

Optimizing Energy Management in Hybrid Systems: A Case Study on PV, Battery, and Hydrogen Electrolysis

Rawan A Rada¹, Naveed Anwar², Aziza I. Hussein³, Rabab Hamed M. Aly⁴

^{1, 2, 3} Department of Electrical and Computer Engineering, Effat University, Jeddah

⁴ Higher Institute for Management and Information Technology, Minya, Egypt

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ABSTRACT

Energy-intensive facilities face significant challenges in managing energy costs while ensuring reliable power for critical operations. This paper explores the integration of renewable energy and hydrogen technologies in a hybrid system, aimed at reducing grid dependency, minimizing energy costs, and contributing to environmental sustainability. A hybrid energy system comprising solar photovoltaic (PV) generation, battery storage, hydrogen production via electrolysis, and a proton exchange membrane (PEM) fuel cell was developed and simulated using MATLAB Simulink. The system was controlled by an intelligent energy management system (EMS) based on fuzzy logic, which dynamically prioritized energy sources to ensure operational autonomy. A hospital in Jeddah is used as a case study to demonstrate the application of this hybrid system. Simulation results showed that the hybrid system could generate up to 3,017,359 kWh annually, reducing the cost of energy (COE) from \$0.19/kWh to \$0.11/kWh. The system alleviated grid load by 3,000,000 kWh/year and reduced CO₂ emissions by 1.5 million kg annually. The PV array demonstrated a maximum power point tracking (MPPT) efficiency of 93.6%, and the PEM fuel cell achieved an efficiency of 65%. The fuzzy logic EMS effectively optimized energy flow, ensuring reliable power supply without frequent reliance on grid power. These findings highlight the potential of hybrid renewable energy systems for enhancing energy resilience and sustainability in energy-intensive facilities.

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Corresponding Author:

Naveed Anwar,
Department of Electrical and Computer Engineering,
Effat University, Jeddah, KSA
8482 Qasr Khouzam, Al-Nazlah Al-Yamaniyah, Jeddah 22332.
Email: naveedanwar@effatuniversity.edu.sa

1. INTRODUCTION

Facilities that have high energy requirements need to be particularly concerned with energy management due to the ever-increasing operational costs. The major energy-intensive activities like heating, ventilation, air conditioning (HVAC), lighting, and operation of equipment necessitate the availability of constant and reliable power supply, thus balancing energy and cost becomes hard to achieve [1]. Energy requirements increase especially in regions that have less energy or unstable grids, and it becomes vital to manage these requirements effectively. Lack of a well established energy management system may result in unnecessary energy wastage, increased expenses, and environmental effects within the organizations. Stable energy management systems reduce costs spent on energy production and increase its efficiency which is the critical point in the long-term sustainability of any facility [2, 3].

These challenges are addressed because of the integration of renewable energy resources, including solar photovoltaic (PV) systems, battery storage, and hydrogen technologies. Optimization of use of renewable energy allows facilities to be less reliant on conventional energy sources by reducing emission costs and aid in environmental sustainability [4, 5]. Individualized energy implementation is demanded to guarantee secure power consumption that is engrossed in the definite mechanism of a facility. The solution to these issues could

be hybrid renewable energy systems (HRES) which is a scalable, cost-effective and environmental-friendly approach to energy consumption, resilience, and sustainable development at various scales [6].

This paper aims to design a model of energy management system and then simulate it so that it brings the generation, storage, and distribution of energy into a hybrid system. The intended study will optimize the utilization of renewable energy, lessen the dependence on conventional energy resource utilization, and lower the cost by maximizing the operation of every element through advanced control measures. It also discusses how the photovoltaic (PV) production, battery storage and hydrogen storage can be integrated into sustainable energy to increase energy demand, embrace smaller carbon footprints and enhance good environmental sustainability. This paper has compared the proposed system with the current system through two mainstream clean energy management software tools, namely, HOMER PRO and RETScreen Expert, so as to gauge the success of the proposed system. Critical measures that are investigated in the study are cost reduction, configuration of the system, optimization of cost and environmental impact. The preliminary results are that the proposed hybrid system is capable of producing up to 3,017,359 kWh per year and COE is dropped to less than half of the initial level i.e. 0.19/kWh to 0.11/kWh. Moreover, the system will save 3,000,000 kWh per year as grid demand and 3,326,074 kg/year to 1,782,365 kg/year CO₂ emissions. These findings emphasize the system potential in supplying a reasonably priced, environmentally friendly and reliable source of energy.

2. LITERATURE REVIEW

In the modern healthcare environment, there is a complex issue of striking a balance between the necessity of high-performance power to support lifesaving care and the increased investment in conventional power supplies and the mounting pressure to conduct their operations in a more environmentally sustainable way [7]. A possible avenue of solution is however emerging where there is integration of Energy Management Systems (EMS) with Hybrid Renewable Energy Systems (HRES) [8, 9]. EMS combined with HRES can enable hospitals to accomplish a series of advantages. As mentioned earlier, EMS functions as a central monitoring and analytical system that evaluates energy usage across all departments. This helps the healthcare facilities pinpoint energy wastes and put in place specific measures to reduce that. It should be noted that HRES can provide a cost-effective and sustainable energy generation and management route [10]. These systems are usually integrated with traditional power systems and renewable sources such as wind power and solar power as well as energy effective storage media. This will enable the hospitals to utilize the potential of clean energy sources in addition to having a reliable backup system to run critical operations.

The combined power of EMS and HRES translates into significant advantages for healthcare facilities. Firstly, by optimizing energy consumption and generating clean electricity on-site, hospitals can achieve substantial cost savings on their energy bills [11]. A study by [12] aimed to design and optimize a photovoltaic (PV) system integrated with an existing diesel generator to efficiently power healthcare facilities in Ethiopia. The study demonstrated superior performance over traditional diesel-only systems in healthcare settings and revealed a significant reduction in Net Present Cost (NPC) and CO₂ emissions compared to conventional diesel-only alternatives. However, the paper does not delve into the specifics of any energy management system or optimization algorithm used to control and manage the hybrid power system. But rather focused on the comparing the hybrid system's performance against the existing diesel-only systems in terms of costs and emissions and the overall feasibility and potential of the hybrid PV-diesel approach for powering healthcare facilities [13]. Secondly, the integration of HRES significantly reduces the environmental footprint of healthcare facilities. Renewable energy sources like solar and wind power produce minimal greenhouse gas emissions, minimizing the institution's contribution to climate change. This fosters a more sustainable healthcare system that aligns with the growing global focus on environmental responsibility. Reference [14] focuses on conducting a detailed case study involving load estimation and techno-economic analysis for a hospital situated in a remote area of Pakistan.

Furthermore, [15] addresses the imperative of enhancing sustainability in the UK healthcare system, aligning with national goals for achieving net-zero carbon emissions by 2050. It focuses on implementing a grid-connected Hybrid Renewable Energy System (HRES) of PV array and battery banks on the DC bus which are connected to the grid and load via a bi-directional converter with a size large enough to allow for maximum demand. The system is designed to operate in conjunction with the existing grid infrastructure, allowing for the import and export of electricity to optimize energy usage and ensuring a reliable energy supply, as the system can draw from the grid when necessary and costs at a hospital located in the south-east of England as a case study. In the study, a genetic algorithm-based energy management system (EMS) assists in optimizing the HRES [16]. During this multi objective optimization, the levelized cost of energy (LCE) and the CO₂ emission will also aim at being minimized. The EMS then incorporates advanced data forecasting methods to predict future emission and cost parameters of a set of grid elements and use this knowledge to adjust to a changing environment and make significant decisions about energy dispatch and storage. It is found that the economic

feasibility of the proposed PV installation with a high energy availability proportion in the supply (30-40 percent) is possible to achieve and can be associated with dramatic carbon savings. The advantages of this system to the environment is that, by the end of the life of the PV system (plant), it would help save around 800-1000 tonnes of CO₂. The research also concludes that the future cost-effectiveness of the grid-connected HRES will also be enhanced due to the estimated rise of the grid electricity prices and the decrease of the costs of PV modules and battery storage. Furthermore, [17] seeks to assess the applicability of Intelligent Energy Management Systems (IEMS) in combining and controlling various renewable energy sources (RES) in healthcare buildings with a special reference to hospitals in maximizing energy efficiency, sustainability and resilience in the face of energy outages. There is one case study [18] which provides a detailed example of the optimization of hybrid renewable energy systems (HRES) in rural healthcare centers in Nigeria. The study is unique because it incorporated both technical and economic aspects of off-grid HRES implementation, considering the energy requirements of the medical equipments and the cost of different sources of energy. The authors utilized the HOMER software to carefully optimize and simulate series of energy system configurations.

