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Viability of a Photovoltaic Diesel Battery Hybrid Power System in Nigeria

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A B S T R A C T

Present study investigates the viability of a photovoltaic-diesel-battery hybrid system for electricity generation in Nigeria. It aims to determine the economic, technical and environmental benefits of running a solar photovoltaic (PV) system in Nigeria climatic conditions. The solar irradiation for Abuja (latitude 9.08 °N and longitude 7.53 °E) and residential energy profile are used. The optimum size of the hybrid system is determined by making energy-balance calculations based on Hybrid Optimization Model for Electric Renewable (HOMER) software. The impact of interest rate and cost of PV system on the optimum configuration is investigated. Sensitivity analysis is performed by varying the annual average solar irradiation based on solar radiation map of Nigeria and diesel price to determine the viability for other locations. Results showed that the use of PV-diesel-battery system in Nigeria can bring benefits of cost saving and emission reduction without compromising the reliability. However, the range of economic benefits depends on the site meteorology, which varies from 21 to 61%.

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INTRODUCTION

Electric power is the most widely used and globally desirable form of energy. It is an essential requirement for meeting the millennium development goals, and for improving the living standard of the citizenry. The reliability and affordability of electric power are, in particular, a critical component for sustainable development in virtually all sectors of the economy. Despite the importance of electricity in the economy, Nigeria is not able to generate adequate and reliable electricity to meet its growing demand [1].

The inadequate supply of electricity has consistently led to load shedding, with adverse effects on domestic, commercial and industrial activities. As a result, most entrepreneurs have resorted to use fossil-powered sources. Diesel generators (DGs) are being used either as supplements to the utility grid or exclusively in remote sites, neglecting both the socio-economic and environmental implications, which could be very alarming [2]. For instance, the cost of electricity production in Nigeria is nine times higher than that of China, and this has crippled the industrial sector [3]. Cost efficient energy solution is a serious problem hindering the economic growth in Nigeria.

The rising need for energy sustainability has made green technology, such as solar, a promising energy source. The solar photovoltaic (PV) system is a clean source of power, which does not emit greenhouse gasses. The use of PV system as a supplement to fossil-powered source can reduce the unit cost of power, but the range of financial benefits depends on the geographical coordinates [4]. The reason is that the solar energy depends highly on weather conditions. Moreover, the viability of a hybrid system is a function of the configuration, which depends on the size or allocated capacity, mix of power sources and the dispatch strategy.

This study examines the viability of the PV-diesel-battery power system for domestic electricity generation in Nigeria. The objectives are to determine the economic, technical and environmental benefits of running a PV system under different climatic conditions. The methods adopted to achieve set objectives are described in the next section. The results are presented and discussed in

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the following section. The conclusion is given in the last section.

METHODOLOGY

Resource and Data

Nigeria is a high insolation country with solar radiation distribution across the different zones as shown in Table 1. The annual average solar radiation varies from 3.5 kWh m^{-2} day^{-1} in the coastal areas to 7.0 kWh m^{-2} day^{-1} along the semi-arid areas in the far North of Nigeria. On the average, Nigeria receives daily solar radiation of 5.5 kWh m^{-2} day^{-1} [5]. These data show that there are good prospects for PV applications in Nigeria.

The monthly average daily solar irradiance data used for the study as shown in Figure 1 extend from 1984 to 2005. These data are supplied by National Aeronautics and Space Administration [6] for Abuja. The daily pattern of domestic electricity consumption in Nigeria described in literature [6] is used. The annual seasonal profile, shown in Figure 2, is synthesized from the daily profile by adding some randomness to account for real-time hourly and daily variations taken as 15 and 10%, respectively.

Methods

The study utilized HOMER software for the design and analysis of the hybrid power system. HOMER allows for comparison with various design options, which makes it easier to assess the techno-economic benefits of different power system configurations. As a result, the software is widely used for the design and simulation of micro-power systems [7]. The proposed photovoltaic-diesel-battery system is composed of a PV system, a diesel generator (DG), a battery storage system, a converter as well as AC loads as shown in Figure 3. The output power of a PV array can be calculated by the given equation [8]:

$$P_{PV} = f_{PV} Y_{PV} (I_T / I_S) , \quad (1)$$

where, f_{PV} is the PV de-rating factor, Y_{PV} is the rated capacity of the PV array (kW), I_T is the global solar irradiation incident on the surface of the PV array (kW m^{-2}), and I_S the standard amount of irradiation used to rate the capacity of the PV array which is 1 kW m^{-2}.

