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Optimal sizing of a hybrid photovoltaic/fuel cell grid-connected power system including hydrogen storage

E. O. Okoduwa [a,*], H. O. Imoedemhe [b], P. E. Orukpe [c]

[a] Department of Electrical and Electronic Engineering, Ambrose Alli University, Ekpoma, Nigeria
[b, c] Department of Electrical and Electronic Engineering, University of Benin, Benin City, 300283, Nigeria

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ABSTRACT

The global energy demand is enormous, yet nonrenewable resources such as fossil fuels, and nuclear power are insufficient to satisfy it. Renewable energy will eventually be the better option. This study investigates the design and optimization of a hybrid photovoltaic / fuel cell (PV/FC) energy system with an H_2 tank linked to the grid. The primary objective of this research is to design and size a PV/FC energy system with an H_2 storage tank to supply the energy needs of a university ICT center that is connected to an inconsistent grid. HOMER's energy-balance algorithms were used to determine the best design architecture. Using mean solar radiation data (22 years) obtained for the University of Benin ICT Center, hourly simulations were performed to determine the optimum configuration in terms of size, cost, and performance of the energy system. Findings revealed that a hybrid PV/FC power system with a 400 kW solar array, a 250 kW FC, a 240 kW inverter, and a 150 kW electrolyzer with an H_2 tank of 700 kg will reliably supplement the inconsistent grid with a high proportion (92%) of renewable resources at $0.1052/kWh. An energy cost reduction of approximately 88 percent and a return on investment of 200 percent with a present value of $98,251,110 could be obtained in less than 2 years over the traditional grid/diesel systems. Using an ideally sized PV/FC hybrid system will alleviate Nigeria's electrical challenges, impeding the country's economic growth. Furthermore, hybrid PV/FC power systems can reduce CO_2 emissions, resulting in a more environmentally friendly and sustainable environment.

1. Introduction

Due to the world's continuously growing population and economy, global energy demand is rapidly increasing. Within the next three decades, a nearly 50% increase is expected [1]. Fossil fuel is the most important resource for meeting present energy demands. The present energy crisis is aggravated by the cost and diminishing supply of fossil fuels [2]. The environmental impact of increased carbon emission, primarily from fossil fuel use, is a major source of concern"[3,4]. The overall efforts to reduce global warming could be hampered if the electrical energy required to meet the energy needs is coming from nonrenewable sources.

Any energy system's principal aim is to generate as much energy as feasible with the least amount of resources. To accomplish these goals, energy systems must be designed such that the components are sized as efficiently as possible. Multiple authors in literature tried to increase the percentage of renewable energy in the overall energy mix, develop various power flow management strategies, minimize CO_2 emission and reduce the cost of energy for various system configurations made up of photovoltaic (PV) cells, wind turbines (WTs), fuel cells (FCs), and batteries.

To satisfy the city of Brest's electric load needs, researchers in [5] proposed an off-grid hybrid PV/FC energy system without battery storage. HOMER-based optimization software was used in the investigation. The findings demonstrated that FCs are a feasible energy alternative to diesel generators with a lower total cost of ownership than diesel engines.

* Corresponding author
E-mail address: Okoduwa.emmanuel@aauekpoma.edu.ng
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Nomenclature

BEDC	Benin Electricity Distribution Company	IES	Integrated Energy System
BT	Battery	IRR	Internal Rate of Return
CFR	Capital Recovery Factor	LPSP	Loss of Power Supply Probability
CO_2	Carbon dioxide	MCDM	Multi-Criteria Decision-Making
COE	Cost of Energy	MTTR	Mean Time to Repair
DC	Direct Current	PE	Polyethylene
FCs	Fuel Cells	PEMFC	Polymer Electrolyte Membrane Fuel Cell
H_2	Hydrogen	PP	Polypropylene
HESs	Hybrid Energy Systems	PS	Polystyrene
HOMER	Hybrid Optimization Model for Energy Renewables	PV	Photovoltaic
		ROI	Return on Investment
HRES	Hybrid Renewable Energy System	WTs	Wind Turbines
ICT	Information and Communication Technology		

In Nigeria, the possibility of a PV/Diesel/BT hybrid system for generating electricity was investigated in [6]. Researchers in [7] suggested a solar PV/FC integrated energy system (IES) for the Jhiriya-Kheda village. They sought to maximize the energy produced with the least investment. HOMER was used to optimize the system under various restrictions and an optimum component sizing was chosen to reduce per-unit cost. They discovered a reduction in energy expenditure of almost 40% in their investigation.