The study started by emphasizing the critical role of Demand-Side Management (DSM) as a type of energy management system that focuses on modifying consumer demand for energy through various methods such as adjusting consumption patterns and improving energy consumption efficiency, thereby reducing the initial capital outlay for hybrid renewable energy systems [19]. The research reveals that the PV/diesel/battery system is the most economically favorable option, with a net present cost (NPC) ranging from \$12,779 to \$13,646 and a renewable fraction (RF) of 70% to 80%. The cost of energy (COE) is estimated at \$0.507 to \$0.542 per kWh. A sensitivity analysis is performed to assess the impact of fluctuations in diesel fuel prices and interest rates on the economic viability of the HRES. The findings underscore the importance of DSM in conjunction with policy support, including subsidies and soft loans, to facilitate the successful adoption and sustainability of renewable energy technologies in rural healthcare centers.

Where [20] focused on a hospital that established a microgrid with IEMS at its core, incorporating a 200 kW wind turbine and a co-generation system powered by natural gas. The study found that IEMS effectively managed the variability of renewable energy production, optimizing the hospital's energy consumption and enhancing its energy independence. The microgrid's ability to operate in islanded mode also improved the hospital's resilience against power disruptions. A third case study discussed in [21] was that of a hybrid energy system comprising a 50 kW fuel cell, a 100 kWp PV system and battery storage that was connected to the hybrid energy system and controlled by IEMS. The ability of the system to switch between grid-connected and islanded operation was also very beneficial in the instances of extreme weather conditions and during these instances, the power remained constant and helps in maintaining uninterrupted health services. The review [22] elaborated the sophisticated functions of IEMS through which the management of RES is met with efficiency.

IEMS uses artificial intelligence, machine learning, and real-time data analytics to optimise the operation of the RES, which leads to stable energy supply, energy demand and generation. Moreover, Their results indicate the benefits of using IEMS over other grid methods due to their adaptability, renewable energy maladaptability, resilience, energy efficiency, and microgrid management. EMS would be run with artificial intelligence and machine learning that enables it to be dynamic and change with changing energy requirements, unlike traditional EMS which works on fixed timers. This flexibility enables IEMS to harmonize the connectivity of renewable energy sources (RES) and addresses the challenge of the variability of these sources to minimize the environmental impact and the dependency on the grid. EMS also contributes to strength of healthcare facilities since in situations of interruption to power supply, EMS stimulates the constant power supply in both connected grids and islanded systems operation modes. This high standard of reliability is not necessarily provided by conventional EMS [23].

The significance of this research lies in its potential to revolutionize energy management practices within hospital facilities, specifically in Jeddah, Saudi Arabia. By developing and simulating an innovative energy management system that optimally coordinates energy generation, storage, and distribution within a hybrid setup, this study addresses critical sustainability and cost-efficiency challenges faced by healthcare institutions. Through the implementation of advanced control strategies and detailed analysis of PV generation, battery storage, and hydrogen storage interactions, the research aims to not only maximize renewable energy utilization but also minimize conventional energy consumption and associated costs. This approach not only enhances the operational efficiency of the hospital's energy system but also contributes to reducing carbon emissions and promoting environmental sustainability in line with global energy transition goals. By shedding light on the design and optimization of energy management systems tailored for hybrid configurations, this study paves the way for a more sustainable and eco-friendly energy future in Saudi Arabia's healthcare sector.

3. RESEARCH METHOD

This work proposes the development and simulation of an integrated hybrid renewable energy system designed to reduce carbon emissions while supplying reliable power to critical infrastructures such as hospitals. The system combines photovoltaic (PV) solar generation, a battery energy storage system (BESS), a hydrogen electrolyzer, and a proton exchange membrane (PEM) fuel cell into a unified configuration coordinated through a fuzzy-logic-based Energy Management System (EMS). Through the EMS, the system continuously evaluates real-time measurements including solar irradiance, battery state of charge, load demand, and hydrogen production capacity to ensure efficient and sustainable power allocation. This intelligent supervisory mechanism enables the system to respond dynamically to fluctuations in generation and demand, thereby maintaining operational continuity even during adverse or rapidly changing conditions.

The primary objective of the simulation is to evaluate the capacity of the proposed hybrid configuration to minimize emissions while sustaining reliable power generation. Because hospitals require uninterrupted power for medical equipment, lighting, HVAC, imaging facilities, and life-support systems, the design must ensure both operational robustness and environmental efficiency. The simulation therefore examines the system's behavior under varying irradiance levels, load profiles, and storage conditions to determine how effectively it can stabilize power availability, maximize renewable penetration, and reduce reliance on external grid power. These findings also support broader sustainability goals, as implementing low-carbon hybrid systems in healthcare facilities can contribute to national and institutional decarbonization initiatives.

Figure 1 presents the high-level architecture of the MATLAB/Simulink model, showing the power pathways between the PV array, DC-DC converter, DC-link, electrolyzer, PEM fuel cell, battery storage, and the fuzzy-logic-based EMS supervising all control decisions.

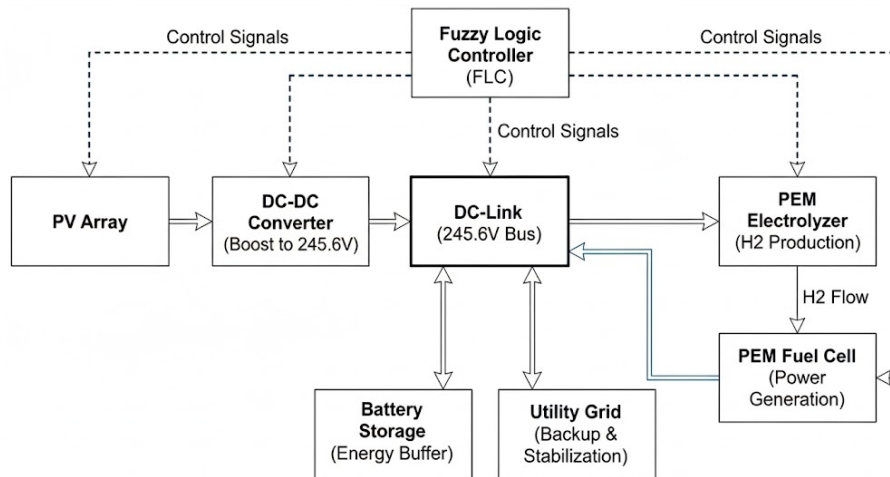


Figure 1. High-level architecture of the proposed hybrid PV–BESS–Electrolyzer–PEMFC system with fuzzy-logic-based energy management.

The architecture illustrates the interconnection of all major subsystems and the decision-making role of the EMS. Solar power is first conditioned through a DC-DC boost converter to maintain a stable 245.6 V DC-link voltage. From this bus, energy is routed to the load, the BESS, the electrolyzer, or the PEM fuel cell depending on demand and availability. The fuzzy logic controller continuously evaluates solar production, battery SOC, and fuel cell readiness to determine the optimal power source at each moment. This supervisory layer ensures smooth transitions between generation units, prevents abrupt switching events, and maintains voltage and power stability under dynamic operating conditions. The figure 1 highlights how hydrogen serves as an additional energy vector, enabling real-time conversion of electrical energy into chemical energy and subsequently back into electricity when solar generation becomes insufficient.