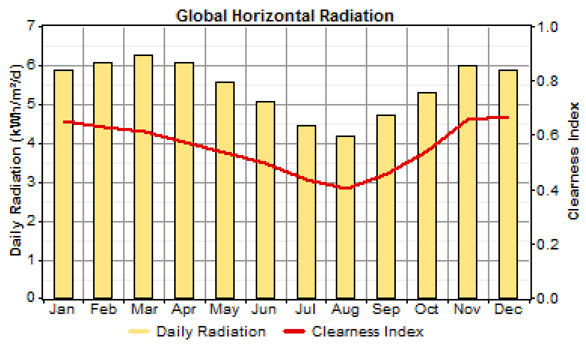

Figure 1. Daily global solar radiation and clearness index for Abuja.

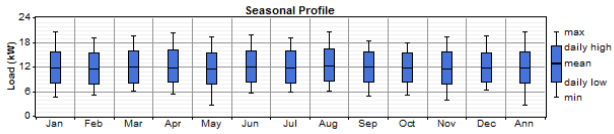

Figure 2. Seasonal load profile for the residential area

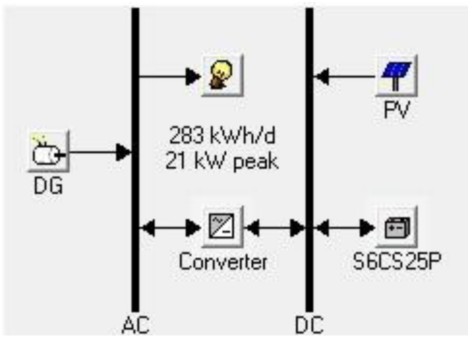

Figure 3. Proposed PV-DG-battery power system configuration.

TABLE 1. Long-term (1984 – 2005) monthly average daily global solar radiation data for different zones in Nigeria[2].

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
North-West	5.53	6.30	6.66	6.81	6.59	6.36	5.66	5.27	5.64	5.87	5.75	5.29	5.98
North-Central	5.83	6.05	6.08	5.82	5.42	4.94	4.45	4.22	4.59	5.08	5.77	5.75	5.33
North-East	5.76	6.31	6.54	6.43	6.11	5.80	5.29	4.98	5.36	5.67	5.80	5.54	5.80
South-West	5.53	5.70	5.61	5.33	5.00	4.47	3.97	3.81	4.09	4.65	5.15	5.37	4.89
South-East	5.64	5.70	5.49	5.20	4.87	4.47	4.05	3.88	4.13	4.48	5.02	5.41	4.86
South-South	5.41	5.46	5.09	4.84	4.50	3.93	3.48	3.52	3.62	4.01	4.59	5.14	4.47

[2] http://eosweb.larc.nasa.gov/sse [accessed: November 20, 2012]

TABLE 2. Primary inputs for power system sizing

Options	Parameter	Specifications
PV	Model	CNSDPV150
	Size (search space)	0 – 200 kW
	Capital	US$ 2000 per kW
	Replacement	US$ 2000 per kW
	O&M per annum	US$ 5 per kW
	Lifetime	25 year
	De-rating factor	90 %
	Operation mode	No tracking System
Battery	Model	Surrette 6CS25P
	Nominal voltage	6 V
	Nominal capacity	1156 Ah (6.94 kWh)
	Lifetime throughput:	9645 kWh
	Round trip efficiency	80 %
	Min. state of charge	40 %
	Size (search space)	0 – 60 strings (4 batteries per string)
	Capital	1200 US$ per battery
	Replacement	1150 US$ per battery
	O&M per annum	10 US$ per battery
Diesel generator	Model	Typical
	Size (search space)	0 – 40 kW
	Capital	500 US$ per kW
	Replacement	450 US$ per kW
	O&M per annum	0.03 US$ per h
	Diesel price	1.05 US$ per liter
	Lifetime	1500 h
Converter	Model	Typical
	Size (search space)	0 – 28 kW
	Capital	300 US$ per kW
	Replacement	300 US$ per kW
	O&M per annum	0 US$ per kW
	Efficiency	90 %
	Lifetime	15 year

