

Article

Integrated Energy System Powered a Building in Sharjah Emirates in the United Arab Emirates

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Abstract: In this study, a green hydrogen system was studied to provide electricity for an office building in the Sharjah emirate in the United Arab Emirates. Using a solar PV, a fuel cell, a diesel generator, and battery energy storage; a hybrid green hydrogen energy system was compared to a standard hybrid system (Solar PV, a diesel generator, and battery energy storage). The results show that both systems adequately provided the power needed for the load of the office building. The cost of the energy for both the basic and green hydrogen energy systems was 0.305 USD/kWh and 0.313 USD/kWh, respectively. The cost of the energy for both systems is very similar, even though the capital cost of the green hydrogen energy system was the highest value; however, the replacement and operational costs of the basic system were higher in comparison to the green hydrogen energy system. Moreover, the impact of the basic system in terms of the carbon footprint was more significant when compared with the green hydrogen system. The reduction in carbon dioxide was a 4.6 ratio when compared with the basic system.

Keywords: green hydrogen; solar PV system; integrated energy system; levelized cost of energy; carbon footprint



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1. Introduction

The transition of energy has developed into a significant problem since it is necessary to reduce global greenhouse gas emissions [1,2]. One of the most promising ways to combat the current climate change concerns is the efficient conversion of hydrogen into an energy source for transportation and industrial purposes [3,4]. Hydrogen is a renewable energy that might help sustainable energy systems [5]. In addition, hydrogen is a clean energy carrier that has drawn a lot of interest and is anticipated to make a substantial contribution to the energy mix in developing low-carbon energy [6]. The cost of hydrogen and the amount of CO₂, which may be emitted in its production, are significantly different depending on the type of energy used, i.e., renewable or nonrenewable sources [7,8]. Steam-reforming of hydrocarbons, including natural gas, is the common method used for hydrogen production [9,10]. In general, when fossil fuels are used to create hydrogen, many emissions are created that are harmful to the environment and to the climate [11]. Therefore, switching to a low-carbon hydrogen production is essential [12].

Green hydrogen, made from water electrolysis using electricity from renewable sources, and blue hydrogen (hydrogen from fossil fuels accompanied by CO₂ Capture) are both free or low-carbon hydrogen [12]. Green hydrogen still costs more than hydrogen produced from fossil fuels. Water electrolysis, a method used for manufacturing hydrogen without CO₂ (green hydrogen in the case of using renewable energy sources) produces

only 4% of hydrogen [13]. The increased production costs are the primary stumbling block for the use of green hydrogen. As a result, most research on green hydrogen contains an economic analysis [14]. The Levelized Cost of hydrogen (LCOH) combining an alkaline water electrolyzer (AWE) with solar energy was found to range from USD 4.55 to USD 4.62/kg [15]. The advances in renewable energies and electrolysis technologies could decrease such a cost.

Various studies were carried out to switch from using fossil fuel-based energy to green hydrogen-based ones. For instance, Karayel et al. [16] studied the potential of green hydrogen production in Turkey using solar energy as the main renewable energy source. The results demonstrated that an average 421.35×10^6 tons of green hydrogen could be produced. Additionally, the study reported that among the 81 cities investigated, a few cities, such as Konya, Erzurum, Van, and Sivas, were the best cities for high hydrogen production capabilities. Kakoulaki et al. [17] investigated the potential of replacing grey hydrogen production in Europe with green hydrogen. The results of the study showed that the available renewable energy sources in Europe, i.e., wind, solar, and hydro, are enough for a green hydrogen production of 9.75×10^6 tons. The study also recommends further studies to be carried out from a techno-economic point of view, including the transportation and the storage of green hydrogen. Bhandari [18] studies the potential of green hydrogen production for the transportation and electricity generation sectors in Niger. It was found that solar PV systems use 5% of the land to secure a total liquid hydrogen production of 11,700 tons by 2040. Using Homer software, Barhoumi et al. [19] investigated the potential of green hydrogen production in Oman for refuelling stations using solar energy based on three different strategies of PV integrated with batteries, fuel cells, or a grid. The LHC “Levelized Hydrogen Cost” of 5.5 EUR/kg in the case of the PV integrated with the grid is lower than the other two options. Hoelzen et al. [20] discussed the potential of green hydrogen applications in the aviation sector. The authors showed that the economic potential of a green hydrogen application in the aviation sector depends on the availability of cheap green hydrogen sources and the available infrastructure for liquid green hydrogen. The potential of green hydrogen production in Ireland was also investigated using solar and wind energies [21]. The techno-economic analysis of the green hydrogen production in Poland was performed by Benalcazar and Komorowska [22]. The authors demonstrated that green hydrogen cost (LCOH) could be produced at lower prices using solar and wind energies, reaching less than EUR 2/kg in 20,250 at a large scale. In general, the increased capacity and the improved technology over time have a significant role in decreasing the cost of green hydrogen production. For Austria, Spain, and Germany, the LCOE “Levelized Cost of Electricity” and LCOH of AWE were analyzed. When societal considerations, such as environmental costs, were taken into account, Austria was the best scenario, although Germany was thought to be the best private LCOH in all situations [23]. A hybrid system using wind turbines and PV panels was proposed in Alexandria, Egypt, for generating electricity and green hydrogen production of 1.9 tons/year [24]. The proposed system demonstrated energy and exergy efficiencies of 16.42 and 12.76%, with a LCOH of 3.73–4.656 USD/kg.

Salameh et al. studied the potential of using solar energy and wind energy integrated with a diesel generator and various energy storage systems, including an electrolyzer for green hydrogen production in Neom city, KSA [25]. In another study, the authors studied the effectiveness of hybrid renewable energy sources in providing for the energy requirements in Khorfacan city in UAE of 13.6 GWh. On a small scale, Rezk et al., studied the combination of the PV, electrolyzer, and the fuel cell in an integrated system for desalination purposes in remote areas [26]. In another study, Lee investigated hydrogen generation utilizing AWE. The authors reported that the electricity cost was the factor that would have the highest impact on LCOH [27]. Since the current in the water electrolyzer varies throughout the day because of variations in the electricity produced by the renewable energy system, the amount of hydrogen produced by the electrolyzer is directly proportional to the current. Using microgrid software Hybrid Optimization Model for Multiple Energy

Resources “HOMER Pro,” the technical and economic performance of a hybrid system (PV-wind-fuel cell) to replace a diesel power plant in Duqm, Oman, with green hydrogen was evaluated [28]. The findings showed a COE “cost of energy” of USD 0.436/kWh, using the PV-wind-fuel cell with reduced noise and CO₂ emissions (205,676,830 kg/year). The levelized cost of energy for the proposed system was USD 0.196/kWh. The levelized cost for the diesel system would rise to USD 0.243/kWh when accounting for the price of USD 100 per ton of CO₂.

Pal et al., [29] performed a techno-economic analysis of a hybrid PV/FC system to provide 14 kW. The system used PV for electricity generation where the surplus energy was used for the power electrolyzer to produce green hydrogen. The system demonstrated an acceptable energy cost of 0.161 USD/kWh. The same group investigated the same system, i.e., PV/FC, for providing the energy requirements in north-east Indian states [30]. The authors used Homer software to model and simulated the proposed system. The system exhibited an economic energy production with an LCOE of 0.509–0.689 USD/kWh and annual green hydrogen production of 1.538–1.856 tons. Using Homer Pro, Kapen et al. [31] analyzed a hybrid energy system composed of PV and a biogas as renewable energy sources integrated with a fuel cell/electrolyzer and a battery as an energy storage system in Cameroon. Both the LCOE and LCOH significantly decreased with the increase in the capacity of the proposed hybrid energy system. The potential of using green hydrogen for refueling stations of fuel cell-based vehicles [32] was investigated by Venkatasatish and Dhanamjayulu [33].

