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Optimizing Solar-Powered Electrolysis Systems for Green Hydrogen Production Using Rat Swarm Optimization and Energy Storage Solutions

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Abstract—This study investigates the performance of a solar-powered electrolysis system for green hydrogen production, utilizing the Rat Swarm Optimization (RSO) algorithm to optimize Maximum Power Point Tracking (MPPT). Two cases are examined: one where the system operates solely on solar energy and another where energy storage is integrated to ensure continuous hydrogen production. MATLAB simulations were used to model both systems under varying environmental conditions. The results show that integrating energy storage significantly enhances system stability and efficiency, mitigating the intermittency of solar energy. In the solar-only scenario, hydrogen production fluctuated directly with solar irradiance, with reduced or no production during low sunlight periods or at night. In contrast, when energy storage was incorporated, the system demonstrated a steady hydrogen production rate by storing excess energy during peak sunlight hours and utilizing it during low solar power periods, ensuring continuous operation of the electrolyzer. Furthermore, the study highlights the advantages of using RSO for MPPT. The RSO algorithm demonstrated faster convergence, higher tracking accuracy, and improved stability compared to traditional algorithms like M&O. These improvements led to enhanced overall system performance, making solar-powered electrolysis systems for green hydrogen production more efficient, reliable, and suitable for practical, real-world applications.

Keywords—Green Hydrogen Production, Maximum Power Point Tracking, Rat Swarm Optimization, Solar-Powered Electrolysis, Energy Storage.

I. INTRODUCTION

Green hydrogen microgrids are emerging as a pivotal solution for creating sustainable energy systems by integrating renewable energy sources like solar and wind with hydrogen production and storage. The ability to generate hydrogen from renewable sources offers a pathway toward decarbonizing energy systems while ensuring energy security. These microgrids, which use a combination of solar, wind, and energy storage technologies, allow for localized energy production and can play a critical role in decarbonizing both the energy and transportation sectors.

Solar energy, being an intermittent power source, presents challenges for consistent hydrogen production. However, when paired with energy storage systems, excess solar energy can be stored during periods of high generation and released during low generation periods. This ensures continuous operation of electrolyzers, which convert electrical energy into hydrogen. Effective energy storage is essential in stabilizing the intermittent energy supply from renewable sources in microgrids, allowing for the consistent production of hydrogen even during periods of insufficient solar or wind energy [1].

Energy storage technologies are vital to the success of green hydrogen microgrids. Various storage solutions, including lithium-ion batteries, solid-state hydrogen storage, and pumped hydro storage, have been studied extensively. These systems enable the efficient use of excess solar power by storing it for later use, thus reducing reliance on fossil fuels. One study indicates that while energy storage is crucial for managing the intermittency of solar power, the cost of these storage systems remains a significant barrier, especially in remote or off-grid locations [2]. To address this, energy storage systems must be optimized to balance performance and cost-effectiveness while ensuring reliability [3].

The hydrogen electrolyzer is one of the most important components in green hydrogen microgrids, as it is responsible for converting electricity into hydrogen. Electrolyzers come in various types, including alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyzers (SOE). Each type has its own advantages and limitations, and the choice of electrolyzer depends on the specific requirements of the application. PEM electrolyzers, for example, offer higher efficiency and faster response times, making them more suitable for fluctuating renewable energy sources like solar [4]. However, their high capital cost is often a challenge, which limits their widespread adoption in large-scale systems [5].

Research into improving the efficiency of electrolyzers is ongoing. A significant area of focus is the development of advanced materials for electrolyzer electrodes and electrolytes, which could reduce operational costs and improve performance. Optimized catalysts have been found to significantly enhance

the hydrogen production rates of PEM electrolyzers, making them more efficient and cost-effective [6]. Additionally, SOEs offer higher efficiency compared to PEM and alkaline electrolyzers but require high operating temperatures, which presents challenges in terms of integration into low-temperature renewable energy systems [7]. Studies have also highlighted the need for more durable materials to withstand the high temperatures and prevent material degradation, a significant obstacle to SOE deployment in real-world applications [8].

