Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

Modeling and Simulation Control of MPPT in Solar Array for Green Hydrogen Production

Ibrahim Imbayah[1*], **Hala J. El-Khozondar**[2], **Mashhood Hasan**[3], **Abdulgader Alsharif**[4].

[1]Department of Energy Engineering, College of Renewable Energy, Tajoura, Libya.
[2]Department of Elec. Eng. and Smart Systems, Islamic University of Gaza, Gaza, Palestine.
[3]EET Department, College of Applied Industrial Technology (CAIT), Jazan University, KSA.
[4]Department of Electrical & Electronics Eng. Faculty of Technical Science, Sabha-Libya.

E-*mail:* [1] ibrahim.alzayani@gmail.com ,[2] hkhozondar@iugaza.edu ,[3] mhasen@jazanu.edu.sa ,[4] ialsharif@ctss.edu.ly .

ARTICLE INFO.

Article history:
Received 11 Feb 2025
Received in revised form 11 Feb 2025
Accepted 12 Apr 2025
Available online 4 May 2025

KEYWORDS

Renewable Energy, Green hydrogen, Maximum Power Point Tracking (MPPT), Fuzzy-Logic Controller (FLC), Solar Array.

ABSTRACT

This article addresses the critical challenge of optimizing solar array performance for electrolysis-based green hydrogen generation. A fuzzy logic controller (FLC) for maximum power point tracking (MPPT) was proposed in this study to maximize the performance of solar arrays in electrolysis-based hydrogen generation. The FLC does away with the need for traditional methods like Perturb and Observe (P&O) by dynamically adjusting the DC-DC converter duty cycle based on real-time temperature and irradiance inputs. Under various climatic conditions, MATLAB/Simulink simulations show a 92% operational efficiency and a 25% increase in hydrogen output, surpassing P&O (78%) and Incremental Conductance (82%). The FLC is a reliable option for scaling renewable energy systems because of its versatility and inexpensive computational cost.

---

*Corresponding author.

DOI: https://doi.org/10.51646/jsesd.v14i1.457

النمذجة والمحاكاة للتحكم في تتبع نقاط الطاقة القصوى في مصفوفة الطاقة الشمسية لإنتاج الهيدروجين الأخضر

ابراهيم امبية، هالة جار الله الخزندار ، مشهود حسن، عبد القادر الشريف.

ملخص: تتناول هذه المقالة التحدي الحاسم المتمثل في تحسين أداء المصفوفات الشمسية لتوليد الهيدروجين الأخضر القائم على التحليل الكهربائي. اقترحت هذه الدراسة وحدة تحكم منطقية ضبابية (FLC) لتتبع نقطة الطاقة القصوى (MPPT) لتعظيم أداء المصفوفات الشمسية في توليد الهيدروجين القائم على التحليل الكهربائي. يغني المتحكم المنطقي الضبابي (FLC) عن الحاجة إلى الأساليب التقليدية مثل مراقبة وملاحظة (P&O) عن طريق ضبط دورة عمل محول التيار المستمر-المتناوب (DC-DC) ديناميكيًا بناءً على مدخلات درجة الحرارة والإشعاع في الوقت الفعلي. وفي ظل الظروف المناخية المختلفة، تُظهر عمليات النمذجة والمحاكاة MATLAB/Simulink كفاءة تشغيلية بنسبة 92 % وزيادة بنسبة 25 % في ناتج الهيدروجين، متجاوزةً بذلك نظام مراقبة وملاحظة (78 %) ونظام التوصيل التزايدي (82 %). يعدّ نظام المتحكم المنطقي الضبابي خيارًا موثوقًا لتوسيع نطاق أنظمة الطاقة المتجددة بسبب تعدد استخداماته وتكلفته الحسابية غير المكلفة.

الكلمات المفتاحية – الطاقة المتجددة، الهيدروجين الأخضر، تتبع نقطة الطاقة القصوى (MPPT)، وحدة التحكم المنطقية الضبابية (FLC)، مصفوفة الطاقة الشمسية.

1. INTRODUCTION

The escalating global demand for sustainable and clean energy solutions is driving rapid advancements in renewable energy technologies. Green hydrogen, produced from renewable sources, has emerged as a promising energy carrier due to its high energy density, environmental benefits, and versatility across various applications [1]. It can be produced through methods like biomass gasification, natural gas reforming, and, importantly, water electrolysis powered by renewable energy, making it a key component in the transition to a sustainable energy future [2]. Hydrogen is also essential for the transmission and storage of renewable energy, which helps power networks maintain a balance between supply and demand. A hydrogen power generator, also known as a hydrogen fuel cell generator, uses a chemical process with oxygen to transform hydrogen gas into energy, with the sole waste being water [3].

The core of these systems is the fuel cell stack, comprising an anode, cathode, and electrolyte. In a fuel cell, hydrogen is supplied to the anode, and oxygen to the cathode. At the anode, hydrogen splits into protons and electrons. Electrons flow through an external circuit, creating electricity, while protons pass through the electrolyte. Hydrogen power generators offer a clean and sustainable energy source, particularly when hydrogen is produced via water electrolysis using renewable energy [4].

Furthermore, there is still work to be done on the distribution and storage infrastructure for hydrogen, which will restrict its wider use. Furthermore, the cost of hydrogen fuel cell technology is still greater than that of alternative energy sources as of right now [5]. Hydrogen has become a very attractive alternative in the quest for sustainability and a cleaner energy future [6]. However, sustaining system stability and supplying energy demands are hampered by the intrinsic erratic nature of solar and wind power. A viable substitute, hydrogen has the potential to spur economic expansion and advancement by generating new sectors and employment opportunities in fuel cells, hydrogen infrastructure, and transportation technologies. Energy security increased by switching to renewable hydrogen-based energy systems because they are more resilient and flexible in the face of volatile fossil fuel costs [7-11].

Fuzzy logic control is suited for power management in renewable energy systems due to its ability to handle uncertainties from variable generation and load demand. Unlike traditional methods, fuzzy control can predict power flow in hybrid systems while considering these uncertainties, improving fuel cell electrolyser lifespan and hydrogen output predictions. Fuzzy power management systems are assessed using stochastic analysis and Monte Carlo simulations, and Hardware-in-the-Loop testing validates their performance [8].

