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Simulation of an Isolated Solar Photovoltaic-Fuel Cell Hybrid System with Hydrogen Storage for Mobile Telecommunication Sites

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Abstract—*This paper presents the simulation of an isolated solar photovoltaic-fuel cell (PV/FC) hybrid system with hydrogen storage for mobile telecommunication sites. The objective was to determine the optimum size, monetary cost and power supply reliability of the PV/FC hybrid system as an alternative source of power to isolated telecommunication sites. The optimum sizing was accomplished based on the energy-balance evaluation techniques using the Hybrid Optimisation Model for Electric Renewable (HOMER) software. Case study simulations were carried out for an off-grid site situated at Sokoto (Lat. 13°10.9'N, Long. 5°20.4'E) using the 22 years monthly averaged solar radiation data. The results showed that a hybrid system made up of 31kW PV generator, 3kW fuel cell system, 12kW electrolyser and a hydrogen storage tank of 4kg can enable a reliable power supply to isolated telecommunication sites at Sokoto at a cost of ₦ 40.02 per kWh. A present worth of ₦77,292,020, a return on investment of 13.1% and an internal rate of return of 12.4% can be derived from the simulated hybrid system compared to the traditional use of diesel-only generator system.*

Keywords: Fuel cell, hydrogen storage, mobile telecommunication, optimum sizing, photovoltaic generator, techno-economic analysis.

1. Introduction

A mobile telecommunication site is made up of a tower on which the antenna and lighting systems are mounted, and a shelter. The tower can be either a micro-cell (with a coverage of 0.1 – 1km) used for cities or a macro-cell (with a coverage of 1 – 35km) used in remote sites (Okundamiya, 2015). The shelter consists of a power amplifier, transceiver, combiner, duplexer, control function, alarm extension system and cooling systems. The telecommunication site can either exist on the peri-

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phery, which can only handle communications for their cell or can be stationed on the core network, to handle communications for multiple cells (Phelan, 2014). In terms of power consumption, the site elements are broadly categorised as the radio-frequency equipment and support system. The radio-frequency equipment (such as the power amplifiers and transceivers) supplies one or more cells/sectors while the support system, which consists of power electronic converters, analogue and digital signal processors, air-conditioning elements and battery backup helps in power/signal processing and conditioning (Lorincz *et al.*, 2012).

A recent estimate indicates that there are about 20,000 mobile telecommunication sites in Nigeria with a corresponding annual growth rate of approximately 20% from 2007 to 2012 (Ajanaku, 2013). In comparison with other developed countries, for instance, the United Kingdom, there are over 52,500 mobile telecommunication sites, yet Nigeria's population is more than twice as large as that of the United Kingdom (Wikipedia, 2014a; 2014b). This figure clearly shows the need for a rapid infrastructural development in the Nigerian telecommunication sector. One of the main problems hindering the rapid evolution of the sector is lack of a reliable and cost-efficient energy solution. The reliability of the utility grid varies between 39 and 66 %. In addition, an estimate of over 93 million people cannot access electricity in Nigeria (Okundamiya, 2016). The exclusive use of fossil-fuelled generators at telecommunication sites or as supplements to the utility grid where available is now a common practice in Nigeria.

The global concern for a sustainable energy technology has increased research interests in the use of renewable resources (Kim *et al*., 2017). Renewable power sources do not supply continuous power due to their intermittent nature. As a result, their power output is often complemented by energy storage device to enhance the system power supply reliability (Okundamiya and Nzeako, 2010; Elbaset, 2011; Okundamiya and Omorogiuwa, 2015). Hybrid power systems are widely used in recent times as they utilise different sources of energy to augment for the shortcomings of each power source. Hybrid system design, mostly, incorporates renewable energy mixes, for example solar photovoltaic, wind and fuel cells (Caren *et al*., 2017; Han *et al*., 2017; Mohammed *et al*., 2014; Okundamiya *et al*., 2014a; Wang *et al*., 2016).

