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Technical Analysis and Economic Assessment of a Stand Alone Solar PV/Fuel Cell Hybrid Power System

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Abstract: *This paper carries out an optimal design study of a stand-alone hybrid photovoltaic and fuel cell power system without battery storage to supply the electric load demand of the village of Ogbududu in Delta State Nigeria. The proposed optimal design study is focused on economical performances and is mainly based on the loss of the power supply probability concept. The simulation was carried out using a commercial software HOMER. Ogbudugbudu, a town located in Ughelli South local government of Delta State Nigeria was chosen as case study for which practical load demand profile with real weather data was used. Results show that the hybrid system is a viable alternative for off-grid power generating systems.*

Key words: *Hybrid Power System, Renewable Energy, Fuel Cell, Photovoltaic, Generation Unit Sizing, Energy Cost, HOMER***.**

INTRODUCTION

Energy is a basic requirement of modern lifestyle. The inability of Nigeria to provide uninterrupted power to her populace (estimated at 205 million with an annual growth rate of 2.5%) (Worldometer, 2020) has stifled the Nation's economic growth and significantly slowed down its industrialization process. It is a well-known fact that steady power has been elusive in Nigeria for a long time; despite the numerous efforts and schemes of successive governments to make this a reality. The recent establishments of successor generating companies (GENCOS) through privatization, the national integration power projects (NIPPS) and integrated power projects (IPPS) have not been able to address the power decadence in the country. Omar *et al.* (2014) suggested that the inability of governments to connect certain villages, towns and cities to the national grid leaves no other choice than for such places to find solace in the use of alternate renewable energies. Saheb *et al.* (2009) claims that it is a growing concern that there is a lack of grid-based electricity supply to rural areas in developing countries and that alternative energy sources such as solar, wind and biomass must be developed. The use of renewable based energy sources in electricity production is still very small compared to fossil-based sources, as a result of which many researches are investigating how renewable sources can be accommodated in hybrid systems so as to increase the systems reliability, cleanness and security (Mohammed *et al.,* 2013). Research suggests that the shortfall in power generation in Nigeria creates a huge gap between demand and supply, making individuals and organizations to look for alternatives to obtain regular supply of power hence the need for a quick, economical and feasible solution.

One of the promising solutions in overcoming this gap between demand and supply of electricity is the solar hybrid systems (Himour *et al.,* 2014). Semaoui *et al.* (2013a) suggested that renewable energy resources - such as wind and solar energies - cannot produce power steadily, since their power production levels change with the season, the month, the day, the hour. Therefore, a hybrid of solar photovoltaic cells and fuel cell has the potential to fully complement each other to produce steady power for optimal performance and reliability (Semaoui *et al.,* 2013b). The complimentary combination of hybrid systems usually leads to a steadier electricity output which would usually be supported by some storage devices to increase the reliability (Kabalci, 2013).

Ogbudugbudu is a town located in Ughelli South local government of Delta State Nigeria. Providing electricity to this region has been a challenging task due to its difficult geographical terrain and it perceived lack of economic benefits, hence the inability of successive governments to connect it to the national grid. To improve the economic activities and social life of the inhabitants of this town, an off-grid hybrid system of photovoltaic and fuel cell is proposed. This work is aimed at modelling, sizing, optimizing and carrying out an economic assessment of the proposed hybrid solar PV/Fuel Cell power system. The proposed hybrid power system model, which will be implemented in HOMER, is depicted in Fig. 1.

