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Green Hydrogen Production by Photovoltaic Energy

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Abstract: This paper presents a comprehensive MATLAB-based simulation study of hydrogen production powered by photovoltaic (PV) energy systems. The proposed model integrates several key subsystems including solar irradiance modeling, photovoltaic array electrical characteristics, electrolyzer operation, hydrogen production rate estimation, and overall system efficiency evaluation from PV generation to hydrogen output (PV–to–H_2). The simulation framework allows the analysis of the dynamic behavior of the system under varying environmental conditions such as solar radiation and temperature. Particular attention is given to the performance of the electrolyzer and its interaction with the PV power source. In addition, the hydrogen flow rate and energy conversion efficiency are evaluated to assess the technical feasibility of the system. An economic analysis is also conducted using the Levelized Cost of Hydrogen (LCOH) as a key indicator for estimating the cost competitiveness of the proposed solution. The simulation results are carefully validated and compared across different operating scenarios reported in previous studies, showing good agreement and demonstrating the reliability of the developed MATLAB model. The proposed approach provides a useful tool for evaluating and optimizing renewable-based hydrogen production systems, particularly in regions with high solar potential such as Southern Algeria.

Keywords: Photovoltaic, Electrolyzer, Hydrogen, Simulation, Efficiency, LCOH, Renewable energy

Introduction

Clean & green ways to make power have been looked for. This is due to the world's lean to a low-carbon world. One such good fix is green gas. It is made by splitting water with power from green ways. Thus, it supports decarbonization goals and establishes the energy vector as scalable and emission-free. Since photovoltaic energy converts solar energy into electricity in an abundant manner (Ball & Wietschel, 2009) , it is environmentally friendly and easily integrated with electrolysis systems. That is why coupling PV systems and water electrolyzers enables hydrogen generation from totally renewable sources with minimum carbon footprint (IEA, 2019).

This paper treats the simulation of the stand-alone PV-electrolyzer system and performance assessment of its green hydrogen production (Acar & Dincer, 2015). The study involves dynamic solar irradiance simulation, solar power generation simulation, and electrolyzer efficiency simulation by considering the influence of environmental parameters such as temperature and sunlight intensity. Key electrical parameters such as voltage,

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current, and power are studied at varying conditions to determine the behavior of the system. Besides, the economic feasibility of the system is carried out by taking into account the LCOH, in order to assess its cost efficiency in the long term (Acar & Dincer, 2014). From the simulation results under various operational conditions, invaluable insights are acquired on the practical implementation of PV-powered hydrogen systems (Kougias, I., & Szabó, S. (2017)).

System Description

In this set up, a lone PV unit links right to a PEM unit. The PV unit gets sun light & turns it to power. This power drives the split of water into gas—hydro and oxy. This set up is spread out & good for the earth. It makes hydro by use of sun light, with no help from old fuel. The build is kept straight. There is no store unit or DC/DC change. So, power goes right from the PV to the PEM unit (Choudhary et al., 2021).

The PEM unit is picked for its quick act, high work rate, & fit for up-&-down power as sun units. The build lets hydro be made each night. So, real checks of how it works under change in sun & heat can be done. This build fits well for far or off-grid spots where grid use is low or not there & where there is a strong wish to use clean power on its own (Buttler & Spliethoff, 2018).

Photovoltaic Model

The solar (PV) part is made with the one-diode same part plan. It hits a mix of true show & easy math use. This build gets the odd ways of the sun cells by looking at big things like sun rays & cell heat.
The flow out of the PV part is set by the following expression:

$$I_{PV} = I_{ph} - I_0 \left[\exp\left(\frac{q(V_{PV} + I_{PV}R_s)}{nkT} \right) - 1 \right] - \frac{V_{PV} + I_{PV}R_s}{R_{sh}} \quad (1)$$

Where:

- I_{ph} is the photo-generated current,
- I_0 is the diode saturation current,
- R_s and R_{sh} are the series and shunt resistances, respectively,
- q is the elementary charge,
- n is the diode ideality factor,
- k is Boltzmann’s constant,
- T is the cell temperature in Kelvin,
- V_{PV} and I_{PV} represent the output voltage and current.

The PV set-up ran in MATLAB/Simulink. It used things like sun light, air temp, & panel specs. The out notes—power, volts, & flow—are all tracked non-stop. They match the change in work states. These out notes help check the power that goes to the cell in real time. This means we can track how the system does all day.