Maximum Power Point Tracking (MPPT) is crucial for ensuring that solar arrays operate at their highest efficiency, especially under variable environmental conditions. Traditional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) are widely used but struggle with rapid changes in solar irradiance and temperature. As a result, newer algorithms like Rat Swarm Optimization (RSO) have been developed. RSO is built to respond more rapidly to solar condition changes, maximizing solar arrays' performance and feeding electrolyzers with optimal power. Previous studies have demonstrated that RSO has higher speed and accuracy than the traditional MPPT algorithms, which is vitally important in optimizing the performance of solar-driven electrolyzers [9].

The combination of solar arrays with energy storage systems in green hydrogen microgrids not only enhances the efficiency of hydrogen production but also assists with the minimization of operational costs. Combining solar arrays with optimized MPPT systems improves the generation and storage of energy, ensuring a continuous supply of electricity to electrolyzers. The economic assessment of these integrated solutions suggests that despite the high initial investment of capital, operational savings from lower energy costs and improved reliability more than compensate over the long term. In addition, optimizing the design of the system allows to reduce the hydrogen unit cost markedly; this is essential for the economic viability of green hydrogen [10, 11].

However, scaling up green hydrogen microgrids is a challenge, despite the new technology. One of the major barriers to the costs are the high capital costs of electrolyzers or energy storage systems, especially in underdeveloped areas. The economic viability of the green hydrogen systems is largely dependent on reducing the costs associated with the various components that comprise the systems; electrolyzers, energy storage systems, and solar arrays. Although capital-intensive sources such as solar energy and wind energy can help us improve our ecology and environment in the future, they are still not economically viable and only affordable due to improved technology and lowered capital costs [12, 13]. The process of PEM electrolyzers will be cheaper in the future, as a result of an economies of scale and improvements in manufacturing processes [14].

Hydrogen evolution is viewed as an important means to accomplishing a low-carbon future in which renewable energy systems are integrated with hydrogen production. Advanced MPPT algorithms can be utilized to optimize the performance of solar panels, enabling green hydrogen microgrids to provide stable, renewable energy when combined with cheap energy storage solutions. Increased efficiency will lead toward lower

costs for green hydrogen, which will be further refuted through the use of optimization algorithms, energy storage systems, and green electrolyzer technology, all playing an important role toward the realization of global carbon reduction objectives [15].

In addition, green hydrogen microgrids may offer many advantages for rural and isolated communities. Green hydrogen microgrids may offer a sustainable and independent power source in remote areas where the centralized power grid is out of reach. Microscale wind turbines could also provide emergency power for public infrastructure during energy shortfalls from natural disasters, temporarily supplementing or replacing grid supply. With the advancements in technology and reduces pricing in the future, green hydrogen microgrids can potentially provide energy access to underserved regions [16].

Green hydrogen microgrids have many applications beyond just energy generation. Green hydrogen systems could also help support the hydrogen economy by allowing hydrogen to be used throughout transportation, industry, and residential heating. Thus, long duration storage and long-distance transport of hydrogen is very important for promoting the use of hydrogen as a clean energy carrier. Thus, the development of green hydrogen microgrids, is an important step toward low-carbon energy future [17, 18].

The green hydrogen microgrids provide a possible source of energy generation and storage method for sustainability. These microgrids integrate solar power, energy storage, and electrolyzers to provide a reliable and cost-effective method for hydrogen production as a fossil fuel alternative. Further research on increasing the efficiency of electrolyzer systems, energy storage technologies, and MPPT algorithms will consolidate the scalability and economic viability of such systems, making them an essential part of achieving a low-carbon energy future. While the initial cost is one of the barriers to widespread adoption of green hydrogen microgrids, their utilization in off-grid areas and remote locations provides a potential path towards energy independence and sustainability [19, 20].

