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RESEARCH ARTICLE OPEN ACCESS

Development of a stand-alone photovoltaic (PV) energy system with multi-storage units for sustainable power supply

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Abstract. The sizing of the energy components is essentially designed to prevent outages and ensuring the reliability of the power supply. This paper focuses on the development of a stand-alone photovoltaic/battery/fuel cell power system considering the demand of load, generating power, and effective multi-storage strategy using a probabilistic sizing algorithm. A computer program was developed and used in the design of component sizing configuration of a stand-alone power system that comprises of a photovoltaic generator (PV), battery, water electrolyzer, a storage gas tank, a fuel cell, and an inverter for a reliable power supply. This program manages the energy flow through the various components of a stand-alone PV/battery/fuel cell power system and provide an optimal technical configuration. The optimum system configuration of a residential building with daily power demands of 69 kWh/day energy consumption is composed of PV arrays resulting in total rated power of 15 kW, 16 units of 6 V, 225 Ah battery bank, 5.5 kW fuel cell, 5.5 kW Water Electrolysis, 16.5 kg hydrogen tank, and a 5.5 kW inverter. Based on the simulation results conducted, it was shown that the sizing and development of a stand-alone PV/battery/FC energy system have been achieved with system reliability (loss of power supply equal to zero). This program could be used as a power monitoring and control system for a stand-alone PV/battery/fuel cell power system.

Keywords: Battery / electricity / electrolyzer / fuel cell / hydrogen / LPSP algorithm / photovoltaic system

1 Introduction

Electricity is one of the most requirements of mankind and it plays an important role in the development of a community as it is used to power up residential buildings. Solar, as the most abundant energy resource on earth, is a major renewable source with great potential for stand-alone applications. Solar energy technologies are the most sustainable renewable energy technologies (RETs) because of their capability to operate with zero or minimal amount of greenhouse gases emissions [1–3]. Solar energy is one of the most popular renewable energy (RE) as the sunshine is ample and available in the wider region as compared to other RE resources [4]. Solar-photovoltaic systems can be localized and decentralized and this allows end-users to generate their electricity wherever they are located [5]. Photovoltaic (PV) power has provided power to many remote communities especially in the developing world where the national grid is technically not viable. PV systems can range from a small system capable of providing power for a single home to a large system that can power a village or an island. The world's largest individual PV power plants that produce more than 250 MWP are Agua Caliente Solar Project in Arizona, the USA, and California Valley Solar Ranch in the USA [6].

The availability of solar energy sources depends on weather and environmental conditions such as insolation level and is characterized by high variability and discontinuity [7–9], given that reliability is a key component of users' requirements [10]. This problem (reliability concerns) is much more serious in the case of off-grid or standalone PV systems especially when they have to provide consistent power [11]. The high unpredictability of the solar resource makes it difficult to forecast energy production. A feasible solution for this problem is that a solar PV system operating as a stand-alone mode must be integrated with an energy storage system to compensate for the differences between the availability of solar power and the power required by the load during the intervals of insufficient generation. Moreover, there is always the need for sufficient capacity storage devices to provide power to the load at night and on extended cloudy days. Therefore, the application of high-efficiency energy storage techniques

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is needed to exploit solar energy sources. PV power system with energy storage system presents an unbeatable option for the supply of small electrical loads at remote locations where there is no access to the power network [12]. The reliability of the system significantly increases when the system is integrated with the provision of a multi-storage device.

Nigeria, being gifted with an abundance of solar radiation, has a wide potential for solar energy applications to meet the electricity demand of remote users. The intermittence of PV generation requires that standalone power systems based on PV should be integrated with other complementary power sources and/or energy storage systems to ensure a reliable power supply. An energy and exergy analysis of photovoltaic battery-fuel cells showed that combining photovoltaic modules, batteries, and fuel cell components could provide a robust energy storage system [2,13]. In integrated PV/Battery/Hydrogen systems, using a modestly sized battery as short-term storage and hydrogen (fuel cell and electrolyzer) as long-term energy storage is therefore very advantageous. In this case, the battery storage is used to shave shorter transitory peaks that may arise due to load power exceeding the power of PV, while hydrogen is produced from excess solar energy during off-peak periods and is then used by the fuel cell to generate electricity during peak load periods and low solar insolation hours. Fuel cells can produce electricity continuously for as long as hydrogen is supplied [14]. The source of hydrogen to the fuel cell can be locally produced from excess power from PV generation using a water electrolyzer.

However, this study contains a single-renewable energy power system (the solar system) with multi-storage units (battery and hydrogen). The objective is to develop system reliability described as the probabilistic index LPSP (Loss of Power Supply Probability) for sizing and development of a stand-alone photovoltaic/battery/fuel cell energy system, considering the demand of load, generating power, and an effective multi-storage strategy. Therefore, this work depends mainly on the proper sizing of the components to avoid outages as well as ensuring the reliability of the power supply.

2 Literature review

Literature review reveals that a lot of studies have been done on the stand-alone Photovoltaic (PV)/Battery(B)/Fuel Cell (FC) system. The performance and cost viability of a PV, fuel cell (FC), and battery-based integrated system with intermittent load conditions are analysed by Patterson et al., 2015 [15]. Bruni et.al, 2014 [16] conducted an experimental and numerical study on integrated PV-FC-Battery to optimize the system using a rule-based control strategy. In this configuration, photovoltaic is the primary source during daylight, and fuel cells act as a backup during the night or when the load exceeds the output power of photovoltaic. During the peak hours, load demand is supported by the photovoltaic, and surplus energy is sent to the battery as energy storage. Battery and fuel cell work simultaneously when the output power of photovoltaic is zero. The control strategy succeeded in increasing the lifetime of components and also cutting down the cost. Hwang et.al, 2009 [17] developed a dynamic model to simulate a stand-alone PV-FC integrated power system. In this system, PV is designed to meet the load demand. During the daylight, when there is excess energy from PV, it will be used to produce hydrogen through the electrolyzer. During the low radiation period, the fuel cell will be the backup system by consuming hydrogen from the hydrogen tank. Rezk et al., 2020 [18] presented a feasibility study of a stand-alone photovoltaic-fuel-cell battery (PV/FC/B) system that supplies a daily load demand of 500 kWh (peak-35 kW) to a small community for the planned grand city NEOM in Saudi Arabia. The PV array was the main source to meet the load demand. During the surplus periods, the battery was charged using extra energy and powered the electrolyzer for hydrogen production. The produced hydrogen was stored for later use. During the deficit periods, the FC and/or battery supported the PV array to meet the load demand. Hybrid Optimization Model for Multiple Energy Resources (HOMER) software was employed to optimize the performance of PV/FC/B, and two benchmarks, the cost of energy (COE) and net present cost (NPC), were used to identify the best size of the PV/FC/B system. Their findings confirmed that a 200 kW PV array, 40 kW FC, 96 batteries, 50 kW converter, 110 kW electrolyzer, and 50 kg hydrogen tank was the best option to supply the load demand. The values of total NPC and COE were $500,823 and $0.126/kWh. Zhang and Huang, 2011 [19] proposed a fault detection method to diagnose the fault of hybrid systems. The proposed system consists of a photovoltaic (PV) panel, fuel cell (FC), and battery (B). All the parts are connected to the DC bus. PV system is the primary source while FC will meet the deficient power. Gencoglu et.al, 2009 [20] designed an integrated system consisting of a photovoltaic, electrolyzer, hydrogen storage tank, fuel cell, and power conditioning unit for a total power load demand of 6.23 kW. The integrated system output power is 7.3 kW with 2.5 kW from PV and 4.8 kW from the fuel cell. Mohammad et al., 2019 [21] used HOMER software to investigate the feasibility of using a hybrid photovoltaic (PV), fuel cell (FC), and battery (B) system to power different load cases, which are intended to be used at the Al-Zarqa governorate in Jordan. A remote residential building, school, and factory having an energy consumption of 31 kWh/day with a peak of 5.3 kW, 529 kWh/day with a maximum of 123 kW, and 608 kWh/day with a maximum of 67 kW, respectively, were considered as the case studies' loads. Jagan et al., 2016 [22] used HOMER to design a stand-alone solar Photovoltaic/Battery/Fuel cell power system based on the cost of energy. They designed the system in such a way that the main power comes from the photovoltaic (PV) panels, while the fuel cell (FC) and secondary batteries are used as backup units. The converter was incorporated since the system will feed an AC load. During the day, the PV array produces much more power than needed by the load, with the surplus going to the electrolyzer and the battery. At night the FC serves the load while drawing hydrogen from the storage tank. The authors specified one sensitivity variable with two