Detailed models of renewable energy systems with hydrogen storage developed, often including batteries for short-term storage and dynamic fuzzy logic controllers. These models integrate sub-models of fuel cells, electrolysers, power conditioning, hydrogen storage, and batteries to evaluate system performance [9]. Integrating fuzzy logic control into solar arrays for green hydrogen production is a key area of research. This paper focuses on developing a fuzzy control-based maximum power point tracking (MPPT) system to maximize solar array performance under diverse atmospheric conditions. The solar array powers the electrolysis process, which is critical for hydrogen production. MPPT algorithms continuously adjust the operating point to match the solar array's maximum power point on its P-V curve [10].

Common MPPT algorithms including Perturb and Observe (P&O) are simpler to implement. These algorithms are vital for maximizing PV system efficiency. However, gradient-based methods can cause an air lock in electrolyser output pipes during rapid gas production changes. Furthermore, they often require precise system parameters and may not fully adapt to solar array variations due to temperature and irradiance changes [11].

The growing need for renewable energy has spurred advancements in solar MPPT systems. Recent research explores hybrid approaches, such as combining neural networks and fuzzy logic [12], and type-2 fuzzy logic controllers for enhanced adaptability [13].

Fuzzy logic controllers offer advantages in managing the nonlinearities of solar power systems [14], and fuzzy-based control strategies have demonstrated improved energy conversion efficiency, especially in partial shading [15]. Integrating fuzzy logic with conventional MPPT methods can also significantly enhance energy harvesting [16]. MATLAB/Simulink is widely used to simulate PV systems and analyze partial shading effects on maximum power point (MPP) [17, 18]. Fuzzy logic and adaptive backstepping control methods, optimized using techniques like antlion optimization, have shown promise in overcoming challenges in MPPT control under complex conditions [19, 20].

This article's contribution offers a thorough method for developing and modeling an MPPT system employing fuzzy logic control for the generation of green hydrogen. Stressing fuzzy logic ensures optimal efficacy and efficiency by providing a trustworthy approach to managing the nonlinear features of solar power systems. The following are important details of solar photovoltaic systems:

- By investigating the integration of hydrogen energy storage within a system that consists of a solar array, energy storage, and an electrolyzer, this work advances knowledge.
- To manage the solar array/energy storage/electrolyzer system, the proposed model incorporates decision-based control at the supervisory level and decentralized adaptive model predictive control (FLC) at the local level.
- To ensure the best possible use of renewable energy resources, solar array electricity is transformed into hydrogen and tracked using a fuzzy control system for maximum power point tracking (MPPT).
- Periodically, the fuel cell and electrolyzer subsystems receive power references from the supervisory controller.
- The local decentralized FLC system receives these power references and uses appropriate cost function minimization to modify the solar array and electrolyzer subsystems to meet the power reference values. To evaluate the efficacy and performance of the suggested control architecture, simulations are run.

The suggested FLC is a competitive substitute for conventional MPPT techniques as it provides more stability and flexibility at a lower computational cost. The FLC represents a breakthrough in solar energy optimization for green hydrogen generation, striking a workable balance for real-time applications, even if more complicated scenarios would call for the accuracy of sophisticated systems like PSO. The construction of the microgrid (PV-Hydrogen) is described in the next section, and the process for creating green hydrogen using MATLAB is explained in section 3. Section 4 presents the simulation results, and the conclusion offers a succinct overview of the main conclusions.

2. STRUCTURE OF A PV-HYDROGEN MICROGRID

The solar PV panels as current sources, with output contingent on cell temperature and solar irradiation. The significant impact of the large-scale integration of renewable energy into current electricity systems has occurred. Microgrids are a crucial part of the energy systems of the future since they are an emerging power system structure that can effectively reduce this impact. Most research on microgrid optimal scheduling is conducted at short-term scales. A few studies take long-term storage in microgrid optimization primarily, while hydrogen is used as a long-term storage solution [21].

Hydrogen is separated by further processing to produce 'grey hydrogen'. In coal gasification, coal is reacted under pressure with oxygen and steam to produce synthesis gas consisting of hydrogen and carbon monoxide. Hydrogen is produced by further processing. Electrolysis uses electricity to split water into hydrogen and oxygen. The carbon footprint is determined by the source of the electricity: electricity generated from hydroelectric power plants or renewable energy sources produces "green hydrogen", while electricity generated from fossil fuels produces "brown/grey hydrogen". Gasification of biomass, such as wood waste, is comparable to coal gasification. "Bio-hydrogen is produced. Hydrogen energy systems connect renewable energy generation with consumption. Excess renewable power is used for water electrolysis to produce hydrogen, which can be stored and later used in fuel cells or other applications.

This maximizes renewable energy use and promotes a sustainable energy mix. Green hydrogen is produced via electrolysis or biomass gasification using renewable sources like solar or wind. These technologies reduce carbon emissions and diversify energy sources. Favorable geographic locations and abundant renewable energy resources enhance green hydrogen viability. Alternatively, thermal energy is used to produce hydrogen from steam. Figure 1 illustrates various hydrogen production pathways [22].

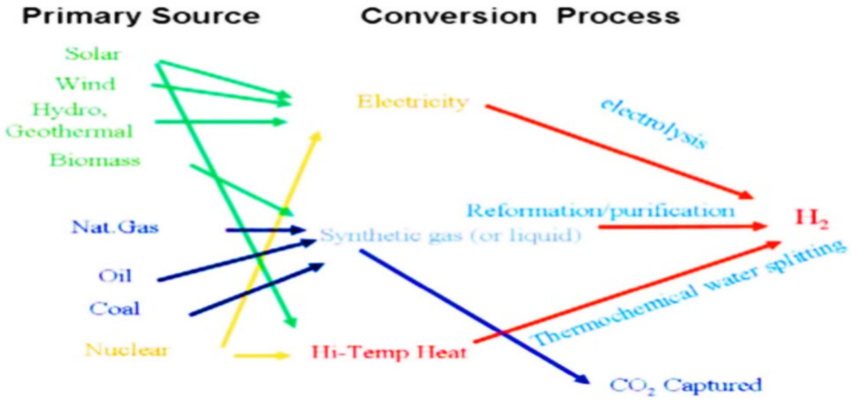

Figure 1. Ways to produce hydrogen.

3. METHODOLOGY

3.1. Routes to Produce Green Hydrogen

Hydrogen energy systems link renewable energy generation and consumption, using surplus renewable power for water electrolysis to produce hydrogen. This stored hydrogen is converted back to electricity via fuel cells or used as a clean fuel. This maximizes renewable energy utilization and promotes a balanced energy system. Green hydrogen production methods include electrolysis and biomass gasification powered by renewable sources like solar or wind (Figure 1). These methods minimize carbon emissions and diversify energy sources. Areas with strong renewable energy resources are ideal for green hydrogen production. Figure 2 shows a MATLAB/Simulink model of hydrogen generation via water electrolysis and solar panels. Solar panels provide electricity to split water into hydrogen and oxygen.