II. METHODOLOGY

A. Hydrogen Electrolyzer

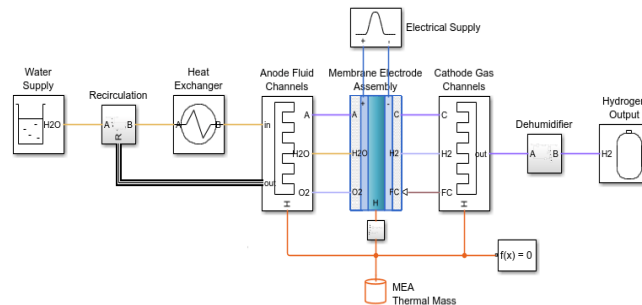


Fig. 1 Hydrogen electrolyzer [21]

Hydrogen electrolysis is the electrochemical device that uses electricity to split water into hydrogen and oxygen as shown in Fig. 1. They have become a cornerstone of renewable energy systems, particularly when paired with energy generators like photovoltaics to produce green hydrogen. Conductive tires will

work with hydrogen-based energy storage systems, where excess renewable energy is utilized to produce hydrogen gas, which can be stored, and then re-converted into electricity by the fuel cells on-demand.

The most commonly used electrolyzers that aim to produce hydrogen are alkaline, polymer electrolyte membrane (PEM), and solid oxide. This makes PEM electrolyzers especially well-suited for pairing with renewable energy sources, like solar resources, since they can function efficiently across a range of power inputs. In such systems, the water is fed into the electrolyzer at the anode side, where it is oxidized to oxygen, electrons, and protons. Protons diffuse through a semipermeable membrane and electrons travel via an external circuit to the cathode where they react with protons to yield hydrogen [22].

In a solar-driven hydrogen production system, the PV panels provide energy to the electrolyzer. Solar array power output can be determined from efficiency, panel area, and solar irradiance:

$$P_{solar} = A \cdot G \cdot \eta_{panel}$$

Where A = area of solar panels (m^2) G = solar irradiance (W/m^2) η_{panel} = efficiency of solar panels. This power is then balanced with the electrolyzer's energy consumption, which can be modeled as:

$$P_{Electrolyzer} = \frac{E_{required}}{Operating\ Time}$$

Where $E_{required}$ is the energy required to produce the hydrogen gas, and t depends on the solar energy available and the efficiency of the electrolyzer. The process of connecting the solar power input to the electrolyzer power demand then allows us to simulate the hydrogen production system performance through the day, where solar availability varies.

III. IMPLEMENTED OPTIMIZATION ALGORITHMS

A. Rat Swarm Optimization (RSO)

To maximize the power extracted from the solar array, the Rat Swarm Algorithm (RSA) [23] is used to optimize the operation of the solar-powered electrolysis system for the generation of green hydrogen. This means that the voltage and current supplied to the electrolyzer is ideally modified by the algorithm at any time, while thus, the energy input is maximized and the maximum hydrogen production is secured. So each rat in the swarm is a potential solution, the position of which represents a certain combination of voltage and current. At each position, the power output produced by the solar array is given as:

$$P_i = V_i \times I_i$$

where P_i is the power, V_i is the voltage, and I_i is the current. Each rat evaluates its position based on the power output and aims to maximize it.

Each rat updates its position based on its own best found position and the best position discovered globally by the swarm. The update rule is:

$$x_i(k+1) = M_k + rand \times (N_k - M_k)$$

where $x_i(k+1)$ is the new position, M_k is the best-performing rat's position at iteration K , N_k is the neighborhood, and $rand$ is a random factor.

The fitness function, based on the best-known positions, is evaluated as:

$$F_i(k) = A \cdot x_i(k) + C \cdot (x_{best}(k) - x_i(k))$$

where A and C control the exploration and exploitation balance, $x_{best}(k)$ is the best position found by the swarm. Each rat's position is updated towards the global best with:

$$x_i(k+1) = |x_{best}(k) + F_i(k)|$$

The algorithm continuously adjusts to these changes, optimizing the operation of the solar array to deliver more power to the electrolyzer and increasing the efficiency of hydrogen production.