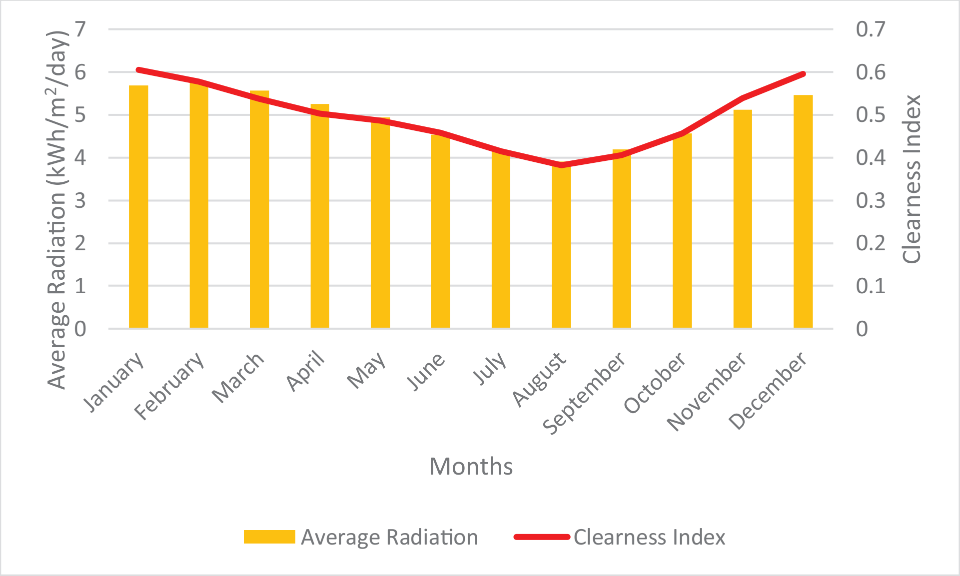

Fig. 1. Solar resources for the studied area.

values; which are the slope of fuel consumption in FC and the marginal fuel consumption of the FC. The sensitivity analysis reveals that the NPC and the COE have increased due to the rise in fuel consumption in the FC from 0.03 to 0.05 L/hr/kW. Castaneda et.al, 2013 [23] studied a stand-alone system that only uses a PV as the main source. A new sizing method was proposed and three control strategies were performed for energy management. Surplus energy from the photovoltaic was sent to the electrolyzer for the hydrogen production process. Fuel cells were utilized when Photovoltaic energy is deficient and works as an auxiliary generator. Zidane and Lalouni, 2017 [24] presented an optimal sizing of a stand-alone system based on photovoltaic panels (PV) and fuel cells (FC) power generation, electrolyzer (EZ), and battery (B) bank as energy storage systems. They aimed to find the optimal size of the set system's components, based on two optimization criteria: reliability, which is based on the concept of the loss of power supply probability (LPSP) and the system cost. For a load and a probability of loss of energy given under the criterion of a minimum price of the system, they calculated the hourly power produced by the photovoltaic generator, the amount of hydrogen stored, and the capacity of the battery required for the application, over a one-year analysis period. Results show that the optimum determination of hydrogen tanks and photovoltaic panels depends on the particular site, the profile of the load required, and also on the efficiency of the components of the stand-alone PV/FC/EZ/B System. The technical design and feasibility of storing electricity from solar energy, in battery banks and hydrogen systems consisting of an electrolyzer, hydrogen storage, and fuel cell has been proven over the last decades, but the challenge remains to improve the reliability of the power supply and overall storage system efficiency. Therefore, this study is to perform accurate system simulation studies on the behaviour of the components, how each interacts with the rest of the system, the reliability of the power supply, and the overall system efficiency.

2.1 System reliability

System reliability is one of the most important issues which must be considered in the design and operation of power systems [12]. Stand-alone PV with storage systems is designed to be self-sufficient in generating, storing, and supplying electricity to the electrical loads in remote areas [5]. To use solar energy resources more efficiently, the optimal sizing of PV systems with energy storage plays an important role in this respect. Reliable supply for load demand under various weather situations is the most important challenge in the design of a stand-alone renewable power with a storage system. Power reliability analysis of a photovoltaic (PV) system has been considered as an important step in the system design process due to intermittent solar radiation characteristics, which highly influence the resulting energy production [25]. The reliability of the system can be assessed using the Loss of Power Supply Probability (LPSP) method for given load profiles and primary power availability [26]. The technical approach is used to achieve the optimal configurations of a stand-alone system in terms of technical analysis which is known as LPSP. Elbaset, 2011 [27] constructed a PV/FC power generation system and presented a computer program to size the system components to match the load, for high operational reliability concerning the objective LPSP.

In this study, the system reliability algorithm is developed according to the concept of LPSP and embedded in the system operation simulation.

2.2 Overview of the study area

The residential building understudy is owned by Mr. Innocent Okafor Ani and is located at Onuafo Aniede in Ogologo-Eji Ndiagu Akpugo which is in Nkanu-West Local Government Area of Enugu State in South-Eastern Nigeria on Latitude 6° 12' 40" N and Longitude 7° 52' 32" E with annual average solar daily radiation of 4.95 $\text{kWh/m}^2\text{/d}$.

Table 1. Energy needed for the household use.