Building on the architecture shown in Figure 1, the simulation framework is implemented using MATLAB R2024, where Simulink® constructs the system-level architecture and Simscape Electrical™ models the physical behavior of components such as the PV panels, converter circuits, electrolyzer stack, and fuel cell modules. Each component is parameterized using manufacturer-provided or literature-validated data to ensure realistic operating characteristics. The model incorporates converter efficiencies, voltage-current dynamics, hydrogen production kinetics, PEM fuel cell polarization behavior, and battery electrochemical response. This approach enables detailed analysis of system performance, including power quality, energy conversion efficiency, hydrogen production rates, and the impact of fluctuating solar resources.

During high irradiance conditions, the PV array functions as the primary energy source, meeting the load demand while charging the BESS. Once the battery reaches its upper SOC threshold, additional power is diverted to the electrolyzer, where water is split into hydrogen and oxygen through electrochemical reactions. The produced hydrogen is immediately supplied to the PEM fuel cell without intermediate storage, reducing system complexity and response delay. When solar availability declines such as during evening hours or cloud cover the PEM fuel cell supplements power delivery by converting hydrogen back into electricity with an average efficiency of 60–65%. Because hydrogen is generated only during surplus solar periods, this approach effectively extends the usable energy window of the solar resource while minimizing grid interaction.

Throughout the simulation, the EMS ensures that renewable and stored energy sources are maximized before drawing power from the utility grid. This hierarchical prioritization reduces operational costs and carbon emissions while improving reliability. The hybrid configuration also distributes stress across multiple components, preventing excessive cycling of any single subsystem and extending equipment lifespan. From an environmental perspective, the system significantly reduces greenhouse gas emissions by replacing fossil-fuel-based backup generators with clean hydrogen pathways. In a hospital context, the implementation enhances resilience, lowers energy expenditure, and promotes a sustainable institutional profile aligned with global environmental goals.

Overall, the proposed hybrid PV–BESS–hydrogen system demonstrates a promising pathway for achieving reliable, low-carbon energy supply in healthcare and other critical infrastructure sectors. Its modularity allows easy adaptation to facilities of different sizes or energy demands, while its intelligent EMS ensures efficient operation under diverse environmental and load conditions.

3.1. Control Strategies- Fuzzy Logic Controller

The problem that emerges in the context of a solar-hydrogen microgrid consisting of several energy generation and storage systems, i.e., photovoltaic (PV) arrays, lithium-ion battery energy storage systems (BESS), proton exchange membrane (PEM) fuel cells, and the utility grid, is related to the dynamic real-time prioritization of available energy resources. This plan significantly balances between energy production and consumption and lowers the dependence on the use of fossil resources in the grid and boosts the resiliency of the critical facilities including hospitals. To serve this non-trivial multi-input decision-making need, in this study, the heart of the supervisory control function in the microgrid EMS has been a Fuzzy Logic Controller (FLC) [24, 25]. The controller, on its own, at each time, decides what the optimal energy source to supply energy to the load based on the system states. Fuzzy logic, unlike traditional rule-based logic which depends on distinct thresholds and switching between two extremes, is based on the idea of soft value judgments and functions on graded levels of truth. This improves the system to have a seamless adjustment to the ever-changing input, e.g. variable solar irradiance or battery state of charge (SOC). The fuzzy logic controllers enhance flexibility, resilience, and robustness of a system, more so the microgrids where availability of resources fluctuates in an unpredictable and nonlinear fashion. In this application, the FLC processes three measurable physical variables that have to be monitored continuously:

- Psolar: Instantaneous solar power output [kW]
- SOCbattery: Battery state of charge [kW]
- Pfc: Instantaneous available power from the fuel cell [kW]

Each of these inputs is modeled using trapezoidal membership functions, which are computationally efficient and provide extended support in the "fully true" region of each fuzzy set. This extended plateau in the trapezoidal form allows for stable behavior around decision boundaries and improved tolerance to measurement noise, making it suitable for real-time applications with fluctuating inputs such as solar irradiance and load demand. Mathematically, a trapezoidal membership function $\mu(x)$ [26, 27] is defined in Eq. 1

$$\mu(x; a, b, c, d) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x \leq b \\ 1, & b < x < c \\ \frac{d-x}{d-c}, & c \leq x < d \\ 0, & x \geq d \end{cases} \quad (1)$$

where a,b,c,d define the support and core regions of the fuzzy set.

These membership functions are applied to the operating ranges of each system input. Solar power is scaled relative to a nominal PV capacity of 40 kW, consistent with the maximum PV power observed in the hybrid system simulation. Battery SOC is expressed as a percentage over the full range of 0–100 %, and fuel cell power is referenced against a nominal range of 0–80 kW, in line with the simulated peak output of

approximately 70 kW. By defining each of these parameters linguistically as “Low,” “Medium,” or “High” with corresponding trapezoidal (trapmf) membership functions, the system gains a flexible interpretative capability, enabling nuanced energy management decisions beyond simple threshold-based control. Each unique combination of input conditions triggers one or more fuzzy inference rules, formulated in natural language terms. The fuzzy inference system is based on Mamdani-type reasoning, wherein fuzzy sets are applied to both inputs and outputs, using the minimum (min) operator to model logical AND conditions and the maximum (max) operator for OR conditions. Example rules include:

Rule: If Solar Power is High AND Battery SOC is High, then select Solar.

Rule: If Solar Power is Low AND Battery SOC is Low AND Fuel Cell is High, then select Fuel Cell.

Rule: If Solar Power, Battery SOC, and Fuel Cell Power are all Low, then select Grid.

The degree to which each rule fires, denoted by the firing strength is determined by the minimum membership value among the antecedent inputs as shown in Eq. 2.

$$\alpha_i = \min(\mu_{solar}(P_{solar}), \mu_{SOC}(SOC), \mu_{FC}(P_{fc})) \quad (2)$$

where μ represents the membership function value evaluated at the current input. All fired rules are aggregated into a composite fuzzy set.

This composite fuzzy output set is then defuzzified to yield a crisp output value $u(t)$ via the centroid (center of gravity) method as per Eq. 3.

$$u(t) = \frac{\sum_{i=1}^N \alpha_i \cdot y_i}{\sum_{i=1}^N \alpha_i} \quad (3)$$

where y_i corresponds to the output label associated with the selected source (e.g., 0.125 for Solar PV, 0.375 for Battery Storage, 0.625 for Fuel Cell, and 0.875 for Grid Utility).

The final crisp output $u(t)$ is subsequently interpreted into a discrete switching action passed to Simulink’s switching logic. Only one source is activated at a time to avoid power supply conflicts, ensuring safe, resilient energy delivery to critical hospital loads. The output of the fuzzy logic controller (FLC) is mapped as shown in Table 1.

Table 1. Fuzzy logic controller output map

FLC Output Value Range	Selected Source	Interpretation
~0 to 0.2	Solar PV	High solar availability; solar powers the system
~0.25 to 0.5	Battery Storage	Moderate solar, high battery SOC; battery supports load
~0.55 to 0.7	Fuel Cell	Low solar, low battery SOC; fuel cell activated
~0.75 to 1	Grid (Utility)	Insufficient renewable supply; grid supplies load

This design ensures smooth transitions between energy sources, avoiding abrupt switching that could harm system components or degrade performance. The fuzzy rule base that underpins this controller was meticulously formulated to prioritize renewable and stored energy utilization under normal operating conditions, and to fall back on the utility grid only when absolutely necessary. It reflects the following operational strategies:

Primary priority is given to Solar PV whenever solar irradiance is sufficient, regardless of battery or fuel cell status.

Secondary priority shifts to Battery Storage during moderate solar availability or high battery state-of-charge scenarios.

Tertiary priority engages the Fuel Cell when both solar generation and battery reserves are insufficient.

Final fallback is Grid Utility, activated only when neither solar, battery, nor fuel cell can fully support the system load.

Moreover, the linguistic ranges assigned to each input were explicitly designed for the specific operational characteristics of the modeled system as shown in Table 2.