IV. RESULTS & DISCUSSION

A. Case 1: Solar-Powered Hydrogen Production

The analysis of the solar-powered electrolysis system for green hydrogen production reveals several key findings related to the system's operation and performance when powered solely by solar energy as shown in Fig. 2

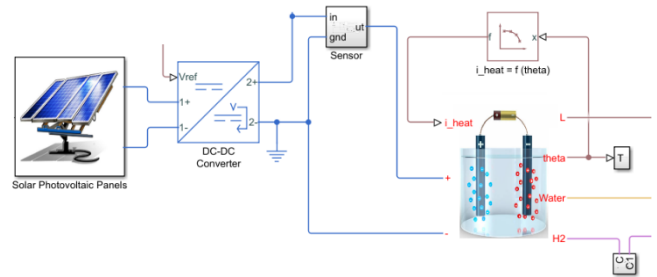


Fig 2. Solar-powered hydrogen production

The results clearly demonstrate the direct relationship between solar power generation and hydrogen production. As expected, hydrogen production follows the pattern of solar irradiance. When solar power input is high, the electrolyzer receives sufficient energy, and hydrogen production increases correspondingly. Conversely, when solar irradiance decreases due to weather conditions or time of day (such as at night), hydrogen production slows down or ceases entirely. This intermittent behavior is a natural consequence of relying on solar power, which is dependent on environmental conditions.

One of the key findings from the simulation is the intermittent nature of hydrogen production. As solar energy generation is not constant, the electrolyzer's hydrogen production is directly tied to solar power availability. When solar irradiance is low, the electrolyzer either slows down or stops operating, which affects continuous hydrogen production. Fig. 3 depicts this, showing how the current used by the electrolyzer fluctuates in response to changes in solar power. As solar irradiance decreases, the current drops, leading to a reduction in hydrogen production.

The solar panels' energy consumption increases as hydrogen production rises, reflecting the system's efficiency in converting solar energy into hydrogen. However, a notable observation is

that during periods of high solar energy, excess power is generated. Without a mechanism to store this excess energy, it is not used for hydrogen production, resulting in an opportunity loss. Fig. 3 also shows the voltage fluctuations, which correspond with the varying energy consumption patterns of the electrolyzer. During periods of high solar irradiance, the voltage increases along with energy consumption, while periods of lower irradiance see reduced energy consumption and a corresponding reduction in voltage, which aligns with reduced hydrogen production.