In [8], the optimal size of a stand-alone hybrid solar and wind energy system was investigated using a novel hybrid optimization approach based on three algorithms. The three hybrid renewable energy solutions were evaluated using the primary goal of reducing complete life cycle costs. The approach offered in their study for optimal scaling of a mixed renewable energy system is a good reference.

The optimization and control solutions for a cruise ship's hybrid renewable power system were investigated in [9]. The intent was to incorporate solar and wind energy systems into small and big ships to make marine transportation more environmentally friendly and sustainable.

In [10] an optimal design for a hybrid wind, FC, electrolyzer, battery, and super-capacitor system was presented. To handle the DC bus, the super-capacitors were employed in their configuration, while the hybrid system's other components were used as a backup. A new concept for a HRES was established in that study. Their research also showed that changing the speed profile can result in a reduction of up to 65.52 percent of the initial cost.

Furthermore, to examine the design of an off-grid hybrid energy system integrating WT, PV, and hydrogen storage, researchers in [11] suggested "a data-driven two-stage multi-criteria decision-making framework". The goals were to reduce the cost of energy, power abandonment rate, and loss of power supply possibility, simultaneously.

In [12], "an experimental and modeling/ simulation study of energy recovery from plastic waste (PP, PE, PS) through batch pyrolysis reactors powered by stand-alone hybrid solar photovoltaic/shrouded wind turbine power system" was proposed. The study's target was to integrate a renewable energy system to recycle solid waste and transform it into alternative and sustainable energy. The results indicate that the proposed hybrid off-grid system is capable of meeting the whole energy requirement of the reactor.

Researchers in [13] proposed the combination of a high-temperature PEMFC system with a hybrid wind/PV system to create a new configuration of the hybrid energy system. According to the findings of their study, the only case for selecting an optimal configuration is to look at the Pareto solution set. However, other parameters can affect the system such as the area of the PEMFC and the number of PEMFC cells, which were not taken into consideration in this study.

In [14], a novel HRES model was investigated for modeling and optimization of an off-grid HRES . The main goal was to lower the system's net present cost, cost of energy, unmet load, and CO_2 emission. The proposed system is economically viable, has reasonable environmental advantages, has a favorable payback period, and emits less pollution, according to the findings of their research.

In [15] the capacity optimization of a "grid-integrated solar/fuel cell energy system" to meet the load demand for an Indian shopping complex was investigated by defining two objectives: the cost of energy bought and sold to the grid, and the control of power flows between system components and the grid. The proposed model is economically viable, according to their findings. It was also discovered that a small center's electricity demand may be met by solar/FC power generation, with the grid serving as a backup, without breaching any limits.

Furthermore, "a novel artificial ecosystem optimization algorithm" for determining the best configuration for a hybrid system that includes PV, WT, and FC was proposed in [16]. The algorithm was created to lower the cost of energy and the likelihood of a power outage. Their research found that a hybrid system with a fuel cell produced the greatest results in terms of energy supply cost.

Researchers in [17] describe a concept of a stand-alone system to meet the electrical needs of a residential customer in rural areas of Algeria. The energy system consists of a diesel/PV/WT/battery system. The authors scaled the components based on the findings of their analysis to minimize the levelized cost of power, resulting in a competitive energy price and a high renewable share of 100 percent for the PV-Battery hybrid design.

Technical and economic analysis of a renewable energy-based hybrid energy system was conducted in [18]. The system was created to satisfy the energy requirements of a single-family home's electrical and hydrogen loads using 100 percent renewable energy sources. The results reveal that the optimum system produces H_2 and electrical energy for $6.85 and $0.685, respectively. The cost of H_2 that was produced was half the market price of H_2 at the time of production.

In recent years, research has focused on the capacity configuration optimization problem of hybrid energy systems. Software tools and optimization algorithms are two types of configuration methods that have been employed in the literature. Using HOMER and MATLAB tools, as seen by their application in scientific studies, has proven to be a beneficial strategy. For capacity optimization, the HOMER software has been widely used. In terms of the technological goal, the majority of previous research has focused on the LPSP, COE, and emission reduction of HESs. Despite the efforts of various writers to develop the PV/FC system for effective operation, the range of economic advantages differs from one site to the next due to varying meteorological conditions. Furthermore, there has been little investigation into the optimal scale of a hybrid PV/FC energy system for the Nigerian landscape. This study was inspired by a research gap in resource allocation for optimum energy production of the PV/FC hybrid system for isolated sites in Nigeria.