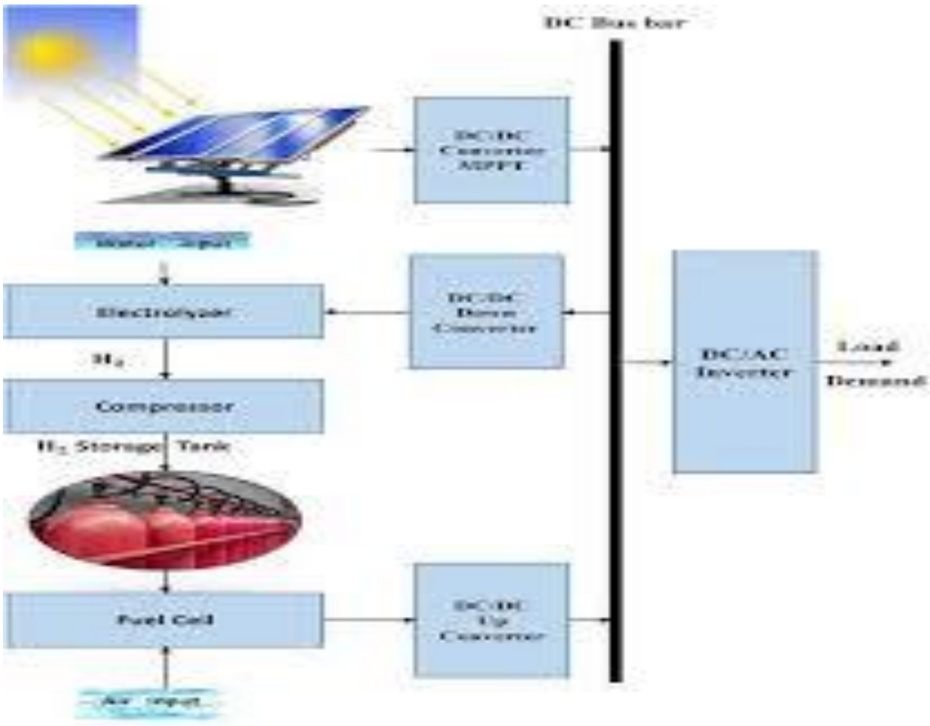

Fig.1 Schematic of the Proposed PV/Fuel Cell hybrid System

MATERIALS AND METHODS

A. Homer Software

HOMER (Hybrid Optimization Model for Electric Renewable) software is commercial software which was developed by NREL (National Renewable Energy Laboratory). It performs hourly simulations of the different combination of components entered and ranks the system according to user specified criteria. In this study, the hybrid power system chosen consists of PV generators, fuel cells, electrolyzer, and a hydrogen tank, HOMER will carry out simulations to determine the best feasible power system configuration that can cope with the load demand of the study area. The analysis is based on the estimation of the installation cost, the replacement cost, operation and maintenance cost, in addition to reliability studies needed to satisfy the load demand. The optimization process is done after carrying out simulations on the best possible configuration of the hybrid power system.

2.2 System Description

The hybrid power system design is dependent on a number of variables and parameters to model and optimize the system cost and component sizes. Thus, before designing the system model, parameters such as solar irradiation, location, and load demand must be evaluated. Data for the simulation will be obtained from. Typical households and business residence in the town, the data will then be implemented in the hybrid optimization modeling software using the electric/ renewable module (HOMER).

A. Case Study

The proposed hybrid power system for the city of ogbududu located in the Delta State, Nigeria. The city is tested using load demand profile with real weather data: The latitude and longitude for the location is (5.5325° N, 5.8987° E) respectively. The project estimated lifetime is about 25 years while the annual interest rate is fixed to 6%. Actual readings for the location were obtained from the NASA atmospheric data centre.

B. Electrical Load Profile

The city of Ogbududu load demand is illustrated in Fig. 2. The city load has been scaled to 115.33 kWh/day. Seasons scale peak load is assumed as 19.17kW. It should be noted that the electrical load was assumed to be constant from January to December of a typical year.