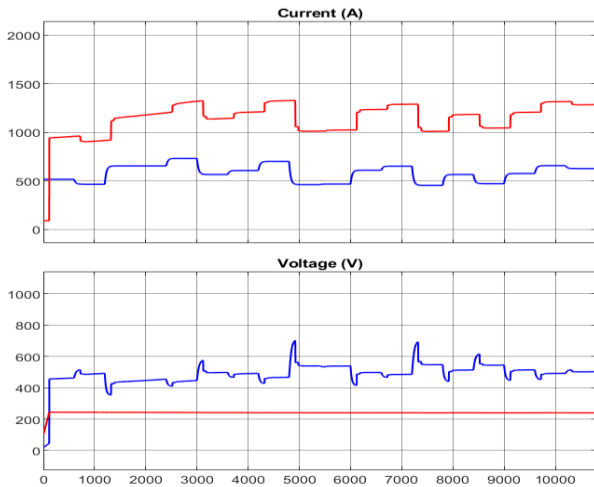


Fig. 3. Current and Voltage for Electrolyzer and Solar

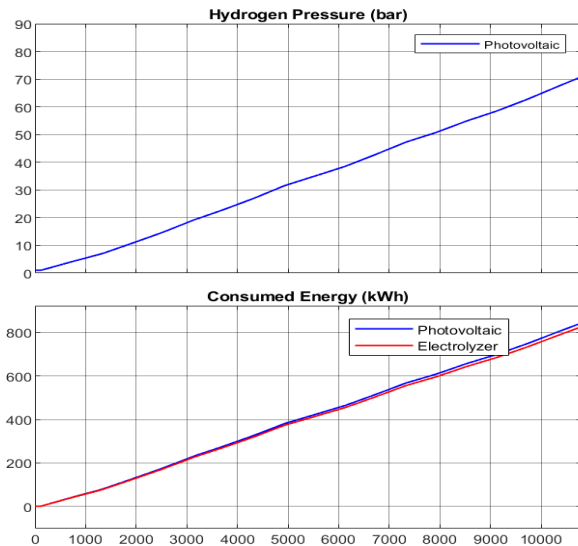


Fig. 4. Hydrogen pressure and consumed energy

Despite the intermittent nature of the system, the results show that the solar-powered electrolysis system can produce hydrogen efficiently during periods of good solar radiation. Fig. 4 shows that hydrogen pressure increases as solar energy availability rises, indicated by the photovoltaic panel's energy input. The overall hydrogen production rate closely tracks the available solar energy, confirming that the system is operating as expected under ideal conditions. However, the inability to produce hydrogen during non-sunny periods highlights the need

for a more robust system that could mitigate these periods of low or zero production. Fig. 4 also shows the consumed energy by both the photovoltaic panel and electrolyzer. The graph indicates that the energy consumption of both increases in tandem with hydrogen production, with the electrolyzer's energy consumption closely tracking the available solar energy and the production of hydrogen.

In summary, solar-powered hydrogen production is effective in utilizing renewable solar energy to produce hydrogen, but its main drawback lies in the intermittency of solar power. Hydrogen production is linked directly to the availability of solar irradiance, and periods of low solar power result in reduced or halted production. To ensure continuous hydrogen supply and improve the overall system performance, a solution to store excess energy or mitigate the effects of low solar power conditions would be beneficial.

B. Case 2: Solar and Energy Storage for Hydrogen Production

In this study, a solar driven electrolysis system with an energy storage unit was evaluated for performance of green hydrogen production as shown in Fig. 5. Results show that with access to energy storage, the operational stability and efficiency of the system was significantly improved, with continuous hydrogen production despite the intermittent nature of solar power.

RSA is incorporated to optimize the power output from solar photovoltaic system to give constant maximum energy input to the electrolyzer. Where this is the RSA that optimizes the set operational parameters of solar panels tracking maximum power point under changing irradiance conditions. This optimization makes the energy utilization more effective, which is more obvious through the higher and more stable hydrogen generation obtained in Case 2. It is also worth noting that with the decrease in energy loss due to less-than-optimal power extraction from the solar array, the RSA improves the overall efficiency of the hydrogen production process.

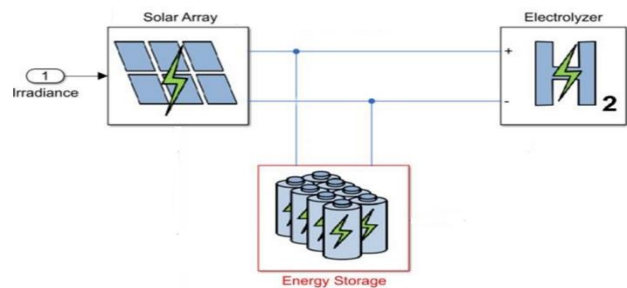


Fig. 5. Solar and energy storage for hydrogen production

Integrating energy storage with the electrolyzer ensures a steady and uninterrupted power feed, essential for continuous hydrogen generation. The pattern of battery charge is depicted in Fig. 6; as represented, battery charge is time-varying, as energy is discharged when solar power is not available (e.g., during nighttime hours). As shown in the hydrogen production graph in Fig. 6, the amount of hydrogen produced increased steadily, demonstrating that implementing energy storage helps to ensure that hydrogen production remains stable, even when

solar irradiance is limited or non-existent. The ability of the energy storage system to mitigate these fluctuations ensures that the electrolyzer operates without interruption, leading to more consistent hydrogen production.