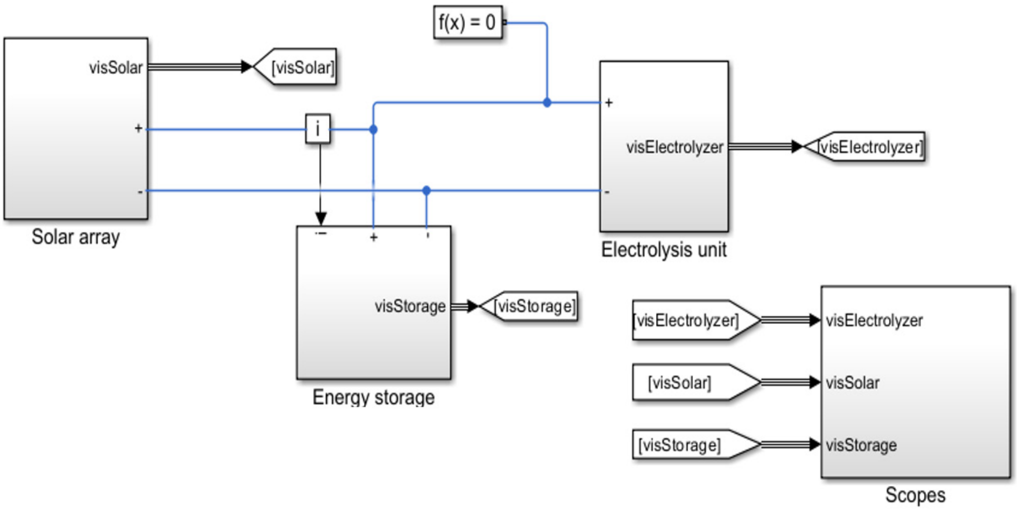

Figure 2. Model of Green hydrogen production from a solar array.

The MATLAB/Simulink program is used to simulate and assess the process's efficiency and performance under different conditions or parameters. Determining a solar array's power production is essential to comprehending its effectiveness and efficiency. By keeping an eye on these specifications, the Power Output (P_{PV}) from Solar Array as displayed:

$$P_{PV} = I_{PV} V_{PV} \qquad (1)$$

Where I_{PV} is the current output of the solar array and V_{PV} is the voltage output. Calculating the amount of hydrogen produced with renewable energy sources, like solar power, requires the use of equation 1. By adjusting for these variables, production rates under different conditions are calculated. The rate at which hydrogen is produced as seen:

$$H \; = E_{H} \; P_{PV} \, \eta_{electrolazer} \qquad (\;\;)$$

Where $\eta_{electrolyzer}$ is the efficiency of electrolyze and EH2 is the energy required to produce 1 kg of hydrogen.

3.2. Solar array conversion system

With the promise of solar hydrogen energy, it is critical to develop solar arrays with high efficiency. A MATLAB/Simulink model for green hydrogen synthesis using solar energy is shown in Fig. 3. Breakthroughs in material science and nanotechnology are driving the development of new photocatalytic materials and nanostructures to improve light absorption, charge separation, and surface activity. These developments are critical to increasing the overall efficiency of solar hydrogen generation. Furthermore, incorporating cutting-edge reactor designs and engineering solutions shows great potential for boosting green hydrogen generation from solar energy, establishing solar energy as a competitive and sustainable energy source in the future.

The photovoltaic (PV) method, sometimes referred to as the solar energy conversion system, converts solar energy directly into electricity. Fig. 3 depicts a solar cell using an electrical equivalent one-diode model, which allows for the representation of the relationship between the PV module current and output voltage within the Simulink/MATLAB model. The MPPT stands for maximum power point tracking system. The input is the temperature (°C) and the irradiance (W/m^2). The output current (i) and the output voltage (v) are the inputs 1 and 2 in Fig. 4.

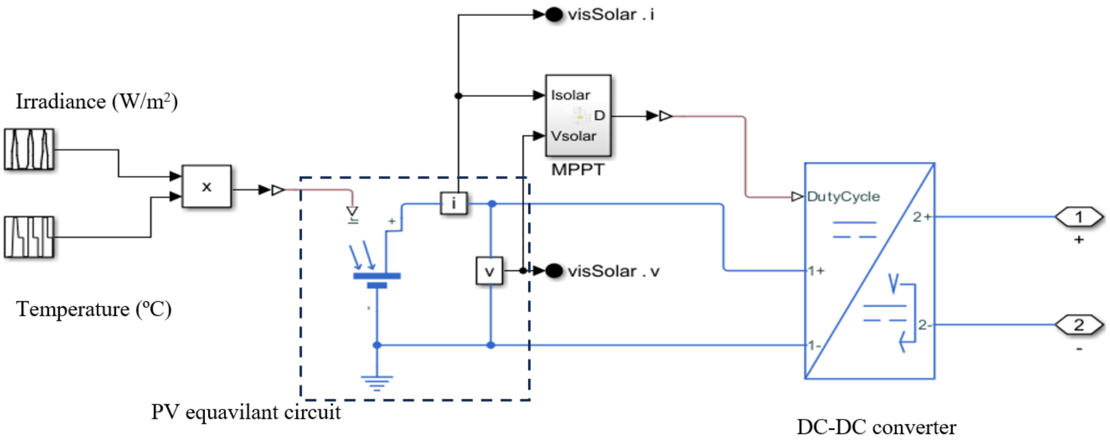

Figure 3. Model of Solar array.