As clear from the above discussion and based on the authors’ best knowledge, few studies applied the use of green hydrogen for buildings that are favored for energy decentralization. In this study, a green hydrogen system was investigated to provide the office building in Sharjah emirate, in UAE, with electricity. The basic hybrid system based on PV-DG-BES “solar PV, diesel generator, and battery energy storage” was compared to a hybrid green hydrogen energy system based on a solar PV, a fuel cell, a diesel generator, and battery energy storage (PV-DG-FC-BES) in terms of energy, economic, and environmental (3E). The aims of this work are as follows:

- Build a hybrid system to produce green hydrogen for a residential office building in Sharjah in the United Arab Emirates.
- Optimize the size of the components of the hybrid system using the optimizer tool in HOMER Pro software.
- Compare the green hydrogen hybrid system with the base case hybrid system based on solar PV, diesel generator, and battery system in terms of the 3E aspects.

2. Energy Resources, Weather Conditions, and Load

A commercial office building in Sharjah emirate (UAE) is the case study of this paper. The office building is located at a latitude and longitude of 25°16′ and 55°19′, respectively. According to Figure 1, the months with the highest and lowest solar insolation levels are June and December. The load includes both the thermal and electrical energy of the building, such as the cooling load, lighting, and appliances. Figure 2 depicts the three-dimensional (3D) geometry of the commercial office structure in Sharjah.

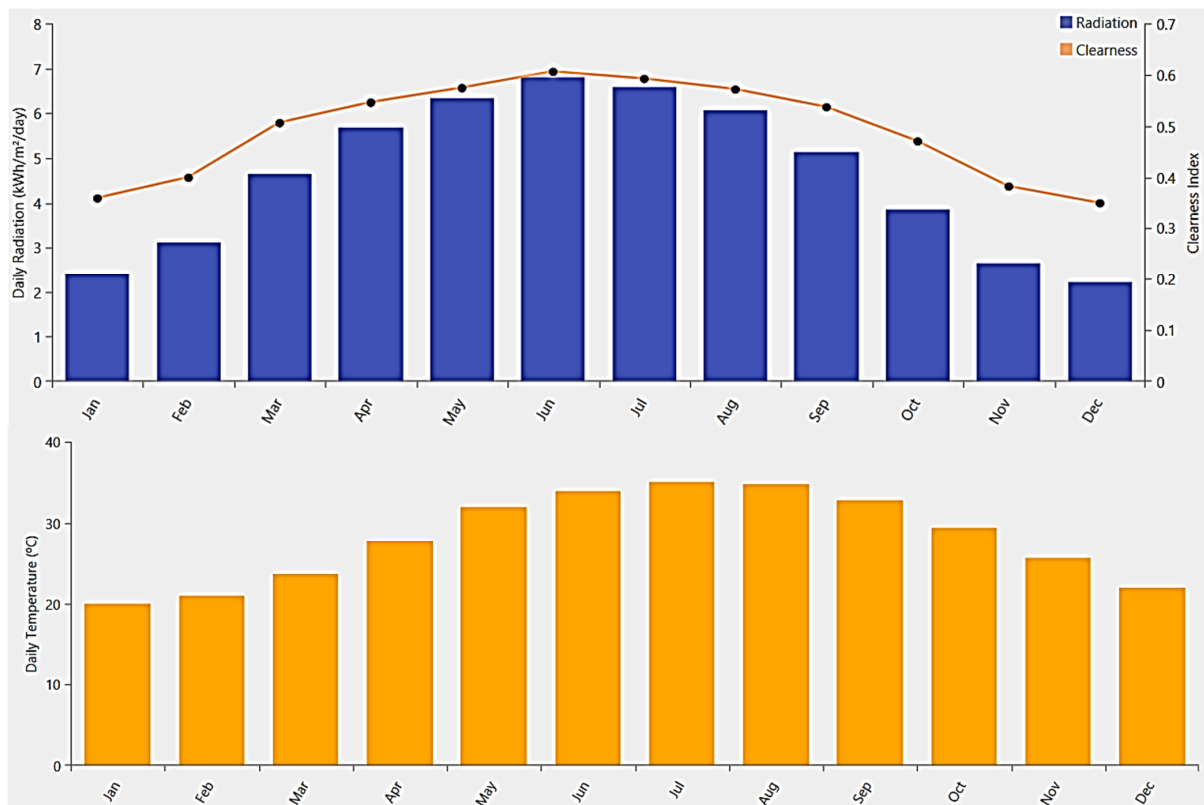


Figure 1. The metrological data for Sharjah city in UAE.

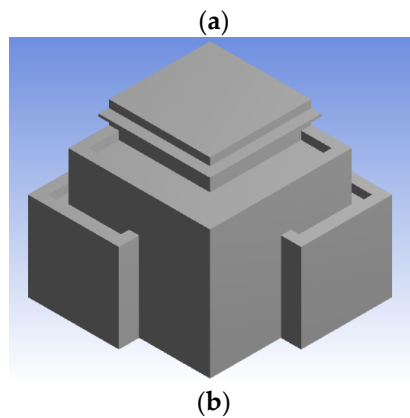
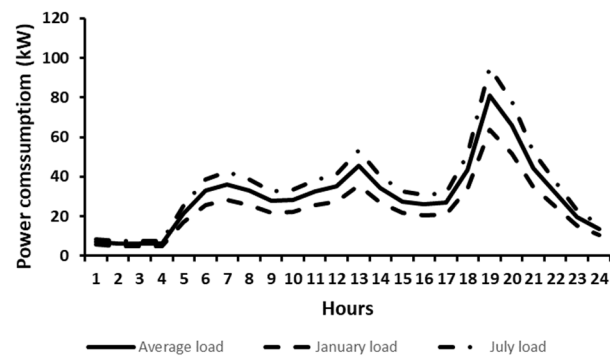


Figure 2. (a) the hourly load profile of the building (b) the commercial office building in Sharjah Emirate.

Table 1. Cont.

System Component	System I (PV-DG-BES)	System II (PV-FC-DG-BES)
Battery	- Generic lead acid - Roundtrips efficiency 80% - Nominal voltage: 12 V - Charge and maximal discharge current: 16.7 A and 24.33 A - Nominal capacity of each battery is 1 kWh. - Throughput lifetime: 800 kWh - Capital, replacement, operation, and maintenance costs are USD 150/battery, USD 150/battery, and USD 10/year, respectively - Lifetime: 10 years - Weight: 11.5 kg of each	
Converter	- Generic 105 kW - Convert direct current (DC) to alternating current (AC) and via versa as a rectifier. - Capital, replacement, operation, and maintenance cost are USD300/kW, USD300/Kw, and USD5/year, respectively	

3.1. Photovoltaic Array

According to Equation (1), the power production from the PV panel (P_{PV}) is influenced by the temperature due to the negative temperature coefficient of power, but it rose with increasing solar irradiance:

$$P_{PV} = P_{PV,STC} f_{PV} \frac{G_T}{G_{STC}} [1 + \alpha_P (T_c - T_{c,STC})] \quad (1)$$

G_{STC} is the amount of solar insolation at 1000 W/m² and 25 °C during standard test conditions (STC), G_T is the actual amount of solar insolation, $T_{c,STC}$ is the solar PV's cell temperature under STC, T_c is the solar PV's cell temperature, f_{PV} is the solar PV's derating factor, and α_P is the temperature coefficient of power.

HOMER Pro automatically set the solar PV panel tilt angle at a value equal to the latitude of the building at 25 degrees, which is thought to be the best yearly tilt angle for the installation of solar PV panels.

Equation (2) can be used to determine the output power production from solar PV arrays with multiple panels connected in both series (N_s) and parallel (N_p):

$$P_{PV,STC} = (N_s \times N_p) P_{mSTC} \quad (2)$$

where P_{mSTC} is the solar PV panel power at a maximum point under STC.

While Equation (3) can be used to determine the PV array's real power as follows:

$$P_{PV} = (N_s \times N_p) P_m \quad (3)$$

P_m is the solar PV panel's maximum power under the actual operating conditions.

The PV panels' maximum efficiency $\eta_{mp,STC}$ at STC is determined as follows:

$$\eta_{mp,STC} = \frac{P_{PV,STC}}{A_{PV} G_{T,STC}} \quad (4)$$

where A_{PV} is the PV panel's area and $G_{T,STC}$ is the actual irradiance at STC.