The de-rating factor accounts for the adverse effects of dust, wire losses, and elevated temperature, on the performance of the PV array [9]. The lifetime (year) of a diesel generator is stated as follows [8]:

$$L_{gen} = L_{gen,h} / N_{gen}\,, \qquad (2)$$

where, $L_{gen,h}$ is the generator lifetime (h), and N_{gen} is the number of hours the DG operates during one year (h year^{-1}). If the diesel generator is running at time t the fuel consumption (L) is calculated by Equation (3) else the fuel combustion at t is zero.

$$F_{gen}(t) = a_o . P_{rat} + a_1 . P_{out}(t)\,, \qquad (3)$$

where, a_o is the generator fuel curve intercept coefficient (L h^{-1} kW$_{rat}^{-1}$), a_1 is the generator fuel curve slope (L h^{-1} kW$_{out}^{-1}$), P_{rat} is the rated capacity of the generator (kW) and P_{out} is the output of the generator at time t (kW). The generator's minimum load ratio is assumed to be 30%.

A battery increases the system investment cost [10], but it is required because of the following benefits. It cancels out unpredicted power fluctuations, stabilizes voltage and frequency, improves the power supply quality, reduces fossil fuel usage and provides security of energy supply [11]. The battery bank lifetime is determined by the following equation [9]:

$$L_{bat} = \min[(N_{bat} E_{lt,tp}) / E_{ann,tp},\ L_{bf}]\,, \qquad (4)$$

where $E_{lt,tp}$ is the lifetime throughput of a battery (kWh), $E_{ann,tp}$ is the annual battery throughput (kWh year^{-1}), L_{bat} is the battery bank life (year), N_{bat} is the number of batteries in the bank and $L_{b,f}$ is the battery float life (year). A deep cycle battery is widely used in renewable systems. The power system described is designed to provide electrical power to a residential area, such as a small estate comprising of 15 households. The design can also power a larger area of about 50 households, but with a daily average energy consumption not exceeding 5.7 kWh per household.

Real-time electric load tends to jump around randomly. As a result, an operating reserve is needed. A power system, which includes renewable sources such as solar requires more operating reserve to guard against random decreases in the renewable power supply. In the case of a rise in energy demand or decrease in solar radiation, the operating reserve prevents the power system from going down.

The primary inputs used for sizing the PV-DG-battery design (Figure 3) are given in Table 2 while the economic and technical constraints options used are given in Table 3. The project lifetime and annual real interest rate considered are 25 years and 3.3%, respectively. The rate corresponds to the current cost of borrowing in terms of dollars.

TABLE 3. System control and constraints inputs

Parameter	Specifications
Simulation step	1 h
Dispatch strategy	Load following
Maximum annual capacity shortage	3 %
Minimum renewable fraction	0 %
Percent of hourly load	10 %
Percent of annual peak load	0 %
Percent of hourly solar output	25 %
Percent of hourly wind output	N/A

The cycle-charging strategy although, is capable of preserving the lifetime of both the battery bank and diesel generator the load-following (LF) strategy is employed. The reason is that the LF approach can minimize excess electricity generation and reduce the total Net Present Cost (NPC) of the system [12].

The economic analysis is assessed by the COE (Cost of Energy per kWh) and the NPC of the system. The HOMER software determines the NPC of the system as the difference between the present value of all the costs of installing and operating the system over its life span. An option or mix of power sources is feasible if the power option can satisfy the load demand subject to the pre-defined constraints. The feasible option with the lowest total NPC and COE is considered as the most viable option.

