International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Evaluation of Conversion Efficiency of Excess Solar Energy into Hydrogen Using Electrolytic Cell

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A B S T R A C T

Energy conversion efficiency and excess energy utilization could be a feasible solution for mitigating the problem of power supply due to energy imbalance between the demand and generation in Nigeria. Solar energy resources is abundantly available but its exploitation through PV system is not always 100% efficient. In order to optimize the efficiency of solar PV power output, an auxiliary electronics device should be integrated with solar PV system to utilize the excess energy produced by the system. A solar PV hydrogen hybrid system was designed, constructed and experimentally tested. The solar PV hydrogen system comprised of solar PV modules of 160 W capacity, charge controller of 30 A capacity, inverter of 1000 W capacity connected to storage batteries of 150 Ah capacity as well as a reversible PEM fuel cell for hydrogen generation. The constructed system was tested under no load and on load conditions while exposing the PV module to sun radiation in Aliero. The effects of input parameters such as sun radiation and useful power input on PV, wind speed and ambient temperature were investigated. The experimental result showed that the PV modules has an average efficiency and fill facto of 18.72% and 0.916. While the average daily excess energy produced by the system was calculated as 150.29Whr/day, 4.00 Whr/day energy was used from the excess energy to power an electrolyser with an average efficiency of 76.15%. The hydrogen stored was later converted to electricity via a fuel cell with an efficiency of 23.05%. The overall efficiency of the system experimentally tested is 3.27%.

Keywords: Renewable Energy, Solar Radiation, Solar PV System, Off-Grid, Efficiency.

1. Introduction

Energy is the capacity to do work and power is the rate of energy delivery. Energy is an essential commodity for most human activities, directly as fuel or indirectly to provide power, light and mobility (Stern, 2011). The main source of energy for the last 150 years has been non-renewable sources like petroleum, natural gas, coal and others. However, the world is running out of this source rapidly and there are detrimental effects of its use such as pollution, climate change and global warming (Jerimiah, et. tal. 2013). Currently the world population is over 7.2 billion and energy demand per person have increased, the increased energy demand issues related to energy safety and environmental impacts related to mainly to the use of non-renewable sources brought up the need to use also other sources of energy that are clean (Radim et. tal. 2015). Therefore, a transition from non-renewable sources towards renewable sources for energy generation is unavoidable. In Nigeria there is an issue of inadequate supply of electricity from the public utilities which has led to a situation where the nation is wallowing in darkness and the economy is underdeveloped despite the country's vast renewable and non-renewable energy resources. The geographical location of Nigeria near the equator and being located within a high sunshine belt are the core promising indicators that an enormous amount of electricity can be generated and utilized in the country by using solar PV modules (Ndeceko, et. tal. 2014). There is unavoidable and serious drawback associated with solar PV modules, the solar PV modules operation is highly seasonal which means we can have periods of limited sun and variation in intensity due to cloudy and rainy days. This drawback is solved by using a solar battery storage system which stores energy generated during peak hours and make it readily available for use when necessary. But when the battery is fully charged, there will be an excess energy which is not utilized. This excess energy in form of electrical energy can be circumvented and stored in other forms for later use. To convert the energy into hydrogen gas, an electrolyser which converts electrical energy into hydrogen gas via water electrolysis is needed. Water Electrolysis is a chemical process that is powered by electrical energy to decompose water into hydrogen and oxygen. The hydrogen gas produced from the electrolysis can further be reconverted to electricity by the use of fuel cell which utilizes hydrogen gas to produce electricity (Ramani, 2006). The efficiency of converting the excess solar energy into hydrogen was evaluated and investigated in this research work.

1.1 Renewable Energy

Renewable energy is energy that has been derived from earth's natural resources that are not finite or exhaustible. Renewable energy resources include solar energy, wind energy, biomass, hydroelectric energy, geothermal energy, hydrogen energy and others (Mikkel, 2017). Nigeria is naturally endowed with abundant renewable energy resources especially solar irradiation (Esan, et. tal. 2019). .

1.1 Solar Energy

Solar energy is the term used for the heat and light which the sunlight contains. Sunlight reaches to earth in the form of photons. Photons are energy packets that contain light in it (Zarma, et. tal. 2017). . Solar radiation incident on the earth's surface varies in intensity with location, season, day of the month, time of day, instantaneous cloud cover and other environmental factors (Corkish, et. tal. 2016). There are basically three ways that we can use the solar energy. The first is by solar cells in which photovoltaic or photoelectric cells are used to convert light directly into electricity. The second is solar water heating in which the heat from the sun is used to warm the water in glass panels therefore no longer requiring gas or electricity to heat the water. The third is solar furnaces which use mirrors to capture the sun's energy into a congested place to produce high temperatures (Zarma, et. tal. 2017). .

1.2 Solar Photovoltaic System

A solar photovoltaic system is a system that supply electric energy to a given load by directly converting solar energy through the photovoltaic effect. (Amuzuvi, et. tal. 2014). . There are basically two kinds of solar power systems through which electricity can be generated. These include: On-grid solar PV system and Off-grid solar PV system (Maddileti, & Likhithasree, 2019).

1.3 On-Grid Solar Photovoltaic System

On-grid solar photovoltaic system is the system that generates electrical power with the help of solar photovoltaic panels and delivers the power to electric utility. Components involved in the system are: Photovoltaic Module, Junction Box, On-Grid Inverter, AC disconnect & Main Panel, Net Meter, Electrical Grid and load (Kumar, et. tal. 2018). Fig. 1 shows a schematic View of on-grid solar PV system. The solar PV modules generates DC power, all the PV strings are joined together at the junction box, the inverter converts the DC power to AC power, the AC disconnect separate the on-grid power inverter from the electrical utility grid, the net meter monitors the inflow and out flow of electricity between the solar PV modules and the utility grid, the electric grid is an electric power network interconnecting the load centers an energy providers.