2. Materials and Methods

Fig.1 depicts the suggested hybrid PV/FC system. PV-array, electrolyzer, hydrogen storage tank, fuel cell (PEMFC) stack, a DC to AC inverter, a utility grid, and an AC load are the main components of the system. The electrolyzer is a device that uses energy to create hydrogen from water through electrolysis. Because the PV generator and FC are DC energy devices, which differ from the alternating current one at the University of Benin ICT Center, the power converter was included. As illustrated in Fig. 2, HOMER calculates the daily, monthly, and annual load profiles. For the study site, an estimated electrical demand of 594.61 kWh/d was derived with a peak power of 229.14 kW. Fig. 3 depicts the mean solar radiation data utilized as inputs to the proposed hybrid PV/FC energy system. The converter converts DC to AC power. When the PV generator produces more electricity than it needs, surplus energy is utilized to power the electrolyzer. The electrolyzer generates H_2, which is accumulated in the H_2 Tank. The FC generates power from stored H_2 which is then used to power the ICT Center's load during periods of high demand or when the solar energy supply is insufficient. For the sake of comparison, the diesel generator has been included.

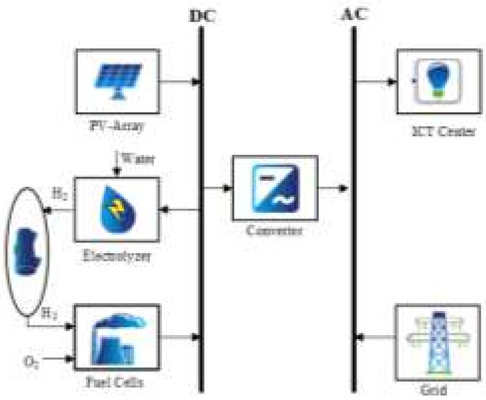

Fig. 1 Model of PV/FC grid-connected hybrid power system.

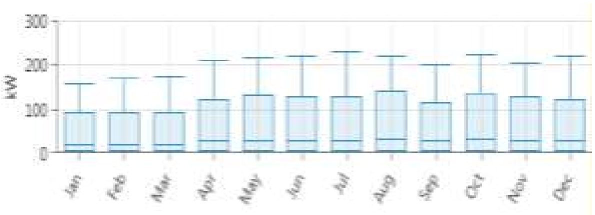

Fig. 2 The ICT Center's seasonal load profile.

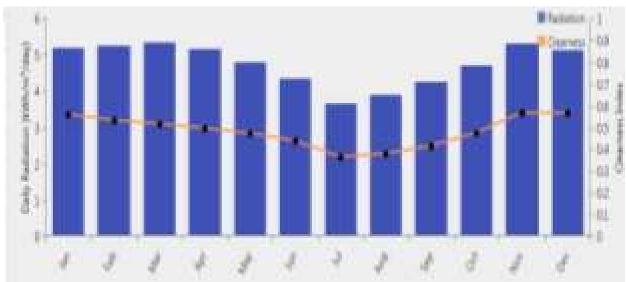

Fig. 3 Mean monthly solar resources (1986–2005) for research site.

2.1. PV Array

Equation (1) can be used to compute a PV array's output power.

$$P_{PV} = C_{PV} D_{PV} \left(\frac{I_T}{I_S}\right) \left[1 - \alpha_p (T_c - T_s)\right] \quad (1)$$

Where C_{PV} denotes the PV array capacity (kW), D_{PV} denotes the de-rating factor (%), I_s denotes solar irradiation during normal test conditions (kW/m^2), I_T denotes solar irradiation incident on PV array (kW/m^2), α_p is the temperature coefficient of power, T_c is the temperature of the PV cell and T_s is the temperature of the PV cell under normal operating conditions.