Fuel cell technology can efficiently utilise hydrogen as a high carrier, especially for low and medium powered applications (Hoeven, 2015). The main electrolysis technologies are the solid-oxide, proton exchange membrane and the alkaline (liquid electrolyte) electrolyses. The liquid electrolyser, unlike others, has no moving parts. Hence, the maintenance and operating costs only involves the replacement of the cell stacks (≈ 2% of the initial cost). Alkaline electrolysis and fuel cells play a significant role in realising the potential of hydrogen (Zhang and Zeng, 2015). The application of fuel cells operating on hydrogen, which can be locally produced with the renewable energy source, as an alternative to the diesel-battery option could significantly reduce the monetary cost of energy. In addition, the design could reduce the contribution of fossil fuels, with a corresponding decline in CO_2 emissions and thereby enhancing the environmental standards of living. Several authors have attempted to design PV/FC system for efficient operation, but, usually ignore the optimum sizing of system component. Lagorse *et al*. (2008) compared the economic performance of different architectures involving solar photovoltaic generators and fuel cells. In contrast, Gomez *et al*. (2009) carried out a simulation study of a PV/FC hybrid power system for a remote telecommunication site. Nevertheless, the range of economic merits varies from one location to another, due to different meteorological conditions (Okundamiya *et al*., 2014b). There are several techniques utilised in the literatures for optimum sizing of hybrid systems but HOMER is the most common and extensively used tool perhaps due to ease of availability of the software and the simplicity of its operation and use (Okundamiya, 2015).

This research paper presents the simulation of a hybrid energy system made up of the solar photovoltaic generator, fuel cell, the electrolyser and hydrogen storage tanks. The objective was to determine the optimum size for a reliable and cost-efficient electricity supply to off-grid telecommunication sites in Sokoto (Nigeria).

2. Methods

2.1 Site and Meteorology

Sokoto is situated in the north-western zone of Nigeria. It lies between latitude 13.06°N and longitude 5.25°E. The entire area is very hot, but peak daytime temperatures during the year are mostly below 40°C. The rainy season spans from June to October with showers of rain, which seldom last long and are diverge from the regular torrential rain known in wet tropical regions. During the cold season, between late October and February, the weather is dictated by the 'Harmattan' wind blowing from Sahara desert. The dusty wind dims the sunlight, thus, reducing the ambient temperatures considerably. The long-term monthly daily averaged values varies from 17.1°C to 27.3°C (for minimum ambient temperature) and 31.2°C to 41.1°C (for maximum ambient temperature), with equivalent values in the range of 16.5–79.3% (relative humidity) and wind speed 8–14.6 m/s, measured at 10m above the surface of the earth. Figure 1 shows the topographic view of the study area.

Fig. 1: Topography of the study site

2.2 Data Collection and Analysis

The weather data sets used for the case study simulations, as shown in Table 1, were retrieved from the database of NASA (National Aeronautics and Space Administration) (http://eosweb.larc.nasa.gov/; accessed on June 10, 2017). These data are satellite-derived, made up of the monthly daily averaged values of global solar radiation data observed from July 1983 to June 2005.

The load data of a practical outdoor mobile telecommunication site used in this study are shown in Table 2. The seasonal electric load profile, depicted in Fig. 2 was derived from the electric load

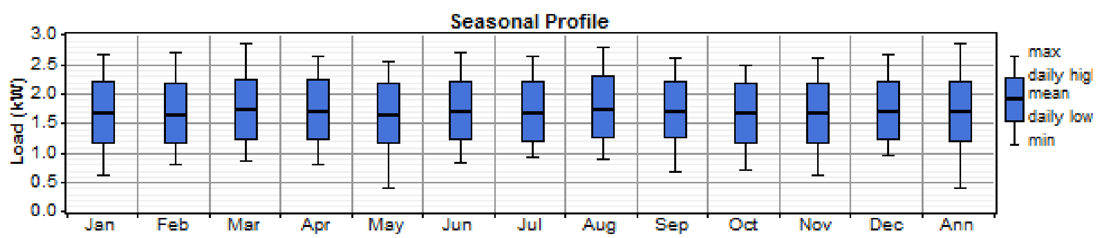
(Table 2) using HOMER software (version 3.9.1), by taken the hourly and daily variations of 10% and 15% respectively. The simulated daily primary direct current (DC) load of 40.8kWh/d with a peak load of 2.85kW were derived for the mobile telecommunication site while the corresponding values of 2.3kWh/d and 0.33kW were deduced for the auxiliary alternating current (AC) loads.