The photovoltaic cells, or PV modules, that are connected in parallel or series to produce the desired output are included in the solar PV system plan in the necessary quantity. The photovoltaic cell model's simple equivalent circuit is arbitrarily defined by the fundamental equation of semiconductor theory. The current generated by the PV as shown:

$$I = I_{pv,cell} - I_{0,cell}\left[exp\left(\frac{qV}{\alpha KT} \right) - 1 \right] \qquad (3)$$

Cells connected in series result in higher output voltages, while cells connected in parallel increase current. Practical arrays made up of a few connected photovoltaic cells, and to identify the PV array's effect, the composition of the array's combined parameters must be determined using the following fundamental equation:

$$I = I_{PV} - I_0\left[exp\left(\frac{V + R_S I}{V_t \alpha} \right) - 1 \right] - \frac{V + R_S I}{R_P} \qquad (4)$$

I_0 is the diode saturation current defined as in equation 5:

$$I_0 = \frac{I_{SC,n} + K_{I\Delta_T}}{exp\left(\frac{V_{OC,n} + K_{V\Delta T}}{\alpha V_t} \right) - 1} \qquad (5)$$

K_I is the temperature coefficient of the short circuit current $I_{sc,n}$, K_v is the temperature coefficient of the open-circuit voltage $V_{oc,n}$, alpha is the diode ideality factor, which ranges from 6 to 8 for LEDs based on GaN epitaxial films, Δ_T is the temperature change, V_t is the thermal voltage equals *kT/q* , where *k* is the Boltzmann constant, *T* is the absolute temperature, and *q* is the elementary charge. The model is simplified using the equation, and the model error equals zero close to the open-circuit voltages. This has implications for other areas of the I–V plot [18]:

$$I_{PV} = \left(I_{STC} + K_I\left(T_{cell} - T_{STC}\right)\right)\frac{G}{G_{STC}} \tag{6}$$

Where I_{PV} states for the real PV array current under the PV surface cell temperature (T_{cell}) and real solar irradiance (G), while I_{STC} is the standard test condition current under standard test conditions of PV cell temperature (T_{STC}) and solar irradiance (G_{STC}), and K_I is tem current - temperature coefficient in. The T_{cell} Estimated by several researchers [23].

As an unknown in equation (4), the R_S and R_P relationship can be computed by solving the fulfillment equation for R_S , which is as follows: $P_{max,m}= P_{max,e}$.

$$P_{max,m} = V_{mp}\left\{ \begin{array}{c} I_{PV} - I_0\left[exp\left(\frac{q}{KT}\frac{V_{mp}+R_S I_{mp}}{\alpha N_S}\right) - 1\right] \\ -\frac{V_{mp}+R_S I_{mp}}{R_P} \end{array} \right\} = P_{max,e} \tag{7}$$

$$R_P = \frac{V_{mp}+R_S I_{mp}}{\left\{V_{mp}I_{PV} - V_{mp}I_0\, exp\left[\frac{V_{mp}+R_S I_{mp}}{\alpha N_S}\right] + V_{mp}I_0 - P_{max,e}\right\}} \tag{8}$$

Where the maximum power output ($P_{max,m}$) and the maximum power output under normal test circumstances ($P_{max,e}$) vary in that the former takes into consideration the photovoltaic cell's series resistance (R_S) and parallel resistance (R_P), while the latter does not.

According to equation 8, a value of RS exists for any value of RP such that the mathematical I–V curve intersects the experimental (I_{mp} ,V_{mp}) point. Finding the values of R_S and R_P for the ideal model solution is the goal:

$$I_{PV,n} = \frac{R_P + R_S}{R_P} I_{SC,n} \tag{9}$$

One possible set of starting conditions is:

$$R_S = 0,\quad R_{P,min} = \frac{V_{mp}}{I_{SC,n} - I_{mp}} - \frac{V_{OC,n} - V_{mp}}{I_{mp}} \tag{10}$$

The link between the highest power points and the short circuit yields the minimal value of RP, as shown in equation (8).

To solve the model, conventional photovoltaic (PV) characteristics are required, including the voltage at the highest power point (V_{mp}) under standard test circumstances (25°C), the rated current (I_{mp}), the open-circuit voltage (V_{OC}), and the short circuit current (I_{sc}). The effect of temperature on the PV panel is not considered. Cells are constructed into modules, which are coupled to produce arrays of parallel branches (MP) and series-connected modules (MS). The current (I_a) and voltage (V_a) of the solar cell arrays may be computed assuming that all modules are identical and subjected to the same ambient radiation as follows:

$$I_a = MPI_{PV} \tag{11}$$

$$V_a = MSV_{PV} \tag{12}$$

Simulate various scenarios and determine how much hydrogen is created from renewable energy sources like solar power by changing the parameters in the I-V relationship.

Changing the maximum power point settings may have a big effect on how quickly hydrogen is produced from solar energy. In Table 1. Hydrogen-generating systems may improve output and efficiency by improving V_{mp} and I_{mp} through effective system design and real-time tracking innovations. Maximum Power Point (P_{max}).

$$P_{max} = V_{mp}\, I_{mp} \tag{13}$$

Where V_{mp} and I_{mp} are the voltage and current at the maximum power point.

Table 1. The maximum hydrogen production scenario.

Scenario	**V_{mp} (V)**	**I_{mp} (A)**	**P_{max} (W)**	**Usable Power (W)**	**Hydrogen Production (kg/h)**
Moderate	30	5	150	105	11.2
High	40	8	320	240	25.7
Lower	25	3	75	48.75	5.2

Table 1 values are illustrative examples to show MPPT's impact on hydrogen production and are not simulation results. "Usable Power" assumes 70% system efficiency, and "Hydrogen Production" is calculated for demonstration using hypothetical electrolyze efficiency and E_{H_2} values.

3.3. The fuzzy control system of solar arrays

By using a fuzzy-control-based MPPT algorithm, we improve the solar array's overall performance and efficiency, providing optimal power generation for electrolysis. One major feature of fuzzy logic control is its capacity to adjust to quickly changing weather conditions. Unlike typical MPPT algorithms, which depend exclusively on gradient information from the P-V curve, fuzzy control considers a larger set of factors, such as temperature, irradiance, and particular fluctuations within the solar array. This complete method enables the system to dynamically modify operating points, significantly increasing power generation while avoiding difficulties such as air entrapment in output pipes [24]. In fig. 4 displays MATLAB/Simulink the modeling of MPPT with a Fuzzy Logic Controller, illustrating the potential benefits of introducing fuzzy-logic control into solar array systems for green hydrogen generation.

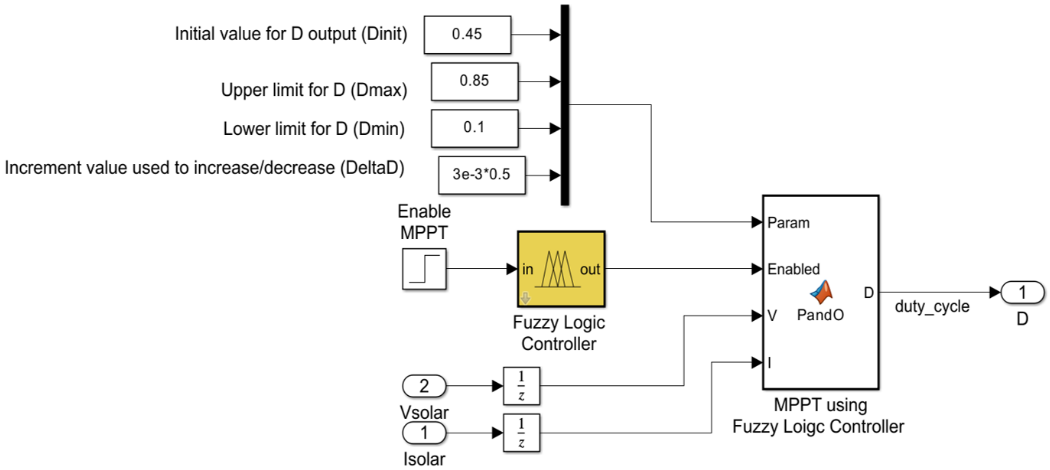

Figure 4. Model of MPPT using Fuzzy Logic Controller.