RESULTS AND DISCUSSION

A comparison of the optimized PV-DG-battery system with PV-battery, DG-battery and DG-only system is given in Table 4. The results show that the optimum PV-DG-battery hybrid system configuration has the lowest total NPC and COE (US$ 517,068 and US$ 0.297 per kW, respectively). As observed, the optimized PV-DG-battery system reduces the NPC by over 38 and 45% compared to DG-only and DG-battery respectively, with a corresponding reduction in the COE. In comparison with the PV-battery system, a decrease in NPC and COE is less than 5%. The moderate reduction in costs suggests that the variation in the cost of either PV system or diesel, and both can significantly influence the range of financial benefits of the PV-DG-battery system.

The effect of varying interest rate and PV system cost on the optimum configuration of the hybrid system (with diesel price fixed at 1.05 US$ per liter) are shown in Fig. 4. The graph provides visual information on the optimum cost of the system, given a projected change in PV system cost and interest rate.

As noticed, a greater than 25% decrease in PV cost and interest rates suggests that the PV-battery system can be a viable option for Abuja and other areas with a similar meteorology. In particular, the PV-battery system gives the optimum cost option of US$ 0.240 per kW at PV capital cost of US$ 1,400 per kW (30% cost reduction) and an interest rate of 1.6% (45% rate reduction). The reason is that lower PV cost increases the contribution of renewable in the hybrid power system and this in turn reduces the total NPC of the hybrid system.

The electrical properties of various energy options are compared in Figure 5. The electricity characteristics vary for different options. A significant change in energy production and consumption is observed for options, which include PV. The variation is due to the intermittent nature of the PV as a source of power. The PV-battery option gives the highest excess energy percent (45%). The power system, which includes renewable such as PV always produces excess energy for few moments to guarantee, continues power supply. It is worth mentioning that the inclusion of diesel generator to provide power for such periods can reduce the COE, because the cost of excess generation is accounted for in the total NPC.

The optimum PV-DG-battery system reduces the excess capacity from 45 to 31% but with the release of pollutant emission into the environment. For example, augmenting PV-battery option with 5% of the electric power production from diesel generator emits 8790 kg of CO_2 per annum as shown in Table 5. However, when compared with the exclusive use of diesel generator as a power source in remote locations, the use of the optimum PV-DG-battery system can reduce the CO_2 emission per annum from 92,606 to 8790 kg year^{-1}. A significant reduction of over 90% in CO_2 emission from residential energy consumption can make the environment more “green” and eco-friendly.

TABLE 4. Comparisons among different power system options

Power Options	PV (kW)	DG (kW)	Battery	Converter (kW)	Initial Capital (US$)	Operating Cost (US$ /year)	Total NPC (US$)	COE (US$/kWh)	Renew Fraction	Capacity Shortage	Diesel (L)	Gen (h)
PV-DG-Battery	96	24	100	20	330,000	11,105	517,068	0.297	0.95	0.00	3,338	970
PV-Battery	126		116	20	397,200	7,729	527,398	0.311	1.00	0.03	0	0
DG-only		24			12,000	49,184	840,503	0.483	0.00	0.00	35,167	8760
DG-Battery		24	48	20	75,600	52,126	953,666	0.548	0.00	0.00	35,095	8,748

TABLE 5. Comparisons of pollutant emissions among different options

	Emissions (kg/year)					
Power Options	**CO_2**	**CO**	**Unburned hydrocarbons**	**Particulate matter**	**Sulfur dioxide**	**Nitrogen oxides**
PV-DG-Battery	8,790	21.7	2.4	1.64	17.7	194
PV-Battery	0	0	0	0	0	0
DG-only	92,606	229	25.3	17.2	186	2,040
DG-Battery	92,417	228	25.3	17.2	186	2,036

