A STAND-ALONE HYBRID POWER SYSTEM BASED ON PV ENERGY AND HYDROGEN FUEL CELLS WITH ENERGY STORAGE SYSTEMS

HAYDER ABDULSAHIB ISSA[1,3], LAYTH MOHAMMED ABDALI[2*], VLADIMIR I. VELKIN[3]

[1]University of Thi-Qar, Thi-Qar, 64001, Iraq

[2]University of Kufa, presidency university of Kufa Najaf, 54001, Iraq

[3]Nuclear power plants and renewable energy sources department, Ural Federal university, 620002 Yekaterinburg

DOI: 10.17973/MMSJ.2024_12_2024102

laithm.abood@uokufa.edu.iq

This article is focused on the construction of a stand-alone residential 5-kW hybrid power system to feed different domestic loads at a typical house in Thi-Qar City, Iraq, including lighting loads, Table fan, Smartphone charger, TV, Microwave and Cooler. The stand-alone residential 5-kW hybrid power system consists of PV generator, PEMFC, storage batteries, Electrolyzer and hydrogen tank. The battery and hydrogen subsystem, composed of a fuel cell (FC), electrolyzer, and hydrogen storage tank, act as energy storage and support systems. The research in steps includes the design of the hybrid system. A program has been used in MATLAB to size system components in order to match the load of the site in the most cost-effective way. Evaluation of the economic feasibility of the same hybrid system when using a solar tracking system for photovoltaic cells. The simulation results demonstrate the hybrid system's ability to supply the required electrical energy to the loads, as well as the increase in hydrogen production when using the solar tracking system, which makes it possible to store excess hydrogen in the long term for later use when the photovoltaic energy decreases according to the seasons of the year.

KEYWORDS

PEM fuel cells (PEMFC), PEM electrolyzer, Power Management System (PMS), Hydrogen tank

1 INTRODUCTION

Modeling and simulation of PV/FC/battery hybrid renewable energy systems is a crucial aspect of understanding and optimizing the performance of these systems. With the increasing focus on renewable energy sources and the need for sustainable and reliable power generation, such hybrid systems have gained significant attention facilities [Abd li 2019a, Gulzar 2023, Asl 2022, Abdali 2020]. The integration of photovoltaic (PV) panels, fuel cells (FC), and battery storage systems allows for a more efficient and reliable utilization of renewable energy. PV panels generate electricity from sunlight, while FCs convert chemical energy into electrical energy. Battery storage systems play a vital role in storing excess energy for later use, ensuring a continuous power supply [Al-Rufaee 2021, Mora 2022, Kuvshinov 2019a]. The modeling and simulation of these hybrid systems involve capturing the complex interactions between various components, such as PV panels, FCs, and batteries. It requires considering factors such as solar irradiance, temperature, load demand, system efficiency, and control strategies [Cheboxarov 2019a, Drwiega 2023, Vologdin 2019]. By developing accurate models and simulations, researchers and engineers can analyze the performance of PV/FC/battery hybrid systems under different operating conditions and optimize their design and operation [Ms 2021]. They can evaluate the system's efficiency, reliability, and economic viability, considering factors such as capital costs, operating costs, and environmental impacts. Furthermore, modeling and simulation enable the exploration of different control strategies and energy management techniques to enhance the system's performance. It allows for the evaluation of various scenarios, such as grid-connected or off-grid operation, optimal sizing of components, and the impact of different renewable energy resources [Abdali 2021, Veerendra 2024, Bozek 2013]. Overall, modeling and simulation play a crucial role in understanding the behavior and performance of PV/FC/battery hybrid renewable energy systems. They provide valuable insights into system design, operation, and optimization, contributing to the development of sustainable and efficient renewable energy solutions. The current study suggests a power management system (PMS) that guarantees continuous power supply and charges the battery at the maximum stated charging rate. The control method mitigates the transient variations in photovoltaic and load power by using a battery. This leads to frequent non-operation of the hydrogen subsystem. Moreover, it eliminates the necessity for a dump load in the system by aligning the power consumption from the two sources (photovoltaic and fuel cells) with the needs of the load and the electrolyzer. The benefit of the battery also lies in making the fuel cell supply power to the load gradually to protect it from sudden loads and thus prolonging the life of the fuel cell [Ogbonnaya 2021]. The simulation results show the distribution of power among the sources, loads, and batteries in a typical daily load scenario and under variable weather conditions. In this work, the focus was on the control strategy, and thus the modeling of air and hydrogen compressors was neglected. The work also focused on increasing the efficiency of the hybrid system using a solar tracking system for photovoltaic panels. In addition to calculating the economic feasibility of the system and the financial recovery in the case of fixed panels and panels supplied with a solar tracking system [Cheboxarov 2019b].

2 MATERIALS AND METHODS

This section analyzes the components of the hybrid system, which includes a group of PV panels, a PEMFC, a battery, a PEM electrolyzer, and a hydrogen tank H_2.

2.1 Modeling PV System

The simplest photoelectric cell is represented as shown in Fig. 1 [Abdali 2019b].