2.2. Electrolyzer

The electrolyzer uses electricity to electrolyze water to generate hydrogen:

$$H_2O \rightarrow \frac{1}{2}O_2 + H_2 \tag{2}$$

The output voltage of the electrolyzer can be computed from equation (3).

$$V_{total} = N_{ele}\left(V_{Nernst} + \frac{RT}{\alpha_a F}\sinh^{-1}\left(\frac{I_{ele}}{2i_{aa}}\right) + \frac{RT}{\alpha_c F}\sinh^{-1}\left(\frac{I_{ele}}{2i_{ac}}\right) + \frac{\theta}{\sigma}I_{ele}\right) \tag{3}$$

Where T is the electrolyzer cell temperature (K), R is the normalized gas constant (8.314 ×10-3 kJ/K.mol), α_a and α_c are the charge transfer coefficients at the anode and cathode sides, i i_{aa} and i_{ac} are exchange current density related to the anode and cathode sides, F is Faraday's constant (96485 mol/C), N_{ele} is the number of electrolyzer cells in series, σ is the cell thickness (μm), and I_{ele} is the current of the electrolyzer.

2.3. Fuel Cell

The PEMFC was considered in this work. The semi-empirical model of the FC was developed using the energy conversion law and the molar conversion principle. The energy balance equation for the FC stack was derived by taking into account six major components: "energy input gases Ein, energy output gases E_{out}, input fuel energy from electrochemical reactions E_{fuel}, electrical energy E_{elec}, energy removed by coolant water E_{cl}, and heat loss to the environment E_{loss}. The following is the energy balance equation:

$$M_s C_s \frac{dT_{s,out}}{dt} = E_{fuel} + E_{in} - E_{out} - E_{elec} - E_{loss} \tag{4}$$

Where he mass of the FC stack is M_s, and the specific heat of the FC stack is C_s.

2.4. Design Considerations for the Utility Grid

The ICT center under investigation is linked to the grid and is supplied by BEDC. Because of the grid's inadequacies, these assumptions were made:

- The grid outage lasts 2 h, and MTTR is 2 h.
- The annual mean outage frequency is 1095, assuming an outage is expected within 8 h.
- The repair time varies. Despite BEDC's establishment of a planned outage period of 2 h, the real outage length in certain circumstances exceeds the scheduled period by up to 90%. Thus, the repair time randomness is 90%.
- The utility grid is unreliable, and power is delivered erratically.
- Due to pending legislation, the cost of reselling electricity to the power grid is \$0. As a result, there is no way to sell electricity to the grid.

2.5. Assessment Criterion

Two assessment parameters: Net present cost (NPC) and Cost of Energy (COE) are utilized to establish the optimal size of the hybrid PV/FC energy system. The NPC was calculated by taking into account the initial cost, replacement cost, operations and maintenance cost, and salvage costs during the project's lifetime.

$$NPC = \frac{C_{total}}{CRF(i,t)} \tag{5}$$

Where t represents project duration, C_{total} denotes total annual cost, i denotes annual interest rate (%), and CFR denotes capital recovery factor

$$COE = \frac{C_{ann\_total}}{E_{total}} \tag{6}$$

Where E_{total} represents total annual electrical energy generated (kWh) and C_{ann_total} signifies the annual cost.

The characteristics of the components utilized in sizing the proposed hybrid PV/FC energy system are listed in Table 1. The estimated system lifespan and inflation are 25 years and 15%, respectively.

3. Results and Discussion

The hybrid PV/FC energy system simulation process have gone through a series of optimization to determine the cost-effective and environmentally friendly design in terms of COE and NPC of the hybrid energy system, which was then compared to the traditional grid/diesel system (baseline system). Table 2 shows the hybrid system's optimum configuration when connected to the grid.

It is possible to supplement the inconsistent grid energy supply using a 400-kilowatt PV array, a 250-kilowatt fuel cell system, a 240-kilowatt power inverter, a 150-kilowatt electrolyzer, and a 700-kilowatt hydrogen storage tank. As illustrated in Fig. 4, the hybrid power system generates 602,282 kWh annually, with 559519 kWh/y (92.9%) coming from the PV array, 16710 kWh/y (2.77%) coming from the FC, and 26053 kWh/y (4.33%) coming from grid energy purchases.