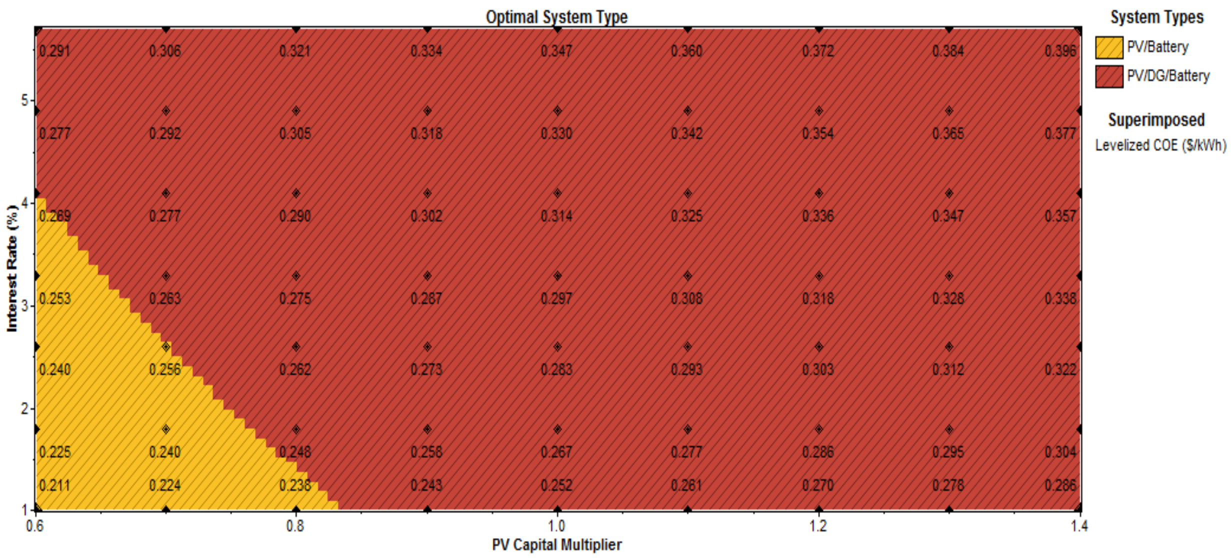

Figure 4. The effect of interest rates and PV costs on the optimum configuration of the hybrid power system.

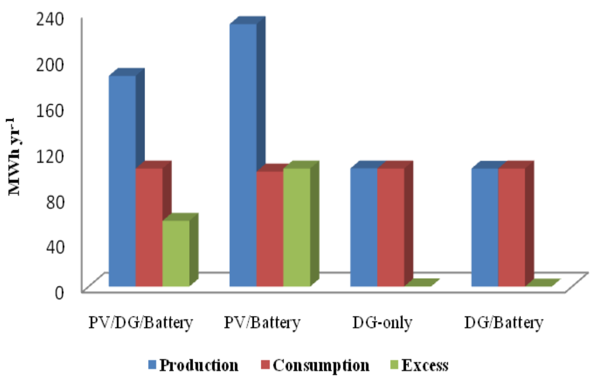

Figure 5. Comparisons of electrical properties among different power system options

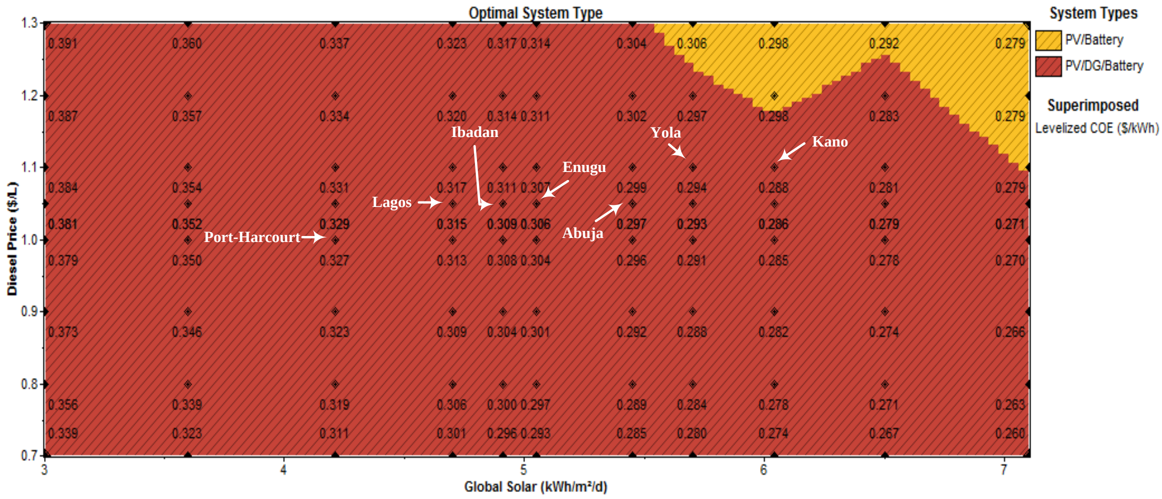

Figure 6. Optimum power system for PV array cost of US$2000 per kW and interest rate of 3.3%.