1.4 Off-Grid Solar PV System

Off-grid solar PV system also known as stand-alone power system has battery storage instead of the connectivity to the electricity grid. It consists of solar panels, charge controller, batteries, inverter and load (Kumar, et. tal. 2018). The off-grid system refers to the support that would be adequate for a living without depending on the grid or other system (Khamisani, 2023). Fig. 2 shows a schematic view of off-grid solar PV system. The solar PV modules generates DC power, the charge controller controls the charging of batteries, the batteries stores energy and feed the load when needed through the DC/AC inverter, the load is powered by the power from the inverter.

1.5 Solar PV Module

The basic building block of a PV module is the solar cell which converts solar energy into electricity. Different solar cells in a unified set, all arranged in the plane represents a solar photovoltaic board or module. PV modules usually have a glass in front of the panel, allowing light to pass through, while ensuring that the semiconductor plate is protected inside the case (Khamisani, 2023). The silicon is treated or "doped" so that when light strikes it electrons are released, so generating an electric current. The solar cell consists of three parts namely n-type layer, the depletion layer and the p-type layer. Light is captivated into the depletion layer. Which consists of neutral atoms, the photons emitted by the sunlight are penetrated into the depletion layer making a free electron and a hole. The free electrons move toward the n-type layer and the holes goes down to the p-type layer. Thereby connecting a wire between the top and bottom layer electrode provides a pathway for the electrons to move towards hole which constitutes an electric current (Maddileti, & Likhithasree, 2019).

There are three dominating cell technologies of solar PV modules in circulation:

- Monocrystalline
- Polycrystalline and
- Thin Film

The practical efficiencies of the three solar PV modules are as follows: - Monocrystalline (15-20%), Polycrystalline (13-16%) and Thin Film (9-11%) (Adeel, et. tal. 2019). The solar PV module adequate sizing with respect to load is very essential, the sizes of the modules and there arrangement for a specific load demand could be determined by using equation 1, 2 and 3.

$$M_T = \frac{P_L}{\eta_D * S_P * P_m} \quad (1)$$

Where $M_T$the number of PV modules is needed for a solar PV system, P_L is the load power, $S_P$is the peak sun hours of a location and P_m represents the module power.

For the Number of modules needed in series M_S, it is given by

$$M_S = \frac{V_{ns}}{V_{ms}} \quad (2)$$

Where V_{ns} is the system nominal voltage and V_{ns} is the module nominal voltage

For the Number of modules needed in parallelM_P, it is given by

$$M_P = \frac{M_T}{M_S} \quad (3)$$

Where M_T represents the number of modules needed and M_S is the number of modules in series.

The efficiency of a PV modules at maximum power, $\eta_{max.STC}$ is given by equation 4.

$$\eta_{max.STC} = \frac{I_{max} \times V_{max}}{A_{PV} \times G_{T.STC}} \times 100 \quad (4)$$

Where $\eta_{max.STC}$is the efficiency under test condition, I_{max} is the maximum output current (A), V_{max} is the maximum output voltage (V), A_{PV} is the area of PV module (m^2) and $G_{T.STC}$ is the radiation at standard test condition (1KW/m^2)

Or

$$\eta_{max.STC} = \frac{F.F \times I_{sc} \times V_{oc}}{A_{PV} \times G_{T.STC}} \times 100 \quad (5)$$

Where F.F is the fill factor equivalent to ratio of maximum load power to maximum input power,

Mathematically.

$$F.F = \frac{I_{max} \times V_{max}}{I_{sc} \times V_{oc}} \quad (6)$$

For the power input of a solar PV module *P* the relationship below is used

$$P = Ir * A \quad (7)$$

Where Ir is the solar Irradiance (W/m^2) and A is the area of the PV module (m^2)

For the power output of a solar PV module (W) the relationship below is used

$$P = I \times V \quad (8)$$

Where I is the output current (A) and V is the output voltage (V).

1.6 Load Demand

Load demand profile determines the number of electric components desired to be powered by electric power system in a particular power system in a particular setting. The electrical energy consumption in Wh/day from a typical office setting in the study area is necessary for adequate component sizing and efficiency power supply from the source to the load. Mehmed et al., (Mehmed, et. tal. 2011) used equation 9 for estimation of total energy demand.

$$E_{ed} = \sum_{i=1}^{n} I_n V_n D_n \quad (9)$$

Where $I_n V_n D_n$ are total power demand and duty cycle of each electrical appliance in a setting.

Batteries are energy storage devices used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed during the night and periods of cloudy weather. In most cases, a battery charge controller is used in the solar PV systems to protect the battery from overcharge and over discharge. The capacity of the required batteries for the system could be determined by using equation 9 as adopted by (Mehmed, et. tal. 2011).

$$Ih = \frac{\alpha E_d}{\eta_s V_s \left(1 - SOC_m / 100\right)} \quad (10)$$

Where, Ih is the required power capacity of the battery, V_s is the voltage supply, $SOC_m$is the minimum state of charge of the battery, α is the days of autonomy and η_s is the system efficiency.

A charge controller is basically a voltage and/or current regulator, to keep batteries from overcharging. It regulates the voltage and current coming from the solar panels and going to the battery (Osaretin, & Edeko 2016). Charge Controller sizing for short circuit current A_{SC} is given as

$$A_{SC} = I_{mp} \times M_P \times 1.25 \quad (11)$$

Where I_{mp} equals to the current at maximum power, M_P is the number of modules in parallel and 1.25 is to take care of the starting current of the equipment.

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits (Gaurav, et. tal. 2015). To determine the size of inverter for the system, equation 12 can be used.

$$INV_R = \frac{PL_{max}}{\eta_L} \quad (12)$$

Where, PL_{max} is the maximum load and η_L is the inverter efficiency.

1.7 Solar PV Hydrogen System

Solar PV hydrogen system comprises of a standard Solar PV system with the addition of an electrolyser, fuel cell and storage tanks. The Solar PV module utilize sun radiation to generate electricity which is stored in the batteries through the charge controller. The energy stored in the batteries is feed into the load through an inverter. When batteries become fully charged the charge controller diverts the excess electricity to damp load. The damp load is usually a heater which dissipate the excess energy into heat to the environment. However, the electrolyser used serves as damp load to utilize the excess electricity and water into hydrogen and oxygen by using principle of electrolysis (Ramani, 2006). The hydrogen could then be used to power a fuel cell which produces electric current into the system.