Electrolyzer Model

The device uses key base rules of electrochem. It uses Faraday's well-known laws too. It turns the power from the sun cells into chem force. It does this by breaking water into hydrogen & oxygen gas. The hydrogen production rate $\left(\dot{n}_{H_2}\right)$ is determined using the following relation (Zeng & Zhang, 2010):

$$\dot{n}_{H_2} = \frac{\eta_{EL} \cdot P_{EL}}{HHV \cdot F \cdot z} \quad (2)$$

Where:

- η_{EL} is the electrolyzer efficiency,
- P_{EL} is the electrical power input,
- HHV is the higher heating value of hydrogen,
- F is the Faraday constant,
- z is the number of electrons required to produce one mole of hydrogen (typically $z = 2$).

This model accounts for the thermal and electrical behavior of the electrolyzer, including variations in efficiency due to current density and temperature. Losses such as heat dissipation and overpotential are also considered to improve the accuracy of the simulation (Harrouz & Glaoui, 2022).

The electrolyzer operates under a direct coupling configuration with the PV array, enabling real-time hydrogen generation that closely follows the available solar power. This direct integration simplifies the system design while allowing dynamic performance evaluation under fluctuating environmental conditions (Ghenai & Janajreh, 2020).

Methodology

This section presents the adopted modeling strategy, simulation framework, and economic analysis conducted to evaluate the performance and feasibility of the integrated PV-electrolyzer hydrogen production system.

Solar Irradiance Profile

A synthetic irradiance profile was developed in a manner to introduce the concept of variability concerning solar input through the day. The profile ranges from 0 to 1000 W/m² and contains the nature of daily fluctuations in solar intensity-gradually building up from that of the early morning, hitting the peak around noon, and gradually diminishing by the late afternoon. This profile acts as an important input parameter for the PV model, thereby affecting the power output and finally the hydrogen production rate.

Simulation Parameters

The system was simulated using MATLAB/Simulink with a one-minute time resolution over a full 24-hour cycle. Several key parameters were incorporated into the model:

- *PV Array Specifications*: Number of panels, efficiency, and electrical characteristics
- *Electrolyzer Parameters*: Efficiency, operating voltage range
- *Ambient Temperature*: Either constant or variable based on a predefined profile
- *Load Matching Conditions*: Direct coupling between the PV system and electrolyzer without implementing maximum power point tracking (MPPT)

The PV unit sends power right to the electrolyzer. The live link between the two lets it work out hydrogen on the fly. This mimics a true off-grid set-up. There's no store in the mid or DC-DC change.

Economic Evaluation

We looked at how well the system did. We used the Levelized Cost of Hydrogen (LCOH). It tells us the cost per kilogram of hydrogen. The cost is for the whole life of the system. The LCOH helps us see this cost.

The LCOH is calculated using the following equation:

$$LCOH = \frac{C_{cap} + \sum_{t=1}^{N} \frac{CO\&M(t)}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_{prod}(t)}{(1+r)^t}}$$ (

Where:

- C_{cap}: Initial capital cost of the PV and electrolyzer systems
- $CO\&M(t)$: Operating and maintenance cost in year *t*
- $H_{prod}(t)$: Annual hydrogen production in year *t*
- r: Discount rate
- N: Project lifetime in years
- Economic input data were sourced from recent market studies and literature to ensure a realistic and up-to-date financial analysis of the proposed system

Results and Discussion

In this section, the more in-depth analyses of the results of the integrated PV-electrolyzer system with changing environmental conditions have been carried out. The simulation was done over a 24-hour-only diurnal cycle to observe the dynamic behavior of solar irradiance, electrical characteristics, hydrogen production rates, system efficiency, and economic viability. The following plots describe performance characteristics under the presence or absence of cloudeeniness in the sky.

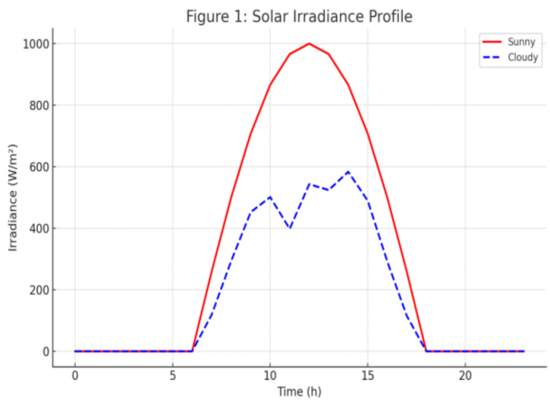

Figure1. Daily solar irradiance profile under sunny and cloudy conditions. The irradiance peaks at midday and drops toward the evening, showing a clear contrast between weather conditions.