By choosing a suitable number for the f_{PV} , as shown in Equation (1), the dust effect was considered due to the desert nature in Sharjah City.

The following Equation (5) is used to calculate the system's fraction of utilized renewable energy (f_{ren}):

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{cons}} \quad (5)$$

where E_{cons} is the total energy consumption and E_{nonren} is the conventional energy source (from DG).

It is worth mentioning that the solar PV panels will be fixed onto the roof of the building; however, the roof area is not enough to install all the solar panels. Therefore, the rest will be installed in the surrounding area of the building as well as on the surface of the parking area of the building.

3.2. Fuel Cell

Fuel cells can convert chemical energy into electricity in an electrochemical reaction [34,35]. The hydrogen that is kept in the hydrogen tank acts as the main fuel and the power is produced from the fuel cell as long as hydrogen and oxygen are supplied to the cell. The amount of the fuel's chemical energy that is not converted into fuel cell electricity (P_{FC}) is transformed into thermal energy and is released as waste heat from the stack (P_{FCT}). P_{FC} can be calculated from the stack's voltage and current as follows:

$$P_{FC} = U_{\text{stack}} I = U_{SC} N I \quad (6)$$

where N and U_{SC} are the number of cells in a series and single-cell voltage respectively.

Based on the HHV_{H_2} "higher heating value of the hydrogen fuel", the actual efficiency of the cell (η_{FC}):

$$\eta_{FC} = \frac{P_{FC}}{\dot{m}_{H_2} HHV_{H_2}} \quad (7)$$

$\dot{m}_{H_2}$ is the gravimetric rate in kg/s and the value HHV_{H_2} is 120 MJ/kg.

3.3. Electrolyzer

An electrolyzer is a device that utilizes electricity in order to produce hydrogen from water. Electrolysis is a process that involves the transfer of the field of an electric current through the water in order to break it down to its composites, i.e., hydrogen and oxygen gases. This is accomplished by electrolyzing the water. As can be seen in Figure 3, the produced hydrogen from the electrolysis process either serves as an external hydrogen load from the system or is stored as compressed hydrogen in the storage tank to use in the FC for the generated electricity. The following expression will give you the electrolyzer's power consumption:

$$P_{EZ} = \frac{\dot{m}_{H_2} HHV_{H_2}}{\eta_{EZ}} \quad (8)$$

where the power consumption is expressed by P_{EZ} , the mass rate of hydrogen in the electrolyzer is $\dot{m}_{H_2}$ in kg/s, and the electrolyzer's efficiency is η_{EZ} . A hydrogen tank is required to store the hydrogen created by the electrolyzer so that it can be used later in a fuel cell or for a generator powered by hydrogen.

3.4. Diesel Generator

If the electricity provided by the solar PV and battery systems is inadequate, the diesel generator is used as a backup power source. The power production from the generator (P_{DG}), which is determined using the following Equation (9), determines the consumption of fuel in the DG (GFC):

$$GFC = F_0 \cdot Y_{DG} + F_1 \cdot P_{DG} < GFC_{P_{DGmax}} \quad (9)$$

where F_0 and F_1 are the manufacturer's fuel consumption coefficients, and Y_{DG} is the DG's nominal (rated) power. The LHV "lower heating value" based DG efficiency is computed utilizing:

$$\eta_{gen} = \frac{3.6 P_{DG}}{GFC \cdot LHV_D} \quad (10)$$

LHVD stands for the calorific value of diesel based on the water vapor, where GFC is the generator fuel consumption rate.

The battery's maximum power, as well as the generator's maximum power, are both utilized to calculate how long the generator will run:

$$P_{DG} \leq P_{DGmax} \quad (11)$$

$$P_{DG} < P_{bat, c}^{lim} \quad (12)$$

3.5. Converter

As shown in Figure 3, the converter is wired between a DC bus and an AC bus. It functions as an inverter of the DC current produced from the PV and the FC to the AC load, operating in both directions depending on the direction of the power flow. Both methods are acceptable for carrying out this process. The converter's model takes into account both its rated capacity and efficiency, which are presumptively stable throughout the entirety of its working range. The rated DC voltage of each string in the PV array can also be used to calculate how many PV modules make up that string. The converter's output power is determined as follows:

$$P_{InvOut} = P_{InvIn} \eta_{Inv} \quad (13)$$

where P_{InvOut} is the output power to the inverter, P_{InvIn} is the input of the power to the inverter, while η_{Inv} is the inverter efficiency.

3.6. Battery Energy Storage System

Batteries play an important role in standalone HRES "hybrid renewable energy systems", which may comprise any type of RES. This is because they are used to store any excess electrical energy and ensure that load demands are met during periods of load shortfall. A battery kinetics model was used throughout the time simulation, allowing for the estimate of the biggest power charge and discharge constraints, $(P_{bat, c}^{lim})$ and $(P_{bat, d}^{lim})$. This type of model would account for all voltage losses based on a capacity degradation brought on by temperature, DOD "depth of discharge," resistance (serial), and rate of deterioration from cycle to cycle. The power of the battery bank can be roughly determined as follows:

$$P_{out} = I V_{output} = V_0 I - R_0 I^2 \quad (14)$$

The SOC "state of charge" of the battery is determined as follows:

$$SOC(t + \Delta t) = \min\{SOC(t)(1 - \delta) + \eta_{ch}(P_{gen} - P_L)\Delta t, SOC_{max}\} \quad (15)$$

where t and Δt are the current time and time interval, δ is the self-discharge coefficient, η_{ch} is the battery's efficiency, power demand is P_L , and the maximum allowed SOC is SOC_{max} .

PV or PV and DG are used for getting the produced power P_{gen} as follows:

$$P_{gen} = \begin{cases} \eta_{inv} P_{PV} & \text{PV only,} \\ \eta_{inv} P_{PV} + P_{DG} & \text{PV and DG.} \end{cases} \quad (16)$$

while the battery is undergoing charging-discharging, the power is limited by $I_{bat, c}^{lim}$ "value of the charging current":

$$P_{gen} - P_L < P_{bat, c}^{lim} = I_{bat, c}^{lim} \cdot V_{bat} \quad (17)$$

V_{bat} is the terminal voltage of the battery terminal.

The PV system can meet the demand for electricity with the help of batteries when there is not enough energy available, such as at night or when there is not enough sunlight. The discharging procedure is complete when the demand power reaches a level that exceeds

the storage system's discharge limit power, and the DG is able to handle the necessary load. Applying the following relationship will allow you to assess how much the SOC has changed:

$$\text{SOC}(t + \Delta t) = \begin{cases} \text{SOC}(t)(1 - \delta) & \text{if } \frac{P_L - P_{\text{gen}}}{\eta_{\text{dch}}} > P_{\text{bat,d}}^{\text{lim}} \\ \max\left\{\text{SOC}(t)(1 - \delta) - \frac{P_L - P_{\text{gen}}}{\eta_{\text{dch}}} \Delta t, \text{SOC}_{\text{min}}\right\} & \text{if } \frac{P_L - P_{\text{gen}}}{\eta_{\text{dch}}} \leq P_{\text{bat,d}}^{\text{lim}} \end{cases} \quad (18)$$

where SOC_{min} is the minimum limit of the SOC and η_{dch} is the discharge efficiency.

Similar to the charging stage, the battery's discharge power $P_{\text{bat,d}}^{\text{lim}}$ is a result of the discharging current's technological constraints ($I_{\text{bat,d}}^{\text{lim}}$):

$$P_{\text{bat,d}}^{\text{lim}} = I_{\text{bat,d}}^{\text{lim}} \cdot V_{\text{bat}} \quad (19)$$

The simulation of the green hydrogen hybrid energy system (PV-FC-DG-BES) was performed based on an hourly basis. The optimization tools inside HOMER Pro were used to optimize the size of both the PV-DG-BES and the PV-FC-DG-BES hybrid energy systems. The simulations were performed for thousands of trial cases and sorted based on the cost of energy COE.