The energy consumption data indicate that both the solar array and energy storage system contribute to the operation of the electrolyzer. During peak solar generation, the electrolyzer draws power primarily from the solar array, while the storage system is charged with any excess energy. During periods of low solar radiation, the storage system discharges to supply power to the electrolyzer, ensuring continuous operation. This dynamic interaction between the solar panels and the energy storage system reduces energy waste by utilizing stored energy during non-ideal solar conditions.

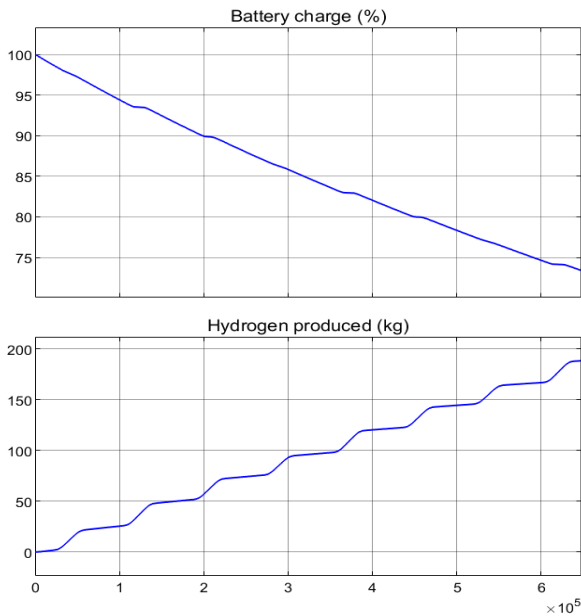


Fig. 6. Battery Charge (SOC) and hydrogen production

Fig. 7 shows the voltages for the battery and grid. The voltage values fluctuate in response to changes in solar irradiance, with the battery voltage rising as the battery stores energy during periods of high solar power and decreasing when energy is used by the electrolyzer. This voltage relationship helps maintain a stable energy supply.

In addition to voltage, the currents for the electrolyzer, solar, and battery systems are shown in Fig. 7.

The graph illustrates how the electrolyzer current fluctuates based on energy demand, with higher current values indicating periods of increased energy consumption by the electrolyzer. Solar current increases with solar irradiance, indicating how the solar panels power the system during periods of high solar power generation. This is the current coming from the battery, which is used to power the load when solar generation is scarce, illustrating how the energy storage system cycles through charge and discharge to balance the power supply. It allows the storage system to charge when solar power output is high and discharge when solar power output is low, enabling a constant and stable energy input to the electrolyzer and facilitating uninterrupted hydrogen production.

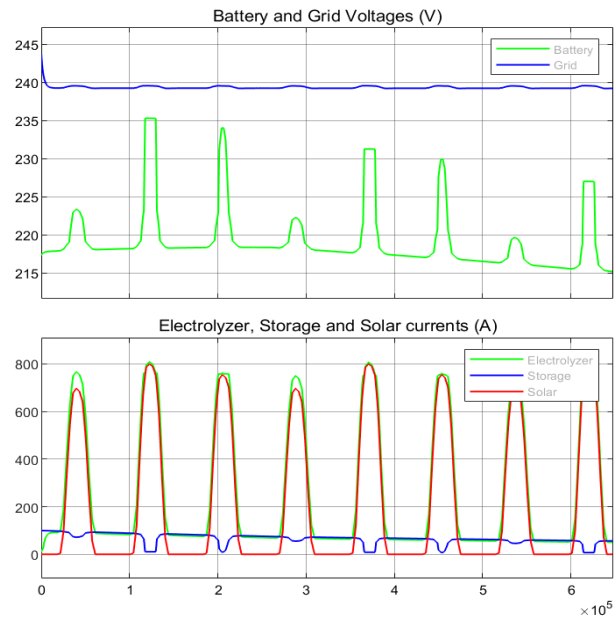


Fig. 7. Voltages for battery and grid, Current for Electrolyzer, Storage and Solar