1.8 Electrolyser

An electrolyser is an electrochemical device that convert electricity and water into hydrogen and oxygen via water electrolysis (Ramani, 2006).The process must have an electrical input, which can be provided by both renewable and non-renewable sources, in this work the excess solar PV modules provided the power.

The energy efficiency of electrolyser η_{EL} can be measured by calculating the energy available from the hydrogen produced by the cell, using the higher heating value of hydrogen (HHV) and dividing this by the energy consumed by the cell as shown below.

$$\eta_{EL} = \frac{\left(\text{HHV of } H_2 \text{ produced}\right) * M_{H_2}}{E} \times 100 \quad (13)$$

Where HHV = higher heating value (kWh)

E = electrical energy input (kWh)

Also, electrolyser efficiency can be expressed in terms of output power and input power.

$$\eta_{EL} = \frac{\text{Output Power}}{\text{Input Power}} \times 100 \quad (14)$$

$$\eta_{EL} = \frac{P_{output}}{P_{input}} \times 100$$

Where $P_{input} = I_{input} \times V_{input}$ (15)

$$P_{output} = \text{hydrogen flowrate}\left(\frac{kg}{hr}\right)*\text{HHV of hydrogen}\left(\frac{KWhr}{Kg}\right) \quad (16)$$

To convert hydrogen flow rate from mg/min to g/min, we multiply the flow rate with the density of hydrogen which is 0.00009g/cm^3.

$$m = e*V \quad (17)$$

Where m = mass of hydrogen

e = density of hydrogen

V = volue of hydrogen

To convert the hydrogen mass flow rate from g/min to Kg/hr, we use the relationship

$$\frac{Kg}{hr} = \frac{g}{min}*\frac{Kg}{1000}*\frac{60min}{1hr} \quad (18)$$

The higher heating value of hydrogen is given as 39.4kWhr/kg or 142MJ/kg [Haynes, 2017].

1.9 Fuel Cell

Fuel cells are electrochemical devices that directly convert chemical energy to electrical energy. They consist of an electrolyte medium sandwiched between two electrodes. One electrode facilitates electrochemical oxidation of fuel, while the other promotes electrochemical reduction of oxidant [Ramani, 2006]. Fuel cells are classified on the basis of electrolyte and the type of fuel used, which determines the electrode reaction and the type of ions that carry the current across the electrolyte. Most fuel cells underdevelopment today use gaseous hydrogen, or a synthesis gas rich in hydrogen, as a fuel [Verma et. tal. 2015]. The efficiency of fuel cell can be calculated as the electrical energy output of the cell divide by the higher heating value of the mass of hydrogen (HHV) used by the cell as shown below [Verma et. tal., 2015].

$$\eta_{fc} = \frac{E}{E\left(\text{HHV of } H_2 \text{ produced}\right)*M_{H_2}} \times 100 \quad (19)$$

Where HHV = higher heating value (kWh)

E = electrical energy output (kWh)

Fuel cell efficiency can also be expressed in terms of cell input power in form of hydrogen gas and output power which is electric power.

$$\eta_{fc} = \frac{\text{Output Power}}{\text{Input Power}} \times 100 \quad (20)$$

$$\eta_{fc} = \frac{P_{output}}{P_{input}} \times 100 \quad (21)$$

2. Methodology

In order to design a solar PV hydrogen system for any location, the peak sun hours of the location, days of autonomy, load demand and other parameters are mostly required. These parameters were essentially used for the estimation of solar panels, charge controller, inverter, electrolyser, fuel cell and battery bank sizes. The study was conducted at the Kebbi State University of Science and Technology, Aliero, located in Kebbi State latitude 12.2737 and longitude 4.451.

2.1 Solar PV Modules Sizing

The renewable energy resource used in this research is solar radiation. The load demand of an office setting was obtained by conducting a survey to identify energy consumption of electrical appliances commonly used by a typical office. The summary of the Office load requirement is presented in Table 1. The size of solar PV module was obtained by using the total load power of 150 W, 5.02 hr peak sunshine hours of the area, 80 W module power, 24V system voltage, and system efficiency of 0.73 in Equation 1. While the number of modules in both series and parallel arrangement were obtained from Equation 2 and 3. The module size was estimated as 0.5 while the number of modules in series M_S was found to be, $M_S = 2$ Modules and number of modules in parallel M_P was found to be $M_P \approx 1$.

Table 2.1 Summary of the Residential Load Requirements

S/N	Component	Quantity	Power Rating (W)	Load Demand (W)	Hours of Operation (hr)	Energy Demand (Whr)
1	Bulb	3	10	30	5	150
2	Fan	1	55	55	5	275
3	Laptop	1	65	65	5	325
	Total			150		750

2.2 Storage Batteries Sizing

Considering the total energy demand of 750 Whr, system efficiency of 0.73, system voltage of 24 V, minimum state of charge of 40%, 5 hours of daily operation and 2 days of autonomy, the battery capacity was estimated to be (142 Ah, 24 V) using Equation 10. Two batteries of 75 Ah 12V capacity were connected in series to have net capacity of 150 Ah 24 V.

2.3 Charge Controller Sizing

The size of the charge controller for charging the battery was estimated by using Equation 11, with maximum power current of 4.44 A, 1 module in parallel and the starting current of 1.25 A the charge controller was estimated to be 5.55 A . A charge controller with 30 A rating was selected for the research.

2.4 Inverter Sizing

By substituting the maximum load power of 150W, 90% efficiency for inverter and 25% of the total load into Equation 12, the inverter specification was estimated to be 167 W. 1000 W inverter was selected for the research.

2.5 Electrolyser Sizing

The size of electrolyser was determined by dividing the energy produced by the PV module by the efficiency of the electrolyser using the standard efficiency of 79% given by the manufacturer. A reversible fuel cell which functions as both electrolyser and fuel cell was used in this work.