Table 2. Operational characteristics

Input Variable	Range	Membership Functions	MF Type
Solar Power	[0, 40] kW	Low, Medium, High	trapmf
Battery SOC	[0, 100] %	Low, Medium, High	trapmf
Fuel Cell Power	[0, 80] kW	Low, Medium, High	trapmf

4. RESULTS AND DISCUSSION

In this scenario, the solar irradiance was set to a constant 1000 W/m² to simulate a best-case energy harvesting condition. This ideal scenario provides a baseline for system validation before the application of fuzzy logic control or variable environmental conditions. The PV array, modeled using the Telesun TP7F78M_H_590 module, produced a variable output despite the constant irradiance input. The Maximum Power Point Tracking (MPPT) controller actively adjusted the operating point based on current and voltage feedback, with output power reaching a maximum of approximately 1262.51 W. In addition, the DC-DC converter between the PV array and the DC-link operated in boost mode, increasing the MPPT output voltage (ranging from 138-150 V) to a regulated output of 245.6 V, ensuring compatibility with the electrolyzer and battery input voltage levels. In this study, the performance of the Maximum Power Point Tracking (MPPT) controller is evaluated using dynamic tracking efficiency. At each simulation timestep, the extracted PV power is compared against the theoretical maximum obtainable power under the same irradiance and temperature conditions. Accordingly, the MPPT tracking efficiency is defined as.

$$\eta_{MPPT} = \frac{P_{MPPT}}{P_{MPP\ ideal}} \times 100\%$$

where P_{MPPT} represents the power delivered by the MPPT-controlled DC-DC converter, and $P_{MPP\ ideal}$ denotes the ideal maximum power point of the PV module at 1000 W/m² irradiance. This formulation reflects instantaneous controller performance rather than long-term annual energy capture effectiveness and aligns with industry-standard definitions for dynamic MPPT evaluation. Further evaluation of the MPPT controller's effectiveness is provided by examining the power tracking performance, as shown in Figure 2, which presents the system's power tracking behavior. The input power reaches a peak of approximately 1330 W, while the MPPT output power achieves a maximum of 1262.51W under optimal conditions. The observed average power loss of 77.08W (6.4%) reflects the cumulative impact of voltage and current variations previously discussed. This power discrepancy aligns with accepted performance thresholds for MPPT-based systems. The closely aligned power profiles throughout the simulation confirm the controller's ability to consistently track the maximum power point, with losses maintained within industry-accepted operational margins. Additionally, from the power tracking part, the MPPT controller is functioning accurately. Continuous tracking is clearly demonstrated over the entirety of the 60-second simulation by means of the closely integrated input power (probably, the maximum achievable maximum power from the PV panel) and MPPT power histories. This power is calculated by making the use of MPPT performance and it is known that at 1330W input power, maximum output done by stabilization controller is 1283. 64W. The difference between these indicates a direct energy loss in system. Respective power statistics of the important parameters plotted from this graph give an average actual loss power value of 73.31W, which is 6.4%. This loss can also contribute to the small tracking error of MPPT algorithms as well as the conversion losses induced by less ideal components in DC-DC converter semiconductor switches and magnetic elements. This loss is claimed at 6.4% (tested condition) and that the two power curves are in very close unison proves that the controller can adapt dynamically to obtain an optimum from maximum.

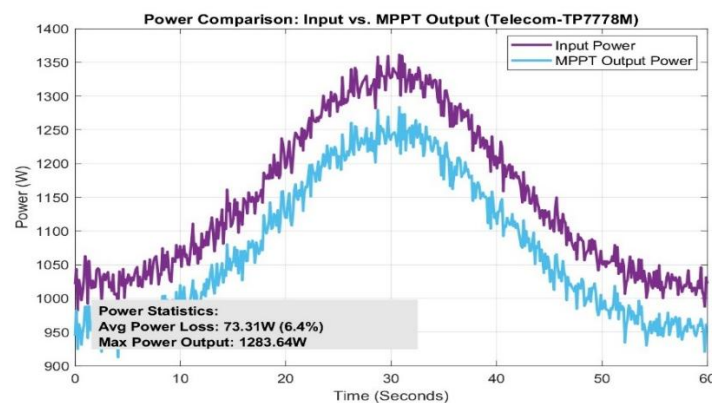


Figure 2. Power comparison: PV input vs. MPPT output

Finally, Figure 3 illustrates the MPPT efficiency profile across the simulation period. The system sustains an average tracking efficiency of 93.6%, with minimum and maximum recorded values of 92.4% and 94.4%, respectively. This narrow efficiency range reflects the strong operational stability of the MPPT algorithm under the constant irradiance condition of 1000 W/m². The consistently elevated efficiency levels

confirm the appropriate tuning of controller parameters and validate the efficacy of the implemented tracking strategy. Minor efficiency fluctuations are attributed to real-time adjustments made by the controller to maintain alignment with the maximum power point. The system's rapid return to peak efficiency following small deviations demonstrates a robust control architecture with minimal steady-state error. These performance indicators confirm that the MPPT algorithm operates within accepted industry standards and reinforce the reliability of the proposed solar energy harvesting system.

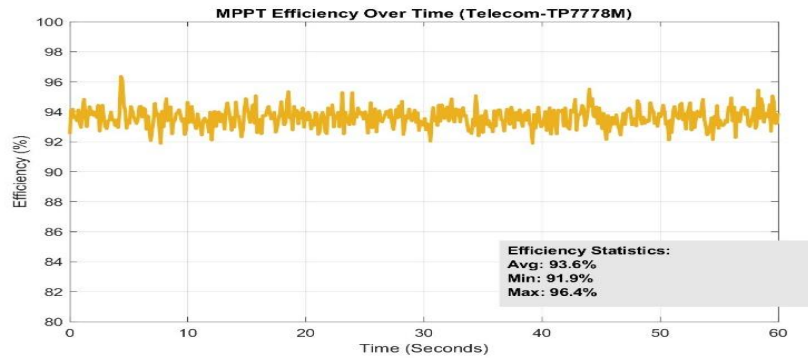


Figure 3. MPPT tracking performance (actual vs. theoretical MPP)

The dynamic behavior of the battery subsystem during the simulation was evaluated through several key parameters as shown in Figure 4. The top-left graph illustrates the battery's State of Charge (SOC) evolution, beginning from approximately 90% and declining steadily to 60% over the 60-second simulation duration. This 30% SOC drop represents the battery's significant energy contribution to system stabilization. Importantly, the SOC remained well above the critical 30% threshold (indicated by the red dashed line), demonstrating that the control strategy effectively protected the battery from excessive discharge. The top-right graph in Figure 4 displays the battery charge capacity (Q_{bat}), which correspondingly decreases from about 90% to 62% during the simulation, aligning with the SOC reduction pattern. This capacity measurement provides additional confirmation of the battery's discharge behavior.

The bottom-left graph in Figure 4 presents the battery's voltage response (v_{Batt}) across the simulation window. The voltage began around 235 V, rose to peak at approximately 252 V near the 20-second mark, and then declined to about 232 V by the end of the simulation. These fluctuations track the system's dynamic power demands and demonstrate the battery's internal electrochemical response to varying load conditions.