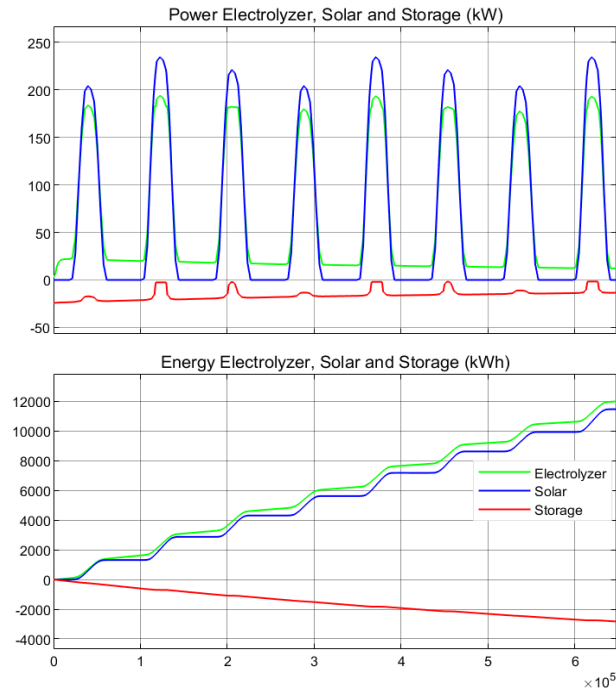


Fig. 8. Power and energy consumption (in kWh)

The energy flow and storage processes are illustrated in Fig. 8 to clarify the interactions of solar power, use/storage of energy, and the energy consumption of the electrolyzer over time. Fig. 8 shows the energy consumption (in kWh) over time for the electrolyzer, solar power, and storage, which remains consistent, demonstrating the system's ability to smooth out fluctuations in energy supply. Fig. 8 also shows how energy from the solar array is efficiently stored in the energy system and utilized by the electrolyzer to maintain continuous hydrogen production. The ability of the storage system to store excess energy and

discharge it during low irradiance periods enhances the overall system efficiency, reducing energy waste.

The inclusion of energy storage improves the overall system performance by providing a buffer against the intermittency of solar power. The results clearly demonstrate that the electrolyzer, when paired with energy storage, operates more efficiently, with continuous hydrogen production observed even during periods of low solar irradiance. The ability to smooth out fluctuations in solar power availability leads to a more reliable and stable hydrogen production process. The total energy consumption over the course of the simulation, coupled with the steady hydrogen output, further highlights the benefits of integrating energy storage into the system. Fig. 3a and 3b show the energy consumption and energy storage dynamics, demonstrating that the electrolyzer operates at a consistent load, improving both energy utilization and the overall efficiency of hydrogen production.

V. CONCLUSION

This study compares two configurations of a solar-powered electrolysis system for green hydrogen production: one using only solar energy and the other integrating energy storage. The solar-only system showed variation in hydrogen production in accordance with solar irradiance, including significant drops in production during low light conditions. Nonetheless, the introduction of energy storage was foundational to enable stable and continuous hydrogen production, enhancing system performance. Additionally, the maximum power point tracking algorithm based on RSO demonstrated better convergence speed, tracking accuracy, stability, and overall system performance, compared to the previously employed M&O algorithm. The findings demonstrate the potential of combining solar power with energy storage and optimized MPPT algorithms like RSO for continuous, efficient green hydrogen production. Future research should focus on further improving RSO's stability for practical applications and integrating additional renewable energy sources, such as wind, to enhance system reliability and scalability for a broader range of environmental conditions.

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