Description of item	Power rating (Watts)	Qty	Total load (Watts)	Daily hour of actual utilization (hr.per day)	Total/hr (Total load x daily hr)
Air-Conditioner	1170	1	1170	9 h (08:00 h − 17:00 h)	1170 × 9 = 10530
CCTV	30	1	30	24 (00:00 h − 24:00 h)	30 × 24 = 720
Ceiling fan	100	14	1400	14 h (08:00 h − 22:00 h)	1400 × 14 = 19600
Computer Laptop	35	1	35	9 h (08:00 h − 17:00 h)	35 × 9 = 315
Computer PC	115	1	115	9 h (08:00 h − 17:00 h)	115 × 9 = 1035
Computer printer	100	1	100	1 h (15:00 h − 16:00 h)	100 × 1 = 100
DSTV Receiver	20	1	20	22 h (06:00 − 17:00 h; 18:00 h − 05:00 h)	20 × 22 = 440
DVD Player	50	1	50	2 h (19:00 h − 21:00 h)	50 × 2 = 100
Electric pressing iron	1000	1	1000	1 h (12:00 h − 13:00 h)	1000 × 1 = 1000
Electric stove	1000	1	1000	2 h (17:00 h − 19:00 h)	1000 × 2 = 2000
Energy Efficient Lighting (indoor)	6	23	138	8 h (04:00 h − 08:00 h; 18:00 h − 22:00 h)	138 × 8 = 1104
Energy Efficient Lighting (outdoor for security)	9	4	36	13 h (18:00 h − 07:00 h)	36 × 13 = 468
Medium size deep-freezer	130	1	130	24 h (00:00 h − 24:00 h)	130 × 24 = 3120
Microwave Oven	1000	1	1000	2 h (06:00 h − 07:00 h; 11:00 h − 12:00 h)	1000 × 2 = 2000
Miscellaneous	100	1	100	11 h (18:00 h − 05:00 h)	100 × 11 = 1100
Refrigerator	500	1	500	9 h (08:00 h − 17:00 h)	500 × 9 = 4500
Sound/Music System	100	1	100	1 h (04:00 h − 05:00 h)	100 × 1 = 100
Washing Machine	280	1	280	1 h (09:00 h − 10:00 h)	280 × 1 = 280
Water bath	1000	1	1000	2 h (03:00 h − 04:00 h; 18:00 h − 19:00 h)	1000 × 2 = 2000
Water pumping machine	1000	1	1000	1 h (13:00 h − 14:00 h)	1000 × 1 = 1000
21” TV with Decoder	150	1	150	9 h (08:00 h − 17:00 h)	150 × 9 = 1350
14” Television	80	8	640	22 h (06:00 − 17:00 h; 18:00 h − 05:00 h)	640 × 22 = 14080
21” Flat Screen TV	100	1	100	24 (00:00 h − 24:00 h)	100 × 24 = 2400
				Total	**69342W**

The data for the solar resource (used in generating Fig. 1) were obtained from the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy website [28]. After scaling on this data, the scaled annual average resource of 5.0 $\mathrm{kWh/m^2/d}$ was obtained for the site.

2.3 Description of the residential building

The residence is a bungalow building; has seven rooms, a computer room, a sitting room, a kitchen, and a library. The energy consumption in the residential buildings has gained an increasing demand recently due to the high comfort standards [29]. The building is furnished with electric power consumptions such as air-conditioner, Closed-Circuit Television (CCTV), computer systems, deep-freezer, Digital Satellite Television (DSTV) receiver, Digital Versatile Disc (DVD) player, electric stove, fans, lighting bulbs, microwave, pressing iron, printer, refrigerator, sound/music system, televisions, washing machine, water bath, and water pumping machine as listed in Table 1. Each room has a fan, lighting bulb, and television, while the sitting room uses air-condition, a lighting bulb, and a TV with a decoder. The miscellaneous load is for unknown loads in the house.

2.4 Load assessment and the pattern of using electricity power within the house

To establish the power needs of the house, an energy audit was carried out based on data provided by the occupant of the house, Mr. Innocent Okafor Ani, and a site visit to evaluate the characteristics of the power system, power requirements, and power system management and operation. The daily power demands for the residential building are tabulated in Table 1 with

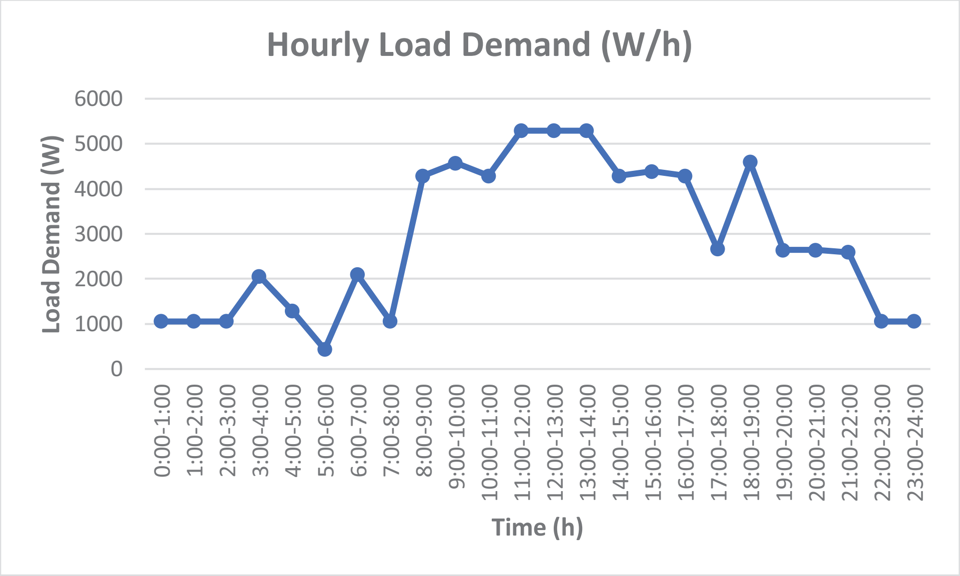

Fig. 2. Hourly load demand profile of the household.

69 kWh/day energy consumption. This Table shows the estimation of each appliance's rated power, its quantity, and the hours of use by the residence in a single day. The annual peak load of 5.3 kW was observed between 11:00 h and 14:00 h as shown in Figure 2, which provides the best possible match with PV output (since these loads typically peak during daytime and afternoon hours), but there is still a need for a backup with a multi-storage system (during the raining season and cloudy days) to achieve reliability of power supply.

2.5 Description of different components of the system

One of the important advantages of using renewable power generator with multi-Storage units is the ability to increase the overall efficiency of the system. The main components studied here include PV, battery storage system, Hydrogen storage systems (electrolyzer/storage/fuel cell), and power electronic interface (direct current (DC)/ alternative current (AC) converter). A brief description of each component of the proposed energy system is summarized as follows.

2.6 PV array

In a PV system, the solar energy is converted to electrical energy by using one or more PV modules. Mainly, the system consists of panels, and various mechanical electrical connectors to produce the desired output. The panels are connected in series and parallel connections to provide the desired amount of voltage and current [30].

2.7 Battery

Batteries are important subsystems in many distributed generation systems as they can be used to effectively shift the availability of renewable energy. Batteries are conventional storage devices used to store excessive energy in a renewable energy system [31,32]. Correct modeling of the voltage, capacity, and lifetime of batteries helps to accurately predict the electrical performance of power systems employing batteries as electrical storage. Batteries have become famous for energy storage recently due to their effectiveness and their technology has proven its competitiveness for remote area applications.

2.8 Electrolyzer

Electrolysis of water using renewable energy resources is one of the most sustainable ways to produce hydrogen. Electrolysis uses the electric current to break down water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) [21]. The hydrogen generated this way normally during peak renewable power can be used when needed to generate electricity using a fuel cell. The process used to split water into oxygen and hydrogen is called water electrolysis and the device that does this is called a water electrolyzer.

2.9 Hydrogen storage tank

The hydrogen produced by the electrolyzer is stored inside a hydrogen storage tank normally at a higher pressure than the outlet pressure of the electrolyzer. A compressor is thus used to compress the hydrogen gas.