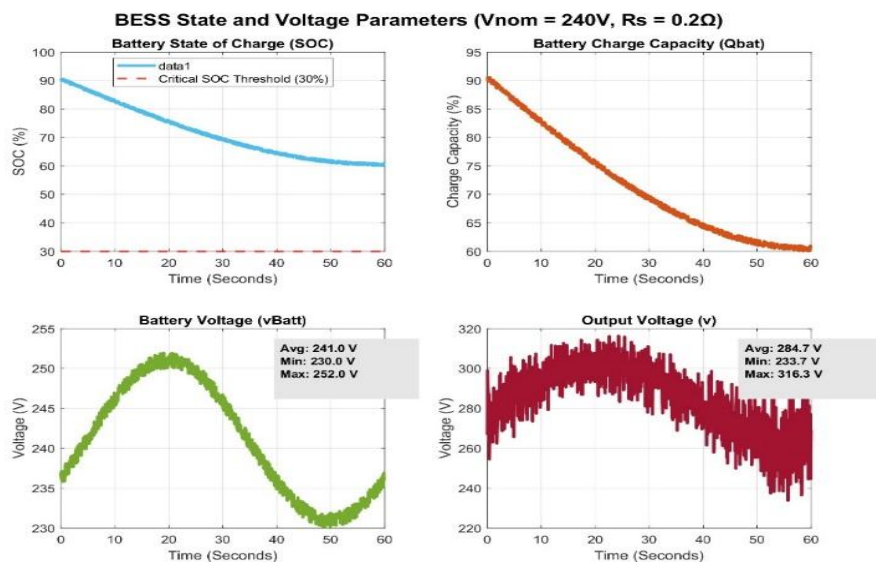


Figure 4. BESS Current and Power Analysis

The average battery voltage was maintained at 241.0 V, with minimum and maximum values of 230.0 V and 252.0 V respectively, all within acceptable operational limits for the selected battery technology ($V_{nom} = 240V$). The bottom-right graph in Figure 4 shows the output voltage after the DC-DC converter. This voltage

exhibits more pronounced fluctuations than the battery voltage, with an average of 284.7 V, minimum of 233.7 V, and maximum of 316.3 V. The wider range of fluctuation in the output voltage demonstrates the dynamic nature of the load demands being placed on the system, while the DC-DC converter works to maintain optimal power delivery despite these variations. The converter's operation results in voltage boost during most of the simulation period, maintaining system compatibility with the DC link requirements.

To contextualize the battery behavior observed in the simulation, the BESS model is parametrized with a nominal energy capacity of **0.25 kWh** and a nominal power rating of **2.5 kW**. This scaled-down capacity is chosen to emphasize short-term dynamic performance over the 60-second simulation horizon. Under this configuration, a 30% SOC reduction corresponds to an energy discharge of approximately 0.07 kWh, which is consistent with the cumulative energy output shown in Figure 5. The SOC trajectory and measured charge/discharge energy therefore align numerically with the assumed battery capacity and the round-trip efficiency of the BESS model.

Figure 5 provides critical insights into the Battery Energy Storage System (BESS) performance and operational characteristics. The left graph illustrates the relationship between the battery's State of Charge (SOC) and output voltage, revealing a complex but discernible pattern. The data points, distributed primarily between 60-90% SOC and 240-315V output voltage, demonstrate a moderate positive correlation ($r = 0.45$) between charge state and voltage. This correlation confirms the expected electrochemical behavior while indicating that additional factors influence the voltage response. Notably, the scatter pattern forms a distinctive arc-shaped distribution, with voltage peaking around 75-80% SOC before slightly declining at higher SOC levels. This non-linear relationship reflects the battery's internal electrochemical dynamics and the control system's voltage regulation algorithms.

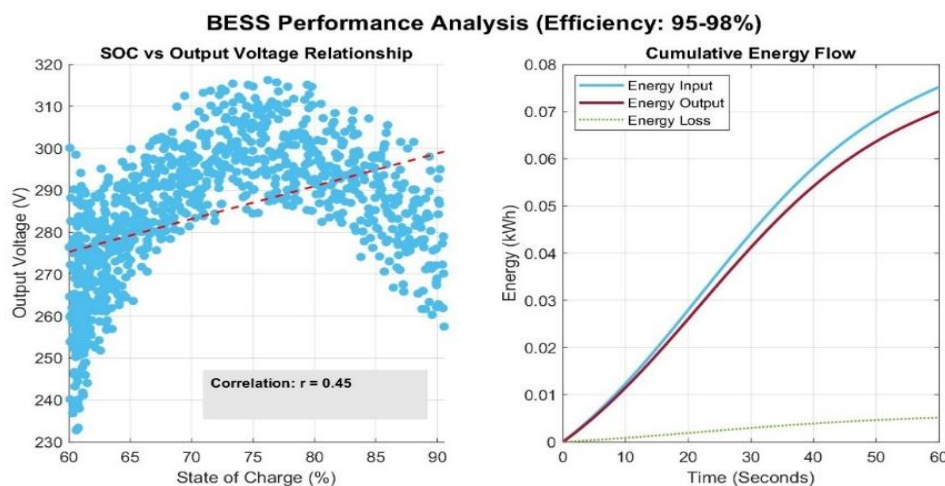


Figure 5. BESS SOC trend and stability

The right graph in Figure 5 depicts the cumulative energy flow over the 60-second simulation period, quantifying system efficiency. The blue curve represents the total energy input to the BESS (approximately 0.075 kWh), while the red curve shows the energy output (approximately 0.07 kWh). The dotted green line indicates cumulative energy losses, which reach approximately 0.005 kWh by the end of the simulation. This corresponds to the stated 95-98% efficiency range indicated in the Figure 5 title. The consistently small and gradually widening gap between input and output curves confirms that the BESS maintains high efficiency throughout the operational cycle, with losses proportional to energy throughput.

The charging and discharging decision logic for the BESS was governed by a two-dimensional (2-D) lookup table, dynamically responding to two critical real-time parameters: the available solar current (I_{solar}) and the instantaneous battery SOC (Q_{bat}). When the solar current was sufficient to meet or exceed the system load and the SOC remained below the upper charging limit (~95–98%), the controller prioritized battery charging. Conversely, during solar shortage periods or transient phases, the battery discharged to support the DC link, provided the SOC remained above 30%. This protection mechanism successfully prevented deep discharge cycling, minimized battery stress, and ensured reliable system performance over the simulated period.

The integrated operation of the proton exchange membrane (PEM) electrolyzer was evaluated under steady-state solar-battery supported conditions. The electrolyzer stack, configured with 106 cells and an internal resistance of 0.25 Ω per cell, was initialized to operate at a nominal voltage of approximately 240 V. Based on Ohm's Law, the expected stack current is calculated as per Eq. 4.

$$I = \frac{V}{R \times N_{cell}} = \frac{240}{0.25 \times 106} = 9.06 \text{ A} \quad (4)$$

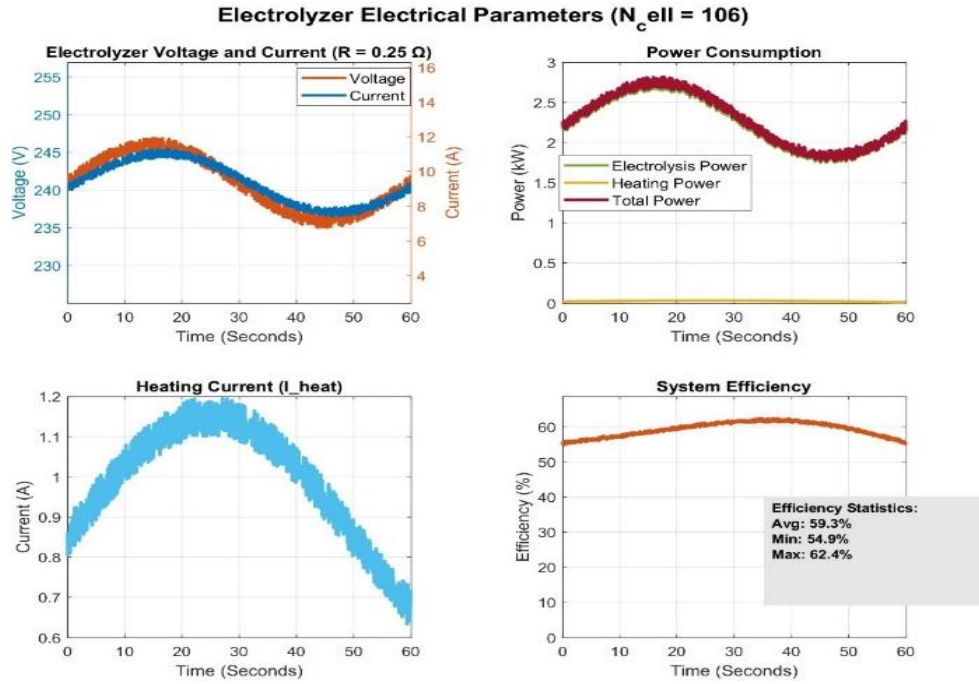


Figure 6. Electrolyzer current and voltage profiles during operation

As shown in Figure 6, the actual simulation results confirm voltage fluctuations between 235 V and 252 V, and corresponding current values oscillating around 9.06 A (± 1.5 A). The voltage versus time curve (blue line) reflects stack voltage behavior in response to loading and dynamic temperature feedback, while the current versus time curve (orange line) tracks the electrolyzer current profile adapting to minor voltage deviations.