3.4. Solar Powered Electrolysis

Electrolytes are generally formed from liquid electrolyte solutions. At high temperatures, the process includes transferring electricity through water, which produces positively charged hydrogen ions and oxygen at the anode. As these ions flow through the liquid electrolytes, they mix with electrons from the external circuit to form hydrogen gas. Concurrently, water dissociates at the cathode, interacting with electrons from the external circuit to produce negatively charged oxygen ions and hydrogen gas. Oxygen ions flow across the membrane, releasing electrons at the anode, which produces oxygen gas. Electrolyzer Voltage Equation An extensive framework for comprehending the voltage needs of electrolyze throughout the electrolysis process is provided by the electrolyze voltage equation, which is represented as.

$$V_{elec} = V_0 + R_{elec} I_{elec} + nFE_{H_2} \tag{14}$$

Offers a thorough foundation for comprehending the voltage needs of electrolyze throughout the electrolysis process. The equilibrium voltage V_0, or the theoretical minimum voltage required to drive the electrochemical process without any losses, is represented by the symbol in this equation, R_{elec} is the internal resistance, I_{elec} is the current through the electrolyze, n is the number of moles of electrons, and F is Faraday's constant. When added together measure the extra voltage needed for the electrochemical process to continue for producing hydrogen and other electrochemical applications, this equation is essential for maximizing the efficiency of electrolyzes and Current Output as shown.

$$I_{elec} = V_{elec} P_{PV} \tag{15}$$

It is essential to comprehend how equilibrium voltage, internal resistance, current, and power interact to enhance the efficiency of electrolyzes. Both the equilibrium voltage and the losses resulting from internal resistance are taken into consideration in the total voltage applied.

Fig. 5 depicts the MATLAB/Simulink equivalent circuit for an electrolyzer, which aids in simulations. This circuit, which simulates the behavior of the electrolyzer's components, simplifies the modeling process. By modeling the electrolyzer system with MATLAB/Simulink, its behavior can be examined under various situations, allowing for performance evaluation and design optimization. The comparable electrolyzer circuit avoids the need for costly and time-consuming experiments, allowing for a better understanding and prediction of the electrolyzer's operations.

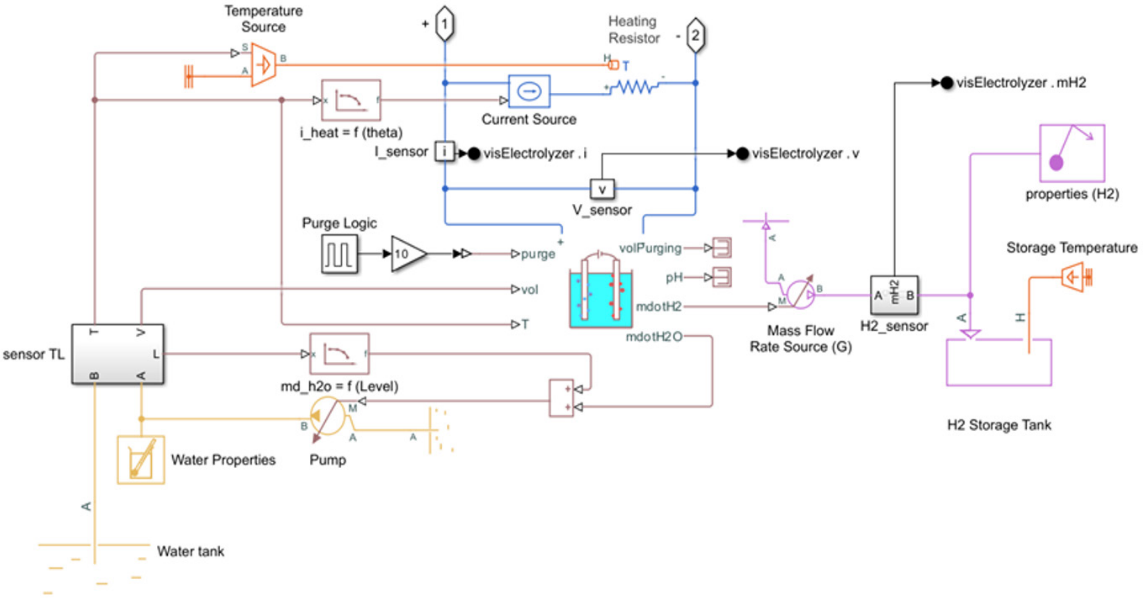

Figure 5. Model of Equivalent circuit of the electrolyze.

MATLAB/Simulink modeling allows analysis under various conditions for performance evaluation and design optimization. While simplifying, experimental validation with a real electrolyzer is necessary to confirm model accuracy and account for electrode properties, water purity, temperature, and other factors affecting electrolyzer efficiency.

3.5. Battery Energy Storage System

The MATLAB/Simulink of energy storage of the basic components and tracks the energy and hydrogen flows over time. You can expand on it by adding more detailed component models, optimization, controls, etc as seen in Fig. 6. The hydrogen energy storage system's parameters are as follows in Table 2.

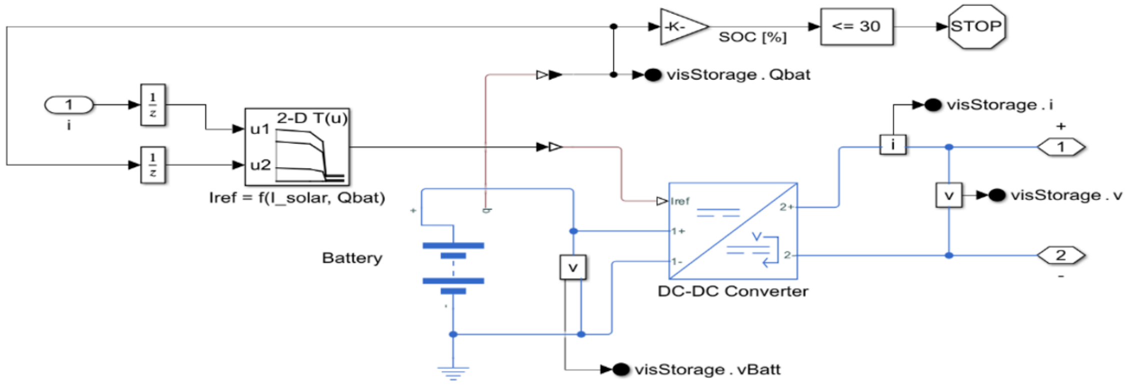

Figure 6. Model of Energy Storage.

