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Hybrid Power System for a Fuel Station Considering Temperature Coefficient

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ABSTRACT

It is crystal clear that appropriate technical sizing has a significant effect on the techno-economic analysis of an off-grid standalone energy system. As a result, this study presents the effect of incorporating the temperature coefficient in the optimal analysis of an off-grid hybrid system using a standard fuel (gas) station in Nigeria as a case study. Comparative analysis with and without the temperature coefficient was performed. The results showed that the inclusion of temperature coefficient leads to extra operation hours of the generator which will result in an increase in fuel consumption and annual operation cost of the diesel generator. Also, the initial cost of the PV/BAT/diesel is relatively higher than the diesel generator but, the generating emission of the hybrid system is lower when compared to the diesel-only which enhances the atmospheric condition of the society.

Keywords: Techno-economic Analysis, Hybrid System, Temperature Coefficient, Fuel Consumption
JEL Classifications: Q4, Q43

1. INTRODUCTION

The increase in population size and rapid urbanization growth across the globe have constrained the public to often depend on the use of fossil fuels as a conventional source of power generation. This, however, does not come without some environmental pollutions with negative consequences on society. Recent studies have attributed the use of fossil fuels as one of the contributors to the alarming climate change and have lately gained significant attention of researchers (Owusu et al., 2016). Over time, in developing countries, and Africa in particular, unreliable power supply is a serious challenge that has overwhelmed the continent, which is neither evenly distributed nor readily available to some inhabitants (Oyedepo, 2012a). More so, depletion of fossil fuels resources calls for promising alternatives and environmentally friendly energy resources. Remarkably, renewable energy sources are freely available in Africa continent, and Nigeria, in particular, considering her positioning on the equator (Oyedepo, 2012b; Shaaban and Petinrin, 2014). Therefore, exploring and utilizing these renewable energy resources are necessary and, have the tendency of improving energy availability, increasing energy stability and even positioned to mitigate the environmental threat posed by the use fossil fuels and, should be considered.

Despite the numerous advantages and positive prospects associated with renewable energy resources, its major setback remains over-reliance on meteorological conditions, which changes from one location to another and, even, time to time. Interestingly, this can be overawed by integrating some of these resources with conventional systems where the strength of one energy source will complement the weakness of another. For instance, a PV/wind/hydro/diesel/battery hybrid system has a promising trend of providing a reliable energy supply with a cost-effective and less polluted environment. This, however, requires appropriate optimum sizing and components configuration. Consequently, several researchers have considered and, developed hybrid energy systems and established the fact that it can substantially enhance power system stability. In addition, it is liable to overcome the deficiencies of the stand-alone renewable energy system and, can significantly mitigate the environmental pollutions peculiar to the conventional fossil fuels energy generation. For instance, Asrari et al., 2012 designed a hybrid energy system for a remote community in the Northern part of Iran. The results of their study demonstrated the viability of the system in term of techno-economic and environmental benefits. Güler et al., 2013 investigated and discussed the analysis of four different circumstances of the designed hybrid energy system for a hotel facility using HOMER software. Li et al., 2013 reported the feasibility analysis of a hybrid system developed for family use in Northern, China. Fazelpour et al., 2014 presented the viability of powering the public facility in the Southern part of Iran with the utilization of solar and wind energy. Although, the simulation results exhibited that diesel-battery system was more economical, however, wind-diesel-battery hybrid system attained a significant 14% reduction in emissions of carbon dioxide when compared to the former.

Analysis of economic sustainability of PV/wind/generator hybrid system designed for a rural area of Southern Ghana was reported by Adaramola et al., 2014, considering the economical aspect using HOMER simulation software. Olatomiwa et al., 2015 discussed a PV/diesel/battery hybrid energy system with a focus on the six geo-political regions, in Nigeria. The results of their investigations showed improved fuel consumption and reduced carbon dioxide emissions. The authors in (Amutha and Rajini, 2016) evaluated the house-hold usage, industrial and farmland energy consumption in a typical rural settlement in Southern, India. The authors configured a PV/wind/hydro/battery hybrid energy formulation using HOMER software. The results of their investigation showed the techno-economic benefits and minimized carbon dioxide emissions when compared to the grid supply. Samson et al., 2019 reported the comparison of powering a space research laboratory with diesel and hybrid energy system with latter exhibited a techno-economic and environmental advantages over diesel generator only.