2.6 Experimental Setup

The materials used in this research were connected in the following order. Two solar PV modules of 80 W ratings were connected in series and mounted on top of the office's roofing with a connecting wire extending to a charge controller of 12V/24, 30 A rating in the office, a Multimeter was connected in between the two components for measuring the output data of the PV modules. The charge controller was connected to two storage batteries of 150 Ahr capacity and an electrolyser, the batteries were linked to an inverter of 1000 W capacity. Two storage containers foe hydrogen and oxygen were also connected to the electrolyser. The office load was connected to the output terminal of the inverter. Pyranometer and Anemometer were used for measuring solar irradiance and ambient temperature.

2.7 Data Collection

To investigate the performance of the PV module, the Solar Irradiance (W/m^2) of the location was measured using Pyranometer and ambient temperature (^0C) was measured using Anemometer, while the solar PV module output voltage (V) and output current (A) were measured using Multimeter. These data were measured from 8:00 AM to 6:00 PM at the intervals of 20 minutes in 4 days from 18th to 21st December 2021. Average hourly data, average daily data and the average data for 4 days was computed. See Table 2 for the 4 days average data. Furthermore, the solar off-grid PV system (standalone) performance was investigated by collecting the following sets of data, the solar irradiance (W/m^2) of the open space, the solar PV module output voltage (V) and output current (A) under load and no load conditions, the input/output voltages (V) and currents (A) of the inverter under load and no-load conditions were also recorded. These data were measured from 8:00am to 6:00pm at intervals of 20 minutes in 5 days from 23rd to 27th December 2021 Average hourly data, average daily data, the average data for 5 days was computed See Table 3 for the 5 days average data. Also, data collected from the reversible fuel cell includes, electrolyser input current (A), electrolyser input voltage (V), electrolyser hydrogen flow rate (mL/min), electrolyser oxygen flow rate (mL/min), fuel cell output current (A) and output voltage (V).

2.8 Data Evaluation

The recorded data from the experimental works were used in physical equations for evaluation of some useful figures of merits. The solar irradiance measured was used to find the input power of the solar PV module by multiplying it with the area of the PV modules by using Equation 7. The current and voltage values at the PV outlet were substituted into Equation 8 to determine the output power of the PV modules. By substituting the input and the output powers into Equation 6 and 7, the fill factor and efficiency of the PV module was obtained.

The output voltage (V) and output current (A) measured from the charge controller were used to find the power output, excess energy of the system and the input energy of the electrolyser using Equation 8. Mass of the hydrogen produced was converted into power using the higher heating value of hydrogen gas as stated in Equations 16 and 18. The output voltage (V) and output current (A) measured from the charge controller and the mass of hydrogen produced were also used to find the efficiency of the electrolyser using Equations 13 and 14. The output voltage (V) and output current (A) measured from the fuel cell and the mass of hydrogen used by the fuel cell were also used to find the efficiency of the fuel cell using Equations 19 and 20. The individual efficiencies of each component was multiplied all together to find the overall system efficiency.

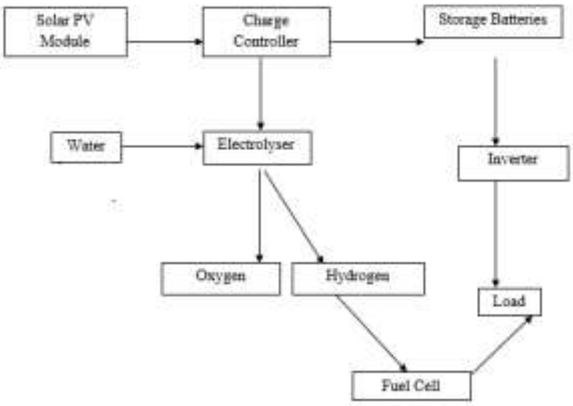

Fig. 1 - Block Diagram of Solar PV Hydrogen System

3. Results and Discussion

3.1 Effect of Solar Irradiance on Short Circuit Current

The correlation between solar irradiance and short circuit current is presented in Figure 2. It showed that Aliero has maximum average daily solar irradiance of 991.58 W/m2. This result is very close with what (Bako, 2022) obtained which is 975.88 W/m2. From this solar irradiance, the two 80 W PV modules of dimension 1.02 m^2 has consequently captured 1011.4 W to produce a short circuit current of 4.38 A which is very close to the manufacturer's specification of 4.49 A at STC (1K W/m2). The maximum value of short circuit current obtained from the solar PV modules is 4.38A which is 97.55% of the predicted value of 4.49 A by the manufacture of the PV modules. The rising and falling of the short circuit current from morning to evening was due to the seasonal and periodic variability of solar radiation.

3.2 Effect of Solar Irradiance and Open Circuit Voltage

The correlation between solar irradiance and open circuit voltage is presented in Figure 3, the result indicated that the open circuit voltage is not much affected by the solar irradiance because the difference between the maximum and lowest voltage attained throughout the day was just 11 V although the solar irradiance varies with a very wide margin. Furthermore, this shows that the power output of PV module is mostly affected by the short circuit current variation while the open circuit voltage is slightly perturbed. Also, the maximum open circuit voltage obtained from the solar PV modules was 46.4 V which is just 3.79% above the predicted value by the manufacturer of the PV modules.