TABLE 6. Comparison between monthly cost of grid electricity and optimized PV-DG-battery hybrid system across Nigeria.

Area	Electricity Distribution Company	Grid Electricity			Proposed Hybrid System		
		Fixed charge, C_f (US$/ month)	Energy charge, COE (US$ /kWh)	Total cost, C_{tot} (US$/ month)	Total cost, C_f (US$/month)	Cost Saving (US$/month)	Cost Saving (%)
Abuja	Abuja	336.52	0.152	444.76	170.48	274.28	61.67
	Jos	185.73	0.165	294.32	170.48	123.84	42.08
Enugu	Enugu	155.97	0.157	258.45	175.64	82.81	32.04
Ibadan	Ibadan	119.83	0.165	225.12	177.37	47.75	21.21
Kanu	Kaduna	149.77	0.180	265.91	165.31	100.60	37.83
	Kanu	191.78	0.165	300.68	165.31	135.36	45.02
Lagos	Benin	239.65	0.136	333.58	180.81	152.77	45.80
	Eko	203.70	0.151	305.15	180.81	124.34	40.75
	Ikeja	167.76	0.148	265.32	180.81	84.51	31.85
PHC	Port-Harcourt	223.67	0.159	330.43	187.70	142.73	43.20
Yola	Yola	154.58	0.145	249.71	168.76	80.96	32.42

‡Note: US$1 ≈ N156.59 (Central Bank of Nigeria, accessed November 18, 2014).

Determination of the viability of proposed photovoltaic-diesel-battery power system option across Nigeria.

Sensitivity analysis is performed by varying the annual average solar irradiation based on solar radiation map of Nigeria and diesel price as shown in Figure 6. The significance of the analysis is that it assists potential investors or energy consumers, and both in selecting the most viable power system option at other locations with a similar energy consumption pattern. The two most viable power system options are PV-DG-Battery and the PV-Battery systems. The area covered by each system is a function of the diesel price and solar irradiation.

For coastal regions or southern part of the country with annual average solar radiation ≤ 5.0 kWh m^{-2} day^{-1} the PV-DG-Battery is the optimum choice irrespective of diesel price. However, as the solar radiation increases, the viability of hybrid power system at relatively high diesel price decreases. The PV-Battery system is the most viable choice in arid regions (north-eastern Nigeria) when the diesel price and solar radiation are greater than US$1.2 per liter and 6.0 kWh m^{-2} day^{-1} respectively. Therefore, any increase in diesel price beyond US$1.2 per liter cannot influence the optimum value at arid sites. In contrast, the optimum cost reduces as the global solar radiation increases, for a given diesel price.

Electric power (utility) grid versus proposed optimized stand-alone photovoltaic-diesel-battery hybrid power system.

For ease of comparison, first, the energy consumption pattern of different households is assumed to be similar to that described in Figure 2. Based on the assumption, the monthly average electricity consumption per household (E_{tot}) is 574 kWh, since the total consumption of considered area is approximately 103,295 kWh per annum. The monthly total cost of energy payable by each household for the photovoltaic-diesel-battery hybrid generation is US$ 170.48 or N 26,695.50[‡]. i.e., the cost of energy per kWh (see Table 4) × monthly total kWh of electricity consumed. The monthly electricity costs payable by each family for selected areas are determined by a similar analysis using the optimized value obtained from the sensitivity analysis shown in Figure 6. For example, at a diesel price of US$ 1.10 per liter, the optimum system cost at Kano situated in the north-western region with approximately 6.0 kWh m^{-2} day^{-1} is US$ 0.288 per kWh. Therefore, the monthly cost of electricity per household at Kano is (0.288 × 574 =) US$ 165.31 or N 25,885.90. Similarly, the monthly cost for Port-Harcourt (PHC) is US$ 187.70 or N 29,391.60. PHC, which is located in south-south zone, has an average global radiation and diesel price of 4.2 kWh m^{-2} day^{-1} and US$ 1.0 per liter respectively.