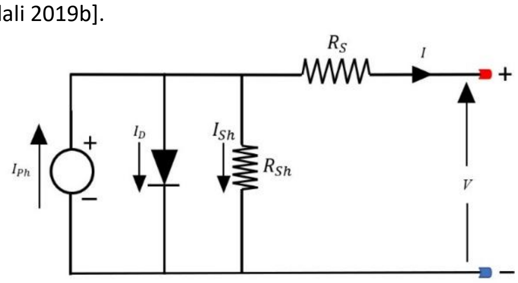

Figure 1. Single-Diode Model

Single-Diode Model: This model represents the behavior of the PV panel as a single diode connected in parallel with a current source, a resistor connected in series and a resistor connected in parallel. The equation for the output current of the PV panel can be represented as:

$$I = I_L - I_0\left[exp\left(\frac{(V + \boldsymbol{I_R} \times R_S)}{(n \times VT)}\right) - 1\right] - \left[\frac{V + \boldsymbol{I_R} \times R_S}{R_L}\right] \quad (1)$$

Where: I is the output current, I_L is the light-generated current, I_0 is the reverse saturation current, V is the output voltage, I_R is the diode reverse current, R_S is the series resistance, n is the diode ideality factor, VT is the thermal voltage, and R_L is the load resistance [Kuvshinov 2019b, Abdali 2023].

This model can be expanded by considering additional parameters to account for the more complex behavior of the PV panel – see Table 1. This model represents the output current of the PV panel with the following equation:

$$I = I_L - I_0\left[exp\left(\frac{(V+\boldsymbol{I_R}\times R_S)}{(n\times VT)}\right) - 1\right] - \left[\frac{V+\boldsymbol{I_R}\times R_S}{R_L}\right] - a \times (T - T_{ref}) \quad (2)$$

Where a is the temperature coefficient of the output current, T is the operating temperature, and T_{ref} is the reference temperature [Kuznetsov 2020].

Table 1. The characteristics of the PV panel used in the work

Rated Power	340 W
Voltage at Maximum power (Vmp)	37.8 V
Current at Maximum power (Imp)	9 A
Open circuit voltage (Voc)	44.5 V
Short circuit current (Isc)	9.75 A
Total number of cells in series (Ns)	60

2.2 Fuel cell Modeling

A FC is a device that uses chemical reactions to convert chemical energy into electrical DC energy. A pair of poles (anode and cathode) and an electrolyte positioned between them compose the FC. Compared to batteries, it offers numerous advantages, including simplicity, low maintenance, high efficiency, and the absence of pollution, making it a green energy source.

The resulting voltage at both ends of the fuel cell is less than the total voltage of the cell. This is due to the internal losses in the cell. The equation (3) indicates the fuel cell voltage [Ogbonnaya 2021, Humar 2011].

$$V_{FC} = M(E_{Ner} - V_{Drop}) \quad (3)$$

Where: V_{FC} is the fuel cell stack; M is the number of single cells; E_{Ner} is the reversible cell voltage (thermodynamic potential); V_{Drop} is the voltage drop of the cell.

$$V_{Drop} = V_{Act} + V_{Ohm} + V_{Con} \quad (4)$$

Where: V_{Act} is the activation voltage drop, which occurs because of the slow reaction at the anode electrode and the cathode electrode; V_{Ohm} is the resistance or (ohmic) voltage drop, it occurs as a result of the resistance of the internal components of the fuel cell, such as the electrodes and the electrolyte resistance; V_{Con} is concentration voltage drop, the gradual reduction in the availability of reactant gases at the electrodes during the progression of the reaction leads to a decline in concentration [Wang 2023, Humar 2011].

The rate of hydrogen consumption at the fuel cell stack can also be found in the following equation:

$$qH_2 = \frac{I_{FC}}{2F} \quad (5)$$

When the fuel cell stack is operating, as a result of chemical reactions, the temperature of the fuel cell fluctuates. The following equation determines the net heat:

$$Q_{net,h} = Q_{chem} - Q_{elec} - Q_{S+L} - Q_{Loss} \quad (6)$$

Where: $Q_{net,h}$ is the amount of net heat; Q_{chem} is the heat resulting from chemical reactions; Q_{elec} is the energy of electrical; Q_{S+L} is the sensible and latent heat; Q_{Loss} is the loss of heat.

During interactions and transitions, the temperature of the fuel cell will change (rise or drop) according to the specific heat capacity of the fuel cell with parameters listed in Table 2. Therefore, the net heat can be expressed as follows:

$$TM_{FC}CS_{FC}\frac{dT_{FC}}{dt} = Q_{net} \quad (7)$$

Where TM_{FC} is the total mass of the FC stack; CS_{FC} is the overall specific heat capacity of the stack [Sinha 2023].

Table 2. The Fuel Cell Properties used in the work

Description	Value
Number of Cells	120
Rated Power	5000W (5kW)
Rated Performance	72V @ 70A
Hydrogen Supply Valve Voltage	12V
Purging Valve Voltage	12V
Blower Voltage	24V
Reactants:	Hydrogen and Air
Ambient Temperature:	5 - 30C (41 - 86F)
Max Stack Temperature:	65 C (149 F)
External Power Supply:	24V (±1V), 8A-12A

2.3 Electrolyzer

PEM water electrolysis uses a solid PEM proton exchange membrane as an electrolyte and pure water as a reactant. Due to the low hydrogen permeability of the PEM electrolyte and the high purity of the produced hydrogen, only water vapor removal is required, which is simple and safe [Bonanno 2024, Abdel-Motagali 2024]. A typical PEM electrolytic cell is mainly composed of an anode end plate, a cathode end plate, an anode and cathode diffusion layer, an anode and cathode catalytic layer, and a proton exchange membrane. Among them, the role of the end plate is to stabilize the components of the electrolytic cell, guide the flow transfer, distribute water and gas, while the diffusion layer plays the role of collecting the flow and promoting the gas-liquid transfer [Khatib 2019]. The core of the catalytic layer is a three-phase interface that consists of the catalyst, the electronic conduction medium, and the proton conduction medium, which is the location of the electrochemical reaction nucleus.