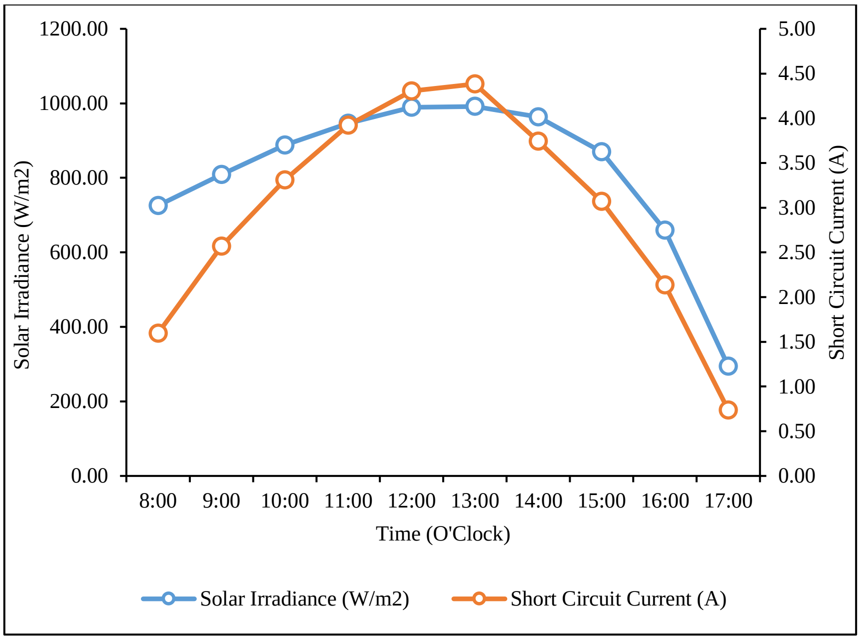

Fig. 2 - Effect of Solar Irradiance on Short Circuit Current

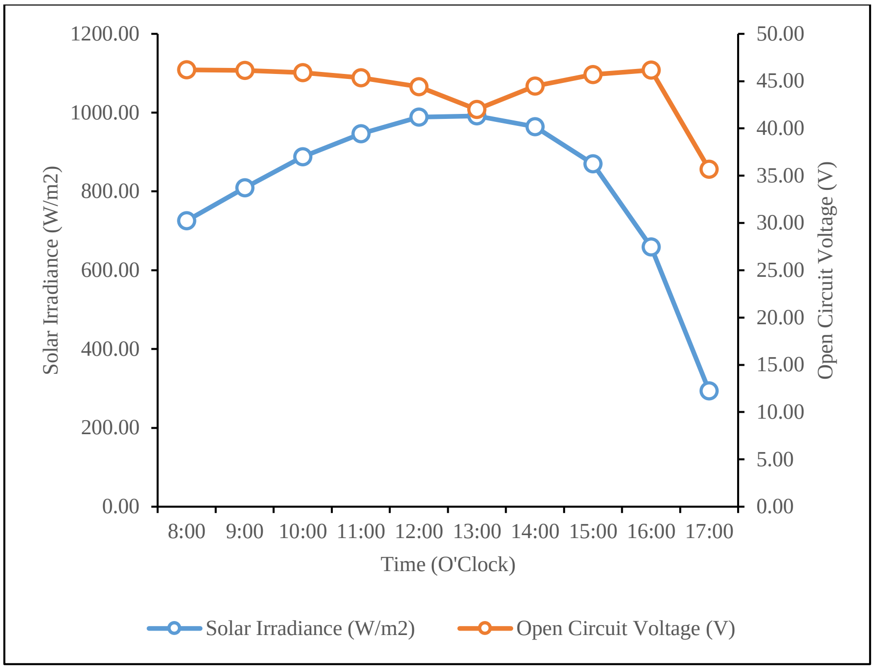

Fig. 3 - Effect of Irradiance and Open Circuit Voltage

3.3 Effect of Solar Irradiance on Ambient Temperature

Figure 3 result showed that ambient temperature varies directly with the solar irradiance because solar irradiance provides heat energy to the environment. But the graph shows that fall in temperature in the late hours of the day is not as rapid as raise in temperature in the morning this is due to the greenhouse effect that slows thermal radiation into space.

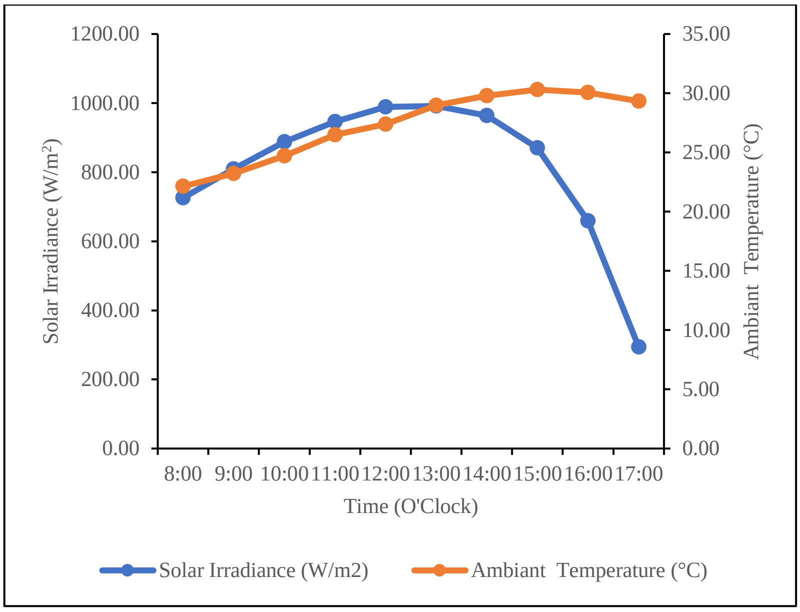

Fig. 4 - Effect of Solar Irradiance on Ambient Temperature

3.4 Effect of Ambient Temperature on Open Circuit Voltage

Figure 5 showed the graph of correlation between ambient temperature and open circuit voltage, the result confirmed that the open circuit voltage decreases with increase in temperature due to a reduction of the intrinsic carrier concentration as stated by (Matthias, et. tal. 2021).