Babatunde et al., 2018 designed a PV/wind/battery system for powering rural health centres in Nigeria. The results showed the techno-economic viability of the hybrid system and its environmental benefits. Application of the hybrid system has also been found useful in the agricultural sector, (Babatunde et al., 2019) and the public lighting system (Babatunde et al., 2019). Although, several studies (Adaramola et al., 2014; Amutha and Rajini, 2016; Asrari et al., 2012; Babatunde et al., 2018; Li et al., 2013; Olatomiwa et al., 2015; Samson et al., 2019) have shown various utilization of hybrid renewable energy resources for both private and public applications. Still, there is no record of its application for gas stations which are predominantly operating on fossil fuels power generation, especially in Nigeria, due to the unreliable power supply peculiar to the developing countries. As a contribution to the studies carried out on the analysis and adoption of renewable energy systems in developing countries, this study presents a techno-economic and environmental viability analysis of powering a gas station with HRES with a specific focus on sub-Sahara. Factors such as temperature coefficient of the panel, ambient temperature, and configuration of installation affect the yield of a PV installation. Usually, the power output and efficiency of a PV solar panel are dependent on the temperature because an increase in the temperature of a PV solar panel decreases its efficiency and power output. In order to elucidate the need of considering the effects of temperature on the optimal configuration of HRES needed to serve the target load, this study compares the results of sizing with and without temperature coefficient. The remaining part of the paper is prepared as follows: Section 2 presents the case study and methodology approach. Results and discussions are provided in Section 3, while conclusions are highlighted in Section 4.

2. CASE STUDY

The selected gas station presented as a case study is located in Maiduguri, in Northern Nigeria. The technical evaluation of the work was based on the assessment of the solar energy potentials of the study area. In Nigeria, in particular, the majority of vehicles are either powered by the premium motor spirit (PMS) or automotive gas oil (AGO) popularly called diesel (Ogunlowo et al., 2015). As a result, gas stations usually operate for about 12 h daily (7:00 am to 7:00 pm [GMT+1]) due to demand from the vehicle owners and operators. Therefore, for effective operations of gas stations, fossil fuels powered generators are mostly employed to curb the incessant power failure. The 12 h operations of this power supply approach has a significant contribution to the growing climate change and constitute a challenge that must be addressed. In order to bridge the identified research gaps, and to minimise its negative consequences on the environment, this study proposes the use of hybrid energy system to power a gas station using, Nigeria, a sub-Saharan Africa. The study employs HOMER software to simulate and derive optimum configuration of components for the case under review.

3. METHODOLOGY

The methodology employed for this study is presented in this section.

3.1. Technical

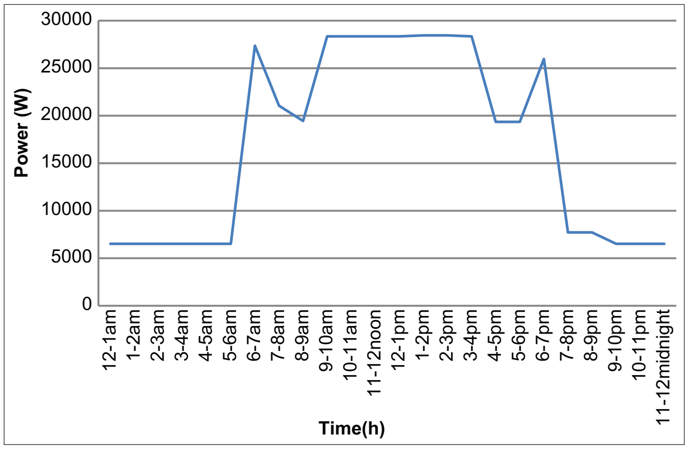
The energy demand of the Nigerian National Petroleum Corporation (NNPC) Mega gas station, Maiduguri is used in this study. The demand profile is depicted in Figure 1, which was calculated based on the estimation of various equipment and appliances used daily. Majority of the appliances operates during business hours (7:00 am-7:00 pm), while only the security and refrigerators will work at nights. A sharp drop observed between 8:00 am-9:00 am and 4:00 pm-6:00 pm may be due to low patronage during these hours- some of the fuel nozzles are not working.