Table 1. Component specifications for scaling the PV/FC hybrid system

PV Array	Module Type	Mono-crystalline
	Maximum power (P_{max})	340 W
	Maximum Voltage (V_{mp})	37.9 V
	Maximum current (I_{mp})	8.97 A
	Short Circuit Current (I_{sc})	9.46 A
	Open Circuit Voltage (V_{oc})	46.6 V
	Module efficiency at 40ºC	20%
	De-rating factor	80%
	Capital Cost	$600/ kW
	Replacement Cost	$450/ kW
	Yearly O&M Cost	$5/ kW
	Module Lifespan	25 years
	Size of the search space	0-2000 kW
Electrolyzer	Type	Generic Electrolyzer
	Lifespan	15 years (75000h)
	Efficiency	75%
	Capital Cost	$500/ kW
	Replacement Cost	$250/ kW
	Yearly O&M Cost	$10/ kW
	search space	0-500 kW
Fuel Cell	Type	PEM
	Fuel type	Hydrogen
	Electrical efficiency	65%
	Lifespan	15000 h
	Capital Cost	$500/ kW
	Replacement Cost	$300/ kW
	O&M cost per operation hour	$10/ kW
	Size of the search space	0-1000 kW
H_2 Tank	Lifespan	25 years
	Capital Cost	$600/ kg
	Replacement Cost	$400/ kg
	yearly O&M Cost	$3/ kg
	search space	0-1000kg
Converter	Lifespan	25 years
	Efficiency	95%
	Capital Cost	$100/kW
	Replacement Cost	$100/kW
	Yearly O&M Cost	$10/kW
	Size of the search space	0-500kW

Because PV-based hybrid energy systems intermittently generate surplus electricity to ensure a constant power supply, the PV generator's power output far surpasses the energy need. Furthermore, the operational reserve is needed to prevent a full system shutdown in the event of an unexpected increase in power consumption. The system's energy discrepancy (217087 kWh/y) can be used to power the electrolyzer's subsystem

Table 3 shows the technological and economic aspects of a grid-connected PV/FC hybrid power plant. As shown, the hybrid PV/FC energy system implementation requires a somewhat high initial capital of $860,000, but the exceptionally low running cost of $20586.09/y suggests greater financial gain when compared to the traditional system (which requires an initial capital of $88,500). The cost of energy (COE) has dropped by 98.58 percent, from $7.39/kWh to $0.1052/kWh, and the dependability index, as evaluated by the LPSP, is now 0.004.

Table 4 compares the baseline and designed PV/FC grid-connected hybrid power systems in terms of the total emission. Table 4 demonstrates that using the proposed PV/FC hybrid power system may reduce CO_2 emission by 88.66 percent (from 145167 to 16465 kg/y) and CO emissions by 99.74% (from 145167 to 16465 kg/y). Sulfur dioxide was reduced by 86.61%, nitrogen oxides were reduced by 86 percent, and unburned hydrocarbons and particulate matter were reduced by 100%. The proposed hybrid system's large reduction of pollutant emissions (on average 93.51%) can help to make the environment greener.

Table 2. Hybrid system's optimum configuration.

Components	Size
PV	400 kW
Fuel Cell	250 kW
System Converter	240 kW
Utility Grid	500,000 kW (26,053kWh/y)
Electrolyzer	150 kW
Hydrogen Tank	700 kg

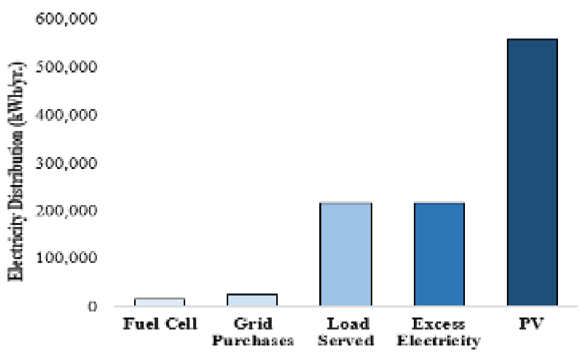

Fig. 4 Annual electricity distribution in developed system.

Table 3. System techno economy.

Parameter	Diesel Gen /Grid System	PV/FC/Grid Hybrid Power System
COE	$7.39 /kWh	$0.1052/kWh
NPC	$100,398,600	$2,147,445
Operating cost	$1,603,945	$20586.09/y
Initial capital	$88,500	$860,000
Renewable fraction	0	92%
LPSP		0.004%

Table 4. System emission characteristics.