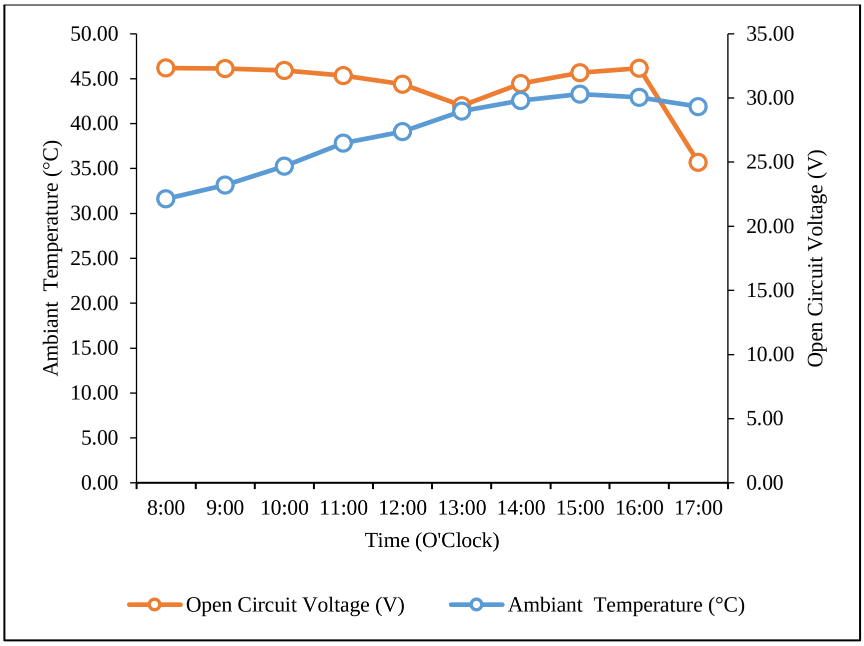

Fig. 5 - Effect of Ambient Temperature on Open Circuit Voltage

3.5 Current-Voltage Characteristics of The Solar PV Modules

Figure 6 presents the graphs of current-voltage characteristics of the PV module for four days average. The average maximum power was 190.92 W, at 4.3 A and 44.40 V. While the short circuit current and open circuit voltage are 4.50 A and 46.21 V. An average efficiency of 18.72% and fill factor of 0.918 were calculated by substituting the values of maximum output power, short circuit current and open circuit voltage values into equation 5 and 6. The maximum short circuit current of 4.5A recorded is very close to the predicted value of 4.49 A by the manufacture of the PV modules. Also, the maximum open circuit voltage of 46.21 V recorded is more than the manufacturer's predicted value of 44.64 V by just 3.52%. For the maximum power output of 190.92W calculated, it is more than the predicted value (168 W) of the manufacturer by 12.00%. The average fill factor of 0.918 recorded from the experiment is just 9.5% more than the maximum predicted value of 0.8383 provided by the manufacturer of the PV modules. Furthermore, the theoretical predicted efficiency of 16.47% is very close to the average efficiency calculated from the experiment (18.72%). The modules average efficiency of 18.72% falls within the range of standard PV module efficiency as mentioned by (Kumar, et. tal. 2018).

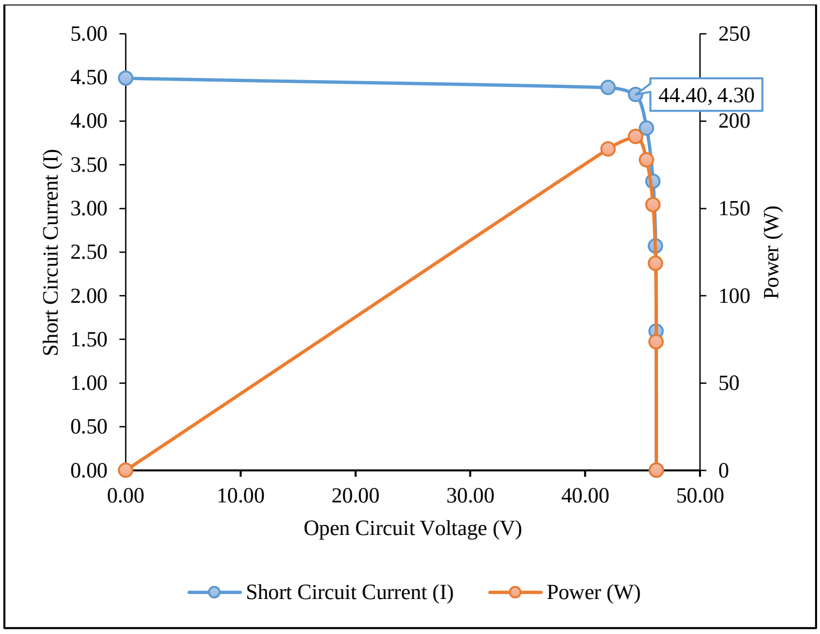

Fig. 6 - I-V Characteristics of the Solar PV Modules

3.6 Relationship Between Fill Factor and Efficiency

The result of correlation between fill factors and efficiencies for four days is presented in Figure 7. The graph clearly shows a linear correlation between the two quantities which means the higher the fill factor, the higher the efficiency and the lower the fill factor, the lower the efficiency.

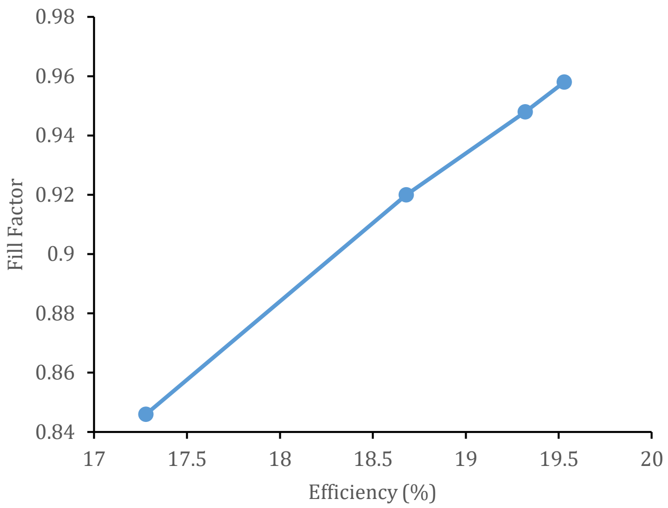

Fig. 7 - Graph of Solar PV Module Efficiency and Fill Factor

3.7 Excess Solar Energy

Table 3.1 shows the excess energy produced by the PV system within the working hours. The excess energy was calculated by subtracting the load energy from the PV output energy under load condition. The load energy and PV output energy were evaluated by multiplying the hourly average powers by 1 hour. The difference between the PV output energy and load energy is the excess energy. The total excess energy per day was calculated as 150.29Whr which is 26.38% of the total energy output (569.70Whr) of the PV modules per day.