3.2. Photovoltaic Generator Model

The output from a PV solar panel can be obtained using the mathematical expression given in equation 1 (Bhakta and Mukherjee, 2016; LLC, 2009; Olatomiwa et al., 2016).

$$P_o = P_m \times D_r \left(\frac{G_i}{G_{STC}} \right) \times \left[1 + \alpha_p \left(T_c - T_{c,STC} \right) \right] \quad (1)$$

Figure 1: Load profile of the gas station



$$T_c = T_a + G_i\left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_r}\right) \quad (2)$$

P_m is the rated output of the module in kW, D_r is the derating factor of the PV module, G_i is solar irradiance of the site under consideration rated in kW/m^2, G_{STC} is the solar irradiance at standard condition. The PV module temperature coefficient is α_p, while the temperature of the module and the temperature at standard conditions are T_c, $T_{c,STC}$ respectively. T_a is the ambient temperature, $T_{c,NOCT}$ is the rated module temperature with a value ranging between 45°C and 47°C, $T_{a,NOCT}$ is the ambient temperature at a nominal temperature of 20°C with a solar irradiance G_r of 0.8 kW/m^2.

In order to include the temperature coefficient in the design of the energy system, the monthly temperature is important. The average minimum and maximum monthly temperatures for Maiduguri are given in Figure 2. The highest temperature is experienced in the month of April (40°C) while the minimum temperature occurs in January (16°C).

The technical details of the components adapted from (Babatunde et al., 2018) are presented in Table 1.

3.3. Battery Bank Capacity Model

Since the solar resource will not be available at night, it is essential that the energy is stored and used at times of insufficiency. In this case, a deep cycle battery is proposed. The rating of the battery bank is obtained using equation 3 (Babatunde et al., 2018). For the case study, the maximum DOD is taken as 40%. This will extend the life span of the battery bank.

$$B_c = \frac{LD \times A_d}{\eta_e \times DoD \times V_s} \quad (3)$$

Where LD, is the energy demand in kWh, A_d is the autonomy, η_e is the round-trip efficiency of the battery, DoD is the depth of discharge and V_s is the rated voltage of the system.

Figure 2: Average minimum and maximum monthly temperatures for Maiduguri

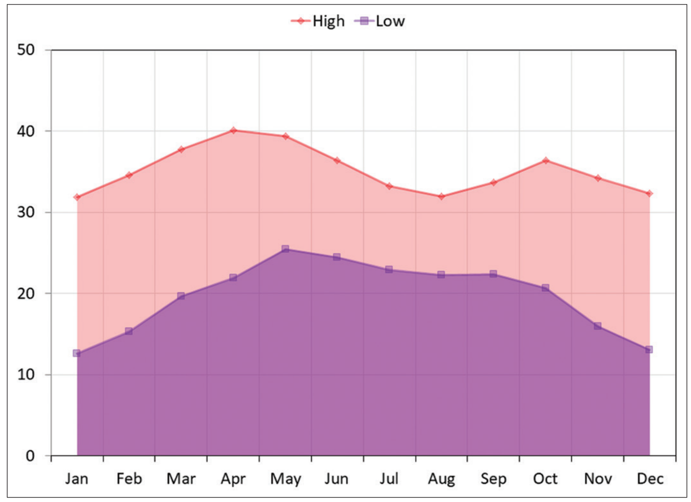


Table 1: The technical details of the components adapted from (Babatunde et al., 2018)

PV	
Parameter	**Value**
Open-circuit voltage	–176.6
Maximum power voltage	54.7
Short-circuit current	6.46
Maximum power rating	327
Maximum power current	5.98
Panel efficiency (%)	20.1
Maximum system voltage (VDC)	600
Cell efficiency (%)	22.55
Power temperature coefficient (^{0}/K)	-0.38
Battery	
Rating	4 V, 600 Ah
Round-trip efficiency (%)	86
Minimum state of charge (%)	40
Diesel generator	
Operational life	15,000 h
Minimum load ratio (%)	30
Generator fuel curve slope (liter/kWh)	0.25

3.4. Diesel Generator

In times of insufficiency of the solar resource, diesel generators are used in supporting the load and charging the battery bank. Best practices require that fossil generators are sized so that they can support the peak load (Schmitt et al., 2003). The quantity of fuel usage for a typical diesel generating set is estimated using equation (LLC, 2009).

$$DG_{cr} = (X.P_g) + (Y.P_{ng}) \quad (4)$$

Where P_g, is the instantaneous power from the diesel generator, P_{ng}, is the nominal power on the nameplate of the diesel generator, while X (0.2461/kWh) is the slope of the fuel curve slope and Y (0.084151/kWh) is the intercept of the fuel curve.

3.5. Economics

In order to evaluate the economic feasibility of the proposed energy system, the total net present cost (TNPC) and the cost of energy are used. This is evaluated using equations 5 and 6, respectively.