Table 3. Technical specifications for 10kW PEM Water Electrolyzer system

Description	Value
Stack: LBE-P12C	12 cell
Size (L x W x H)	620 X 910 X 720 mm
Power Consumption	< 10 kW
Hydrogen Gas Production/h	up to 2000 L per hour
Oxygen Gas Production/h	up to 1000 L per hour
Pressure	0 - 5 bars
Temperature	10 - 60°C
Hydrogen Gas Purity	99.97 - 99.99%
Input Voltage	380 VAC, 3 phases

When operating the electrolyzer PEM of the type specified in Table 3, the operating voltage of a single cell is the sum of both the reverse voltage and the overpotential. It is called the operating cell voltage and can be obtained through the following equation:

$$V_{EL,cell} = V_{EL,Rev} + \mu act + \mu\Omega \quad (8)$$

Where: $V_{EL,cell}$ is the single cell operating voltage; $V_{EL,Rev}$ is the reverse voltage; µact, µΩ are the activation losses and ohmic losses respectively [Kuhnert 2023].

The electrolyzer stack consists of a group of cells connected in series, so the terminal voltages of the electrolyzer stack are as follows:

$$V_{EL,stack} = MV_{EL,cell} \quad (9)$$

The following equation gives the hydrogen production rate:

$$H_2 = \frac{\mu_{Cell} I_{EL,cell}}{2F} \mu_F \quad (10)$$

Where: μ_{Cell} is the number of electrolytic cells; $I_{El,cell}$ is the total current applied across the cell; μF is the Faraday efficiency.

2.4 Battery modeling

Battery modeling refers to the process of creating a mathematical representation or simulation of a battery's behavior and performance. This modeling is done to understand and predict how a battery will behave under different operating conditions, such as varying load demands, temperature, and state of charge [Kuvshinov 2021, Guryev 2019]. The work used a lithium-ion battery, due to its high efficiency and ease of integration into hybrid renewable energy systems. Battery modeling equations are mathematical equations that describe the behavior and performance of a battery system. These equations typically represent the electrochemical processes occurring within the battery and are used to understand and predict its voltage, current, and capacity [Yang 2022].
The voltage on the battery terminals is described as

$$V_{BAT} = E_{BAT,0} - I_{BAT} R_i - C\frac{q}{q - I_t}(I_t + I^F) + Zexp\,(t) \quad (11)$$

Where: V_{BAT} is output voltage of battery; $E_{BAT,O}$ is constant voltage of battery; C is polarization constant (V/(Ah)) or polarization resistance (Ω); q is capacity of battery; $I_t = \int Idt$ is actual battery charge (Ah); Z is exponential zone time constant inverse Ah^{-1}; R_i is internal resistance (Ω); I_{BAT} is current battery (A); I^F is Filtered current (A).
The term "state-of-charge" (SOC) refers to the amount of capacity that is still available inside the battery [Becherif 2023]. It is in the form of a percentage of capacity. SOC is defined as the following:

$$SOC(t) = 100\left(1 - {\int Idt}/{q}\right)\% \quad (12)$$

2.5 Modeling H_2 Tank

During peak periods, if the power produced from the PVs sources is low, the necessary amount of hydrogen is used to feed FCs to compensate for the leakage (shortage) in the required power. The hydrogen energy at any (t) is illustrated as follows:

$$EH_2t(\Delta t) = EH_2t(t-1) + P_{Ele} - H_2t - PH_2t - fc(t)\eta st\_t) \times \Delta t \quad (13)$$

Where: $EH_2t(\Delta t)$ and $EH_{2t(t-1)}$ are the amounts of energy kept in the tank at times t and (t − 1), respectively; $PH_2t\text{-}fc(t)$ is the power supplied to the FC; ηst_t is the hydrogen tank efficiency, which is taken as 95% for all operations [Kesana 2023, Minuto 2023].
The amount of stored hydrogen (MH_2,st,TK)can be obtained by finding the difference between the quantity of hydrogen produced from the electrolyzer (MH_2,pro,Ele) and the quantity of hydrogen consumed by the fuel cell (MH_2,con,FC), as shown in the following equation:

$$(MH_{2,st,TK}) = (MH_{2,pro,Ele}) - (MH_{2,con,FC}) \quad (14)$$

The pressure of stored hydrogen can be calculated as follows:

$$\frac{d}{dt}(p_{H2}) = \frac{RT_{TK}}{\theta_{TK}} MH_{2,st,TK} \quad (15)$$

Where: T_{TK} is the temperature of the tank; θ_{TK} is the volume of the hydrogen storage tank.