4. Results and Discussion

In this study, we used both the hybrid energy systems solar PV-DG-BES and solar PV-DG-FC-BES to produce the electrical energy to power an office building in Sharjah, as shown in Figure 4. The load profile includes the cooling load, lighting, and other appliances inside the office building. The weight percentage for the solar PV and the diesel generator of the PV-DG-BES was 80.9% and 19.1%, respectively, whereas the weight percentage for the solar PV, fuel cell, and the diesel generator of the PV-DG-FC-BES system were 87.7%, 9.25%, and 3.06%, respectively. Solar PV was selected as the main electrical power supply for running the electrical load for the office building in Sharjah, such as HVAC system components, lighting, and other electrical appliances. Solar PV provides the electrical power required for the electrolyzer. The electrical power needed for the electrolyzer used during the fuel cell operation means that the electrolyzer consumes electrical energy from the solar PV and provides the hydrogen required for the fuel cell operation. The function of a hydrogen tank is to store the excess hydrogen if the fuel cell is off and to use it for future operation. The excess electrical power from the solar PV is not only used for running the electrolyzer but is also used for charging the battery during the high peak production of solar PV. The DG is used as a backup if there is a low power production from the PV, FC, and BES.

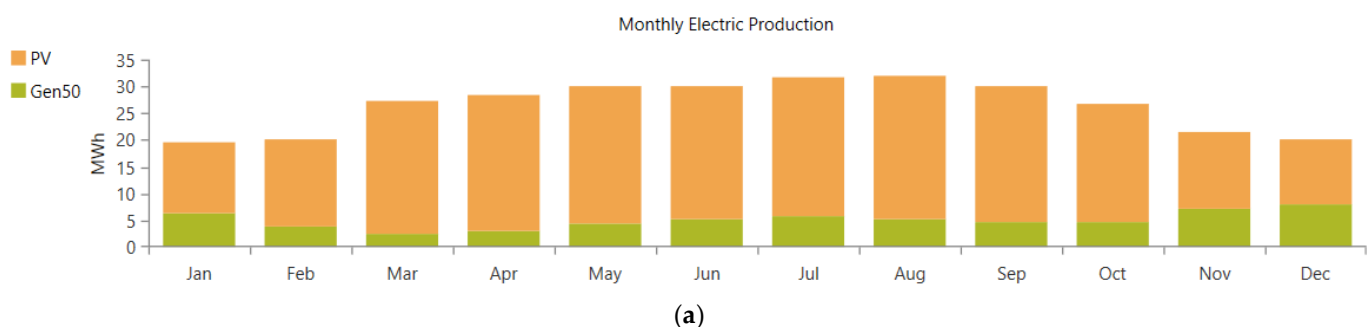


Figure 4. Cont.

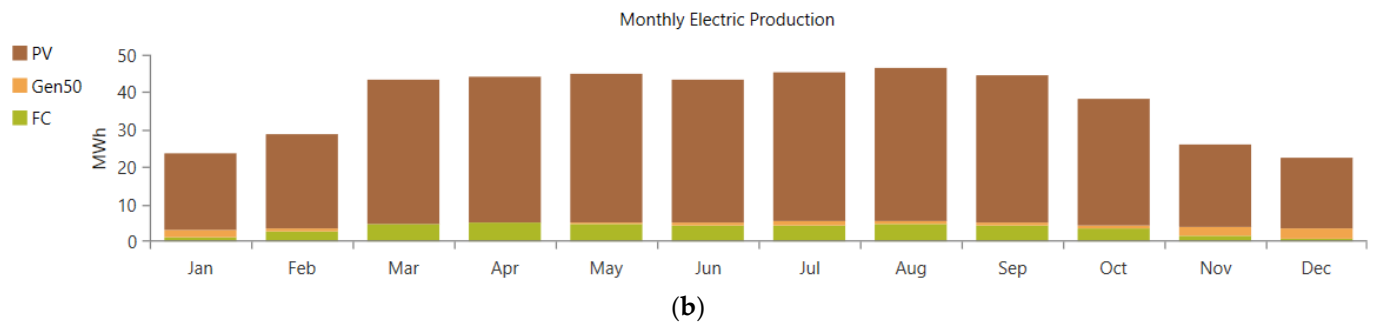


Figure 4. Monthly average electrical power supply from both hybrid systems for the office building in Sharjah city in UAE. (a) hybrid solar PV-DG-BES and (b) hybrid solar PV-DG-FC-BES systems.

Figure 5a–d shows the hourly electrical power basis for both of the hybrid systems on the minimum and maximum loads in the months of January and July. The only curve that was below the x-axis is the BES curve when it is working in the discharging mode. The hourly electrical power basis for the PV-DG-FC-BES system is also shown for the month of March where all the hydrogen (green) produced from the solar PV system and the diesel fuel consumption is zero.