Table 1: Monthly daily averaged values of global solar radiation (kWh/m^2/d) for a duration of 22 years for site under study

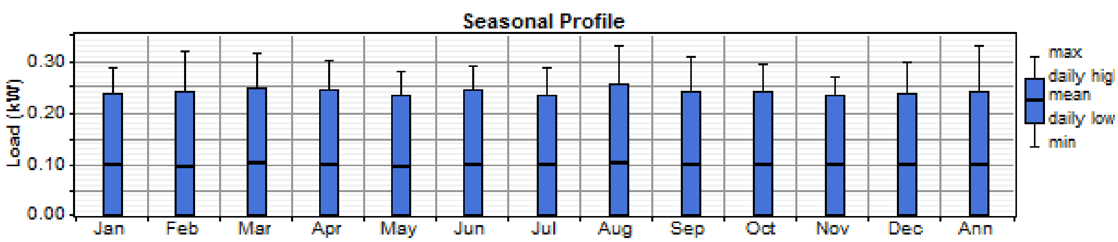
Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Sokoto	5.47	6.41	6.87	7.15	7.03	6.91	6.26	5.73	6.01	6.03	5.79	5.25	6.24

Table 2: Power consumption of a practical mobile telecommunication site (Okundamiya, 2015)

Load type	Components	Use (h/d)	Period in use	Power consumption (kW)
Main telecom load (DC)	Base transceiver station	24	0.00 h – 23.00 h	1.0
	Signal transmitter	24	0.00 h – 23.00 h	0.5
	Transceiver unit	24	0.00 h – 23.00 h	0.2
Auxiliary load (AC)	Cooling system	varies	varies	0.2
	Lighting	13	18.00 h – 7.00 h	0.1



(a)



(b)

Fig. 2: Seasonal electric load profile of the mobile telecommunication site under study (a) DC (b) AC

2.3 Design and Process Simulation

The schematic of the simulation model used to analyse the isolated PV/FC hybrid power system is illustrated in Fig. 3. The HOMER software was utilised for the process simulation and analysis because it permits comparison with different design options. The assessment makes it simpler to calculate the economical, technical and environmental merits of various power system configurations.