TNPC, also known as life cycle cost is the present value of all costs associated with installation, maintenance and replacements of all system components minus the present values of all associated incomes brought in by the system. Cost of energy (COE) is the ratio the average cost in kWh to the total energy served. Details of these can be accessed in (Babatunde et al., 2018).

$$TNPC = \frac{C_{tac}}{CRF(r, L_{proj})} \quad (5)$$

$$COE = \frac{C_{tac}}{E_s} \quad (6)$$

Where C_{tac} is the total annualized cost, $CRF()$ is the factor responsible for the recovery of the capital, r is the interest rate (%) and L_{proj} is the project lifetime, E_s is annual load served. The inflation and discount rates are 6% and 10% respectively.

3.6. Environmental

Since the hybrid system has an environmental advantage over the diesel generator in term of the greenhouse gas emission reduction. The reduced emission can be deduced to be from the PV source. However, the estimated carbon dioxide is often derived based on the fuel used by the generator. Based on the report of (Jakhrani et al., 2012), various values of carbon dioxide in relation to diesel generator per litre are listed as 3.2, 3.15 and 3.0 kg CO_2. Therefore, this work adopts an emission value of 2.66 kg of CO_2 per litre (Babatunde et al., 2018). Others include: CO-6.5 g/L, UH-0.72 g/L, PM-0.49 kg/L, and NO_x- 58g/L (Babatunde et al., 2019). The emissions are therefore evaluated using:

$$E_x = E_f, x \times TFC_{ann} \quad (7)$$

Where E_f, x is the emissions factor for pollutant x and TFC_{ann} total annual fuel consumption.

4. RESULTS AND DISCUSSION

Presented in this section is the results and discussion of the energy system analysis. The optimization results with respect to component sizing, economic implication and emission analysis are depicted in Table 2.

4.1. Techno-economic

Table 2 presents the comparison of the PV/DG/BAT system and the diesel-only system. The optimal system that will serve the gas station consists of 125 kW PV panel, 50kW diesel generator, 150 Surrette 4KS25P batteries and 50kW converter with a cycle charging dispatch strategy. For this system, it will require an investment cost of $197022, while the cost of energy (COE) is $0.174/kWh. The annual operation cost and total net present cost for the optimal system are $10152 and $326793, respectively. When these values are compared with the present mode of electricity generation in the gas station (diesel only generator), there is an increase of more than 900% in terms of the investment cost. The diesel-only generator is far cheaper as compared with the PV/DG/BAT system. An investor may be tempted to pick the

Table 2: Optimization results

		Unit	Proposed system without temperature coefficient	Proposed system with temperature coefficient	Diesel Gen. system
	PV		125	130	-
	Label	(kW)	50	50	50
	Converter		50	50	0
	Battery	(No)	150	150	0
	Ren. Fraction	(%)	84	0.81	0
	Diesel consumption	(L/yr)	10,988	12,663	80287
	Gen hours of operation	(hr/yr)	736	855	8759
	PV output		171,122	155,717	0
Technical	Gen. output		32,178	36,972	181,005
	Total generation	(kWh/yr)	203,299	192,689	181,005
	AC Primary Load Served		146,730	146,730	146,725
	Unmet Load		0	0	4
	Excess Electricity		23663	13,000	34280
	Total Capital Cost	($)	197022	202,647	19231
	Total NPC		326793	350,002	652034
	COE	$/kWh	0.174	0.187	0.348
	Tot. Ann. Cap. Cost	($/yr)	15412	15,852	1504
Economic	Tot. Ann. Repl. Cost		1656	1,808	10649
	Total O&M Cost		1133	1,234	6738
	Total Fuel Cost		7362	8,484	32115
	Total Ann. Cost		25564	27,379	51007
	Operating cost		10152	11,527	49502
	CO_2		28936	33,346	211423
	CO		71	82	522
Emission	UHC	(kg/yr)	8	9	58
	PM		5	6	39
	SO_2		58	67	425
	NO_x		637	734	4657

diesel-only generator due to the huge gap between the investment costs for the two energy systems. However, the TNPC and COE of the diesel-only energy system is approximately double that of the PV/DG/BAT system. Also, the annual operation cost of the diesel-only generator is close to 400% more than that of the proposed hybrid energy system (PV/DG/BAT).

With the inclusion of temperature effects, the size of the PV panel increased from 125kW to 130kW for serving the same load (Table 2). Meanwhile, the quantity of total PV power output considering the inclusion of temperature parameters also experienced a decrease (from 171122 to 155,717 kWh/yr). Since the PV output with the inclusion of temperature coefficients is lower, the generator attached to the energy system will need to operate an extra 119 h annually to meet the required energy demand of the gas station. This is evident in the monthly energy production, which shows that the monthly contribution of diesel generator increases on a monthly basis when the effect of temperature is included in the design (Figure 3).

