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Analysis of Key Parameters Affecting the Performance of Solar-Driven Electrolysis

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ABSTRACT

As the world seeks sustainable and environmentally friendly energy solutions, hydrogen has emerged as a promising alternative to traditional fossil fuels. Harnessing renewable energy sources, especially solar energy, offers a clean method for hydrogen production that can be used in various sectors. This study explores the design and performance of a solar-powered electrochemical system for hydrogen production via water electrolysis. The research investigates the impact of key operational parameters, including electrolyte pH, electrode surface area, and sunlight incidence angle, on hydrogen yield and system efficiency. Utilizing a conventional alkaline electrolyze coupled with monocrystalline solar panels at varying angles, experiments demonstrate that alkaline conditions (pH 9) and increased electrode surface area significantly enhance hydrogen generation. Among the tested angles, 45° provided optimal solar radiation absorption, resulting in higher hydrogen output. Comparative analysis indicates that while traditional power sources offer greater stability, solar-driven systems present a promising, environmentally friendly alternative for sustainable hydrogen production. The findings suggest potential improvements through advanced electrode materials, solar tracking, and system optimization for real world applications, emphasizing the role of renewable energy in advancing clean hydrogen technologies.

Keywords: Solar energy conversion, Hydrogen production, Water electrolysis, Renewable energy, Sustainable fuel.

تحليل العوامل الرئيسية المؤثرة على أداء التحليل الكهربائي المدعوم بالطاقة الشمسية

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ملخـــــــص البحـــــــث

بالنظر إلى سعي العالم نحو حلول طاقة مستدامة وصديقة للبيئة، برز الهيدروجين كبديل واعد للوقود الأحفوري التقليدي. إن استغلال مصادر الطاقة المتجددة، وعلى وجه الخصوص الطاقة الشمسية، يوفر وسيلة نظيفة لإنتاج الهيدروجين يمكن استخدامها في مختلف

القطاعات. تستكشف هذه الدراسة تصميم وأداء نظام كهربائي كيميائي يعمل بالطاقة الشمسية لإنتاج الهيدروجين عبر تحلل الماء الكهربائي. تبحث الدراسة في تأثير المعايير التشغيلية الرئيسية، بما في ذلك درجة حموضة الإلكتروليت، ومساحة سطح الأقطاب، وزاوية سقوط أشعة الشمس، على إنتاج الهيدروجين وكفاءة النظام. من خلال استخدام خلايا كهربائية قلوية تقليدية متصلة بألواح شمسية أحادية البلورة بزوايا مختلفة، تظهر التجارب أن الظروف القلوية (9 pH) وزيادة مساحة سطح الأقطاب تعزز بشكل كبير من إنتاج الهيدروجين. من بين الزوايا المختبرة، كانت زاوية 45° هي الأفضل في امتصاص الأشعة الشمسية، مما أدى إلى زيادة في إنتاج الهيدروجين. تشير التحليلات المقارنة إلى أن أنظمة الطاقة التقليدية توفر استقرارًا أكبر، في حين أن الأنظمة التي تعتمد على الطاقة الشمسية تقدم بديلاً واعدًا وصديقًا للبيئة لإنتاج الهيدروجين المستدام. وتقترح النتائج تحسينات محتملة من خلال مواد قطب متقدمة، وتقنيات تتبع الشمس، وتحسين النظام لتطبيقات العالم الحقيقي، مع التأكيد على دور الطاقة المتجددة في تعزيز تقنيات الهيدروجين النظيف.

الكلمات الدالة: تحويل الطاقة الشمسية، إنتاج الهيدروجين، التحليل الكهربائي للماء، الطاقة المتجددة، الوقود المستدام.

1. INTRODUCTION

The search for sustainable and clean energy ses has emerged as atop worldwide concern dueto the economic and environmental problems cau sed by an overreliance on fossil fuels [1]. Due to its special qualities as a clean energy carrier that only produces water when burned and drastically lowers hazardous emissions, hydrogen has become one of the most promising substitutes for traditional fuels [2]. Water electrolysis using renewable energy sources, especially solar energy, is one of the most effective and sustainable ways to produce hydrogen. If an efficient system is in place to transform solar energy into electrical energy and use it for electrolysis, this method makes it possible to generate hydrogen sustainably[3].