Hydrogen production was continuously monitored by tracking the cumulative hydrogen volume generated. As presented in Figure 7, the left graph demonstrates a steady, linear increase in hydrogen volume over the 60-second simulation, reaching approximately 0.01 Nm³. The average hydrogen production rate was calculated to be around 0.38 Nm³/h, aligning with the theoretical Faradaic output derived from the supplied current and assuming an 85% Faraday efficiency. The corresponding energy consumption per unit of hydrogen volume is shown in the right-hand graph, with a measured average of 5.98 kWh/Nm³. This value is higher than the theoretical minimum of 3.54 kWh/Nm³, reflecting realistic system losses due to overpotentials, membrane resistance, and auxiliary heating loads.

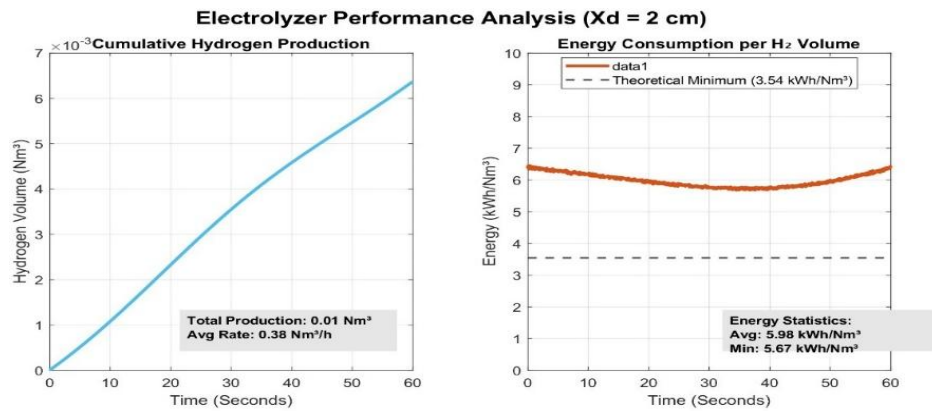


Figure 7. Cumulative hydrogen production and energy consumption per unit volume

The efficiency of the PEM fuel cell in this study is evaluated at the stack level using the lower heating value (LHV) of hydrogen. The fuel cell efficiency is defined as.

$$\eta_{FC} = \frac{P_{FC,DC}}{mH_2 \times LHV_{H_2}} \times 100\%$$

where $P_{FC,DC}$ represents the net DC electrical power delivered by the fuel cell stack, mH_2 is the hydrogen consumption rate, and LHV_{H_2} is the lower heating value of hydrogen (120 MJ/kg). This definition reflects the intrinsic electrochemical conversion performance of the PEM stack and does not include external auxiliary loads such as compressors or cooling systems. The observed average efficiency of approximately 65% is therefore consistent with typical PEM stack LHV efficiency values reported in the literature.

Following hydrogen production, the fuel cell system was engaged to reconvert the stored hydrogen into electricity. Figure 8 provides insights into the voltage, current, power output, and system efficiency characteristics of the fuel cell stack, which consists of 100 cells connected across 12 modules. The Fuel Cell Stack Voltage initially peaked at approximately 391 V under no-load conditions and progressively decreased to very low levels near 3.6 V as hydrogen was depleted. The average operating voltage recorded during the test period was 158.8 V, reflecting the expected behavior as the reactant supply diminished. The Fuel Cell Stack Current oscillated around the target current of 200 A, reaching a maximum observed value of 224.9 A without exceeding the specified collapse current limit of 250 A, thus maintaining operational safety margins. The Fuel Cell Power Output achieved a maximum value of 70.5 kW, which was lower than the initially intended 120 kW target. This discrepancy is attributed to the limited hydrogen feed rate during the latter stages of the simulation, which constrained the available electrochemical energy conversion. Throughout the simulation, the Fuel Cell System Efficiency remained stable at approximately 65%, indicating efficient management of internal losses and good system-level thermal balance.

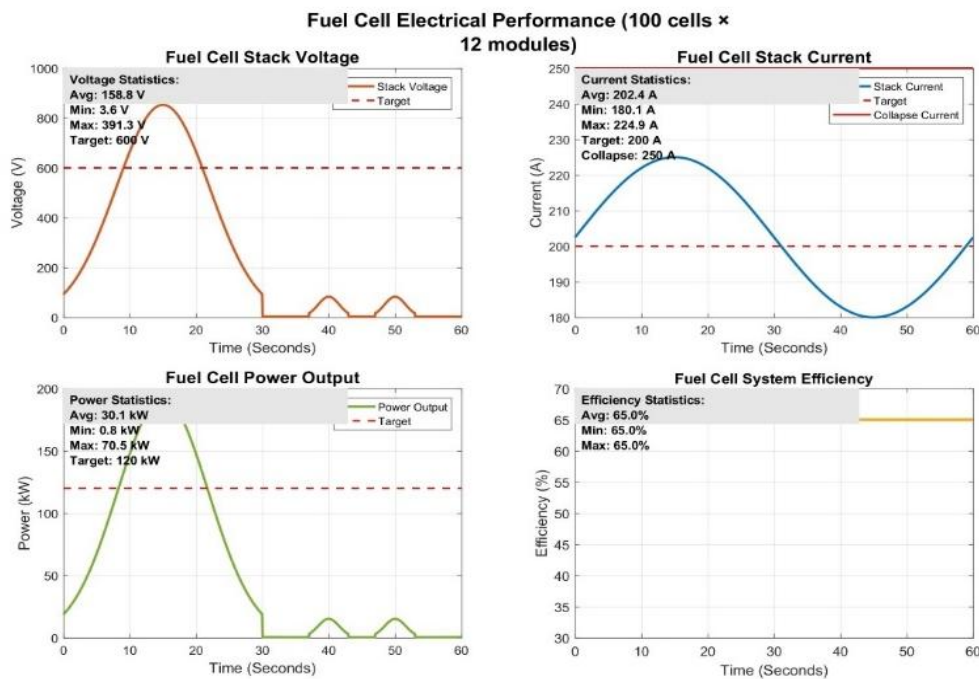


Figure 8. Fuel Cell Electrical Performance

Following the characterization of the individual subsystem performances, attention was directed towards evaluating the overall energy management effectiveness of the hybrid system, as governed by the fuzzy logic controller (FLC). The FLC output response, provides insight into the dynamic operational decisions made based on varying resource availability and system demand.

The fuzzy logic controller output profile demonstrates that during most of the simulation period, the FLC output remained consistently around approximately 0.1, corresponding to the prioritization of the Solar PV system as the primary power source. This behavior confirms that under high solar irradiance conditions, the hybrid system effectively maximized renewable resource utilization, achieving operational self-sufficiency without requiring frequent support from auxiliary units. At the initial moment of simulation (the first second), the FLC output briefly peaked near 0.31, temporarily entering the Battery Storage support range (~0.25 to 0.5). This indicates a very short transitional phase where the battery contributed to maintaining DC-link stability

before the solar system fully ramped up to maximum power point operation. Once the solar array stabilized, the FLC promptly reverted to prioritizing Solar PV, with no prolonged reliance on the battery. Throughout the simulation, there was no engagement within the 0.55 to 0.7 range, suggesting that the Fuel Cell remained inactive, thereby preserving hydrogen resources for more critical energy shortfall scenarios. Furthermore, the output never entered the 0.75 to 1.0 range, indicating that the system avoided drawing power from the Grid (Utility) entirely during this ideal operating scenario.