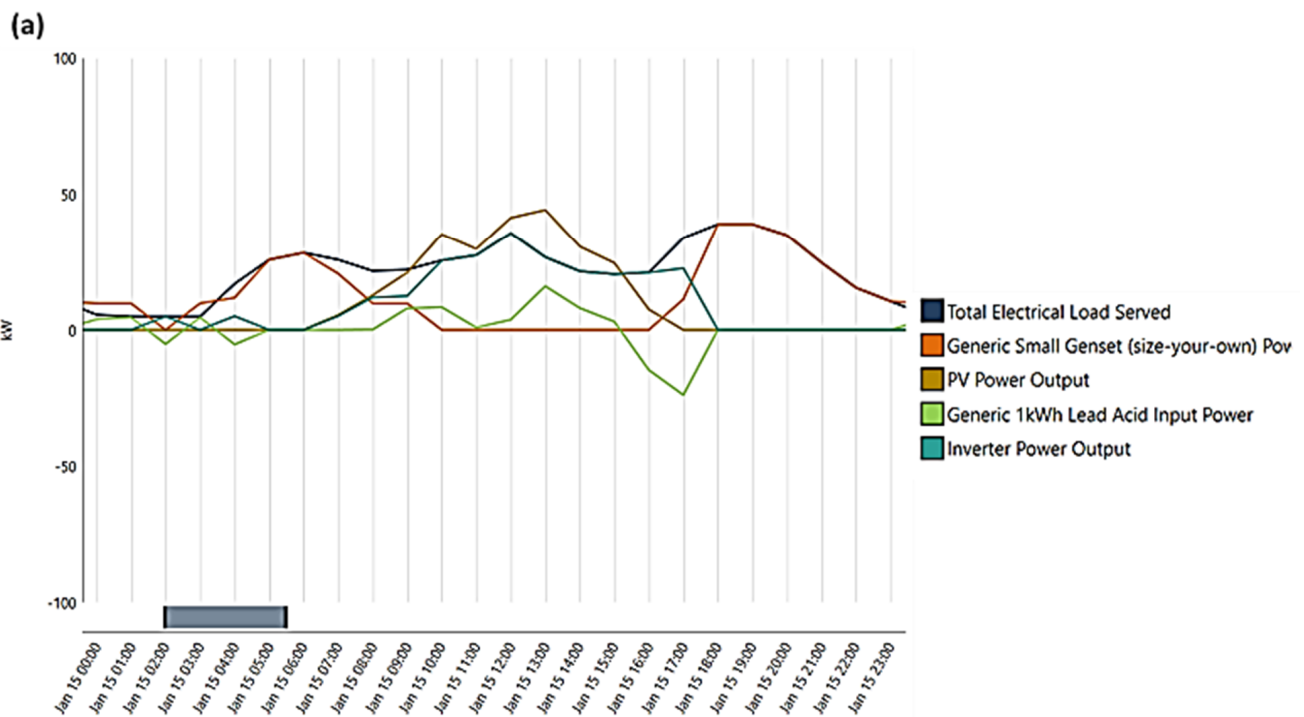
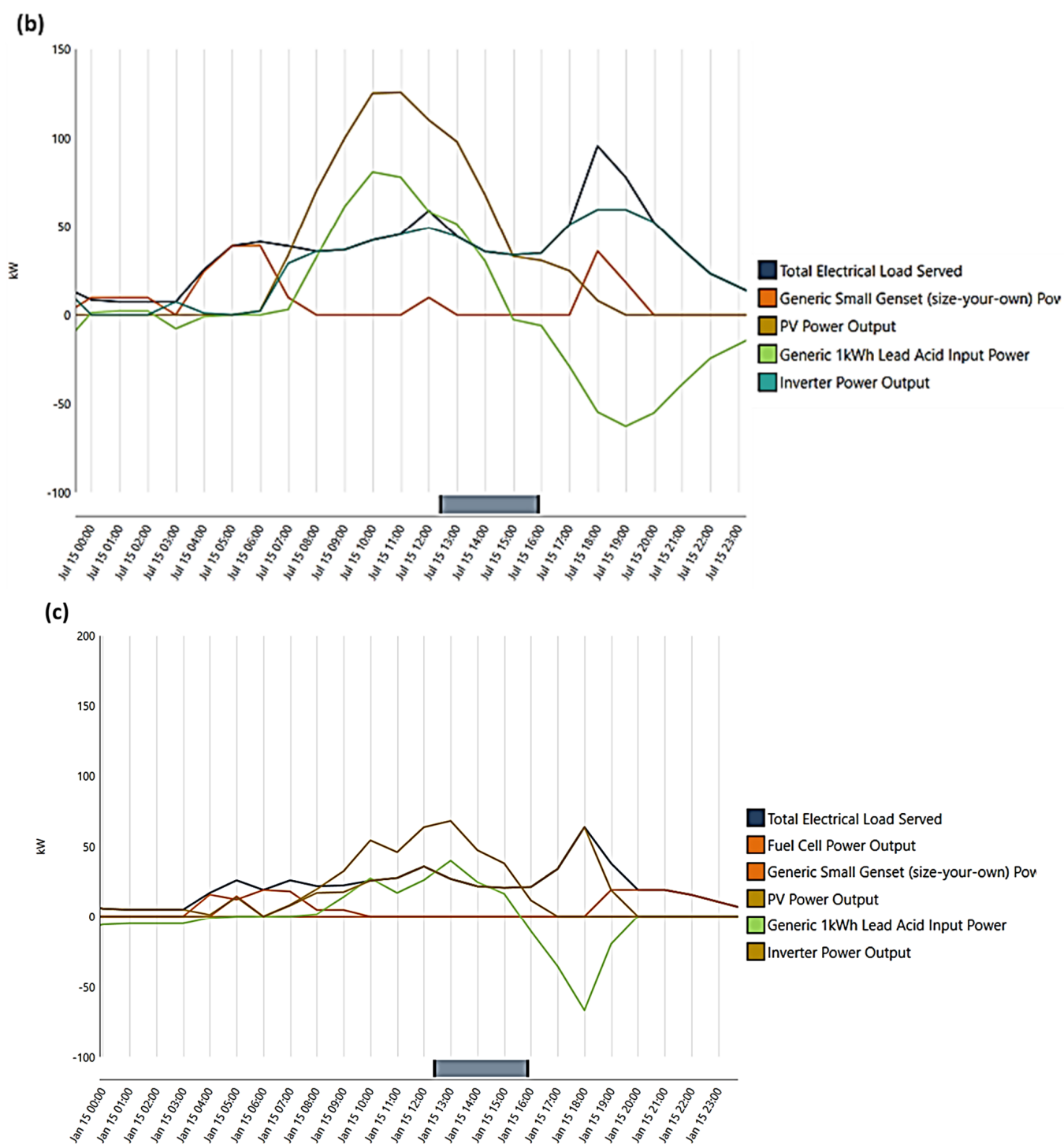


Figure 5. Cont.



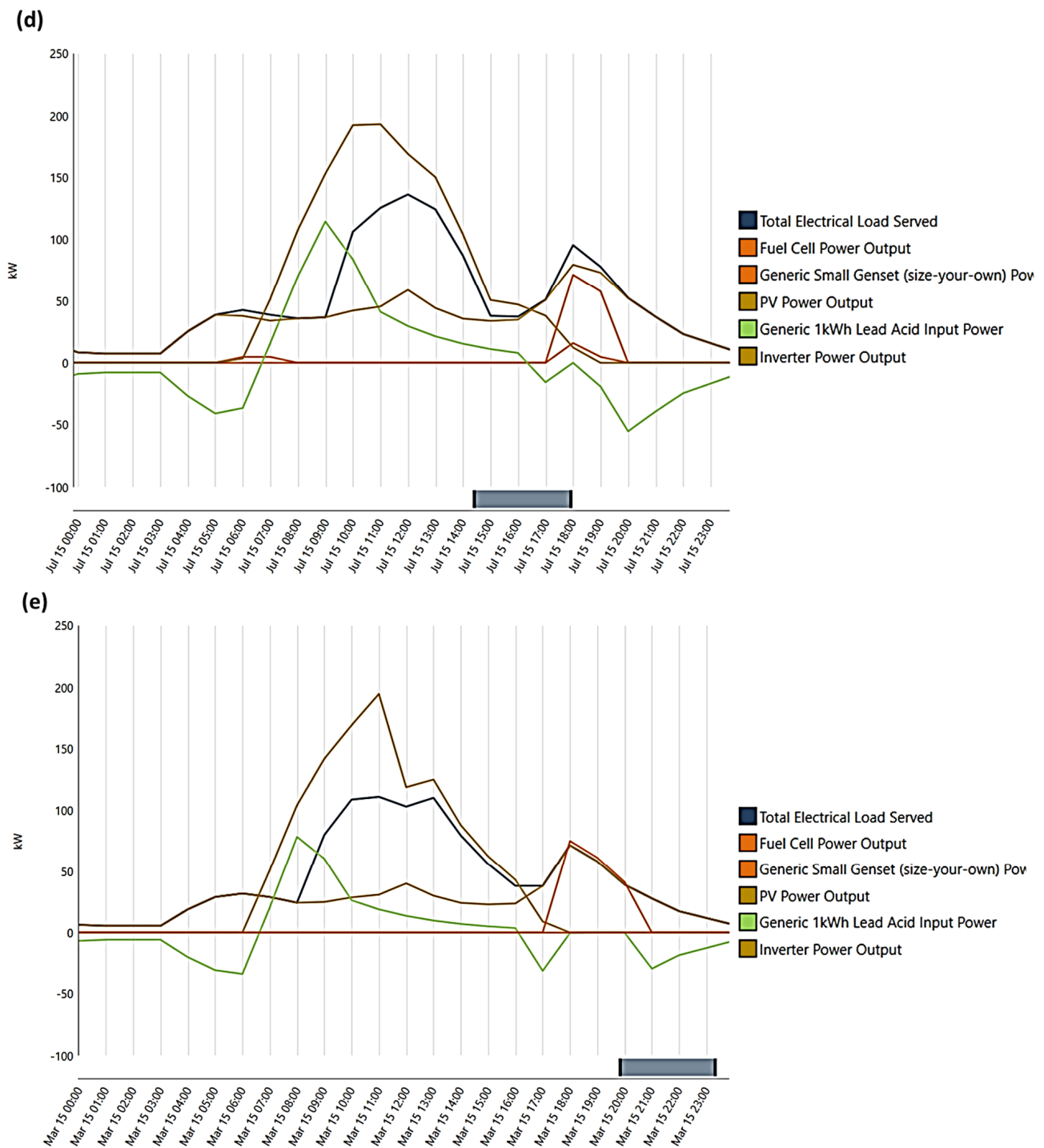


Figure 5. Hourly electrical power supply for (a) PV–DG–BES, January, (b) PV–DG–BES, July, (c) PV–DG–FC–BES, January, (d) PV–DG–FC–BES, July, (e) PV–DG–FC–BES, March.