2.6 Control of a stand-alone hybrid system based on solar cells and fuel cells

Figure 2 displays a diagram of a standalone PV/fuel cell/battery system consisting of solar PV cells, dc-dc converters, FCs, electrolyzers, hydrogen tanks, and a residential load. FCs act as backup storage systems, whereas solar works as the primary source. The fuel cell serves as a secondary (auxiliary) source to meet the required power [Benlahbib 2020, Kamel 2021].

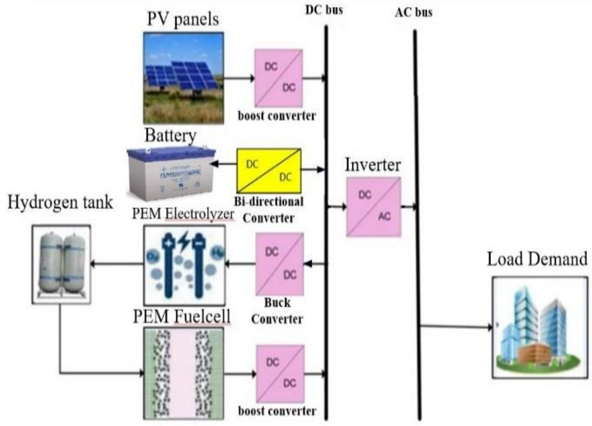

Figure 2. Block diagram of a hybrid standalone renewable energy system

A DC bus connects the PV panels and the PEM fuel cell to the storage modules as shown on Fig. 2. Both the PV panel system and the PEM fuel cell connect to the DC bus via the dc-dc boost converter. We use a bi-directional converter to connect the battery and a Buck converter to connect the electrolyzer to the DC bus. These converters control the system units and regulate the flow of power between the system components. Finally, the power sources and storage units are connected to the residential load through the inverter. A simulation study was conducted for a residential load with a peak load of 3 KW, as shown in Figure 3.

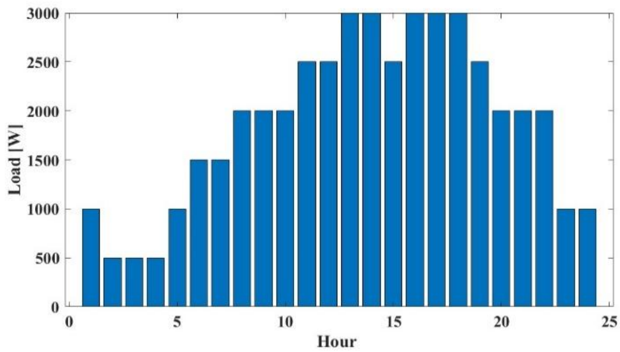

Figure 3. Daily load curve

The peak load is 3 kW, and the lowest load is 1 kW. In this work, the battery was considered a primary backup source, so calculations were made to choose the appropriate battery bank for the system. In order to determine the size of PV system, the total energy required from PV is equal to the energy required by electrolyzer added to the energy required by load during daytime in addition to energy required by battery charger then divide on number of operating hours gives kW of PV panels. Taking into account the weather conditions, including levels of irradiation and temperature, during the year's seasons. For this purpose, MATLAB was used to calculate the size of the components of the hybrid system and determine the working hours for each component.

3 RESULTS AND DISCUSSION

System work results during the day

Figure 4 displays the electrolyzer load during day time. The electrolyzer works from 8 a.m. to 6 p.m. However, electrolyzer cannot work at night.

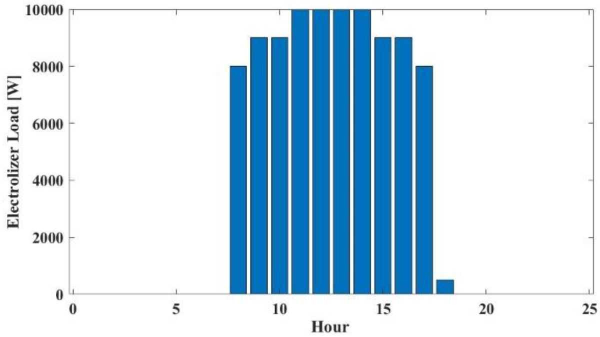

Figure 4. Electrolyzer load during daytime

According to the manufacturer's data,the hydrogen generation using a 10 kW electrolyzer is 2000 per hour. Since it is working for 11 hours, the total generated hydrogen is 18500 L.

The fuel cell works from 6 p.m. to 11 p.m. (total of 5 hours), as displayed in Figure 5. During this time, the fuel cell supplies the total residential load.

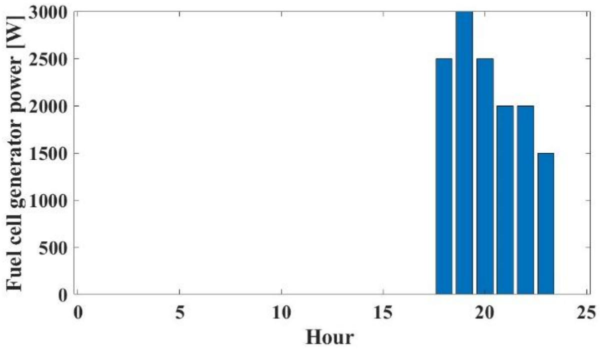

Figure 5. Fuel cell generator output power

The generated and consumed power per one day. The fuel cell operates for 5 hours, from 6 p.m. to 11 p.m. However, batteries supply the load from 12 o'clock at night to 8 a.m. and from 5 p.m. to 6 p.m., as shown in Figure 6. When battery power is positive, this means the battery is discharging. Negative power is obtained while the battery is charging.