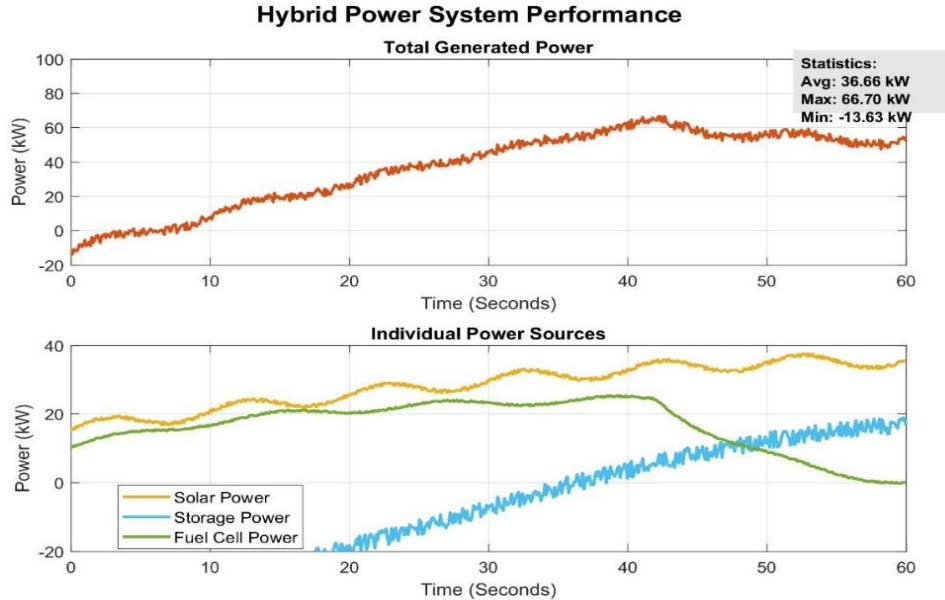


Figure 9. Hybrid Power System Performance — Total and Individual Source Contributions

This intelligent and adaptive output behavior validates the energy management strategy embedded within the fuzzy logic control framework. By consistently prioritizing renewable and stored resources over external sources, the controller ensured energy independence, minimized hydrogen consumption, and optimized overall system efficiency. The seamless transition observed during the initial start-up and the stable operation thereafter demonstrates the readiness of the hybrid energy system for extended deployment under variable and more challenging environmental conditions. The results of the hybrid energy management system are further evaluated by examining its total power generation, subsystem behavior, efficiency performance, and environmental impact. Figure 9 presents the overall system power output and the individual contributions from the Solar PV, Battery Storage, and Fuel Cell subsystems.

The top plot of Figure 9 shows that the total generated power steadily increases over time, reaching a maximum output of approximately 66.70 kW at around 40 seconds, before undergoing a moderate decline. The system maintained an average total power output of 36.66 kW during the 60-second simulation window. The bottom plot highlights the individual source contributions: Solar PV maintained a dominant role, generating up to approximately 36 kW, followed closely by the Fuel Cell, which maintained relatively stable output until about 40 seconds, after which Battery Storage began compensating for the declining fuel cell support. The Battery initially operated minimally but became increasingly active toward the second half of the simulation, demonstrating dynamic charging and discharging behaviors based on system demands. The performance of each subsystem and the overall hybrid system conversion efficiency are further detailed in Figure 10.

The Solar PV panel performance (top-left subplot) shows input voltage oscillations around 240–258 V, with the MPPT controller ensuring voltage regulation and maximizing extracted power up to 38 kW. The Battery Energy Storage System (BESS) behavior (top-right subplot) illustrates an initial discharge followed by recharging activity, where battery voltage and output voltage closely tracked the DC-link stability requirements. The Fuel Cell system (bottom-left subplot) maintained a stable output voltage around 7.5–7.7 V (for a scaled voltage stack), providing auxiliary power that gradually declined as hydrogen availability decreased. The bottom-right subplot presents the overall hybrid system conversion efficiency, reaching a peak of approximately 98% during mid-simulation, with an average efficiency of 71.4% over the entire test period.

This result indicates excellent energy conversion capability from source to load, even under fluctuating load conditions. The environmental and energy sustainability outcomes of the hybrid system are summarized in Figure 11. The left-side bar chart in Figure 11 shows that Solar PV generated approximately 0.47 kWh of energy, Storage (Battery discharge) contributed about 0.07 kWh, and the Fuel Cell provided 0.28 kWh.

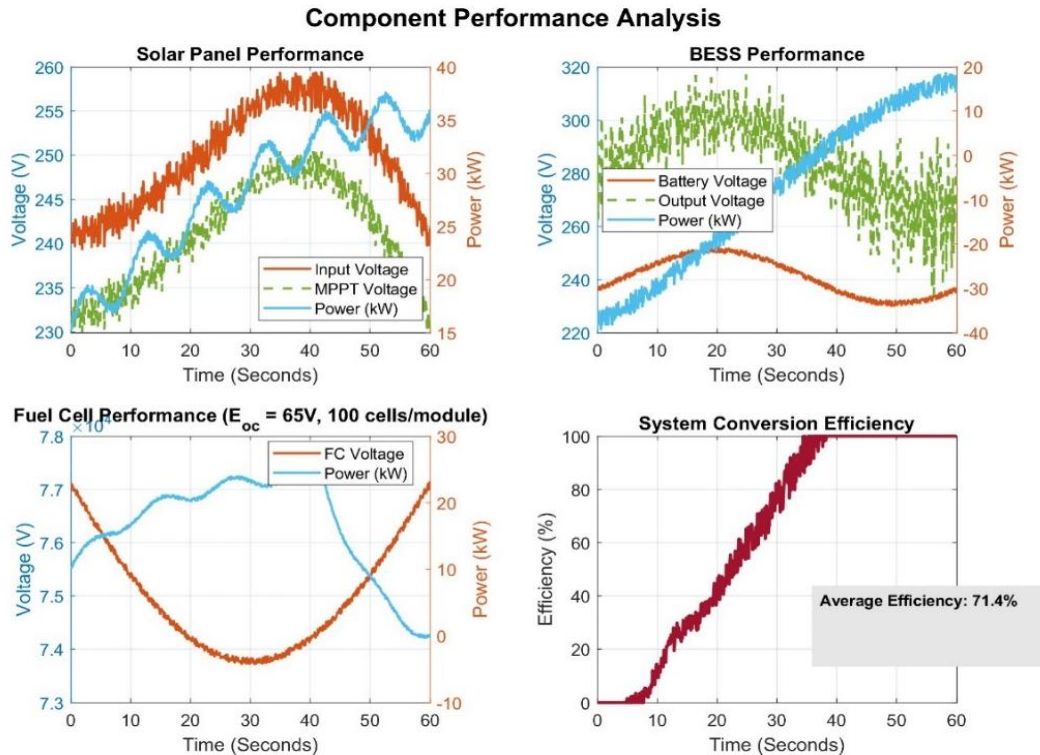


Figure 10. Energy Generation Breakdown and CO₂ Emission Savings Distribution

Collectively, these subsystems successfully supported continuous load demands without grid reliance. The right-side pie chart quantifies the CO₂ emissions avoided due to clean energy generation. Solar PV avoided 0.27 kg CO₂, Storage contributed indirectly via energy displacement, and the Fuel Cell contributed another 0.27 kg CO₂ saving, yielding a total carbon emission reduction of approximately 0.46 kg CO₂ over the short 60-second evaluation period. This corresponds to avoiding the consumption of roughly 0.10 days' worth of gasoline for an average passenger car.