The goal of this study is to design and build high-performance solar cells that can effectively convert solar radiation into electrical energy in order to support the electrolysis of water to produce hydrogen. Analyzing performance - influencing elements, testing prototype systems to assure practical feasibility, and assessing the electrical and optical characteristics of new semiconductor materials are all part of the study. The objective is to create an integrated system that optimizes hydrogen production while consuming the least amount of energy, making the process both environmentally and economically viable.

The ultimate goal of this study is to develop a dependable, environmentally responsible process for producing hydrogen in order to further the development of sustainable energy technologies. These developments promote a more sustainable and greener future by supporting applications in energy storage, transportation, and industrial operations.

Several research that aim to improve solar hydrogen generation through cost reduction, environmental impact evaluations, hybrid solar-wind systems, low-cost catalysts, and electrolyser technology developments. Enhancing the practical deployment, stability, and efficiency of sustainable renewable energy solutions is the main goal. The creation of sustainable energy technology has emerged as a major field of study in recent years. Of them,

Solar-powered electrochemical cells have attracted a lot of interest because of their potential to use water splitting to generate clean energy[4]. In order to optimize cell design and hydrogen production, these researches investigate variables that affect cell efficiency, such as pH levels, electrode surface area, and light incidence angle[5].According to Fujishima and Honda, that by showing water splitting with a TiO_2 photo electrode under UV light, they invented the idea of solar-driven hydrogen synthesis[6]. Their experimental setup achieved about 1% solar-to-hydrogen (STH) efficiency with a platinum cathode and titanium dioxide anode immersed in an electrolyte[7]. Although their research demonstrated that electrolysis could be directly powered by sunshine, its drawbacks included its low efficiency and dependence on UV radiation. This study inspired additional research on visible-light absorption and cutting-edge materials like perovskites and III-V semiconductors, laying the foundation for the creation of photo electrochemical (PEC) cells. Multi-junction solar cells combined with proton exchange membrane (PEM) electrolyzers were the focus of their analysis of integrated photovoltaic (PV)-electrolyzer systems, according to the National Renewable Energy Laboratory (NREL)[8]. Around 18% STH efficiency was attained in their lab-scale tests, highlighting the significance of voltage matching and quick PEM responsiveness to solar variations. Although they pointed out the high expenses of III-V cells, they predicted that future efficiencies using improved materials may reach 25%. Maximum power point tracking (MPPT) was suggested by the study for practical uses and durability testing in a range of scenarios[9]. Molybdenum disulfide (MoS_2) was studied by Jaramillo and associates as a low-cost substitute for platinum in the hydrogen evolution reaction (HER). Although stability in acidic PEM settings remained an issue, their experiments in both alkaline and acidic media demonstrated that MoS_2 exhibited HER activity comparable to platinum at a tenth of the cost. In an effort to lower costs and increase the scalability of electrolyzer systems, their study sparked additional investigation into earthabundant catalysts. Schmidt and colleagues examined the cost, dynamic response, and efficiency of PEM and alkaline electrolysers[10]. Despite their higher capital expenditures (~$1,500/kW), their findings indicated that PEM electrolysers were viable for solar integration due to their higher efficiency (about 70%) and faster response times. On the other hand, alkaline systems, which were less expensive (around $800/kW), had less flexibility and a lower efficiency of about 60%. The study highlighted new alternatives including anion exchange membrane (AEM) electrolyzers and suggested PEM technology for solar applications[10]. According to Al-Ashouri and collaborators, to have created 29.5% efficient perovskite-silicon tandem solar cells and PEM electrolyzers, which allowed them to get a 19% sun-to-hydrogen (STH) efficiency. They showed how to fabricate things in scalable ways, but stability[11].

2. MATERIALS AND METHODS

By choosing appropriate materials, building the system, and creating controlled experimental circumstances, this study seeks to methodically examine these elements. The process entails carefully adjusting variables like the electrolyte pH level, electrode surface area, and angle of solar radiation incidence while keeping an eye on crucial elements like voltage, current, and the amount of hydrogen gas generated. The data obtained from meticulous testing and precise measurements will be examined to investigate the connections among these elements and identify the ideal circumstances that improve the efficiency of hydrogen production.