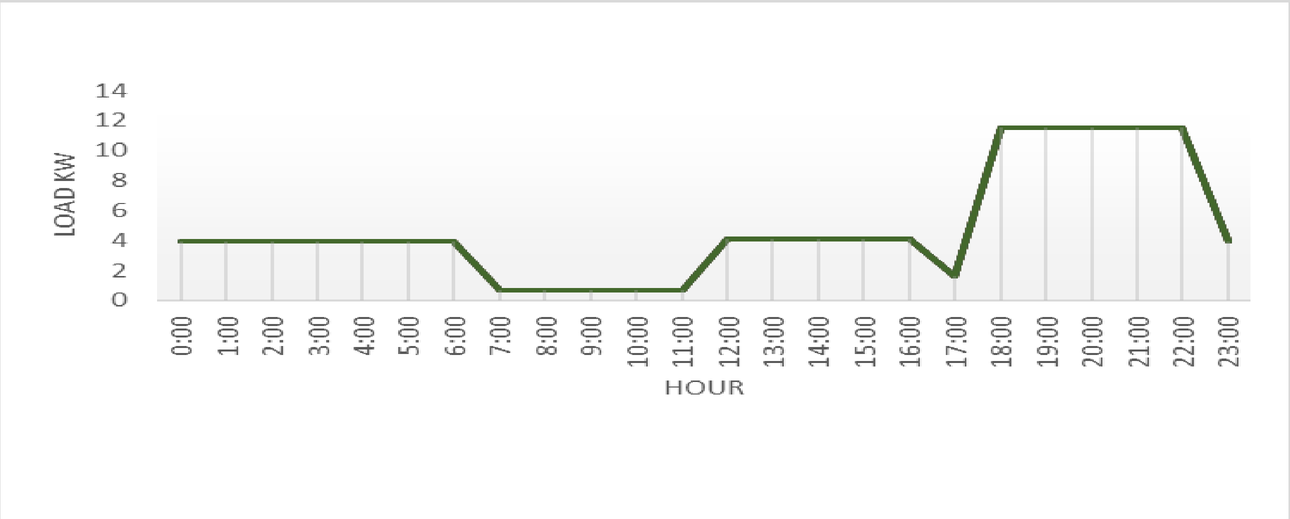

Fig. 2. Hourly Average Load Variation in a Day

C. *Solar Resource and PV Generator Data*

For the city of ogbudududu the solar radiation data were not available in HOMER hence the solar irradiation data for the city of Warri was obtained from the NASA Atmospheric Data Center. Fig. 3 depicts the solar radiation profile over a one-year period. The annual average solar radiation for this area is about 4.53 kWh/m²/day. The array slope angle for the PV generator is set to 49^0 and the array azimuth is 0^o which is referring to the south direction. The lifetime for this PV array system is estimated at 25 years with a de-rating factor of 80% and a ground reflectance is 20%. The clearness index and average the solar radiation are shown in Table 1.

2.3 Hybrid System Modeling and Operational Control Strategy

A. Hybrid System Modeling

The village of Ogbudugbudu is expected to receive a sizable amount of solar radiation throughout the year as shown in Fig. 3, this however should be adequate to generate electric power. A hybrid power system that consists of a PV generator with an FC system fed by hydrogen is therefore a feasible solution. In addition, it should be noted that FCs with hydrogen tank are used in off-grid hybrid power systems. The optimization process consists in determining the optimal value of the decision variable chosen by the authors and over which they have optimal control and for which HOMER can consider multiple possible values in its optimization process. In this study, decision variables include:

- The PV array size;
- The FC size;
- The Electrolyzer size
- The Hydrogen Tank
- The DC/AC converter size