Figure 6a,b represents the performance of the PV-DG-BES system. As expected the system depends on both PV and DG to produce power with any excess of electrical power produced being sent to BES for storage. The PV-DG-BES system relies heavily on the PV for electric power production due to shorter daylight hours (winter session) and the abounded insolation in the UAE throughout the year. Whereas the diesel fuel consumption and the SOC were very high in the summer season due to longer daylight hours even though the amount of insolation is at its highest in comparison to the rest of the year. The highest fuel consumption of DG occurs at 6 PM corresponding to the time of peak load

as shown in the hourly and daily mapping distribution in Figure 2a. On the other hand, Figure 6c–e shows the level of fuel consumption (diesel), fuel stored (hydrogen), and the battery's electrical charge or state of charge (SOC). The monthly fuel consumption amount was very high during the winter season due to the decrease in solar radiation in Sharjah during this period of the year. Moreover, the monthly fuel storage amount was very high during April and May due to the better performance of the solar PV, which was working at the optimum operating temperature. Similar to the fuel consumption, the amount of electrical storage or SOC of the battery was very low due to the aforementioned reason for the fuel consumption. Moreover, the level of diesel fuel consumption, the level of hydrogen storage, and the SOC are shown in Figure 6c–e, respectively, based on the hourly and daily mapping distribution. This mapping distribution clearly shows how the hybrid solar PV, DG, FC, and BES provides electrical power for the office building in Sharjah. This mapping distribution reflects how the hybrid energy system meets the load profile of the office building. Moreover, the highest fuel consumption occurs at 6 PM, corresponding to the load peak, while the highest fuel storage also happens at 6 PM in the months of March and April due to the best performance of solar PV and in August due to a long time of operation. Furthermore, the SOC for the battery has the highest and lowest values in the afternoon and before sunrise due to the full charging process and the full discharge process.

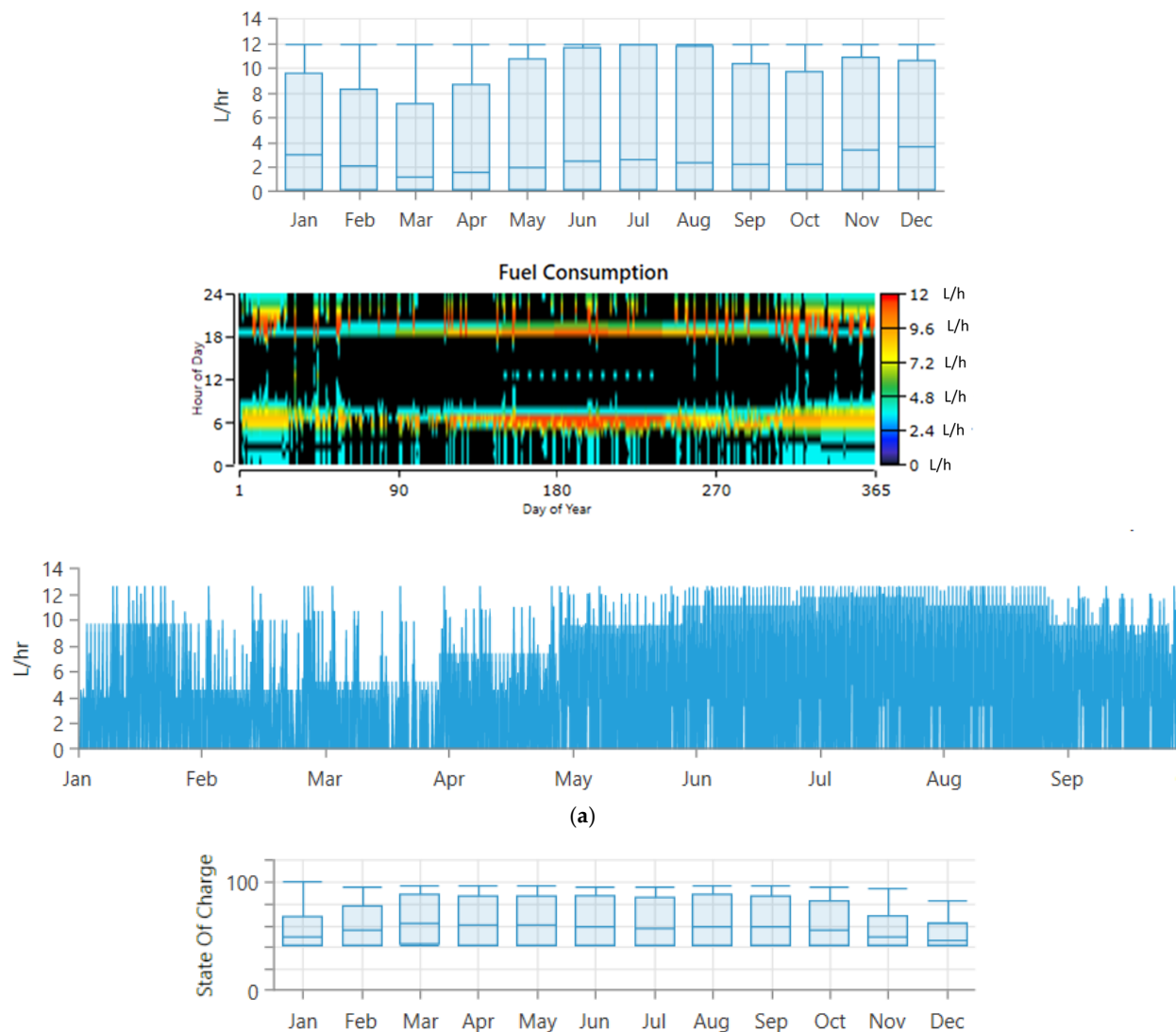


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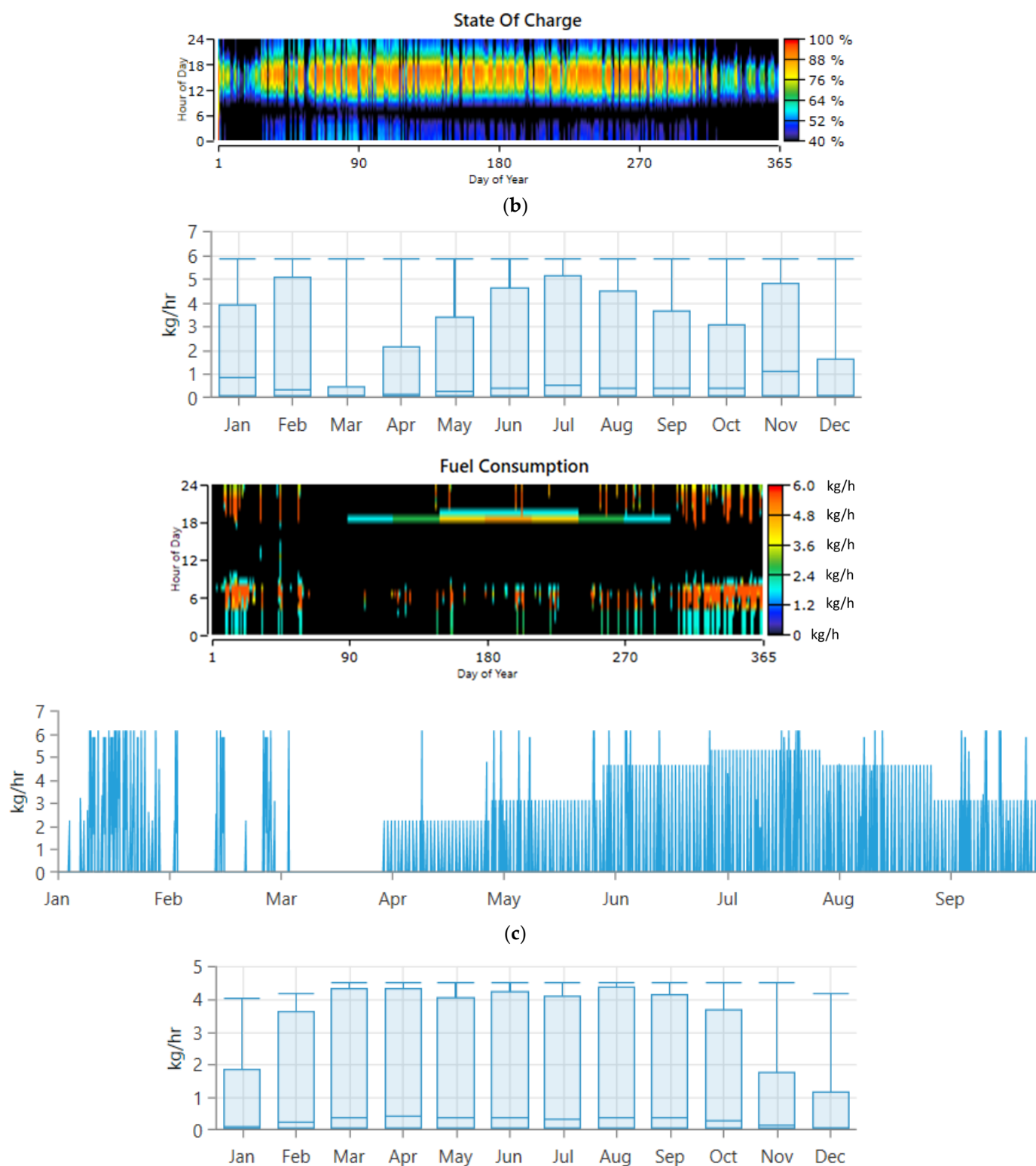