Figure 4 shows the Energy production of PV panel and gasoline generator, battery SOC and excess energy for a typical month

Figure 3: Monthly energy production (a) without temperature coefficient (b) with temperature coefficient

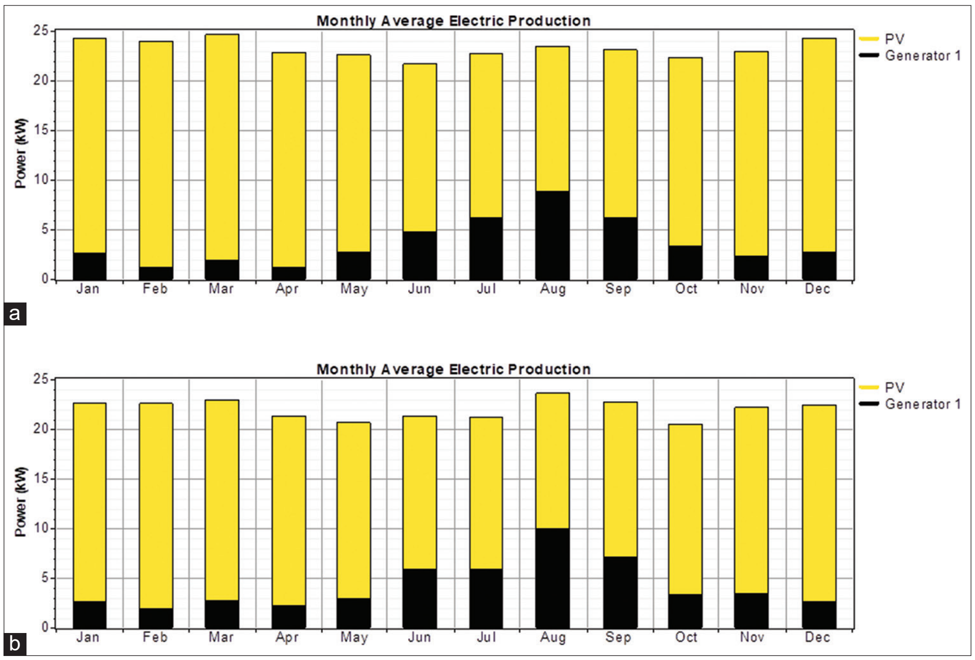
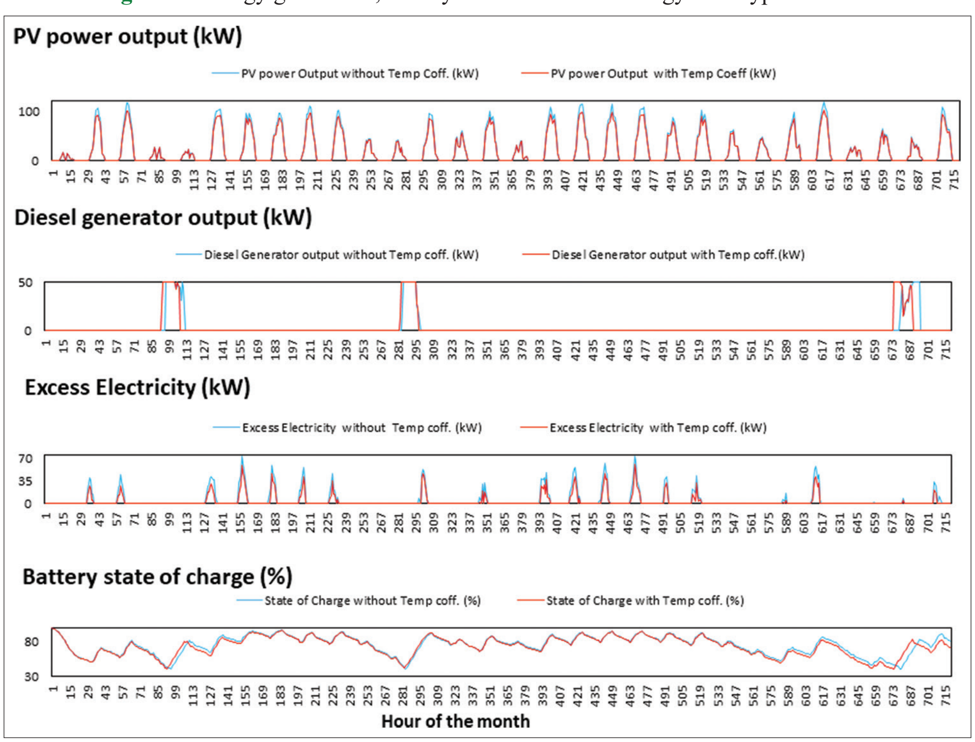