Table 2. The Hydrogen Energy Storage System's Parameters.

Parameter	Stand for	unit
P load	load demand	5% kW
E grid	power from the grid	10% kW
P electrolyzer	power electrolyzer	0.7% KW
P generated	Fuel cell power generated	0.5% kW

These parameters include data on load demand, grid power; electrolyze power, fuel cell power output, and other pertinent variables that are necessary to use hydrogen as a viable energy storage option. It gives a thorough overview of the capabilities and constraints of hydrogen energy storage devices by describing these factors.

The fundamental formulas that explain a battery's state of charge (*SoC*) and the energy it can hold. Let us dissect the equations and provide further explanation. Equation of State of Charge (*SoC*) The following is the State of Charge (*SoC*) equation as shown:

$$SoC(t)=SoC(t-1)+\left(C_{battaryICharge}-I_{disCharge}\right).\Delta t \qquad (16)$$

This formula adjusts the battery's state of charge according to the charging and discharging operations occurring right now. Over a time interval Δt the *SoC* rises with the charging current and falls with the discharging current. The expression ($C_{batteryIcharge}-I_{discharge}$) denotes the addition to the state of charge from charging, whereas $I_{discharge}$ denotes the decrease in the state of charge as a result of discharging. And the equation Energy Stored in the Battery is shown:

$$E_{stored}=SoC.C_{battary}.V_{battery} \qquad (17)$$

Using the battery's voltage, capacity, and state of charge as inputs, this formula determines the total energy contained in the battery. The battery's *SoC*, capacity, and voltage all directly correlate with the amount of energy stored.

4. SIMULATION RESULTS AND DISCUSSION

Simulation results illustrate the effectiveness of the fuzzy logic controller in maintaining optimal power output for the solar array, even under varying weather conditions. The system can adapt to solar irradiance and temperature changes by dynamically adjusting the electrolyte's power consumption, ensuring consistent and efficient green hydrogen production. Figure 7 shows the energy consumption figures derived from the simulations offer a significant understanding of the effectiveness of the various processes modeled for hydrogen production. To lower manufacturing costs and their negative effects on the environment, the objective is to identify techniques that minimize the energy input per unit of hydrogen produced (kWh/kgH_2).

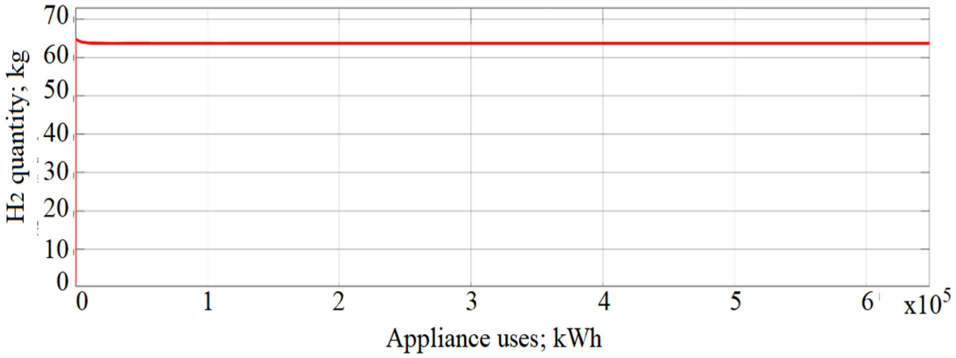

Figure 7. Energy consumption [kWh / kgH_2].

Figure 8 shows the power output of electrolyze solar panels, and a storage system in kilowatts (kW), as well as the energy output of these systems in kilowatt-hours (kWh). The power output in kW represents the rate at which these systems are generating or storing energy at any given moment, while the energy output in kWh represents the total amount of energy that is generated or stored over a while. This figure shows the capacity and performance of electrolyzes, as well as for analyzing their potential to provide a reliable and sustainable source of energy.

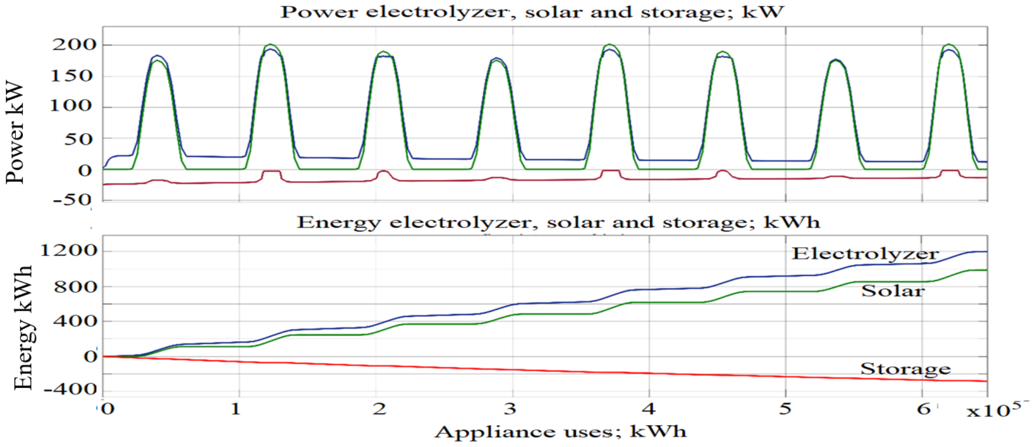

Figure 8. Power electrolyze, solar, and storage [kW]. Energy electrolyze, solar, and storage [kWh].

The power outputs of the solar array electrolyze, and energy storage system shown in this figure, are all expressed in kilowatts (kW). Dynamic Response The power production varies due to shifting solar conditions, as seen in the image. To maintain optimal hydrogen production in reaction to these variations, a reliable control system needs to adjust the electrolyte's power consumption dynamically. As the battery charges and discharges to power the loads and electrolyze, the voltage stays constant. In addition to remaining steady, grid voltage also supplies extra electricity when needed to augment solar energy. To run, the electrolyzed current takes energy from the grid or batteries. The maximum ratings of batteries and solar panels set limits on their respective currents. Solar energy powers batteries, which discharged as needed to power loads and electrolyze. The amount of hydrogen generated during the simulation period is in line with the electrolyte's operation.