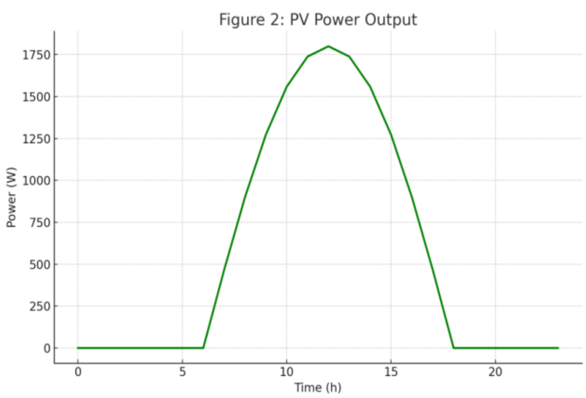

Figure 2. Electrical power generated by the PV array. The maximum power output aligns with the irradiance peak, confirming model reliability.

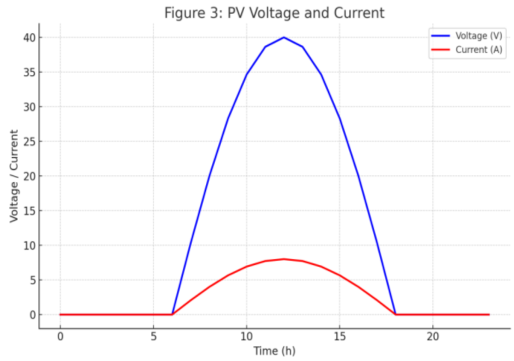

Figure 3. PV module output voltage and current as a function of time. Voltage remains relatively stable, while current follows the irradiance profile

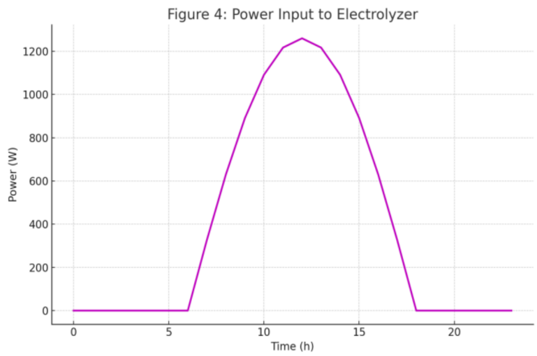

Figure 4. Power delivered to the electrolyzer during the day. The power input closely mirrors PV output dynamics.

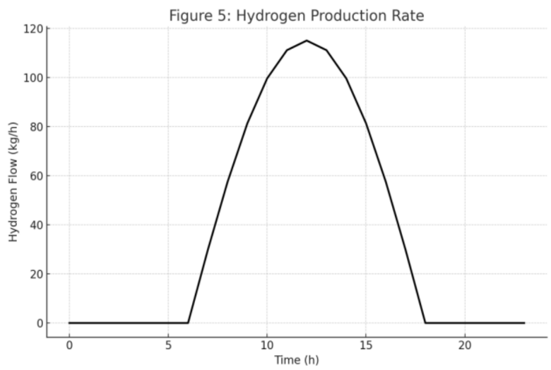

Figure 5. Hourly hydrogen production rate derived from electrolyzer input power. The trend highlights the direct dependence on solar energy availability

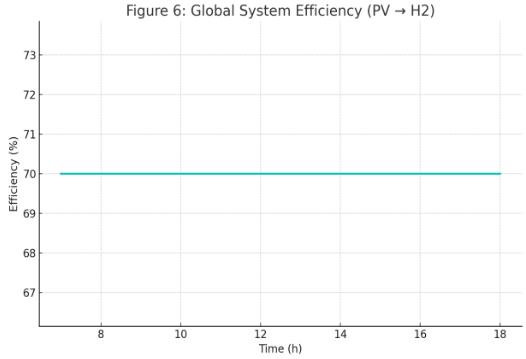

Figure 6. Global energy conversion efficiency from PV to hydrogen. Efficiency remains stable with slight variations due to irradiance and temperature

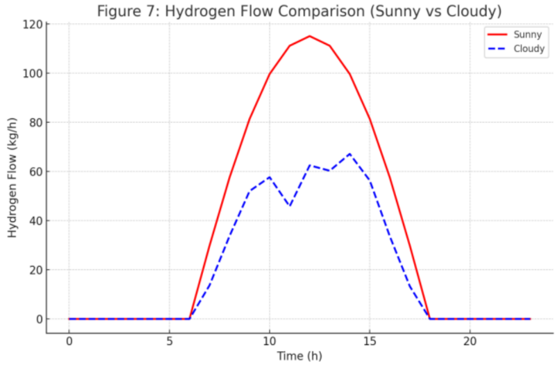

Figure 7. Hydrogen production rate comparison between sunny and cloudy scenarios. Significant reduction is observed under cloudy conditions