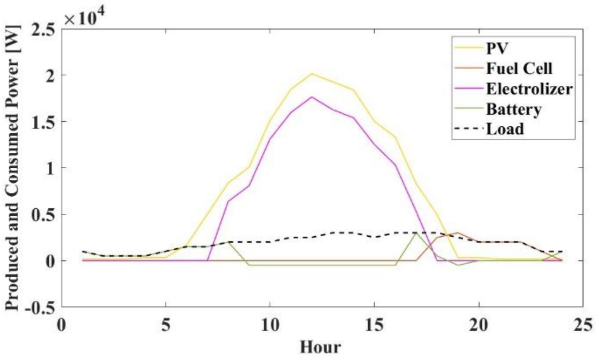

Figure 6. Generated and consumed power per one day

The hydrogen flow rate for the suggested fuel cell generator is 65 L/min. Then, the hydrogen average consumption in a fuel cell generator is about 48.61 x 60 minutes = 2400 L/hour. If the operating time is 5 hours, the consumption is 14583 L. The hydrogen and oxygen gas production are shown in Figure 7, and the hydrogen consumption by the fuel cell generator is shown in Figure 8. From Figure 8, the hydrogen consumption is proportional to the load power supplied by the fuel cell.

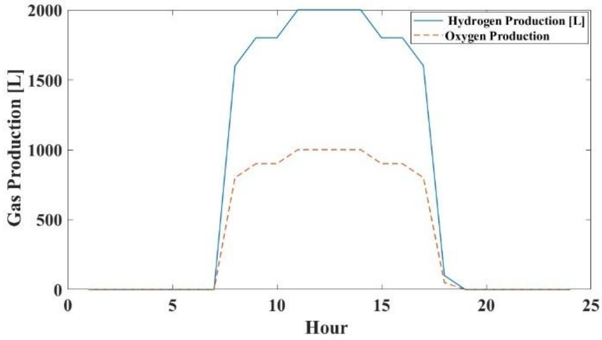

Figure 7. Gas production using electrolyzer

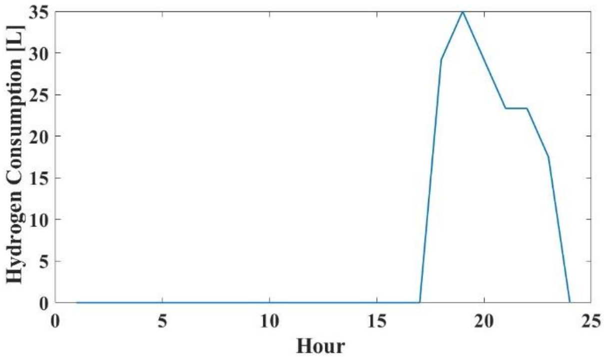

Figure 8. Hydrogen consumption

This study compares a hybrid system that uses fixed-tilt PV panels with a solar tracking system-equipped PV panel.

To calculate the energy production from the PV panels, in addition to the amount of hydrogen and oxygen produced by the electrolyzer of the proposed hybrid system in the case of fixed PV panels, and in the case of using solar tracking technology.

To do this, MATLAB/Simulink is used to simulate a model of the proposed hybrid system as shown in Figure 9. This model is based on the average solar radiation and temperature for each month of the year at the proposed site, as well as the load consumption profile and data from the manufacturer for each system component.

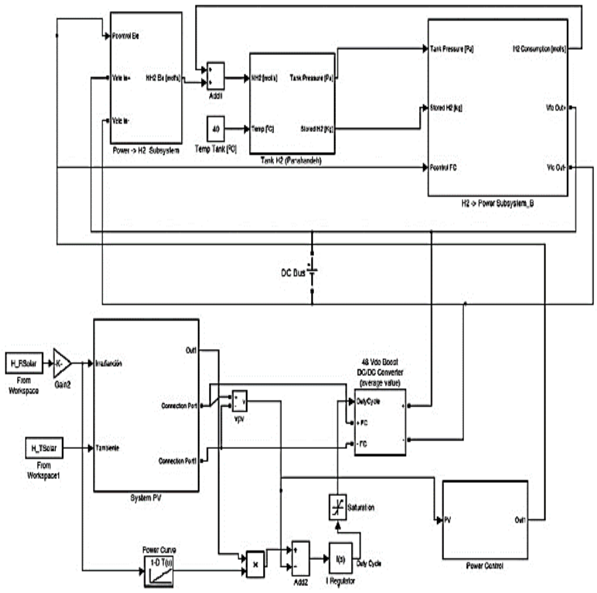

Figure 9. A hybrid system model using MATLAB/Simulink

According to the simulation results, the photovoltaic system pumps 2768 MWh/year of energy when the solar panels are at a fixed tilt, while the hydrogen production is 316654 m^3/year of hydrogen and 158329 m^3/year of oxygen, as shown in Figures 10 and 11.