2.10 Fuel cell

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent [33]. The fuel cell process comprises converting chemical energy to electrical energy via electrochemical reactions [34]. The electrochemical reaction produces an electric current when gaseous/liquid are fed as fuels to the electrode (anode) compartment, simultaneously, an oxidant is fed continuously to the cathode compartment. The first references to hydrogen fuel cells appeared in the 1838 edition of The London and Edinburgh Philosophical Magazine and Journal of Science, where Welsh physicist and barrister William Grove wrote about the development of his first crude fuel cells. The history of fuel cells can be found in Thareny et al., 2021 [35]. Fuel cells are different from batteries in that they require a continuous source of fuel and oxygen or air to sustain the chemical reaction, whereas in a battery the chemicals present in the battery react with each other to generate an electromotive force [36]. The fuel cell is the best option to be used as a backup energy source in a stand-alone system because of its eco-friendly operations and high-energy-density of hydrogen. Thus, the PV/Battery/Fuel Cell can be driven indefinitely by refuelling the hydrogen storage tank via the water electrolyzer that is supplied when the PV power exceeds the load demand. Fuel cells that are used in residential buildings and inaccessible areas for primary and backup power have units of between 1 and 10 kW [37]. Fuel cell technology is gaining attention worldwide due to its renewable nature, and with only water as the primary by-product of its exhaust stream, the fuel cell is a zero-emission technology [38,39]. The fuel cell provides energy for future applications.

2.11 Power electronic converters

Power electronic converters are used to control the flow of electrical power between an electrical source (AC and DC components) and a load so that the destination is supplied with current, voltage, and/or frequency that is well suited to it. This is done with a small power loss as possible occurring on the way or with the highest conversion efficiency possible. The power electronic converter used in this paper is DC to AC conversion.

2.12 System configuration

For this study, the system architectural configuration is composed of PV panels, a battery, a hydrogen storage subsystem, an inverter, and electrical loads. A hydrogen storage system consists of water electrolysis to produce hydrogen from surplus power from renewable energy, a hydrogen (H_2) storage tank to store the generated hydrogen for later use and a fuel cell system to reproduce electricity when needed by using the stored hydrogen. Therefore, the Hydrogen subsystem consists of three major blocks, namely hydrogen generation (electrolyzer), hydrogen storage tank, and hydrogen fuel cell. In this configuration, the primary source of energy is the sun; and as a single-renewable energy system, the radiant energy of the sun is converted into electricity by PV panels. In the multi-storage system, a battery is connected to the DC bus to absorb power from and to supply power to the DC bus, while a hydrogen tank is used to absorb excess PV power through a water electrolyzer (the method for the production of hydrogen as shown in Figure 3 involves water electrolysis using electricity from PV power to split water into hydrogen and oxygen) and to supply power to the DC bus through fuel cell when there is a PV generation deficit. Therefore, the PV panels, the battery, and the fuel cell work with DC, while the inverter converts the DC to AC to supply electricity to the electrical loads and the electrolyzer as shown in Figure 3.

2.13 Method of sizing of energy system

The optimization technique used here to optimize the stand-alone PV/Battery/Fuel Cell system is an iterative approach based on the reliability of power supply using LPSP as the objective function to find the optimum configuration (including its specific values) of stand-alone PV with multi-storage units. Binayak et al., 2015 [6] described the iterative approach as a mathematical procedure performed using a computer that generated a sequence of improving approximate solutions for the optimization problem until a termination criterion is reached. This approach is used in this study and is embedded in the system operation of the LPSP algorithm to optimize the PV/Battery/Fuel Cell system for a given load.

2.14 Optimization principle – reliability of power supply (RPS)

Reliability of power supply is based on the concept of the probability of loss of power supply from a stand-alone renewable power system that is unable to meet the load demand. Scimone, 2010 [40] defined probabilistic index of LPSP as an assessment of the reliability of the system that takes into account the load demand profiles, the availability of primary energy source, and, if present, the capacity, and performance of charging and discharging of the storage system which the resulting evaluations lead to good results for the determination of the size of the storage system that ensures an acceptable continuity of load power supply.

The methodology for the reliability of power supply as shown in Figure 4 can be summarized in two steps:

- During the extra power generated from the stand-alone PV energy system, the surplus power is used to charge the battery, and a new state of charge (SOC) is calculated until the battery capacity is full. Additional energy after a full charge of the battery is sent to the electrolyzer for the production of hydrogen, which will be stored in the hydrogen storage tank for later use.
- During the deficiency of power generated from the stand-alone PV energy system, energy stored in the battery is used to meet the demand load, and new SOC is calculated until the battery bank capacity drops to the minimum level; then the fuel cell converts the generated hydrogen into electrical energy to supply the load and at the same time charges the battery.

Therefore, the sizing method consists of determining the optimal number of the photovoltaic modules, the batteries, fuel cell capacity, hydrogen generator capacity (electrolyzer), and hydrogen tank capacity according to the optimization principle.

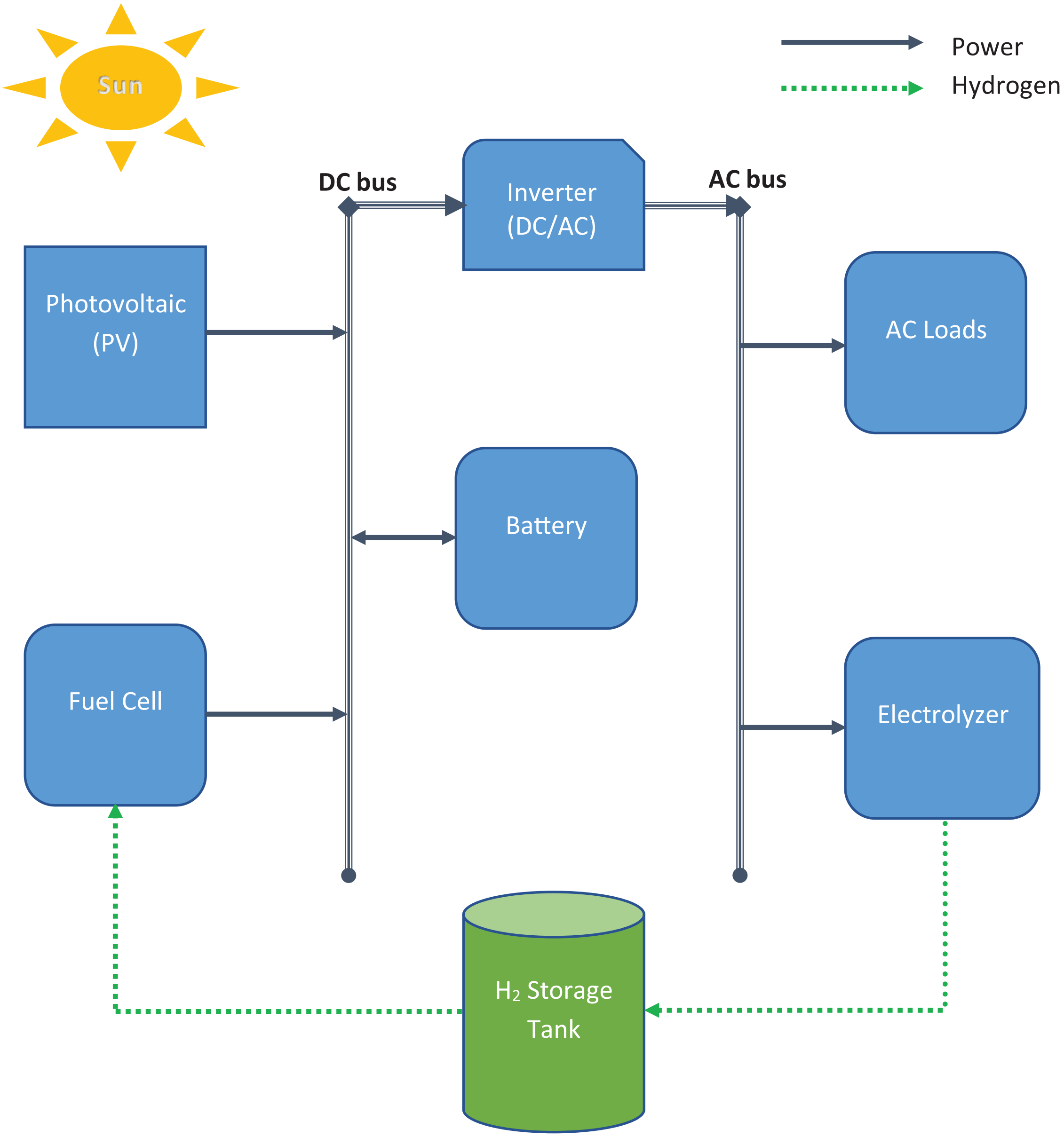

Fig. 3. System architectural configuration of a single-renewable system with the multi-storage unit.