Second, where the grid power network is available, the electricity distribution company can satisfy the required energy demand. Moreover, the effect of the grid interconnection fee (a one-time fee paid for connecting to the grid) on the monthly total cost of energy payable by each household is negligible. Based on this assumption, the monthly total cost of grid electricity consumed is calculated as [13]: $C_{tot} = 1.05*(C_f + E_{tot} \times COE)$, where C_f is the monthly fixed charge (US$). The factor (1.05) account for the 5% value added tax charged on grid power consumption in Nigeria. The monthly cost of energy for R3-residential consumers for selected areas across Nigeria is compared with that of the proposed hybrid system in Table 6. The monthly grid electricity tariffs (fixed and energy charges used) of the different electricity distribution companies for R3-residential consumers are obtained from the revised multi-year-order-tariff (MYTO-2)[3].

In terms of grid versus off-grid application, Abuja is the most viable location for siting the proposed PV-DG-Battery hybrid power system. A monthly cost saving in the range of 123 – 274 US$ per month (42 – 62 %) can be achieved depending on the electricity distribution company serving the considered consumer. On the other hand, the lowest financial gain of US$ 47.6 per month (21%) would be realized if the proposed hybrid power system is sited at Ibadan. In addition to the cost benefits, the proposed energy system has a negligible downtime. In contrast, the power supply reliability of the utility grid network in Nigeria varies from about 39% in the northern region to 66% in the southern region. On the average, energy consumers can only access the grid power for only 13 hours daily [6].

[3] http://www.nercng.org/ [Accessed: August 13, 2014]

CONCLUSION

The viability of a photovoltaic-diesel-battery hybrid system running under varying climatic conditions has been determined by making energy-balance calculations based on HOMER software. The economic, technical and environmental benefit of the hybrid system is a function of the configuration, which depends on the size, site meteorology, mix of power sources and the dispatch strategy. Results showed that the use of PV-diesel-battery system in Nigeria can bring benefits of cost saving and emission reduction without compromising the reliability. In particular, the range of economic benefits varies from 21% in the southern to 61% in the northern part of Nigeria. A significant reduction of over 90% in CO_2 emission from residential energy consumption can make the environment more “green” and eco-friendly.

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Persian Abstract

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چکیده

پژوهش حاضر بقای یک سیستم ترکیبی فتوولتائیک-دیزل- باتری برای تولید برق در نیجریه را بررسی می کند. هدف آن تعیین منافع اقتصادی، فنی و زیست محیطی اجرای سیستم های خورشیدی فتوولتائیک (PV)در شرایط آب و هوایی نیجریه می باشد. تابش خورشیدی برای ابوجا(Abuja)عرض ۹/۰۸ درجه شمالیو طول جغرافیایی۷/۵۳ درجه شرقی و مشخصات انرژی مسکونی استفاده می باشد. اندازه بهینه از سیستم ترکیبی با محاسبات موازنه انرژی بر اساس مدل بهینه سازی ترکیبی برای برق تجدید پذیر نرم افزار (HOMER) تعیین می شود. تاثیر نرخ بهره و هزینه سیستم PVدر پیکربندی مطلوب انجام شده است. تجزیه و تحلیل حساسیت با تغییر تابش خورشیدی به طور متوسط سالانه بر اساس نقشه تابش خورشیدی از نیجریه و قیمت دیزل برای تعیین بقا برای نقاط دیگر انجام می شود. نتایج نشان داد که استفاده از سیستم باتری PV دیزلی در نیجریه می تواند مزایای صرفه جویی در هزینه و کاهش انتشار گاز گلخانه ای بدون به خطر انداختن اعتبار را به ارمغان بیاورد. با این حال، طیف وسیعی از منافع اقتصادی بستگی به سایت هواشناسی دارد، که از ۲۱تا ۶۱درصد تغییر می کند.