Figure 4: Energy generation, battery SOC and excess energy for a typical month



(January). The state of charge of the battery did not go below 40% (maximum DOD) for any hour of the month. The increase in the operational hours of the generator will consequently increase the diesel fuel consumption as well as the annual operations and maintenance cost of operating the energy system when compared with the system design without the consideration of temperature effect.

As expected, this effectively pushed the cost of energy from 0.174 to 0.187 \$/kWh. Also, the renewable fraction of the energy system reduced from 84% to 81% while the excess energy also reduced by more than 45.06 %. The graphical representation of the annualized costs for the PV/DG/BAT (with and without temperature effects) system and the diesel generator only system is given by Figures 5 and 6, respectively. For the PV/DG/BAT system, the capital cost account for the major part of the annualized cost while for the diesel generator, the money spent on fuel accounts for the major part of the annualized cost.

4.2. Emission

The emission analysis in this study shows that the PV/DG/BAT system will emit the following: 28936 kg of CO_2, 71 kg of CO, 8kg of UHC, 5 kg of PM, 58 kg of SO_2 and 673 kg of NO_x. When the temperature effect is included in the system design, the values increases to 33346kg of CO_2, 82 kg of CO, 9kg of UHC, 6 kg of PM, 67 kg of SO_2 and 734 kg of NO_x. These values are compared with the diesel-only generator; it is observed that there is a reduction of more than 600% on each pollutant. This will go a long way in reducing the emissions that cause climate change and health-related challenges attributed to emissions.

Figure 5: Annualized cost for the PV/DG/BAT energy (a) with temperature coefficient (b) without temperature coefficient

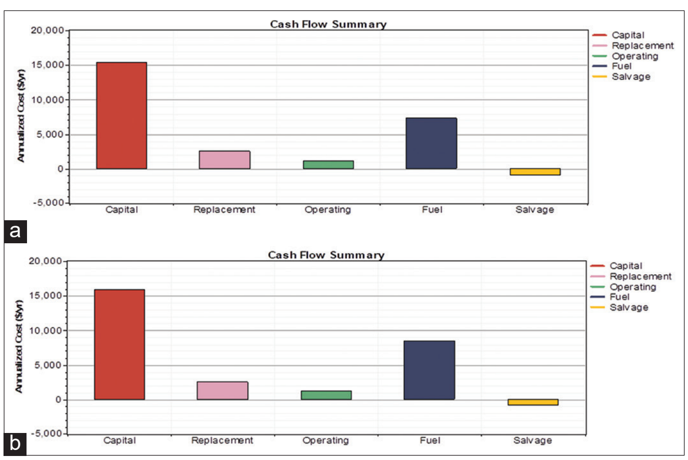
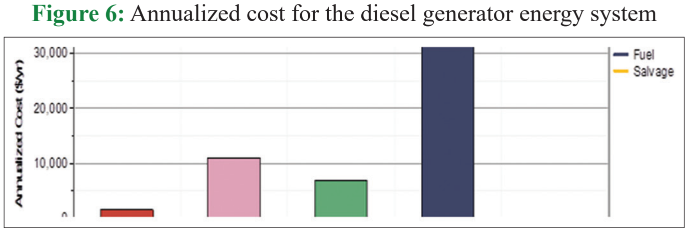


Figure 6: Annualized cost for the diesel generator energy system



5. CONCLUSIONS

This study has presented the sizing and optimization of a hybrid renewable energy system for a gas station. The study employed the NNPC mega station, Maiduguri, as a case study. The results of the techno-economic-environmental analysis have demonstrated the importance of this study. Also, it is evident that designers of such a system should take into consideration the effect of temperature on the PV panel and its impact on the techno-economic details of an optimal system. This investigation can serve as a planning tool for similar applications in Nigeria and other developing countries. However, government intervention such as the provision of a low-interest loan, subsidized policy on the procurement of renewable energy components is recommended. This will reduce the initial capital cost associated with renewable energy components and will make it more economically viable. It will further encourage investment in large energy projects with a tendency of minimizing carbon dioxide and improves the environmental conditions.

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