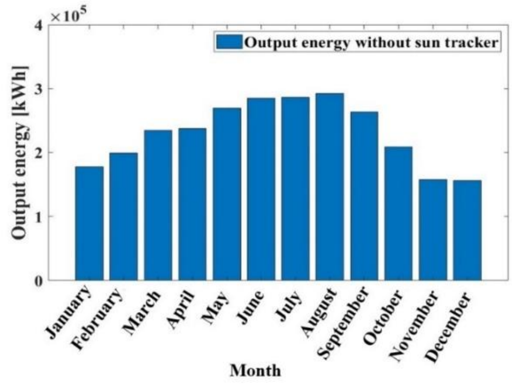

Figure 10. The hybrid system utilized fixed-tilt PV panels to pump energy over a period of one year

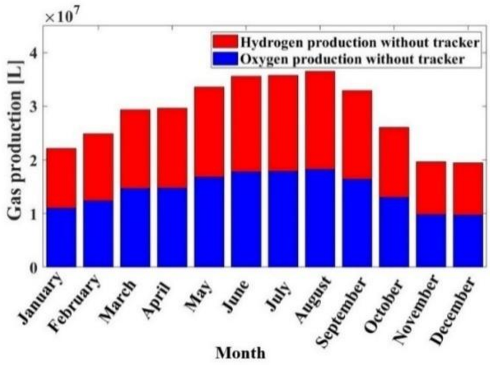

Figure 11. Hydrogen and oxygen produced per one year

While the second study focuses on moving photovoltaic cells (solar tracking), the annual generated energy increased by 12.32% to 3108 MWh/year. We also observe a 10.44% increase in hydrogen gas production to 352038 m^3 and an increase in oxygen production to 176018 m^3, both of which increase when using the sun tracking system, as shown in Figures 12, 13 and 14.

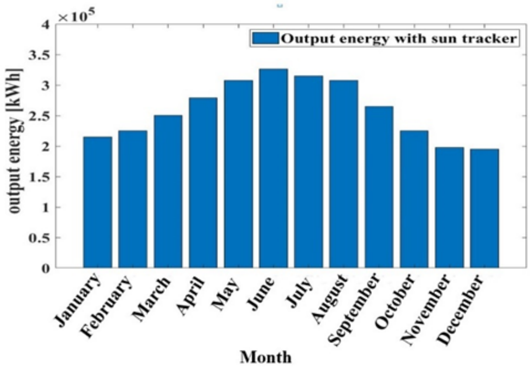

Figure 12. The hybrid system utilized moving PV panels (solar tracking) to pump energy over a period of one year

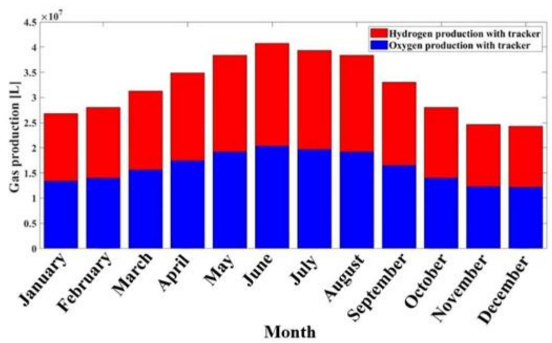

Figure 13. Hydrogen and oxygen produced per one year

Feasibility study and Economic analysis of PV / fuel cell system

To analyze economic feasibility and cash flow, a MATLAB code was written to calculate the economic parameters of the proposed stand-alone hybrid renewable energy system, based on input data summarized in Table 4. To calculate the economic parameters of a proposed stand-alone hybrid renewable energy system using MATLAB, one may follow the following steps:

1. Define the necessary variables for the calculation, such as initial investment cost, operation and maintenance expenses, fuel costs (if applicable), revenue generated, lifetime electricity generation, and project lifetime.
2. Calculate the total lifetime costs by summing the initial investment cost, operation and maintenance expenses, and fuel costs (if applicable). You can assign these values to variables.
3. Calculate the LCOE by dividing the total lifetime costs by the total lifetime electricity generation. Assign the result to a variable.
4. Display the LCOE in dollars per kilowatt-hour or cents per kilowatt-hour, depending on your preference.

Table 4. Input data for MATLAB code

Parameter	Qty	Unit Price ($)
PV module	48	270
Installation cost	20%	
Operation and maintenance cost	10%	
Interest rate	6%	
Discount factor	2.3%	
Project life	25 Years	
FC capital cost	1	27,062
Cost of Electrolyzer		11000
Batteries	20	420
Inverter	1	1000
replacement cost of inverter	1	500
Sun tracker	12	500