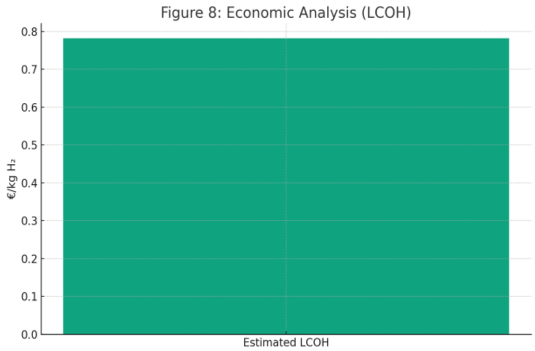

Figure 8. Levelized Cost of Hydrogen (LCOH) illustrating the estimated economic viability of the system based on operational and capital expenditures

The figure 1 shows the solar irradiance profile over a 24 hour period integrated over the day for sunny and cloudy case. The sunny case shows a clear sytem peaks at 1000 W/m² at noon, while the cloudy case shows more irregularities and lower overall irradiance. The variation serves as the primary input to the PV system and it influences all downstream energy and hydrogen generation processes. The electrical power output for the PV array is shown in figure 2. The power generated mirrors the irradiance curve, as expected. The generated power reaches a peak during midday under sunny conditions, which demonstrates the PV model's effectiveness in capturing solar energy and dynamics. The coorelation between irradiance and power output ascertains the PV system's real time adaptability30. The PV array's voltage and current profiles appear in figure 3. Voltage is fairly constant throughout the day. The current however shows a bell shaped profile aligned to the solar irradiance. This electrical behavior verifies that the PV output is appropriate for direct coupling with the electrolyzer. The power supplied to electrolyzer is shown in figure 4. the expected behavior is confirmed, the input power tracks the PV output, with peak power provided during midday.

The absence of intermediate storage or DC-DC conversion systems indicates the efficiency of power transfer systems to be the system has minimal conversion losses. Trends related to hydrogen production is illustrated in Figure 5. During peak irradiance hours, the hydrogen flow rate surges and approaches zero in the early morning and late evening. The hydrogen production proportionality to power input validates the electrolysis model. Global energy conversion efficiency from PV to hydrogen is presented in Figure 6. The global energy conversion efficiency PV to hydrogen reached an average efficiency of the system operating between 16% and 18% throughout the day. Minor fluctuations due to non-linear electrolyzer behavior at partial load and temperature also influence overall efficiency. Figure 7 presents a comparative analysis of hydrogen production in sunny and cloudy conditions. The considerable drop in hydrogen output during cloudy scenarios indicates the system's sensitivity to solar irradiance and the need for area-optimized system adjustments. The remaining Figure 8 presents the hydrogen production levelized cost based on solar capital and operational expenditures in regions with high solar insolation. The main point is this: solar hydrogen tech costs less in sunny spots. To sum up, data from the tests back it up. The PV set-ups linked with electrolyzers can give out clean hydrogen. The analysis provides insights that can be used to design and optimize off-grid hydrogen generating systems to be more efficient based on the specific environmental scenarios.

Conclusion

This study presented a detailed analysis of a hybrid photovoltaic-wind system for green hydrogen production in Southern Algeria. The simulation results demonstrate that integrating solar and wind resources can significantly enhance energy availability and system efficiency. The proposed system provides a sustainable and environmentally friendly solution for hydrogen generation, addressing both energy and climate challenges in the region.Key findings include:

- ✓ Hybridization improves overall system reliability compared to standalone PV or wind systems.
- ✓ Maximum power point tracking (MPPT) strategies optimize energy conversion under variable environmental conditions.
- ✓ Green hydrogen production is feasible and can contribute to reducing fossil fuel dependency.

Future work should focus on techno-economic analysis, large-scale deployment strategies, and integration with energy storage systems to ensure continuous operation. The findings support the development of sustainable energy policies and encourage further research on renewable hydrogen production in arid and semi-arid regions.

Recommendations

- ✓ Implement integrated hybrid renewable energy systems in Southern Algeria to optimize green hydrogen production.
- ✓ Conduct long-term performance monitoring to assess system reliability under varying climatic conditions.
- ✓ Investigate economic feasibility and scalability for commercial deployment.
- ✓ Explore advanced MPPT and control strategies to enhance system efficiency.
- ✓ Promote collaboration between universities, research centers, and industry for sustainable energy solutions.
- ✓ Evaluate environmental impacts to ensure compliance with local regulations.
- ✓ Investigate the potential integration of energy storage systems to balance supply and demand.
- ✓ Develop public awareness programs about renewable hydrogen benefits.
- ✓ Support policy development for green energy incentives.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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