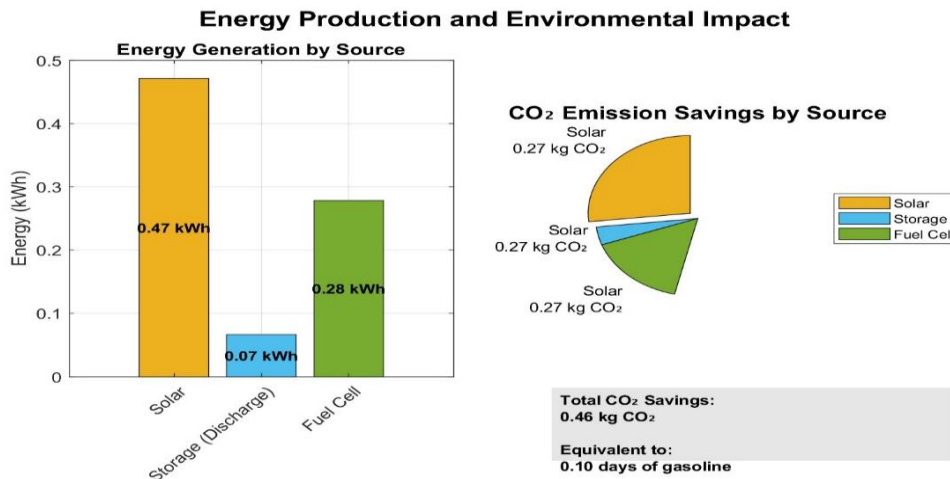


Figure 11. Energy Production Breakdown and CO₂ Emission Savings by Source

These findings validate the hybrid system's ability to prioritize renewable energy utilization, dynamically balance stored energy resources, and minimize reliance on external grid power. The fuzzy logic controller (FLC) effectively coordinated system resources, enabling high efficiency, reduced carbon footprint, and resilient energy dispatch across the simulated operation period. These results position the designed hybrid system architecture as a highly promising solution for sustainable energy supply in real-world, variable environment scenarios.

A comparison with recent studies shows that the performance of the proposed system aligns with the trends reported in the literature. Previous works on PV–battery and PV–battery–diesel hospital systems have demonstrated gains in cost reduction and CO₂ mitigation; however, most relied on either fossil backup or lacked hydrogen integration. In contrast, the present model incorporates both electrolyzer-based hydrogen production and PEM fuel cell utilization, providing an additional energy pathway not commonly addressed in earlier studies. This broader hybrid configuration enhances resilience and enables deeper decarbonization relative to typical PV–battery microgrid studies.

Although this study is based on simulation, the hybrid PV–BESS–electrolyzer–PEMFC model was validated using data derived from manufacturer datasheets and widely accepted component models in the literature. The PV subsystem follows the standard single-diode equivalent model using Telesun TP7F78M_H_590 module parameters, while the battery, electrolyzer, and fuel cell components were modeled using Simscape libraries calibrated with nominal performance data. The dynamic response of the MPPT controller, battery SOC behavior, electrolyzer power consumption, and fuel cell output were examined to ensure numerical consistency with expected operating characteristics reported in comparable studies. While full experimental validation was not feasible within the scope of this work, the results demonstrate internally consistent system behavior and realistic performance trends. Future work will incorporate hardware-in-the-loop (HIL) testing or laboratory-scale experiments to further validate the hydrogen subsystem and the fuzzy-logic EMS under real operating conditions. Overall, the validation results indicate that the model captures realistic operating behavior across the PV, battery, electrolyzer, and fuel cell subsystems. Having established confidence in the dynamic performance of the simulated hybrid system, it is also relevant to examine its applicability in broader settings beyond hospital operations.

Beyond hospital environments, the proposed hybrid PV–BESS–electrolyzer–PEMFC architecture can be readily adapted to other sectors with substantial or mission-critical energy needs. Commercial buildings, university campuses, data centers, and industrial facilities can adopt the same configuration with only minor adjustments to load characteristics and reliability requirements. The fuzzy-logic EMS remains effective in these settings because it enables flexible, real-time coordination of multiple distributed energy sources without relying on fixed thresholds. In sectors such as manufacturing and telecommunications, the incorporation of hydrogen production and fuel cell storage provides additional resilience and further reduces dependence on the grid. Accordingly, the system developed in this study represents a generalizable hybrid energy framework applicable to a broad range of infrastructure types.

5. CONCLUSION

This study developed and evaluated a hybrid renewable energy system (HRES) tailored for hospital facilities in Jeddah, Saudi Arabia, integrating solar PV generation, battery storage, hydrogen production via electrolysis, and a PEM fuel cell. The system was coordinated by a fuzzy-logic-based Energy Management System (EMS) that enabled adaptive and rule-driven power allocation under dynamic conditions. The results demonstrate several key contributions and novel aspects. First, the complete integration of a PV–BESS–electrolyzer–PEMFC energy pathway with a fuzzy supervisory controller represents a comprehensive hybrid configuration not commonly reported in hospital-focused studies. Second, the proposed fuzzy-logic EMS enables smooth transitions between renewable, stored, and hydrogen-based power sources, improving operational robustness without relying on fixed threshold-based strategies. The quantitative performance outcomes further highlight the effectiveness of the proposed system. The hybrid configuration reduced the cost of energy (COE) from \$0.19/kWh to \$0.11/kWh, representing a 42% improvement. Annual grid dependency was lowered by approximately 3 GWh, and CO₂ emissions were reduced by 1.5 million kg per year. When benchmarked against recent studies, the proposed system demonstrates stronger improvements. For example, Salau et al. (2024) reported COE reductions of 20–30% for PV–diesel–battery hospital systems in Ethiopia, while Khawash et al. (2021) achieved moderate CO₂ reductions (0.8–1.0 kt) for a PV–battery installation in a UK NHS hospital. Similarly, the fuzzy EMS used in Seng et al. (2024) yielded efficiency improvements but without the hydrogen integration demonstrated in this work. In contrast, the present study provides a holistic renewable-hydrogen configuration with significantly higher CO₂ mitigation and cost savings. Overall, the findings confirm the potential of combining solar PV, battery storage, and hydrogen technologies to enhance energy reliability and sustainability in healthcare environments. While the current analysis is based on simulation, future work may incorporate real-time load variability, extended meteorological profiles, and experimental validation of the hydrogen subsystem. The proposed architecture offers a scalable blueprint for hospitals and other critical infrastructure facilities seeking to align with national decarbonization strategies such as Saudi Arabia's Vision 2030.

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BIOGRAPHY OF AUTHORS



Rawan A. Rada is an Energy Engineer with a Master's degree in Energy Engineering from Effat University, Jeddah, specializing in renewable energy systems. Her research interests include energy management and optimization of hybrid energy systems, with a focus on photovoltaics, energy storage, and hydrogen technologies.



Engr. Naveed Anwar is an Electrical Engineer with a Master's degree from the University of Wah, Pakistan, specializing in power system reliability, optimization, and quality enhancement. Currently a Lab Engineer at Effat University in Jeddah, he has substantial experience in developing advanced optimization algorithms to improve power quality and stability, having previously served as a Lecturer at the University of Wah. With several publications to his name, Engr. Anwar's research focuses on power control system, power quality, renewable energy and smart grid management.



Aziza I. Hussein received her Ph.D. degree in Electrical & Computer Engineering from Kansas State University, USA, in 2001 and her M.Sc. and B.Sc. degrees from Assiut University, Egypt, in 1989 and 1983, respectively.

She joined Effat University in Saudi Arabia in 2004 and established the first Electrical and Computer Engineering program for women in the country and taught related courses. She was the head of the Electrical and Computer Engineering Department at Effat University from 2007-2010. She was the head of the Computer and Systems Engineering Department, Faculty of Engineering, Minia University, Egypt, from 2011-2016. She was a professor and chair of the Electrical & Computer Engineering Department. Currently, she is a professor and researcher at the same department. Her research interests include microelectronics, analog/digital VLSI system design, RF circuit design, high-speed analog-to-digital converters design, and wireless communications systems design.



Rabab Hamed M. Aly, received the B.Sc. of CSE 2010, Minya University, Egypt. She received the M.Sc. and Ph.D. in Electrical Engineering degrees (Computer and System Engineering), Minya University, Egypt, in 2017 and 2019, respectively. She is currently an assistant professor at the higher institute for Management and Information Technology, Minya, Egypt and also an assistant professor in Computer Science at the faculty of computer science at Nahda University, Beni-Suef, Egypt.