Figure 8 presents the correlation between excess energy and local time. The result showed that at 08:00AM the energy generated by the PV modules was 54.55Whr from which 46.23Whr was used to power the system, the difference was calculated as 8.32Wh which represents the excess energy at that hour. The peak excess energy of 27.37Whr was obtained at 12:00 pm when the PV modules output energy was 72.79Whr. Between 08:00 am to 04:00 pm the net excess energy was positive, but after 04:00 pm it became negative. This is due to the fact that between 08:00 am to 04:00 pm the PV output energy was greater than the load energy demand and for the last two hours, the load energy was greater than PV output energy. Part of the excess energy was used to power the electrolyser, because the electrolyser used only 4.00 Whr to function. Consequently, 146.29 Whr excess energy still remained.

Table 3.1 Summary of Excess Energy Produced By the System

PV Output Energy-On load (Whr)	Load Energy (Whr)	Excess Energy (Whr)
54.55	46.23	8.32
61.71	45.58	16.13
65.15	45.13	20.02
67.32	46.28	21.04
72.79	45.42	27.37
71.40	45.59	25.81
63.15	45.16	17.99
59.95	46.34	13.61
44.29	46.14	-1.85
9.39	46.50	-37.11

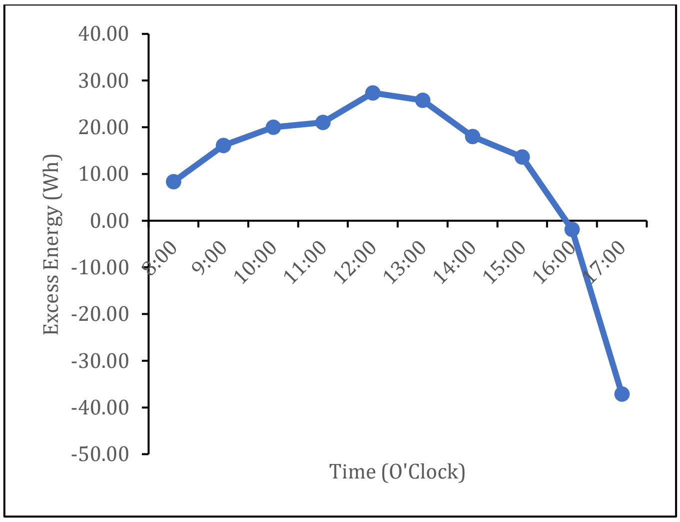

Fig. 8 - Graph of Correlation between Excess Energy and Local Time.

3.8 Results of Solar PV System Performance

By considering the correlation between PV modules under load and no load outputs and useful power inputs as presented in Figures 9 and 10, the result indicated that the PV modules with 1.02 m^2 dimension captured maximum useful power input of 805.42W and generated 75.88 W under no load conditions. While, under load condition, the PV modules harnessed 805.42 W to generate 72.79 W as shown in Figure 9 These results showed that the PV power output under load is always less compared to when it is under no load condition as shown in Figure 10. The results also showed that the PV output power depends on the useful power input which in turns depends on the intensity of solar radiation.

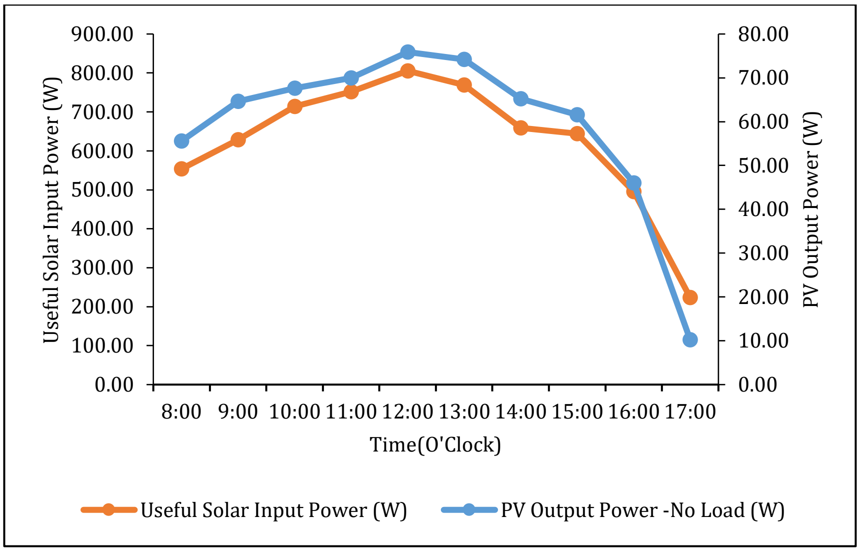

Fig. 9 - Graph of the Correlation between the Useful Solar Input Power and Useful Solar PV Output Power under No-Load Condition.