Figure 9 displays Grid and battery voltage referring to the graphic that displays the battery and electrical grid voltage levels. It might show how the voltage varies over time or in various scenarios. Solar currents and battery storage have to do with the current produced by the solar panels and the current that passes through the electrolyze used to store hydrogen. It displays the movement of power into and out of the system. The battery charge shows the proportion of the battery that is still charged. It gauges the battery's level of fullness or the difference between its current and maximum capacity energy storage. Figure 9 also shows how much hydrogen gas electrolyze generates, measured in kilograms. It represents the efficiency of the hydrogen production process or the total output over a specific period.

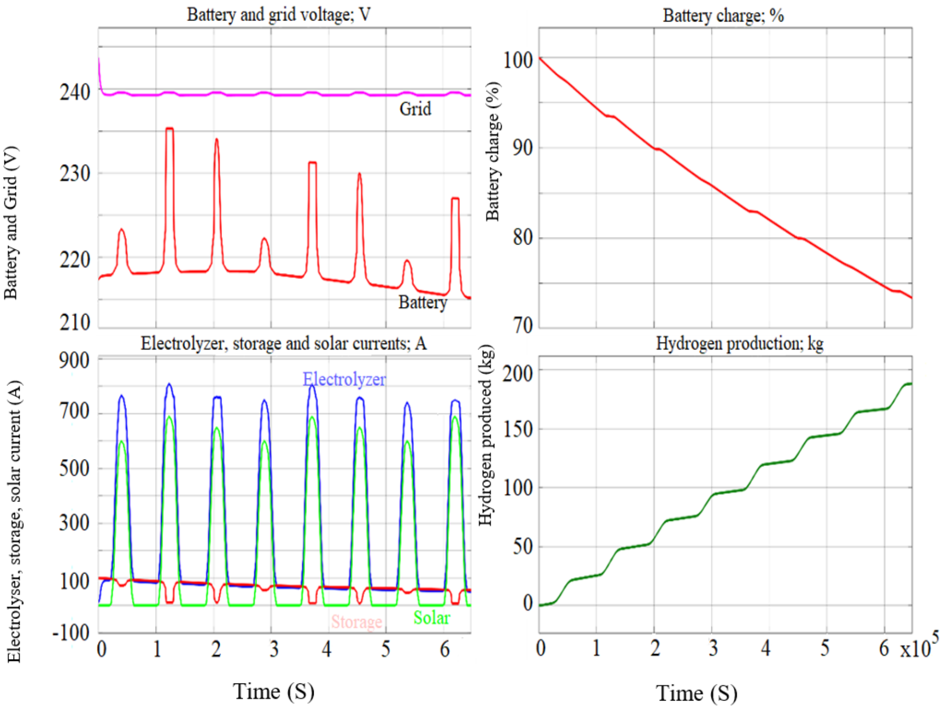

Figure 9. Battery and grid [V]. Electrolyzer, storage, and solar currents [A]. Battery charge [%], Hydrogen produced [kg].

Analysis of these figures, the solar MPPT-hydrogen generation system's performance was examined. It finds areas for optimization and improvement based on the power outputs, energy consumption, and system dynamics. Future research and development initiatives aiming at improving the efficacy of green hydrogen-generating systems are guided by the comprehensive study conducted here. Validating these results and guaranteeing the robustness of the suggested control strategies will require additional testing in a range of environmental circumstances.

Simulations show an increase in hydrogen production by approximately 25% compared to traditional MPPT methods, with the system achieving an operational efficiency of 92% under varying environmental conditions. This 25% improvement is based on simulation comparison and may not directly translate to all real-world scenarios. Similar studies show:

1. Type-2 Fuzzy Logic Control: produced enhanced performance metrics that are consistent with our study's findings, demonstrating the type-2 fuzzy logic control's efficacy in photovoltaic-

hydrogen production systems. According to their research, fuzzy logic control can adjust to shifting external factors, improving system performance as a whole [21].

2. Fuzzy-Based MPPT Control Systems: Major gains in energy extraction efficiency were reported in the development of a fuzzy-based MPPT control system for solar power generation. Their outcomes support our conclusions and highlight the benefits of fuzzy logic in handling the complexity of solar energy production [21].

3. Gradual Behavior MPPT Algorithm: Incremental conductance MPPT algorithms show encouraging solar system efficiency [20]. Ref [20] reports comparable efficiencies (94.07% and 93.98%) to this study's 92%. However, direct comparison is limited by simulation setup differences. These instances highlight a larger pattern in the literature that suggests fuzzy logic-based advanced control algorithms can improve the efficiency of renewable energy systems. By incorporating such techniques, efficiency increased, and green hydrogen generation is supported, enhancing its potential as a major component of future energy solutions [19].

5. CONCLUSIONS

This research optimizes solar systems for green hydrogen production using fuzzy logic control, highlighting hydrogen's role in renewable energy. Fuzzy logic control in solar arrays enhances hydrogen production, and system efficiency, and reduces operational costs. Simulation results demonstrate significant MPPT improvement for green hydrogen production using the proposed FLC-enhanced P&O MPPT method. This approach contributes to scalable, sustainable renewable energy systems by maintaining feasibility and cost-effectiveness while improving efficiency, stability, and flexibility. Simulation results align with other research, underscoring fuzzy logic controllers' effectiveness in optimizing solar energy systems for green hydrogen production.

Author Contributions: I I: conceptualization, methodology, data curation, writing original draft, formal analysis, visualization, supervision, writing review and editing. H J. El: investigation, conceptualization, methodology, supervision, writing original draft, and writing review and editing. M H: conceptualization, data curation, supervision. A A: Formal analysis, visualization, supervision, and writing review and editing.

Funding: The authors have not disclosed any funding.

Data Availability Statement: The data are available at request.

Conflicts of Interest: The authors declare that they have no known conflicts of interest.

REFERENCES

[1] R. Hren, A. Vujanović, Y. Van Fan, J.J. Klemeš, D. Krajnc, L. Čuček. "Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment," Renew Sustain Energy Rev, 173 (2023), doi:10.1016/j.rser.2022.113113.