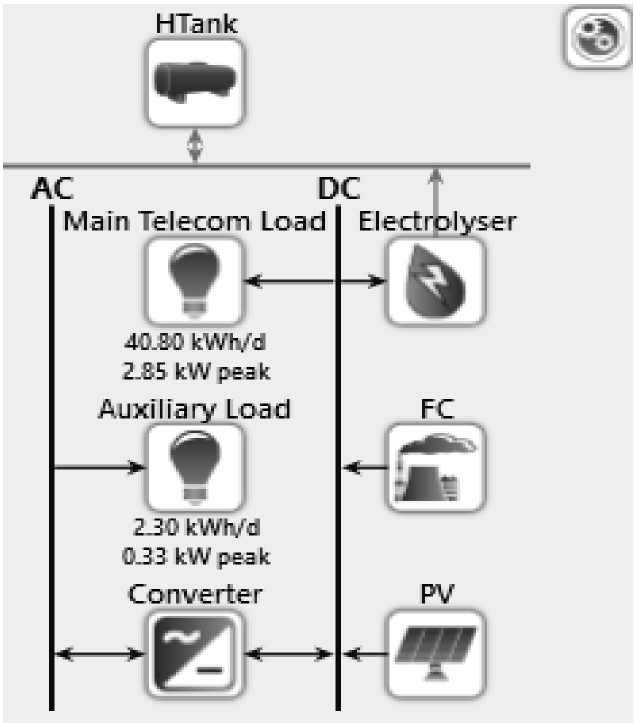


Fig. 3: Process simulation architecture of the PV/FC hybrid system under study

The model consists of the PV generator, fuel cells (FC), the electrolyser and hydrogen storage tanks (HTank) and the power electronic converter. The inclusion of the power converter is because the PV generator and fuel cell are DC energy types, which is different from the auxiliary load (AC) of the telecommunication site (Table 2). The converter converts power between AC and DC. The excess electrical power produced by the PV generator is used to power the electrolyser. The electrolyser produces hydrogen gas for storage in the Htank. The fuel cells generate electricity using the stored hydrogen gas as fuel, which in turn powers the telecommunication site during high-load demand period or when there is a deficit supply in solar energy.

The data described in the previous section were applied as input to simulate the performance of the PV/FC hybrid energy system under study for a typical year. The input parameters utilised for the size simulation are shown in Table 3. The project lifetime and the expected inflation rate assumed are 25 years and 11.5% respectively. The load-following control strategy was used as it can minimise surplus electricity production and reduce the total net present cost (NPC) of the power project (Okundamiya and Omorogiuwa, 2016). The economic analysis of PV/FC hybrid energy system was assessed in terms of Cost of Energy per kWh (COE) and the NPC of the system and then compared with the base case (traditional diesel-only) system. The results are presented and discussed in the following section.

Table 3. Input parameters for sizing the PV/FC hybrid system under study (Okundamiya and Ojieabu, 2017; Zhang and Zeng, 2015)

Option	**Parameters**	**Specifications**
PV	Size (search space)	0 – 50 kW
	Capital	₦300,000/kW
	Replacement	₦300,000/kW
	O&M per annum	₦30/kW
	De-rating factor	95 %
	Lifetime	25 years
	Operation mode	No tracking System
Fuel Cell	Size (search space)	0 – 20 kW
	Capital	₦152,750/kW
	Replacement	₦137,475/kW
	O&M per annum	₦25/kW
	Lifetime	40,000h
	Minimum load ratio	1%
Electrolyser	Size (search space)	0 – 30 kW
	Capital	₦152,750/kW
	Replacement	₦152,750/kW
	O&M per annum	₦1,800/kW
	Lifetime	20 years
	Efficiency	85 %
Hydrogen Tank	Size (search space)	0 – 15 kg
	Capital	₦3,055/kg
	Replacement	₦3,055/kg
	O&M per annum	₦153/kg
	Lifetime	25 years
	Initial tank level	10 %
Controller	Capital	₦15,275
	Replacement	₦12,220
	O&M per annum	₦0
	Lifetime	25 years
Converter	Size (search space)	0 – 5 kW
	Capital	₦13,000/kW
	Replacement	₦13,000/kW
	O&M per annum	₦130/kW
	Lifetime	20 years
	Inverter/Rectifier input efficiency	95 %

Note: ₦1 ≈ $(1/305.5), (Central Bank of Nigeria, accessed June 9, 2017)

3. Results and Discussion

The simulation results showing the optimum size of the hybrid system components and the monetary cost are depicted in Table 4. The optimum size configuration of the isolated hybrid power system made up of 31kW solar photovoltaic array, 3kW fuel cells, 12kW electrolyser and a hydrogen tank of 4kg can enable a reliable and cost-efficient electric power supply to Sokoto at a cost of ₦ 40.02 per kWh. Table 5 shows the economics of the hybrid system options under study compared with the regular diesel-only power (base) system, taking into account the costs of installation, maintenance and operation of the system. As observed, the positive value of the present worth shows that over ₦77,292,020.0 (with a corresponding annual worth of ₦5,484,060) can be saved by installing the PV/FC hybrid power system options as an alternative to the diesel-only power system.