2.15 Operating strategy of the algorithm for the probability index

A program for calculating the total available energy generated by the PV array, the optimum size of the battery bank, the hydrogen generated by water electrolysis, the energy generated by the fuel cell, and the capacity of the hydrogen tank is developed for a given load. The program's optimization is based on the reliability of the power supply and its objective function is on the loss of power supply probability. The flow chart diagram is shown in Figure 4.

The total available energy generated $EG(t)$ by PV array for hour t, can be expressed as follows:

$$EG(T) = NPV \times EPV(t), \tag{1}$$

Where NPV is the number of PV modules in a PV array, $EPV(t)$ is the energy generated by aPV module (kW) for hour t.

The power produced by the solar photovoltaic system in a given time T is then compared with that required by the load in the same interval. If there is no difference between these two quantities, that is $EG(t) = {}^{EL(t)}/_{\eta_{inv}}$, then $LPS = 0$; or otherwise, the difference of these two quantities is positive, which means $EG(t) > {}^{EL(t)}/_{\eta_{inv}}$, then the surplus will be used to charge the storage system.

In other words, the generated power is subjected to the following constraint:

$$EG(t) \geq {}^{EL(t)}/_{\eta_{inv}}. \tag{2}$$

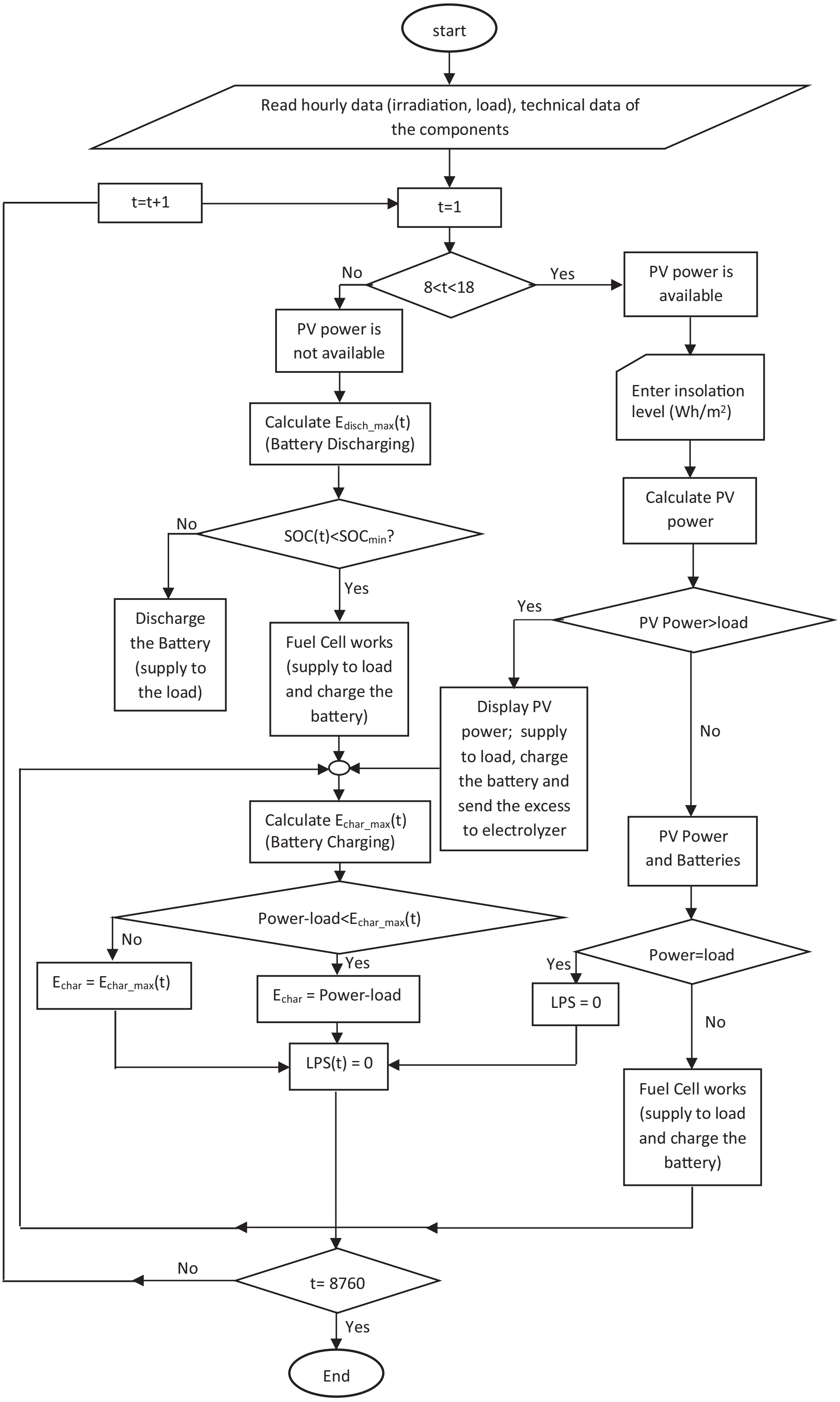

Fig. 4. Program flow chart for the development of a single-renewable energy power system with a multi-storage unit.

Table 2. Monthly results of each of the components of the PV/Battery/Fuel cell energy system.

Month	A single-renewable energy power system					Multi-storage system			
			Photovoltaic (PV)			Battery	Fuel cell (FC)		
	Incident solar (kWh/m2)	Electricity generated (kW)	Electricity Supplied to the load (kW)	Charging the battery	Excess electricity sent to the electrolyzer	Discharged and Supplied to the load	Hydrogen generated and stored in the tank	Electricity supplied to the load	Charging the battery
January	192.285	2401.076	987.628	239.282	1174.166	427.515	1174.166	874.649	299.517
February	188.814	2401.533	845.398	226.867	1329.268	425.589	1329.268	1004.386	324.882
March	213.213	2420.957	1094.416	232.446	1094.095	411.872	1094.095	792.623	301.472
April	194.312	2336.745	1045.610	219.627	1071.508	395.701	1071.508	781.803	289.705
May	186.037	2411.949	1049.806	221.725	1140.418	419.038	1140.418	826.317	314.101
June	166.744	2333.732	936.894	215.577	1181.261	408.659	1181.261	867.973	313.288
July	158.916	2401.312	905.257	226.365	1269.690	420.576	1269.690	955.024	314.666
August	153.817	2185.687	971.970	199.718	1013.999	379.553	1013.999	724.017	289.982
September	167.880	2329.750	892.323	217.040	1220.387	409.230	1220.387	907.573	312.814
October	191.792	2414.301	1051.274	216.828	1146.199	422.554	1146.199	821.824	324.375
November	194.054	2342.064	1023.349	224.026	1094.689	409.988	1094.689	788.972	305.717
December	187.409	2410.131	1015.452	227.093	1167.586	423.486	1167.586	853.230	314.356
Total	**2195.273**	**28389.237**	**11819.377**	**2666.594**	**13903.266**	**4953.761**	**13903.266**	**10198.391**	**3704.875**

In the case of storage systems, the battery charge efficiency is set equal to the round-trip efficiency, and the discharge efficiency is set equal to 1, while the electrolyzer is set to use the excess power from the solar system to produce hydrogen and store it to the hydrogen tank, the fuel cell in other hand is set to use the stored hydrogen to generate electricity that will be used to compensate the shortage and charge the battery; two cases were considered in expressing current energy stored in the storage systems for hour t.