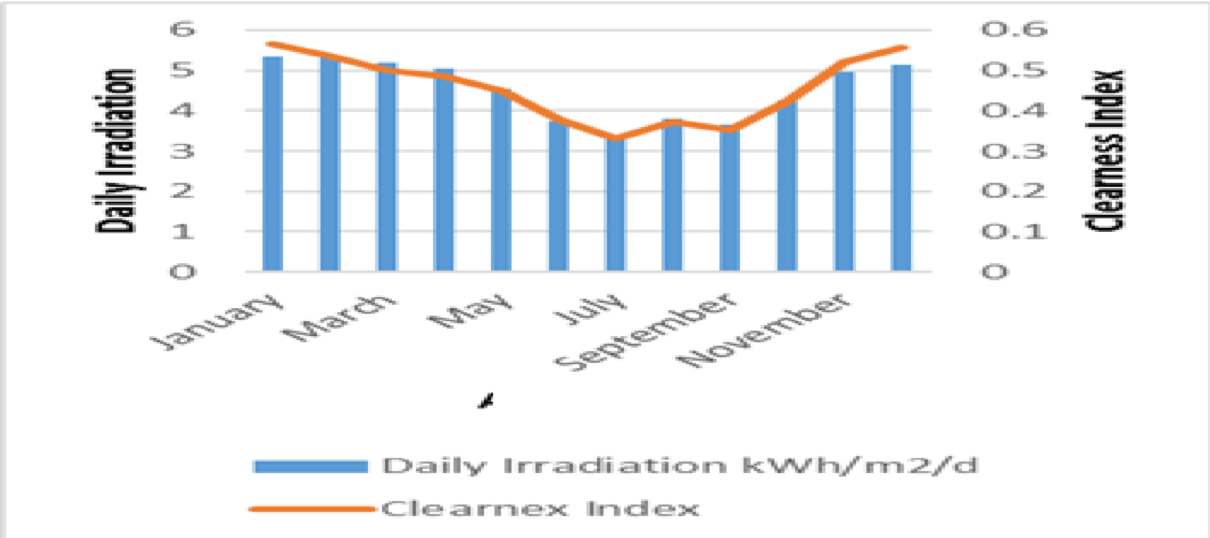

Fig. 3. Monthly Solar Radiation Profile

Table 1. Clearness index and Average radiation

Month	Clearness index	Average radiation (kWh/m2/day)
Jan.	0.561	0.950
Feb.	0.532	1.630
March	0.499	2.890
April	0.486	4.550
May	0.452	5.730
June	0.382	6.040
July	0.333	5.850
Aug.	0.373	4.960
Sept.	0.353	3.800
Oct.	0.423	2.150
Nov.	0.519	1.240
Dec.	0.552	0.810

The annual electrical load is to be met by the hybrid power system with a 100% rate. The annual real interest rate is 0.2%. The real interest rate is equal to the nominal interest rate minus the inflation rate. The project lifetime is 25 years.

The model constraints include:
- Maximum annual capacity shortage is 0%;
- Operating reserve is considered to be 10% of the hourly load.

HOMER input data are given by Tables 2 and Table 3 (Beccali *et al.*, 2008; Silva *et al.*, 2010; Karakoulidis *et al.*, 2011)

B. Operational Control Strategy

The operational control strategy (power management) is summarized by the following steps:
- In normal operation, the PV generator supplies the load demand. The excess power will be used to feed the electrolyzer for hydrogen production and storage in the tank. If the hydrogen tank is full, the power will be diverted to a dump load.
- If the PV generator power is less than the load demand, FCs will generate the remaining power to supply the load demand. FCs should fully supply the load demand in case of no radiation.

RESULTS AND DISCUSSION

The HOMER-based optimization of the PV/FC hybrid system is summarized by Table 4. The achieved configuration should supply power to the study city and is able of meeting its load demand continuously throughout the year.

Table 2. Input Data on Option Costs

Options	Capital Cost ($)	Replacement Cost ($)	O&M ($)
PV	$3000.00/kW	$3000.00/kW	$10.00/yr
FC	$3000.00/kW	$3000.00/kW	$0.01/yr
Converter	$300.00/kW	$300.00/kW	$0.00/kW
Electrolyzer	$2000.00/kW	$2000.00/kW	$0.00/kW
Hydrogen Tank	$1500.00/kW	$1500.00/kW	$0.00/kW

Table 3. Sizing, Simulation and Optimization Input Parameters

Options	Options on size and unit numbers	Life	Other Information
PV	0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260	25 yrs	Derating Factor 80%
FC	0, 10, 20, 30, 40, 50	40,000 hrs	Minimum Load Ratio 1%
Converter	0, 10, 20, 30, 40, 50	20 yrs	Inverter Efficiency 95%
Electrolyzer	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100	yrs	Efficiency 80%
Hydrogen Tank	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100	20 yrs	Initial Tank Level 10%