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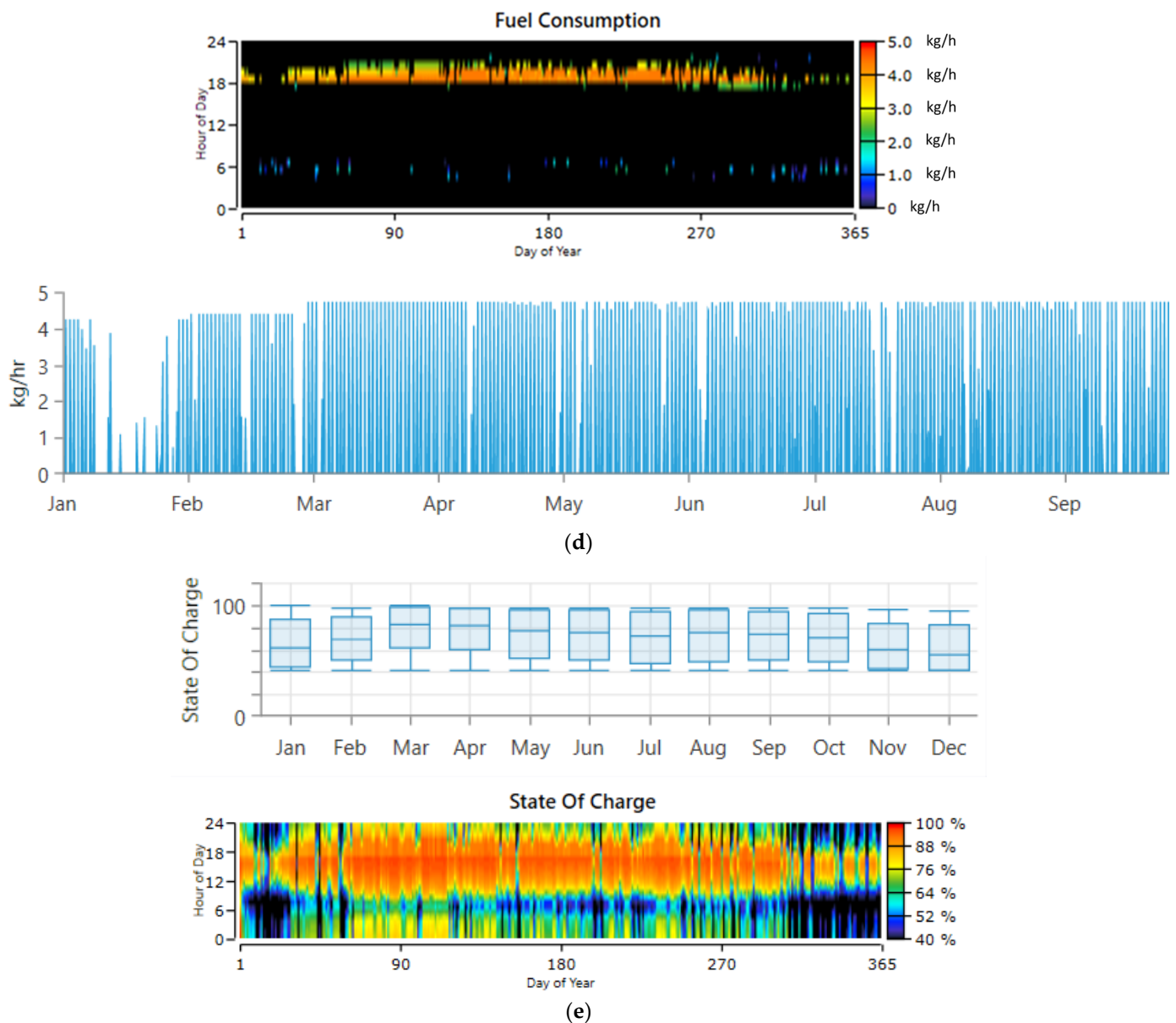


Figure 6. (a) the level and mapping distribution of diesel fuel consumption for PV–DG–BES, (b) the level and mapping distribution of state of charge for PV–DG–BES, (c) the level and mapping distribution of diesel fuel consumption for PV–FC–DG–BES, (d) the level and mapping distribution of stored hydrogen fuel for PV–FC–DG–BES, (e) the level and mapping distribution of state of charge for PV–FC–DG–BES.

The economic aspect of both the hybrid systems was compared in terms of cost of energy (COE) USD/kWh. The COE for the PV-DG-BES and PV-FC-DG-BES systems were very similar to each other being 0.305 USD/kWh and 0.313 USD/kWh, respectively. Even though the capital cost of the PV-DG-FC-BES system is higher than the capital cost of the PV-DG-BES system, the replacement costs of the PV-DG-BES system was higher than the replacement cost of the PV-DG-FC-BES system as shown in the cash flow diagram in Figure 7.