(1) If the difference of these two quantities is positive, that is, the generated power from the PV array exceeds that of the load demand, $EG(t) > {}^{EL(t)}\big/_{\eta_{inv}}$, then the surplus will be used to charge the batteries with the round-trip efficiency, and if there exists excess energy after charging the battery (the batteries are full), the electrolyzer could transfer the remaining energy to a hydrogen tank. It can be expressed as follows:

$$ESS(t) = EB(t-1).(1-\sigma) + EE(t) + \left(EG(t) - {}^{EL(t)}\Big/_{\eta_{inv}}\right).\eta_{batt,inv}.\eta_{ele}. \quad (3)$$

(2) When the load demand is greater than the available power generated from PV array $EG(t) < {}^{EL(t)}\big/_{\eta_{inv}}$, then the deficit of power required will be delivered by the storage device. In this case, if the total energy available is not sufficient to provide power to the load, the batteries will be discharged by the amount that is needed to cover the deficit and if the battery storage system is not sufficient enough to compensate for the shortage, then the fuel cell supplies the shortage and charge the battery. In this case, there will be no loss of power supply; i.e., $LPS = 0$. It can be expressed as follows:

$$ESS(t) = (EB(t-1).(1-\sigma)) - \left({}^{EL(t)}\Big/_{\eta_{inv}} - EG(t)\right) - EFC(t). \quad (4)$$

where $ESS(t)$ is the energy stored in a storage device in hour $t(kW)$, $EB(t–1)$ is the energy stored in a previous hour (kW), σ is the hourly self-discharge rate of the battery bank, $EE(t)$ is the energy the electrolyzer send to hydrogen tank, $EL(t)$ is the load demand in hour $t(kW)$, η_{inv} is the efficiency of the inverter, $\eta_{batt,inv}$ is the round-trip efficiency of the batteries, η_{ele} is the electrolyzer efficiency, and EFC (t) is the energy from the fuel cell.

Finally, an inverter converts electrical power from DC into AC form. Inverter losses are due to the inverter's DC/AC efficiency (η_{inv}).

$$PINV_{LOAD(t)} = \left(PPV_{inv(t)} + PB_{inv(t)} + PFC_{inv(t)}\right) \times \eta_{inv}, \quad (5)$$

Where, $PPV_{inv(t)}$, $PB_{inv(t)}$, and $PFC_{inv(t)}$ are the energy transferred from the PV generation unit, battery, and fuel cell at time t, respectively. $PINV_{LOAD(t)}$ is the total energy supplied to the load at time t.

3 Results of the computer simulation

A computer program was developed and used to build a stand-alone PV/Battery/Fuel Cell power system model. Data inputs to the program are hourly load demand,

Table 3. Monthly electricity supplied to the load through the inverter.

Month	PV, Battery, and FC electricity supplied to the load through inverter			Inverter (kW)		AC load	
	PV Electricity Supplied to the load via inverter	Battery Discharged and Supplied to the load via inverter	FC Electricity supplied to the load via inverter	Electricity received from the PV, Battery and FC	Electricity supplied to the AC load	AC load demand (kW)	AC load served (kW)
January	987.628	427.515	874.649	2289.792	2149.602	2149.602	2149.602
February	845.398	425.589	1004.386	2275.373	2149.602	2149.602	2149.602
March	1094.416	411.872	792.623	2298.911	2149.602	2149.602	2149.602
April	1045.610	395.701	781.803	2223.114	2080.260	2080.260	2080.260
May	1049.806	419.038	826.317	2295.161	2149.602	2149.602	2149.602
June	936.894	408.659	867.973	2213.526	2080.260	2080.260	2080.260
July	905.257	420.576	955.024	2280.857	2149.602	2149.602	2149.602
August	971.970	379.553	724.017	2075.540	1941.576	1941.576	1941.576
September	892.323	409.230	907.573	2209.126	2080.260	2080.260	2080.260
October	1051.274	422.554	821.824	2295.652	2149.602	2149.602	2149.602
November	1023.349	409.988	788.972	2222.309	2080.260	2080.260	2080.260
December	1015.452	423.486	853.230	2292.168	2149.602	2149.602	2149.602
Total	**11819.377**	**4953.761**	**10198.391**	**26971.529**	**25309.830**	**25309.830**	**25309.830**

system components, and data for the solar resource of the site. The program determines as its output the size of system components (the number of PV arrays, battery capacity, rated power of fuel cell, the power rate of electrolysis, and capacity of hydrogen tank). In the charging mode of the multi-storage system, the program generates an output signal that assigns a percentage of the surplus power to the battery and the remaining power goes directly to the water electrolysis; while in discharging mode of the multi-storage system, the program generates an output signal that assigns a percentage of the required power to the battery and the remaining power is requested from the fuel cell. The optimum system configuration by the sizing application is composed of PV arrays resulting in total rated power of 15 kW, 16 units of 6 V, 225 Ah battery bank, 5.5 kW fuel cell, 5.5 kW Water Electrolysis, 16.5 kg hydrogen tank, and a 5.5 kW inverter. The output results presented for a one-year simulation are shown in Tables 2 and 3, while Figures 5–10 were provided for a clear understanding of the optimal design.

4 Discussion

4.1 Energy production and load demand

The total yearly electrical consumption is 25310 kWh. The PV provides 44% of the load which represents 11819 kWh; the battery provides 18% of the needs, which represents 4954 kWh; and the FC provides 38% (10198 kWh) as presented in Figure 5. Figure 6 shows that the PV excess production is stored at 16% by the battery and 84% by the electrolyzer.

In the solar resources, the month of March has the highest incident solar (213 kWh/m^2) as well as the highest electricity generated by the PV system (2421 kW), while August has the least incident solar (154 kWh/m^2) as well as the least electricity generated by the PV system (2186 kW) as shown in Figure 7. In August, it was observed from Figure 8 that to ensure a reliable supply without interruption, the fuel cell due to the low electricity generated by the PV (caused by low incident solar) supplies to load the highest electricity (1004 kW) and charges the battery (325 kW) to improve the overall system efficiency.