Table 4. Optimization Results of the Hybrid PV-FC Model

Units	Hybrid Photo-voltaic and Fuel Cell
PV (kW)	120
FC (kW)	20
Converter (kW)	16
Electrolyzer (kW)	50
Hydrogen Tank (kg)	100

The optimal configuration is found after carrying-out several simulations with a 3.39 kWh/m²/day solar radiation and an annual average clearness index of 0.452, and considering different PV, FC, electrolyzer, hydrogen tank, and converter capacities: The PV capacity has been allowed to vary from 0 to 8000kW, the FC power has been considered to change from 0 to 2200kW, the electrolyzer and the converter capacities have been allowed to vary from 0 to 2200kW, the hydrogen storage capacity has been allowed up to 956000kg. In this context, a load-following control strategy was used. The achieved hybrid power system TNPC is 8,942,636$ while its capital cost and cost of energy (COE) are 4,197,750$, 0.120 $/kWh, respectively for one year. Table 5 and Table 6 summarize the proposed power system different costs. In terms of power, Table 7 shows the monthly average power production of each renewable source. In addition, Tables 7 gives the annual electric energy production and consumption, respectively. In addition, Table 8 gives the hybrid power system annual emissions.

Table 5. Net Present Costs of the Hybrid System

Component	**Capital ($/yr)**	**Replace. ($/yr)**	**O&M ($/yr)**	**Salvage ($/yr)**	**Total ($/yr)**
Electrolyser	100,000.00	56,158.38	0.00	0.00	(12,741.96)
Fuel Cell	60,000.00	98,838.37	153,270.84	0.00	(22,003.78)
Hydrogen	150,000.00	0.00	0.00	0.00	0.00
PV	360,000.00	166,797.15	18,902.87	0.00	(103,209.92)
System	4,883.84	$2,742.68	0.00	0.00	(622.30)
System	674,883.84	324,536.58	172,173.71	0.00	(138,577.96)

Table 6. Annualized Costs of the Hybrid System

Component	**Capital ($/yr)**	**Replace. ($/yr)**	**O&M ($/yr)**	**Salvage ($/yr)**	**Total ($/yr)**
Electrolyzer	6,348.24	3,565.07	0.00	0.00	(808.89)
Fuel Cell	3,808.94	6,274.50	9,730.00	0.00	(1,396.85)
Hydrogen Tank	9,522.36	0.00	0.00	0.00	0.00
PV	22,853.67	10,588.68	1,200.00	0.00	(6,552.01)
System Converter	310.04	174.11	0.00	0.00	(39.51)
System	42,843.25	20,602.36	10,930.00	0.00	(8,797.26)

Table 7. Annual Electric Energy Production of the Hybrid System

Component	Production(kWh/yr)	Percent (%)
PV	133,798	80
Generator	33,554	20
Total	167,352	100

Table 8. Annual Emissions of the Hybrid System

Emission		
Pollutant	**Emissions**	**Units**
Carbon dioxide	-21	kg/yr
Carbon monoxide	13	kg/yr
Unburned hydrocarbons	1	kg/yr
Particulate matter	1	kg/yr
Sulphur dioxide	0	kg/yr
Nitrogen oxides	117	kg/yr

CONCLUSION

This paper dealt with the optimal design of a stand-alone hybrid PV/FC power system without battery storage to supply the electric load demand of the city. The proposed optimal design study was focused on economic performance and was mainly based on the loss of the power supply probability concept. The HOMER-based optimization study using the total net present cost has clearly shown that the proposed hybrid power system and in particular fuel cells are a viable alternative to diesel generators as a non-polluting reliable energy source with a reduced total cost of maintenance. It has also been shown that a fuel cell generator could efficiently complement a fluctuating renewable source as solar energy to satisfy growing loads.

CONFLICT OF INTEREST

This research work was carried out by us and there is no conflict of interested associated with it.

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