Pollutants	System Emissions (kg/y)		Emission Reduction (%)
	Diesel Gen /Grid System	PV/FC/Grid Hybrid Power System	
CO_2	145167	16465	88.66
CO	263	0.702	99.74
Unburned Hydrocarbon	14	0	100
Particulate Matter	2.25	0	100
Sulfur Dioxide	533	71.4	86.61
Nitrogen Oxides	250	35	86

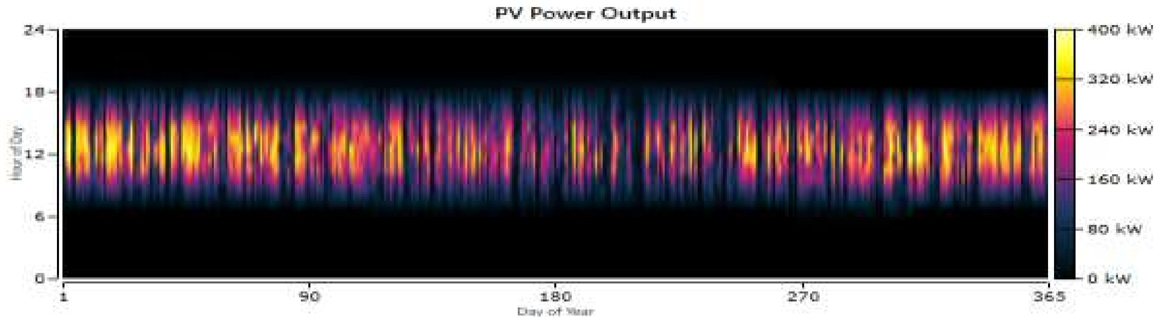

Fig. 5 PV-array output (kW).

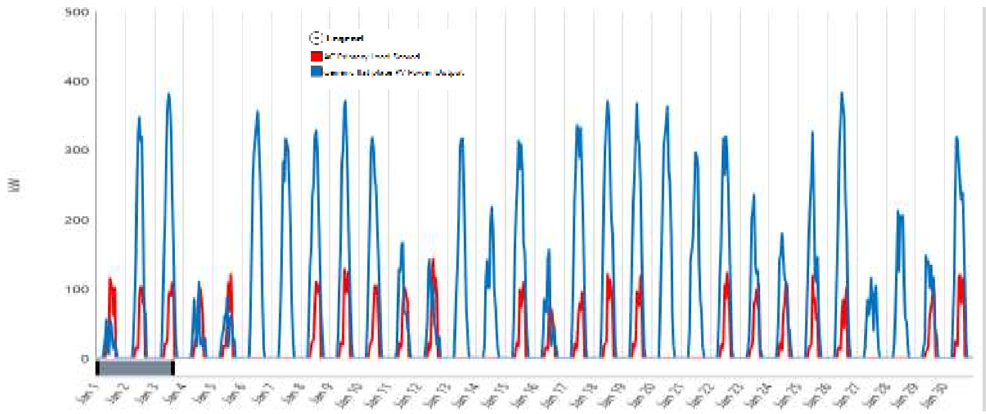

Fig. 6 Time series plot of PV-array output (kW) against load served.

Table 5. Cost-benefit analysis of the proposed hybrid power system.

Index	Value
Present Worth ($)	98,251,110
Annual Worth ($/y)	1,571,023
ROI (%)	200
IRR (%)	205
Simple Payback (y)	1.49
Discounted Payback (y)	0.46

As shown in Table 5, installing the PV/FC energy system with H_2 Tank (Storage) instead of a diesel generator system saves $98,251,110 (or $1,571,023) annually. This saves over 98 percent on energy costs (from $7.39 to $0.105/kWh). The high ROI indicates that the monetary benefits outweigh the costs. As illustrated, the PV/FC energy system has a 200 percent ROI over the traditional grid/diesel system. The IRR index measures a project's fund worth. The project's IRR of 205 percent compares well to the basic system.

The PV system produces an average of 1533 kWh per day for 4393 hours, with a capacity factor of 16%. Figs. 5 and 6 show the simulation results for the PV array subsystem. Fig. 6 presents the time series plot of the PV-array against the load served. As observed, the PV-Array generated a considerable amount of excess Electricity that far outweighs the load demand. This excess electricity is used by the electrolyzer for hydrogen production. For periods when the PV array output falls short of the load requirements, the FC-subsystem and the utility grid are used to augment this capacity shortage. This hybrid arrangement reduces the LPSP to 0.004.