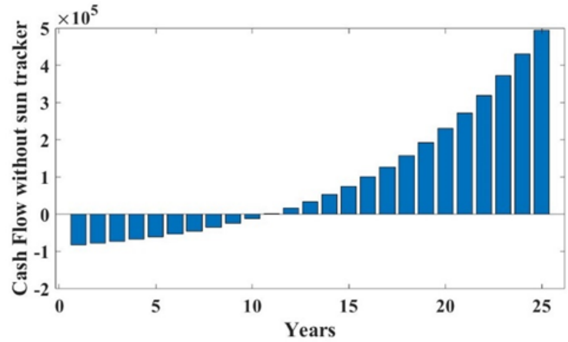

Figure 13. Cash flow of the proposed system as a bar type without tracker

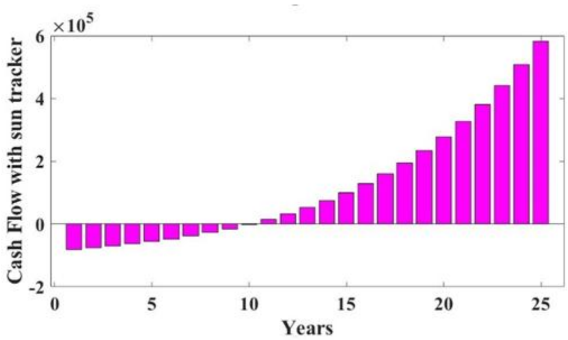

Figure 14. Cash flow of the proposed system as a bar type with sun tracker

4 CONCLUSION

Overall, a comprehensive economic analysis of a PV/fuel cell and battery standalone energy system should consider various factors such as capital costs, operational expenses, revenue streams, and project lifespan to determine its financial viability. Sun trackers increase the output energy of solar panels by orienting them to face the sun throughout the day, maximizing their exposure to sunlight. This increased energy production can lead to cost savings or revenue generation, depending on the specific context. By generating more electricity, the cost per unit of energy produced can be reduced, making solar energy more cost-effective compared to other sources such as fossil fuels. The total system cost is 82934$. The total generated kWh is 70520000. The LOCE is equal 13 cents without sun tracker and 11 cents with using sun tracker. Additionally, the increased energy output can potentially offset or even eliminate the need to purchase electricity from the grid, further reducing energy costs.

Acknowledgments

We thank the colleagues of the university of Thi-Qar (Republic of Iraq) and ministry of higher education and scientific research of Iraq.

REFERENCES

[Abdali 2019a] Abdali, L.M., Ahmed, H., Anssari, O. Modeling and simulation of tidal energy. ARPN J. Eng. Appl. Sci., 2019, Vol. 14, No. 11, pp. 3698-3706. DOI: 10.3923/jeasci.2019.3698.3706.

[Abdali 2019b] Abdali L.M. et al. A novel design of 7-level diode clamped inverter. ARPN J. Eng. Appl. Sci., 2019, Vol. 14, No. 11, pp. 3666-3673. DOI: 10.36478/jeasci.2019.3666.3673.

[Abdali 2020] Abdali L.M., et al. Study of hybrid wind–solar systems for the Iraq energy complex. Renew. Energy Sources, 2020, Vol. 56, No. 4, pp. 284-290. https://doi.org/10.3103/S0003701X20040027.

[Abdali 2021] Abdali L.M., et al. Developing a thermal design for steam power plants by using concentrating solar power technologies for a clean environment. Acta Montanistica Slovaca, 2021, Vol. 26, No. 4, pp. 773-783. DOI: https://doi.org/10.46544/AMS.v26i4.14.

[Abdali 2023] Abdali L.M., et al. Combined energy systems based on renewable energy sources. MM Science Journal, 2023, Vol. 5. No. December, pp. 7131-7135.

[Abdel-Motagali 2024] Abdel-Motagali, Ali, et al. Evaluating the performance of hybrid proton exchange membrane for PEM water electrolysis. Int. J. of Hydrogen Energy, 2024, Vol. 49, pp. 87-102.

[Al-Rufaee 2021] Al-Rufaee, F.M., et al. Development of hybrid photo-wind power systems with a diesel generator to overcome energy shortages. E3S Web of Conferences, 2021, Vol. 270, Art. No. 01029.

[Asl 2022] Asl, A.A., et al. Modelling and controlling a new PV/FC/battery DC–DC converter suitable for DC motor. J. of Engineering, 2022, Vol. 6, pp. 567-582. DOI: 10.1049/tje2.12138.

[Becherif 2022] Becherif, M., et al. Initial state of charge estimation of battery using impedance measurement for electrical vehicle applications. Sustainable Energy Technol. and Assess., 2022, Vol. 53, 102727. doi.org/10.1016/j.seta.2022.102727.

[Benlahbib 2020] Benlahbib, B., et al. Experimental investigation of power management and control of a PV/wind/fuel cell/battery hybrid energy system microgrid. Int. J. of Hydrogen Energy, 2020, Vol. 45, pp. 29110-29122.

[Bonanno 2024] Bonanno, M., et al. Review and prospects of PEM water electrolysis at elevated temperature operation. Adv Mater Technol, 2024, Vol. 9, No. 2, 2300281.

[Bozek 2013] Bozek, P. Robot path optimization for spot welding applications in automotive industry. Technical Gazette, 2013, Vol. 20, No. 5, pp. 913-917.

[Cheboxarov 2019a] Cheboxarov, V.V., et al. An offshore wind-power-based water desalination complex as a response to an emergency in water supply to northern Crimea. Appl. Sol. Energy, 2019, Vol. 55, No. 4, pp. 260-264. https://doi.org/10.3103/S0003701X19040030.

[Cheboxarov 2019b] Cheboxarov V.V., et al. Some results of a study of wave energy converters at sevastopol state university. Appl. Sol. Energy, 2019, Vol. 55, No. 4, pp. 256-259. doi.org/10.3103/S0003701X19040029.

[Drwiega 2023] Drwiega, A., et al. Maximization the latent heat storage unit (lhsu) energy saving using simulated annealing algorithm. MM Science J., 2023, Vol. June, pp. 6489-6494.