It was also observed from the results in Tables 2 and 3 that to accommodate the load demand for all the months, excess electricity was generated by the PV system, and this excess electricity generated was consumed by the electrolyzer to generate hydrogen. The electricity generated differs from month to month and depends on the incident solar. The highest electricity generated is observed in March (2421 kW), while the least is in August (2186 kW), the month most affected by raining season. In February, the PV supplied to the load the least electricity (845 kW), while the fuel cell becomes ON often to serve the load and at the same time charge the battery (which becomes a load when charging). These results (Tabs. 2 and 3) also show that the power supply is greater than the load demand. It is worthwhile noting from Figure 9 that the PV renewable solution

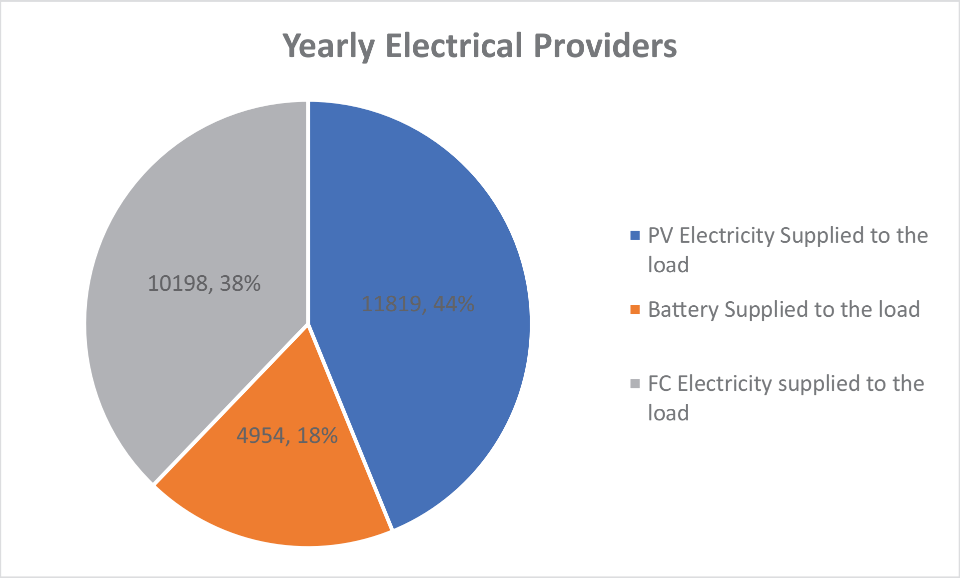

Fig. 5. Breakdown of electrical providers.

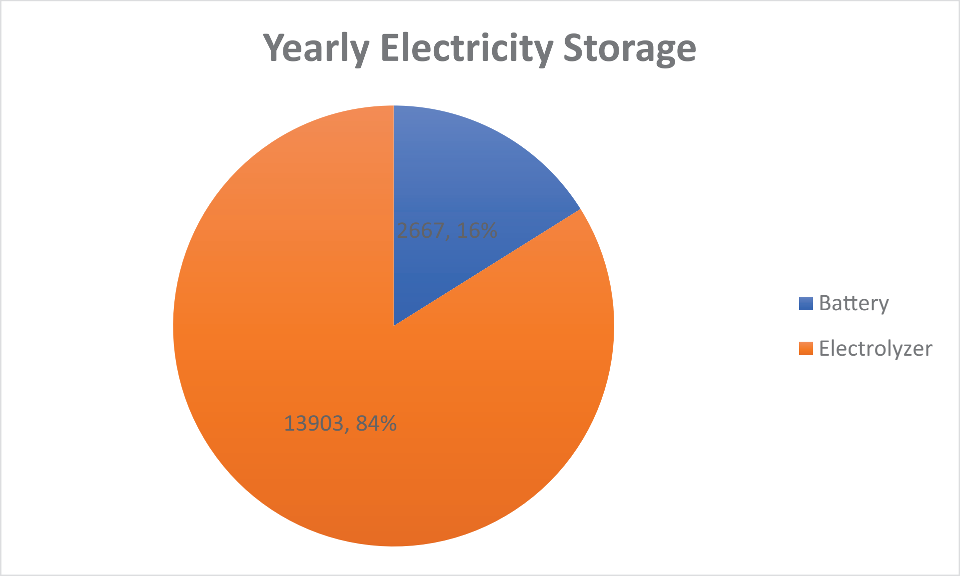

Fig. 6. PV excess storage.

supported by multi-storage (Battery/Fuel cell) served the load effectively with no loss of power supply; i.e., LPS = 0.

As presented in equation (5), DC/AC inverter losses occur before the initially provided energy can be consumed by an AC load and the results are shown in Table 3. Therefore, inverter losses are the monthly differences between energy received by the inverter and the energy supplied to the load by the inverter which is indicated by the down-bars filled with water droplets colour shown in Figure 10. In this Figure 10, the inverter losses by months were: January (140 kW), February (125 kW), March (149 kW), April (143 kW), May (145 kW), June (134 kW), July (131 kW), August (134 kW), September (129 kW), October (146 kW), November (142 kW), and December (142 kW).

Finally, from the design results, the objective of this study is to develop system reliability for sizing and development of a stand-alone photovoltaic/battery/fuel cell energy system where the LPS = 0 has been achieved.

5 Conclusion

In this work, the loss of power supply probability (LPSP) method for the sizing and development of a standalone PV system with multi-storage units (battery and hydrogen) considering the demand of load was implemented. This sizing application known as the LPSP algorithm is used in the design of component sizing configuration of a single-renewable energy power system based on multi-storage

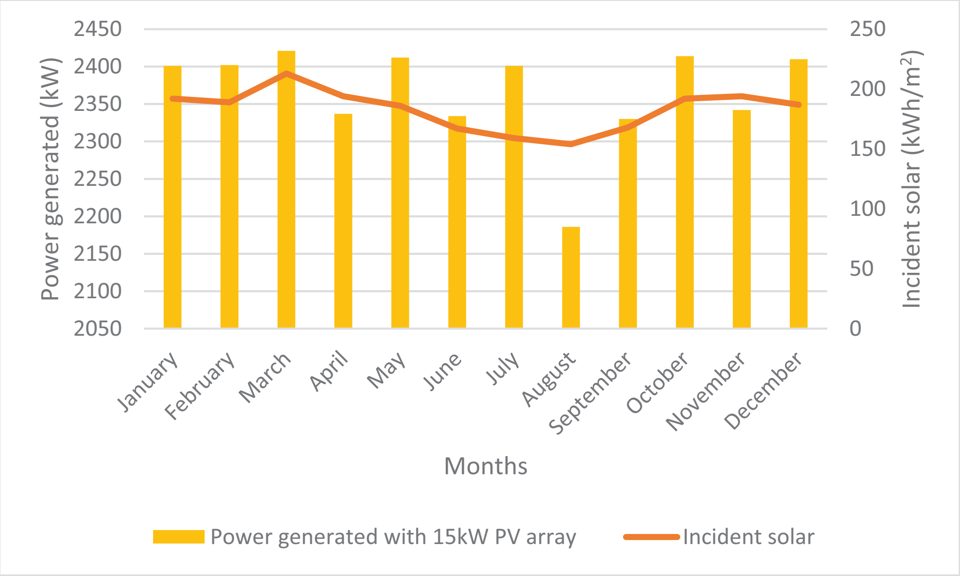

Fig. 7. Monthly PV power generated versus incident solar.

