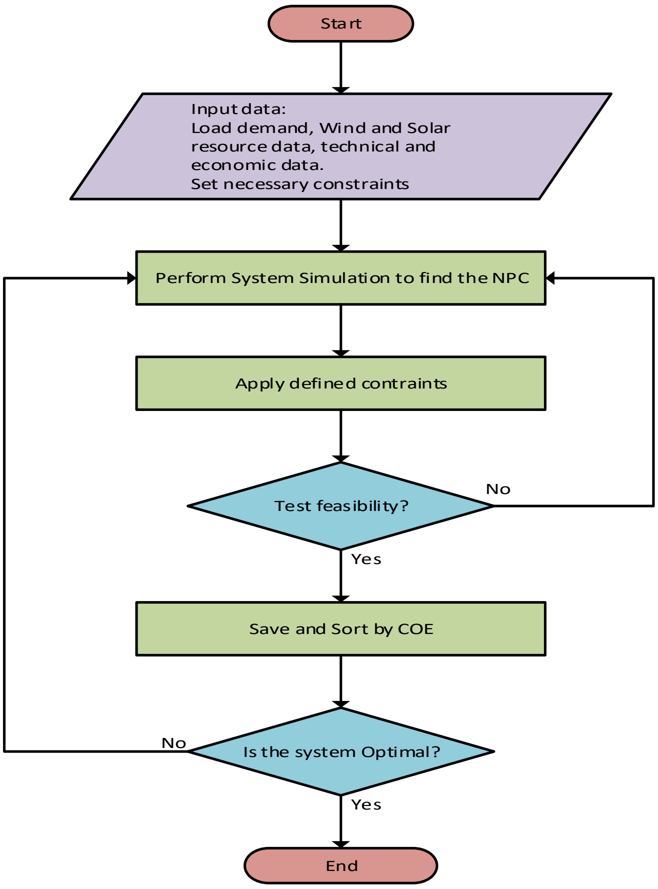

Figure 7. Optimization process within HOMER

5. EXPERIMENT AND ANALYSIS

Simulations carried out in HOMER with the parameters described in section 4.4 produced an optimal hybrid design employing the existing 1320kW diesel generator along with PV system rated at 2100kW, 4 wind turbines at 100kW each and 800kW converter with 3600 battery. Table 4 shows the results of the simulation of the optimal design with a net present cost NPC of $ 7,787,078.

Table 4. Optimal system design

Components	Optimal Design
PV (kW)	2100
Wind	4
Generator (kW)	1320
Battery	3600
Converter (kW)	800
Initial capital	$ 6,654,000

Operating cost ($/yr)	$164,861
Total NPC	$ 7,787,078
COE ($/kWh)	0.26
Renewable fraction	0.95

A significant deduction is that the hybrid RES system provides the bulk of the energy requirement of the WTP which is the primary aim of this study. In addition, the low energy contribution from the generator will ensure that the generator has prolonged use since its exposure to frequent breakdown and maintenance routine will be minimal.

A breakdown of the total cost of each component is shown in Table 5. It is evident that the PV system and battery units carry the bulk share of the total cost at $2,940,000 and $2,412,984 respectively.

Table 5. NPC of the DG system

Component	Capital ($)	Replace-ment ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	2,940,000	0	0	0	0	2,940,000
Wind	1,400,000	101,866	274,917	0	-39,680	1,737,104
Generator	0	0	801	421,819	-740	421,880
Battery	2,070,000	253,661	123,713	0	-34,390	2,412,984
Converter	244,000	34,184	0	0	-3,074	275,110
System	6,654,000	389,711	399,430	421,819	-77,883	7,787,078

A significant deduction is that the hybrid RES system provides the bulk of the energy requirement of the WTP which is the primary aim of this study. In addition, the low energy contribution from the generator will ensure that the generator has prolonged use since its exposure to frequent breakdown and maintenance routine will be minimal.

Table 6 shows energy output of components of the hybrid system indicating that the load of WWTP is met by 70% contribution from PV system with 25% addition from wind turbines while the generator supplies the balance of 5% of the total kWh generation per year. This ensures that RES components supply the bulk of the energy demand of the plant as initially planned which ensures sustainability of the design. The monthly average electricity production and excess energy production from the system is illustrated in Figure 8 and Figure 9 respectively. It is noted from Figure 9 that excess energy production is dominant in the months of February, May, June and September due to the combined effect of high solar radiation, wind speed and load demand experienced in these months. Consequently, the state of charge of the batteries during this period is maintained at a state of charge higher than 85% as shown in Figure 10. It shows a time series, average hourly value of the energy content of the batteries over a period of 12 months. During this period, the batteries received an energy input of 2,128,977kWh/yr and gave an energy output of 1,845,184kWh/yr causing a lifespan of 16 years for the storage system.