Table 4: Optimum size specification for the PV/FC hybrid system model for Sokoto, Nigeria

Architecture					Cost			
PV (kW)	FC (kW)	Electrolyser (kW)	HTank (kg)	Converter (kW)	COE (₦)	NPC (₦)	Operating Cost (₦)	Initial Capital (₦)
31	3	12	4	0.30	40.02	37,331,631.8	429,572	11,622,645

Table 5: Economics of the simulated PV/FC hybrid system versus with diesel-only system at Sokoto, Nigeria

Compare Economics	Present Worth (₦)	Annual Worth (₦/y)	ROI (%)	IRR (%)	Simple Payback (y)	Discounted Payback (y)
PV/FC hybrid versus Diesel-only	77,292,020	5,484,060	13.1	12.4	7.52	6.00

The return on investment (ROI) index specifies the financial merits an investor can derive from a project. A high ROI index suggests that the merits of an investment compare favourably to its financial cost. As shown, the PV/FC hybrid system has an ROI index of 13.1% compared to the diesel-only system, which is reasonable. On the other hand, the internal rate of return (IRR) considers the time value of fund in assessing an investment. An IRR index of 12.4% shows the project compares favourably to the base system. The payback period (y) indicates the difference in financial cost between the current system and the base case system. The simple payback can be derived using the nominal cash flow while the discounted payback is computed using the discounted cash flow (Okundamiya and Ojieabu, 2017).

The electrical properties of the simulated hybrid energy system are shown in Table 6. The variation, between the generated and consumed power, is due to the irregular nature of the solar resource, the operating reserve and the low capability of the hydrogen technology. It is worthy of note that the efficiency of the hydrogen scheme is not more than 50%; hence, a large amount of power is lost in the hydrogen storage system. As a result, the power production of the PV generator greatly exceeds the energy demand.

Table 6: Electrical properties of the simulated PV/FC hybrid system at Sokoto, Nigeria

Energy Production			**Energy Consumption**		**Excess Energy**		**Shortage Capacity (%)**	**Unmet Electric Load (%)**
Component	**(kWh/y)**	**(%)**	**Load**	**(kWh/y)**	**(kWh/y)**	**(%)**		
PV	60,265	87.7	Telecom	14,752	29,492	42.9	1.08	0.928
FC	8,483	12.3	Auxliary	833				
			Electrolyser	23,628				
Total	68,748	100	Total	39,213				

Table 7 shows the emission characteristics of the simulated hybrid system. The negative value of CO_2 emission shows that the hybrid system can assist to mitigate CO_2 emissions from other sources and hence, could help in making the surroundings cleaner and more eco-friendly. Apart from the monetary benefits that can be derived from the simulated hybrid system when implemented, power supply reliability greater than 99% (deficit supply of 0.93% as shown in Table 7) can be realised.

Table 7: Emissions properties of simulated PV/FC hybrid system at Sokoto, Nigeria

CO	***CO_2***	***Unburned Hydrocarbon***	***Sulfur Dioxide***	***Particulate Matter***	***Nitrogen Oxides***
0.102	-0.160	0	0	0	0.0102

4. Conclusion

This research paper described the simulation of a photovoltaic-fuel cell system for mobile telecommunication sites in isolated regions. The objective was to determine the optimum size, financial cost and power supply reliability of the hybrid system as a substitute source of power to remote sites. The optimum sizing was accomplished based on the energy-balance evaluation techniques using HOMER software. Case study simulations were carried out for a remote site at Sokoto using the 22 years monthly averaged solar radiation data. The results showed that a hybrid system configuration made up of 31kW PV generator, 3kW fuel cell system, 12kW electrolyser and hydrogen storage tank of 4kg can enable a reliable power supply at a cost of ₦ 40.02 per kWh. Compared to the traditional use of diesel-only generator systems, the present worth, return on investment and internal rate of return of ₦77,292,020, 13.1% and 12.4% respectively can be derived when simulated hybrid system is implemented in Sokoto. The implementation of the hybrid system can help to resolve the electricity problems hindering the expansion of the mobile telecommunication sector in Nigeria. Moreover, the hybrid system can mitigate CO_2 emissions from other power generation sources to make the environment cleaner and more eco-friendly.

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