[2] I. Imbayah, M. Hasan, H. El-Khozondar, M. Khaleel, A. Alsharif, and A. A. Ahmed, "Review paper on Green Hydrogen Production, Storage, and Utilization Techniques in Libya," Solar Energy and Sustainable Development Journal, vol. 13, no. 1, pp. 1–21, 2024. doi: 10.51646/jsesd.v13i1.165.

[3] A. Behzadi, S. M. Alirahmi, H. Yu, and S. Sadrizadeh, "An efficient renewable hybridization based on hydrogen storage for peak demand reduction: A rule-based energy control and optimization using machine learning techniques," J. Energy Storage, vol. 57, no. September 2022, p. 106168, 2023, doi: 10.1016/j.est.2022.106168.

[4] K. Shivarama Krishna and K. Sathish Kumar, "A review on hybrid renewable energy systems," Renew. Sustain. Energy Rev., vol. 52, pp. 907–916, Dec. 2015, doi: 10.1016/j.rser.2015.07.187.

[5] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, "Hybrid energy storage system for microgrids applications: A review," J. Energy Storage, vol. 21, no. August 2018, pp. 543–570, 2019, doi: 10.1016/j.est.2018.12.017.

[6] O. M. Mohammed, "Renewable Energy: Sources, Integration, and Application: Review Article," J. Eng. Res. Reports, vol. 20, no. 12, pp. 143–161, Sep. 2021, doi: 10.9734/jerr/2021/v20i1217426.

[7] R. Dufo-López, J. L. Bernal-Agustín, and J. Contreras, "Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage," Renewable Energy, 2007. pp. 1102-1126, doi: 10.1016/j.renene.2006.04.013.

[8] M. H. Cano, K. Agbossou, S. Kelouwani and Y. Dubé. "Experimental evaluation of a power management system for a hybrid renewable energy system with hydrogen production." Renewable Energy. 2017. pp. 1086-1098. doi: 10.1016/J.RENENE.2017.06.066.

[9] A. Bilodeau and K. Agbossou. "Control analysis of renewable energy system with hydrogen storage for residential applications." Journal of Power Sources. 2006. pp. 757-764. https://doi.org/10.1016/J.JPOWSOUR.2005.04.038.

[10] H. J. El-Khozondar, R. J. El-Khozondar, K. Matter, "Simulation and Implementation of Incremental Conductance MPPT Algorithm for PV System", Journal of Mechatronics, 3(2), 174-178, 2015. http://www.aspbs.com/jom.htm. http://dx.doi.org/10.1166/jom.2015.1102

[11] M. Benghanem, N. Chettibi, H. Almohamadi. "Type-2 fuzzy-logic based control of photovoltaic-hydrogen production systems". International Journal of Hydrogen Energy (2023), pp. 35477-35492, https://doi.org/10.1016/j.ijhydene.2023.05.360.

[12] K. Ullah, M. Ishaq, F. Tchier, H. Ahmad, and Z. Ahmad, "Fuzzy-based maximum power point tracking (MPPT) control system for photovoltaic power generation system," Results Eng., vol. 20, p. 101466, 2023. doi: 10.1016/j.rineng.2023.101466.

[13] O.M. Babatunde, J.L. Munda, Y. Hamam . "Hybridized off-grid fuel cell/ wind/ solar PV / battery for energy generation in a small household: A multi-criteria perspective", International Journal of Hydrogen Energy, 2022, pp 6437-6452, https://doi.org/10.1016/j.ijhydene.2021.12.018.

[14] J.-K. Shiau, Y.-C. Wei, and B.-C. Chen, "A study on the fuzzy-logic-based solar power MPPT algorithms using different fuzzy input variables," Algorithms, vol. 8, no. 2, pp. 100-127, 2015. doi: 10.3390/a8020100.

[15] T. M. de Lima and J. A. C. B. Oliveira, "FPGA-Based Fuzzy Logic Controllers Applied to the MPPT of PV Panels—A Systematic Review," in IEEE Transactions on Fuzzy Systems, vol. 32, no. 8, pp. 4260-4269, Aug. 2024, doi: 10.1109/TFUZZ.2024.3392846.

[16] R. Thankakan and E. R. Samuel Nadar, "Application of fuzzy logic-based MPPT technique for harvesting the heat energy dissipated by the wind generator stator windings to power single-phase AC grid systems," Neural Comput. Appl., vol. 32, pp. 15155-15170, 2020. doi: 10.1007/s00521-020-04865-z.

[17] K. Matter, H. J. El-Khozondar, R. J. El-Khozondar, T. Suntio," Matlab/Simulink Modeling to study the effect of partially shaded condition on Photovoltaic array's Maximum Power Point", International Research journal of engineering and Technology, 2 (2),697-703, 2015. https://www.irjet.net.

[18] H. J El-Khozondar, R. El-Khozondar, K. Matter, "Parameters influence on MPP value of the photo voltaic cell," Energy Procedia, 74, 1142 – 1149, 2015.

[19] A. Hossein, M. Khosravi, M. Soroush, S. Ghamari. "Robust adaptive backstepping control of H-bridge inverter based on type-2 fuzzy optimization of parameters." IET Power Electronics (2024). pp. 603-617. https://doi.org/ 10.1049/pel2.12669.

[20] M. Benghanem, N. Chettibi, A. Mellit, H. Almohamadi. “Type-2 fuzzy-logic based control of photovoltaic-hydrogen production systems.” International Journal of Hydrogen Energy (2023). pp. 35477-35492.

[21] Y. Qiu, Q. Li, Y. Ai, T. Wang, W. Chen, H. Bai, M. Benbouzid, S., Liu, F. Gao, “Optimal scheduling for microgrids considering long-term and short-term energy storage” Journal of Energy Storage. (2024). pp. 112-137. https://doi.org/10.1016/j.est.2024.112137.

[22] A. E. Farrell, D. Sperling, S. Arons, A. Brandt, M. Delucchi, A. Eggert, et al., “A low-carbon fuel standard for California Part 1: Technical analysis,” UC Berkeley: Transportation Sustainability Research Center, 2007.

[23] A. Hafez, N. Fathi, M. Hamdan, S. Alsadi, “Technical and economical feasibility of utility-scale solar energy conversion systems in Saudi Arabia,” Iranian Journal of Science and Technology, Transactions of Electrical Engineering, vol.44, 2020, 213-225. doi. 10.1007/s40998-019-00233-3.

[24] Z Han, X Yao, S Yuan, H Dong, S Ma, Y Dong - Energy Reports. “Research on the control strategy of photovoltaic hydrogen generation system based on Fuzzy PI control”. EnergyReports (2023), pp. 35477-35492. doi. 10.1016/ j.egyr. 2023.02.079.