Table 6. Energy output of the hybrid DG system

Production	kWh/yr	%
PV array	3,691,483	70
Wind turbines	1,322,789	25
Generator	279,267	5
Total	**5,293,539**	**100**

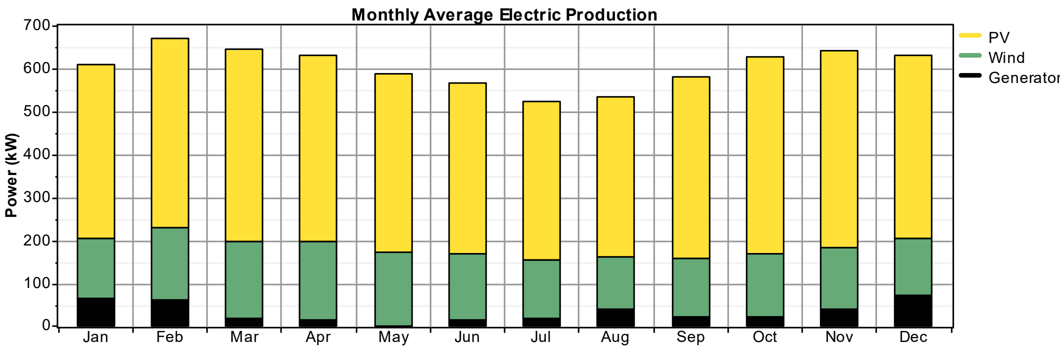

Figure 8. Monthly electricity production of the hybrid DG system

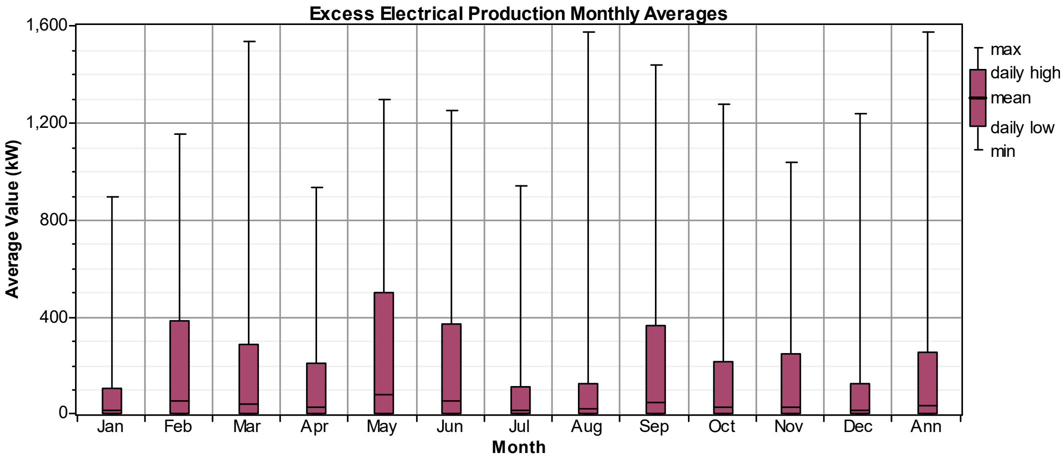

Figure 9. Average monthly excess energy production

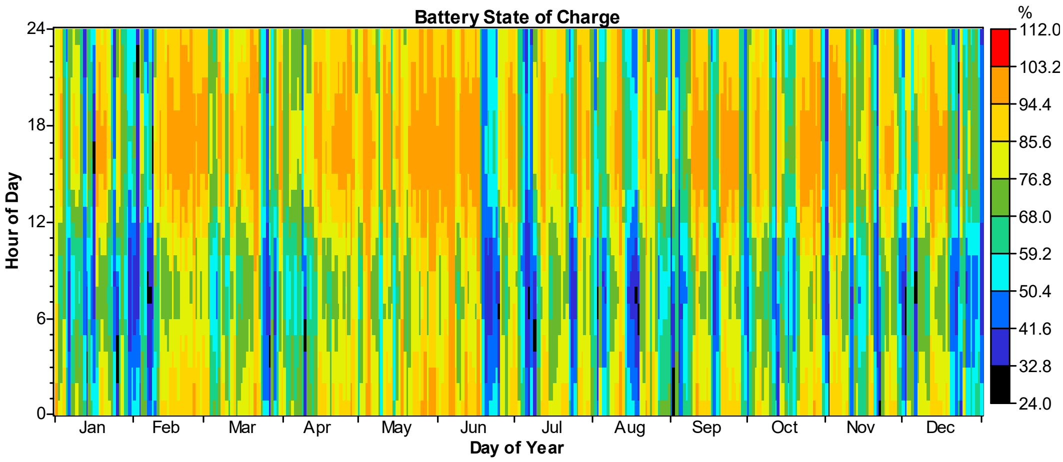

Figure 10. Average monthly state of charge (SOC) of the batteries

The cash flow during the lifecycle of the project shows that operation and maintenance cost is fairly constant in the years following the initial capital investment, until after the year 16 when some components are replaced. This operation and maintenance cost arises from the diesel generator fuelling as presented in Figure 11.

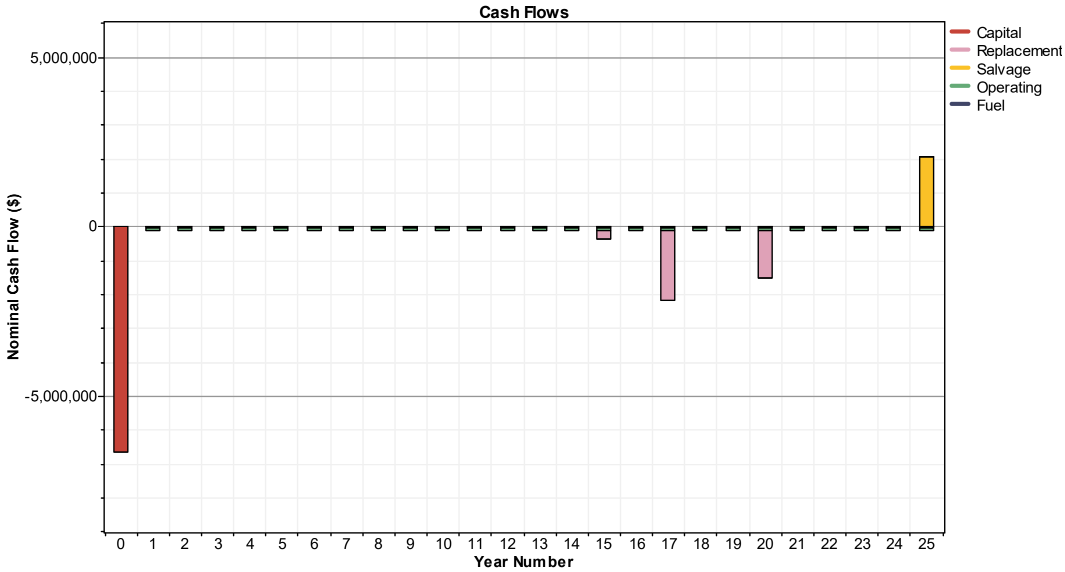

Figure 11. Cash flow from the optimal hybrid system

6. CONCLUSION

In this study, a hybrid solar PV-wind DG system was integrated with a diesel generator for the water treatment plant at Wudil using the HOMER software. The optimal design included solar PV, wind, batteries and converter system. The significant findings based on the results of the simulation include:

- The optimal system configuration after simulations proposed a system with 2100kW PV system, 4 wind turbines at 100kW each, 800kW converter with 3600 battery. This is in addition to the existing 1320kW backup diesel generator.
- The system has a total NPC of $7,787,078, an initial capital cost of $6,654,000 and operating cost per annum of $164,861. The renewable energy fraction is 95% at a cost of energy of $0.260 per kWh.
- Although the renewable energy fraction is high, the intermittent nature of the system makes it undispatchable. Hence, the need to use the existing diesel generator when output is low from the PV-wind hybrid system.
- An analysis of the lifecycle of the project also reveals that except for the replacement of the batteries and wing turbines by 17 years and 20years respectively, the system operating cost is fairly constant after the initial capital cost.

If recent climate change issues and current trend in crude oil prices is anything to go by, the cost of diesel will continue to be a source of increased operating cost of the system. In addition, it is expected that the continuous improvements in renewable energy DG technologies will sustain the fall in the cost of the system. When such system is applied to critical infrastructure like water treatment plant as conducted in this research, sustainable development for nations is ensured. This is even more important for developing countries like Nigeria with modest potential for RES.

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