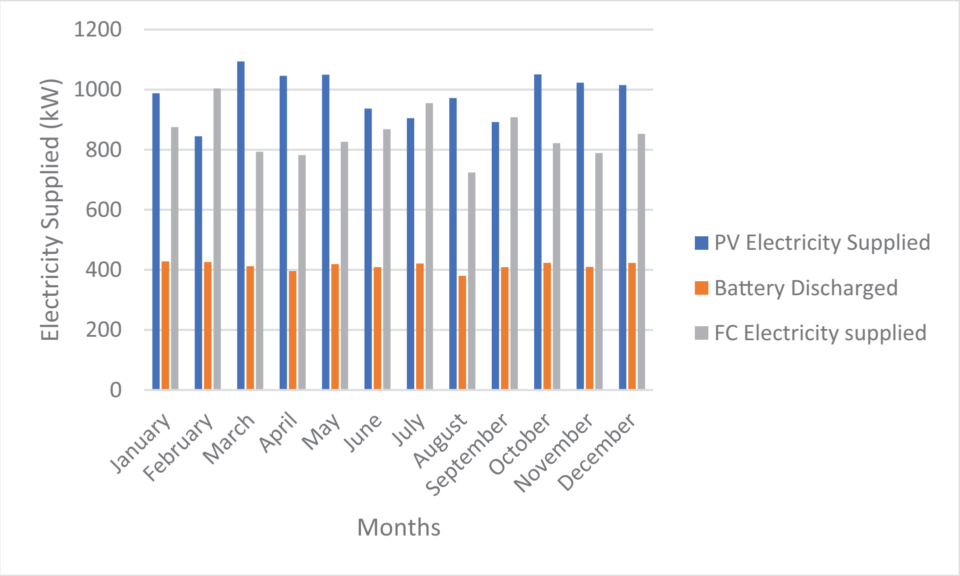

Fig. 8. Monthly electricity supplied by each of the PV, Battery, and FC.

units for a reliable supply of the requirements of the residential load. The system is designed in a way that the multi-storage system was used to achieve power stability and reliability, and the method is based on the principle of a technical strategy that depends on the reliability of the power supply taking into account the load profile. A synopsis of the LPSP algorithm is thus: whenever there is enough solar radiation, the household electrical load can be powered totally by the PV electricity, and the surplus will be used to charge the batteries, and if there exists excess energy after charging the battery (the batteries are full), then the electrolyzer could use the remaining energy to generate hydrogen. During periods of low solar radiation, the deficit of power required will be delivered by the storage device. In this case, the batteries will be discharged by the amount that is needed to cover the deficit and if the battery storage system is not sufficient enough to compensate for the shortage, then the fuel cell supplies the shortage and charge the battery. The system's performance is evaluated based on the reliability of power supply under widely varying load consumptions. In determining the most suitable stand-alone PV/battery/fuel cell power system to supply a given load, the algorithm optimizes the sizing of the energy system according to the loss of power supply probability concept. Applying this method, the simulation results show that the optimal configuration

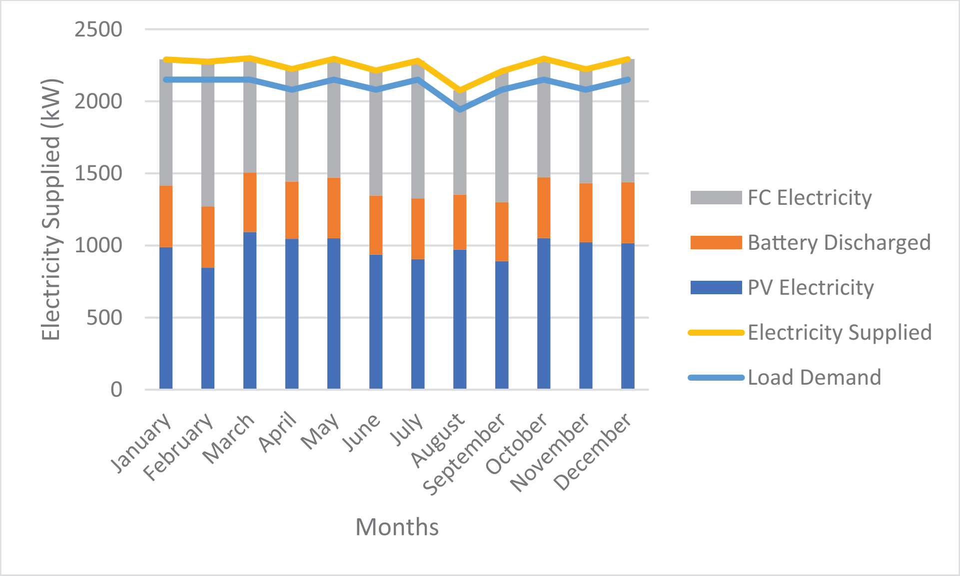

Fig. 9. Monthly electricity supplied versus load demand (LPS = 0).

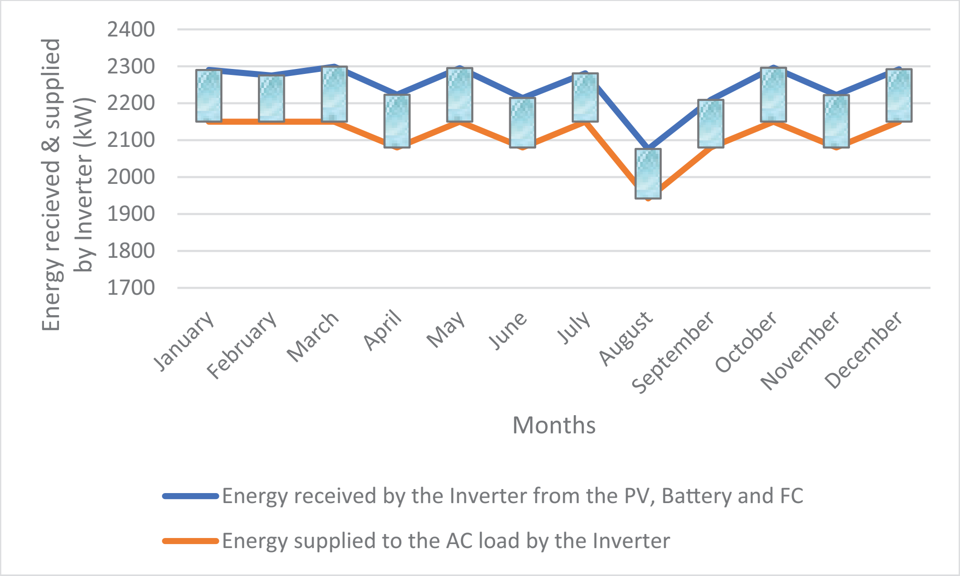

Fig. 10. Inverter losses by month.

which meets the desired system reliability requirements of a residential building with daily power demands of 69 kWh/day energy consumption is comprised of PV arrays resulting in total rated power of 15 kW, 16 units of 6 V, 225 Ah battery bank, 5.5 kW fuel cell, 5.5 kW Water Electrolysis, 16.5 kg hydrogen tank, and a 5.5 kW inverter; showing that the sizing and development of a stand-alone PV/battery/FC energy system have been achieved with system reliability LPS = 0. This developed program could be used during the process of design and analysis of the electrical power process of a stand-alone PV/Battery/Fuel Cell power system model for sustainable power supply for daily needs in any area.

Nomenclature

AC	Alternative Current
B	Battery
CCTV	Closed-Circuit Television
COE	Cost Of Energy
DC	Direct Current
DSTV	Digital Satellite Television
DVD	Digital Versatile Disc
EZ	Electrolyzer
FC	Fuel Cell
HOMER	Hybrid Optimization Model for Multiple Energy Resources

LPSP	Loss of Power Supply Probability
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
PV	Photovoltaic
RE	Renewable Energy
RETs	Renewable Energy Technologies
RPS	Reliability of Power Supply
SMSE	Surface Meteorology and Solar Energy
SOC	State Of Charge
TV	Television

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Conflict of interest

The author(s) declare that they have no conflict of interest.

Data availability statement

The data that support the findings of this study are available on request from the author.

Author contribution statement

The author did all the research work of this study.

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