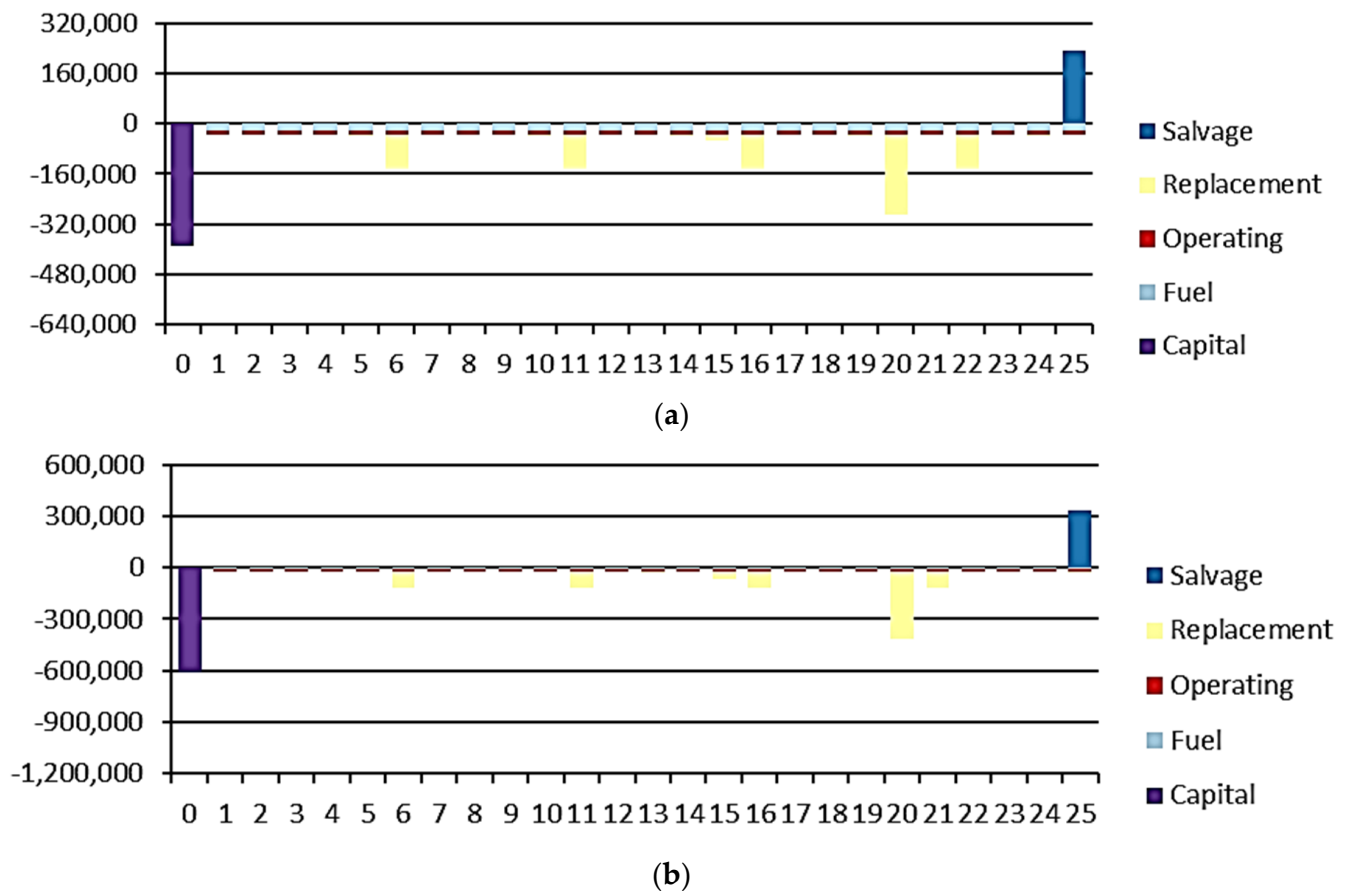


Figure 7. Cash flow for both hybrid energy systems (a) PV–DG–BES (b) PV–DG–FC–BES.

The comparison between the two hybrid systems in terms of the carbon footprint was also performed based on the emission gases responsible for greenhouse gases, such as carbon dioxide, unburned hydrocarbons, particulate matter, Sulphur dioxide (SO_x), and nitrogen oxides (NO_x). The impact of each aforementioned item on the environment is shown in Table 2.

Table 2. Pollution from both PV-DG-BES and PV-DG-FC-BES hybrid energy system.

Pollutant	Basic Hybrid System	Hydrogen Hybrid System
CO ₂ “Carbon Dioxide” (kg/yr.)	54,293	11,864
CO “Carbon Monoxide” (kg/yr.)	339	90.5
Unburned HC “Hydrocarbons” (kg/yr.)	14.9	5.07
Particulate Matter (kg/yr.)	2.03	1.67
SO ₂ “Sulphur Dioxide” (kg/yr.)	133	29.1
NO _x “Nitrogen Oxides” (kg/yr.)	319	215

The results from this study were compared with some of the other studies in the literature [36–38]. The solar PV-DG with different energy storage technologies was studied by [36]. The COE was within the range of this study. Moreover, the PV-DG-BES hybrid system was studied by [37]; the COE varied from 0.392 to 0.465 USD/kWh with the load profile and the capacities of the components being close to the data found in this study. Furthermore, the PV-DG-FC-BES hybrid system was used for a small community in NEOM city in Saudi Arabia, the COE was 0.126 USD/kWh with the load being similar to the load used in [37] but the COE was dependent on the cost of the diesel fuel and the derating factor of solar PV.

5. Conclusions

The commercial office building in Sharjah, United Arab Emirates, was built to use a hybrid green hydrogen system based on PV-DG-FC-BES technology. The load profile of the office building was met by the electric energy generated using the basic PV-DG-BES and hybrid green hydrogen systems. The total load comprises the demands of the office lighting, cooling, and other equipment. The COE for the base case and green hydrogen energy systems was 0.305 USD/kWh and 0.313 USD/kWh, respectively. While the operation and replacement expenses for the basic system were the greatest, the capital cost of a green hydrogen system was greater than the basic system. The basic system had a much greater carbon footprint and pollution from gas emissions, such as carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, Sulphur dioxide, and nitrogen oxides than the green hydrogen system.

In this work the comparison between the PV-DG-BES system and the PV-FC-DG-BES system was conducted in order to show how green hydrogen is produced using renewable energy resources, such as solar photovoltaic. The study shows that green hydrogen can be produced during the months of March and April when the abundance of solar radiation and the performance of solar PV cells were the highest in comparison to the other months. Moreover, green hydrogen can be produced throughout the year by increasing the electrical power production of the PV system with the COE being high in this case. The hydrogen production in this study was mainly based on renewable resources as in the PV system. Furthermore, different control strategies will be applied to the diesel generator in future studies to minimize its operating hours and emissions.

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Nomenclature

AWE	Alkaline water electrolyzer
A_{PV}	The PV panel's area.
COE	The cost of energy
CO_2	Carbon Dioxide
CO	Carbon Monoxide
DOD	Depth of discharge
E_{cons}	The total energy consumption
E_{nonren}	The conventional energy source
f_{PV}	The solar PV's derating factor
f_{ren}	The system's fraction of utilized renewable energy
F_0 and F_1	The manufacturer's fuel consumption coefficients
G_T	The actual amount of solar insolation
GFC	The consumption of fuel in the DG
GFC	the generator fuel consumption rate.
G_{STC}	The amount of solar insolation at 1000 W/m ² and 25 °C during STC
HC	Hydrocarbons
$HOMER Pro$	Hybrid Optimization Model for Multiple Energy Resources
HHV_{H_2}	Higher heating value of the hydrogen fuel
$HRES$	Hybrid renewable energy systems

$I_{bat, c}^{lim}$	Value of the charging current
$LCOH$	The Levelized Cost of hydrogen
$LCOE$	Levelized Cost of Electricity
LHV	Lower heating value-based DG efficiency
$LHVD$	The calorific value of diesel based on water vapor
$\dot{m}_{H_2}$	The mass rate of hydrogen in the electrolyzer in kg/s
N	The number of cells in series
N_s	Solar PV arrays with multiple panels connected in series
N_p	Solar PV arrays with multiple panels connected in parallel
NO_x	Nitrogen oxides
$PV-DG-FC-BES$	Solar PV, a fuel cell, a diesel generator, and battery energy storage system
$PV-DG-BES$	Solar PV, a Diesel Generator, and Battery Energy Storage
$PV-DG-FC-BES$	Solar PV, fuel cell, diesel generator, and battery energy storage
P_{PV}	The power production from the PV panel
P_{mSTC}	The solar PV panel power at a maximum point under STC.
P_m	The solar PV panel's maximum power under the actual operating conditions
P_{EZ}	The electrolyzer's power consumption
P_{DG}	The power production from the generator
PL	The power demand
P_{FC}	The amount of the fuel's chemical energy that is not converted into fuel cell electricity
P_{InvOut}	The output power to the inverter,
P_{InvIn}	The input of the power to the inverter
$p_{bat, d}^{lim}$	The battery's discharge power
P_{out}	The power of the battery bank
RES	Renewable energy system
STC	Standard test conditions
SOC	Battery's electrical charge or state of charge
SOC_{max}	The maximum allowed SOC
SOC_{min}	The minimum limit of the SOC
SO_x	Sulphur oxides
$T_{c,STC}$	The solar PV's cell temperature under STC,
T_c	The solar PV's cell temperature,
t	The current time
UAE	United Arab Emirates
U_{SC}	Single-cell voltage
V_{bat}	the terminal voltage of the battery terminal.
YDG	The DG's nominal power.
α_p	The temperature coefficient of power.
δ	The self-discharge coefficient
$\eta_{mp,STC}$	PV panels' maximum efficiency at STC
η_{FC}	The actual efficiency of the Fuel cell
η_{EZ}	The electrolyzer's efficiency
η_{Inv}	The inverter efficiency.
η_{ch}	The battery's efficiency
η_{dch}	The discharge efficiency
Δt	Time interval

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