[Gulzar 2023] Gulzar, M.M., et al. An innovative converterless solar PV control strategy for a grid connected hybrid PV/wind/fuel-cell system coupled with battery energy storage. IEEE Access, 2023, Vol. 11, pp. 23245-23259.

[Guryev 2019] Guryev, V.V., Yakimovich, B.A., Abdali, L.M., Al Barmani, A.G. Improvement of methods for predicting the generation capacity of solar power plants: The case of the power systems in the Republic of Crimea and city of Sevastopol. Applied Solar Energy, 2019, Vol. 55, pp.242-246.

[Humar 2011] Humar, I., et al. Rethinking energy efficiency models of cellular networks with embodied energy. IEEE Network, 2011, Vol. 25, No. 02, pp. 40-49.

[Kamel 2021] Kamel, A.A., Rezk, H., Abdelkareem, M. Enhancing the operation of fuel cell-photovoltaic-battery-supercapacitor renewable system through a hybrid energy management strategy. Int. J. of Hydrogen Energy, 2021, Vol. 46, No. 8, pp. 6061-6075.

[Kesana 2023] Kesana, N.R., et al. Modelling of fast fueling of pressurized hydrogen tanks for maritime applications. Int. J. of Hydrogen Energy, 2023, Vol. 48, No. 79, pp. 30804-30817.

[Khatib 2019] Khatib, F.N., et al. Material degradation of components in polymer electrolyte membrane (PEM) electrolytic cell and mitigation mechanisms: A review. Renewable and Sustainable Energy Reviews, 2019, Vol. 111, pp. 1-14.

[Kuhnert 2023] Kuhnert, E., Hacker, V., Bodner, M. A review of accelerated stress tests for enhancing MEA durability in PEM water electrolysis cells. Int. J. of Energy Research, 2023, Vol. 1, 3183108.

[Kuvshinov 2019a] Kuvshinov, V.V., et al. Storage system for solar plants. Appl. Sol. Energy, 2019, Vol. 55, No. 3, pp. 153-158. https://doi.org/10.3103/S0003701X19030046W.

[Kuvshinov 2019b] Kuvshinov, V.V., Abdali, L.M., Kakushina, E.G. et al. Studies of the PV array characteristics with changing array surface irradiance. Appl. Sol. Energy, 2019, Vol. 55, pp. 223-228.

[Kuvshinov 2021] Kuvshinov, V. V., et al. Experimental studies on receiving surfaces of flat solar collectors. Surface Eng. and App. Electrochem., 2021, Vol. 57, No. 6, pp. 715-720.

[Kuznetsov 2020] Kuznetsov, N.P., et al. Investigation of the losses of photovoltaic solar systems during operation under partial shading. J. of Applied Engineering

Science, 2020, Vol. 18, No. 3, pp. 313 - 320. https://doi.org/10.5937/jaes18-24460.
[Minuto 2023] Minuto, F.D., et al. Modeling hydrogen storage at room temperature: Adsorbent materials for boosting pressure reduction in compressed H2 tanks. J. of Energy Storage, 2024, Vol. 90, 111758.
[Mora 2022] Mora, J.M., et al. Analytical-based simulation approach for an anion exchange membrane fuel cell. Energy Conv. and Manag., 2022, Vol. 273, 116382.
[Ms 2021] Ms, K., et al. Mitigation of circulating current with effective energy management in low-power PV-FC-battery-microgrid. Int. Trans. on Electrical Energy Systems, 2021, Vol. 31, No. 6, e12899.
[Ogbonnaya 2021] Ogbonnaya, C., et al. Prospects of integrated photovoltaic-fuel cell systems in a hydrogen economy: A comprehensive review. Energies, 2021, Vol. 14, No. 20, 6827.
[Sinha 2023] Sinha, A.A., et al. Comprehensive review on integration strategies and numerical modeling of fuel cell hybrid system for power & heat production. Int. J. of Hydrogen Energy, 2023, Vol. 48, No. 86, pp. 33669-33704.
[Veerendra 2024] Veerendra, A.S., Mohamed, M.R.B., Garcia Marquez, F.P. Energy management control strategies for energy storage systems of hybrid electric vehicle: A review. Energy Storage, 2024, Vol. 6, No. 1, e573.
[Vologdin 2019] Vologdin, S.V., et al. Analysis of various energy supply scenarios of Crimea with allowance for operating modes of solar power planta. Appl. Sol. Energy, 2019, Vol. 55, No. 4, pp. 229-234. https://doi.org/10.3103/S0003701X1904008X.
[Wang 2023] Wang, Y., Yang, X., Sun, Z., Chen, Z. A systematic review of system modeling and control strategy of proton exchange membrane fuel cell. Energy Reviews, 2023, 100054.
[Yang 2022] Yang, S., et al. Multi-scale battery modeling method for fault diagnosis. Automotive Innovation, 2022, Vol. 5, No. 4, pp. 400-414.

CONTACTS:

Layth Mohammed Abdali
University of Kufa, Presidency University of Kufa Najaf
54001, Iraq
laithm.abood@uokufa.edu.iq

Hayder Abdulsahib Issa
University of Thi-Qar
Thi-Qar, 64001, Iraq

Vladimir I. Velkin
Nuclear power plants and renewable energy sources department
Ural Federal university, 620002 Yekaterinburg