The electrolyzer subsystem has an annual hydrogen production of 4,128 kg/y consuming a total of 217,087 kW/h of Electrical energy with a capacity factor of 16.5%. As shown in Figs. 7 and 8. As observed in Fig.8, the electrolyzer produces a maximum output of 2.85 kg/h of hydrogen and takes about 1.5 months to fill the hydrogen tank to a full capacity of 700 kg. Once the hydrogen tank is filled, the electrolyzer is only called into hydrogen production when there is a depletion of stored hydrogen as shown in Fig. 8.

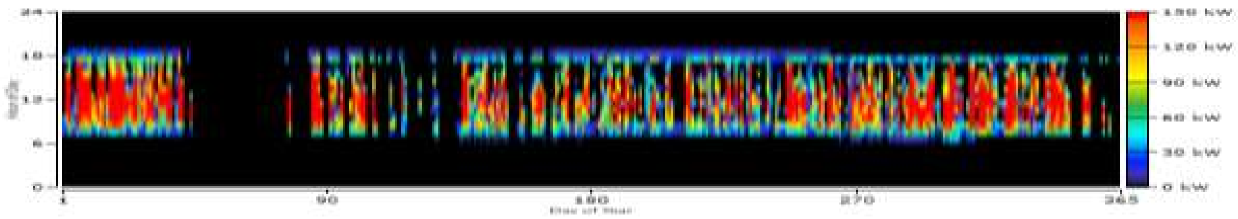

Fig. 7 Simulation result for electrolyzer yearly input power (kW).

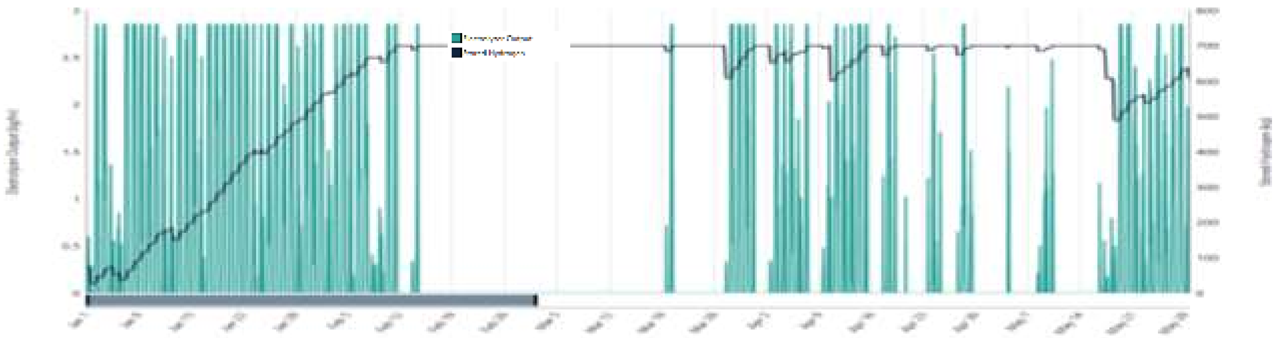

Fig. 8 Time series plot of electrolyzer output against stored hydrogen.

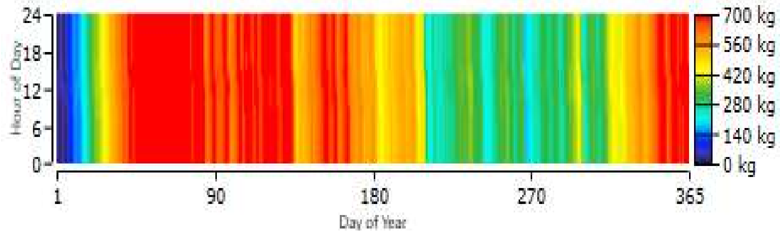

Fig. 9 Annual stored hydrogen tank level.

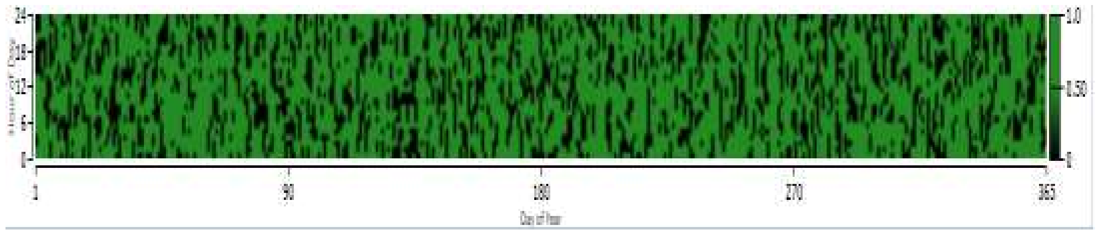

Fig. 10 Simulated grid outages.