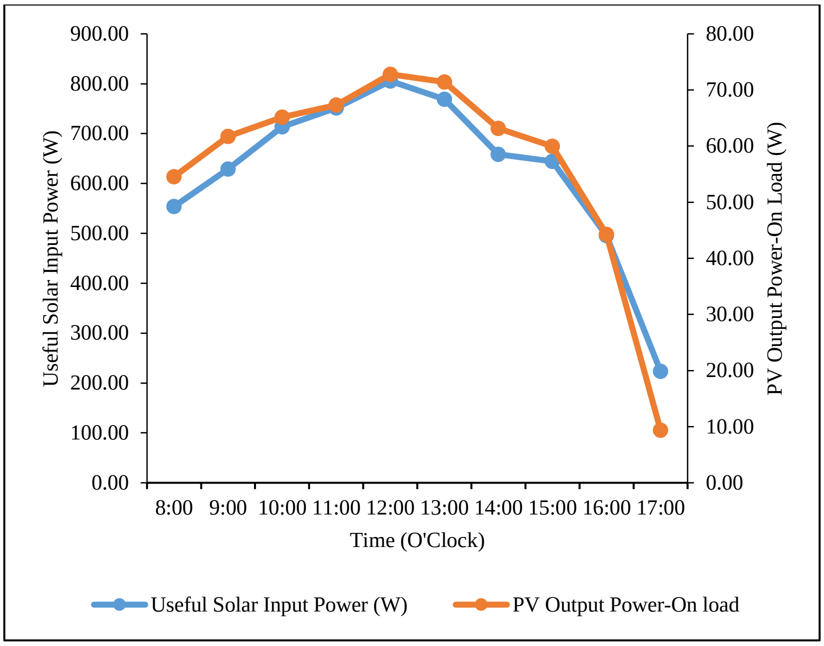

Fig.10 - Graph of the Correlation between the Useful Solar Input Power and Solar PV Output Power On-Load Condition.

3.9 Result of Electrolyser Performances

The result from Figure 11 showed the efficiencies of the electrolyser under variable input power values. The ratio of output to input is what gives the efficiency of the converting excess energy into hydrogen and also represents the efficiency of electrolyser. The efficiencies were found to be (84.19%, 82.12%, 81.73%, 76.34%, 72.12%, and 67.82%) and the average efficiency of the electrolyser was calculated as 76.15%. This value is in tandem with what (Wang, et. tal. 2022) stated as the standard efficiency of PEM electrolyser which is between 67% and 82%.

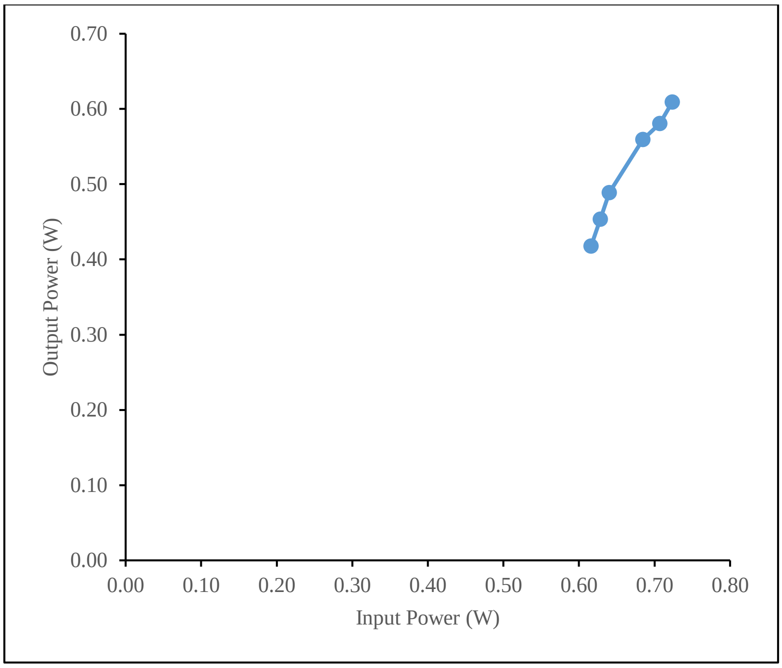

Fig. 11 - Graph of Correlation between Electrolyser Input and Output Powers

It can be seen from the graph that the intercept on the input power axis is not zero, this implies that for an electrolyser, certain threshold of input power must be exceeded before it can produce any useful output power.

3.10 Results of Fuel Cell Performances

The data from Table 3.2 shows fuel cell performance. The efficiencies of the fuel cell were calculated by the taking the ratio of output power to the input power. The average efficiency of the fuel cell was calculated as 23.05%. The average value is less than the standard fuel cell efficiency of 40%-60% as stated by (Gholam, 2023).

Table 3.2 Summary of Fuel Cell Performance

Voltage(V)	Current(A)	Fuel Cell Output Power(W)	Fuel Cell Input Power(W)	Efficiency (%)
0.450	0.320	0.144	0.609	23.65
0.440	0.300	0.132	0.581	22.73
0.435	0.290	0.126	0.559	22.55
0.420	0.270	0.113	0.489	23.21
0.410	0.255	0.105	0.453	23.07
0.402	0.240	0.096	0.418	23.09

3.11 Total Efficiency of the System

The total efficiency of the system was calculated by multiplying the efficiencies of solar PV modules (18.72%), electrolyser (76.15%) and fuel cell (23.05%). For the conversion of solar radiation to hydrogen gas, the efficiency is 18.64% of 76.15% which is 14.19%. This value is above what (Thomas, & Nelson, 2010). achieved (i.e. 12.4%). The value is also within the range achieved by (Gül, & Erisin, 2020) who calculated the efficiency of converting solar radiation to hydrogen gas using PEM electrolyser as within 13.7-15.7%. The overall efficiency of the system was found to be 3.27%. Which is above what (Jerimiah, F. et. tal., 2013) were able to achieved (i.e. 2.35%).

Conclusion

The off-grid solar PV hydrogen system has been experimentally tested and evaluated both under no load and on load conditions. The specifications of PV modules, storage batteries, charge controller and inverter for supplying a typical load demand of an Office in Aliero were determined. The total power production of the system is from the solar PV modules and fuel cell and all depend on intensity of solar radiation. Excess energy from the system was realized by subtracting load demand power from total power produced from the modules. An electrolyser utilized the excess energy of the system and produced both hydrogen and oxygen gases. The hydrogen was later used to power a fuel cell which utilizes the gases to produce electricity. The efficiencies of the system was evaluated. The results revealed that solar PV hydrogen system is technically and economically feasible. Therefore solar PV hydrogen system could be used to mitigate the problems of power generation and consumption.

Acknowledgements

Our profound respect and gratitude goes to the Head of Physics Department Kebbi State University of Science and Technology Aliero, Nigeria and the entire staff members of the Department for their kind support and advice during this research.

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