The H_2 Storage Tank has a maximum capacity of 700 kg with an energy content of 233333 kWh. The average daily hydrogen consumption is 9.61 kg. Simulation results for The H_2 Storage Tank are presented in Fig. 9. As presented in Fig. 9, there is a capacity shortage only at the beginning of the operation and after about 1.5 months of production and usage, the electrolyzer can fill the hydrogen tank. After the initial shortage, the tank level remains at close to full capacity for over 70% of the time in a year. At the end of the year, the tank level is over 98%. This is because the PV/FC hybrid arrangement produces a lot of excess energy as observed earlier which can be channeled into H_2 production and even resold to the grid.

The utility grid is unreliable and is dispersed sporadically. The simulated result for grid outages for the study site is shown in Fig. 10. As shown, the black sports represent grid outages simulated for a year. The result shows that the utility grid is highly unreliable with a considerable number of outages. This shortcoming of the grid for the research location is mitigated by the proposed PV/FC hybrid power system. Due to the pending enabling legislation, the cost of reselling electricity to the power grid is $0. As a result, there is no way to sell electricity to the grid. If the necessary legislation and mechanisms for energy resale to the grid are in place, the increased financial advantages stated in Table 6 may be realized, which might stimulate the wider use of PV/FC hybrid energy systems in other areas of the economy.

4. Conclusion

Global interest in alternative power technologies is rising in response to the growing demand for a sustainable electricity supply. Inadequate electricity has led to the development of several hybrid energy systems. The techno-economic gains that may be obtained from a hybrid power system that incorporates renewable resources are dependent on the meteorology of the location. This research looked at the design and optimization of a PV/FC Grid connected hybrid power system to meet the load requirement of the University

Table 6. Simulation results of added benefits when legislation and mechanisms for energy resale to the grid are in place.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge ($)
January	754	7,791	-7,037	84.1	102.56
February	547	20,429	-19,876	76.7	74.44
March	711	23,587	-22,876	69.4	96.70
April	1,307	12,493	-11,186	162	177.80
May	2,719	10,243	-7,524	163	369.80
June	3,134	5,016	-1,882	166	426.19
July	3,951	1,172	2,779	156	537.37
August	4,858	2,479	2,379	186	660.67
September	2,369	3,642	-1,273	160	322.13
October	1,819	3,420	-1,601	138	247.37
November	2,430	5,951	-3,521	148	330.49
December	1,454	12,976	-11,522	163	197.75
Annual	26,053	109,201	-83,147	186	3,543

of Benin ICT Center in an inconsistent grid area. The energy-balance algorithms of HOMER were used to determine the best design architecture. The hourly simulations determined the hybrid system's optimum size, cost, and performance. According to the results, a hybrid PV/FC power system with a 400-kW solar array, a 250-kW FC, a 240-kW Inverter, and a 150-kW Electrolyzer with an H_2 Tank (storage) of 700 kg can reliably supplement the inconsistent grid with a high proportion (92%) of renewable resources at $0.1052/kWh. An energy cost reduction of approximately 88 percent, an ROI of 200 percent, and a present value of $98,251,110 could be obtained in less than 2 years over the traditional grid/diesel systems. The deployment of the PV/FC hybrid system may potentially assist in resolving the ICT Center's current power difficulties at a cost savings of more than 98%. Although the simulated PV/FC hybrid system creates surplus power that may be resold to the grid. Due to the pending enabling legislation, the cost of reselling electricity to the power grid is $0. As a result, there is no way to sell electricity to the grid. If the necessary legislation and mechanisms for energy resale to the grid are in place, the increased financial advantages stated in Table 6 may be realized, which might stimulate the wider use of PV/FC hybrid energy systems in other areas of the economy. Furthermore, hybrid PV/FC power systems can reduce CO_2 emissions, resulting in a more environmentally friendly and sustainable environment.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

ORCID

E. O. Okoduwa https://orcid.org/0000-0001-5899-4720
H. O. Imoedemhe https://orcid.org/0000-0001-5903-3817
P. E. Orukpe https://orcid.org/0000-0003-1317-7924

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