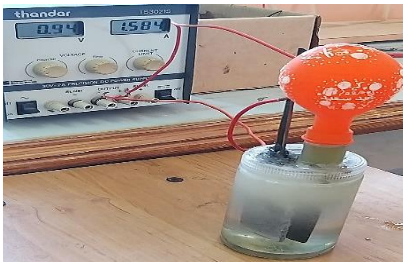

Fig1. Conventional alkaline electrolyser for hydrogen production.

The experiments used a monocrystalline solar panel, composed of 36 cells with size 23.5 cm 35.0 cm a power rating between 20 and 50 W. It has a voltage around 17–18 V at maximum power and is protected by a tempered glass cover and an aluminum frame. Additionally, an electrochemical cell with iron electrodes, electrolyte solutions at pH 7 and 9, a gas collection balloon, a graduated tube, and measurement devices for voltage and current were used. Tools for adjusting the panel's angle at 30°, 45°, and 60° were also employed[12].

Fig 2. Solar panal with different angles.

The analysis was based on fundamental laws such as Ohm's law, Faraday's law of electrolysis, and the ideal gas law. These principles helped interpret electrical measurements, gas production, and energy conversion during the experiments.

Fig3. alkaline electrolyser with solar power for hydrogen production.

3. THEORY AND CALCULATION

3.1 System description and procedure

Electrolysis units are the most commonly utilized systems for producing high-purity hydrogen through the process of water splitting[13]. The process of water electrolysis relies on the movement of electrons, facilitated by an external circuit. During water splitting, a specific amount of DC electricity must be supplied to both electrodes, which are separated by an aqueous electrolyte exhibiting high ionic conductivity[14]. The overall reaction that takes place in an electrolyzer system is as follows:

$$H_2O\ (l) + \text{electrical energy} \rightarrow H_2\ (g) + 1/2\ O_2(g). \quad (1)$$

Our system uses a conventional alkaline electrolyser for hydrogen production, where water is split through electrolysis using a sodium hydroxide (NaOH) electrolyte. The chemical reactions at the electrodes are:

$$\text{Cathode: } 4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \quad (2)$$

$$\text{Anode: } 4OH^- \rightarrow O_2 + 2H_2O + 4e^- \quad (3)$$

3.2 Design and Assembling System

To protect it and preserve the stability of the electrolyte volume, the electrochemical cell was intended to be housed inside a plastic casing. The electrolyte solution was completely buried in two iron electrodes. To guarantee the transfer of electricity produced by the reaction, the electrodes were attached to the solar panel using safe electrical wires. The apparatus had a mechanism for gathering hydrogen gas, which was pipe to the cell and directed toward the balloon.

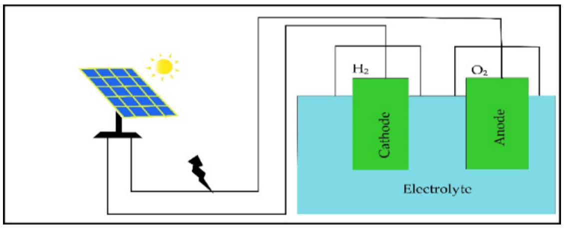

Fig4. Flow diagram for electrolyser with solar power.

3.3 Experimental Procedures

Prepare a pH 7 electrolyte and select electrode areas (20 or 30 cm²). Connect the cell to the solar panel set at a 30° angle and run for 5 minutes to stabilize. Measure voltage, current, and hydrogen volume. Repeat the process at 45° and 60°, then change pH to 9 and repeat for all angles and areas. Record all data with details of conditions.

Results Analysis:

Data are analyzed through statistical methods and graphs to examine how the radiation angle affects hydrogen volume and electrical performance, how electrode surface area influences energy conversion efficiency, and how pH variations impact reaction rate and hydrogen production. The aim is to identify optimal conditions for maximum cell performance.

Table 1. Results Using a Conventional Power Source at pH 7 with an Electrode Surface Area of 20 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	1.79	0.96	26	20.62	300
5	2.43	1.07	36	31.2	300
5	2.48	0.38	27	11.31	300
5	2.31	0.69	38	19.13	300
5	1.6	1.19	29	22.85	300

Table 2. Results Using a Conventional Power Source at pH 7 with an Electrode Surface Area of 30cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	1.7	1.19	30	24.28	300
5	1.73	0.83	28	17.23	300
5	1.59	0.45	34	8.59	300
5	2.18	0.63	33	16.48	300
5	1.9	1.03	37	23.48	300

Table 3. Results Using a Conventional Power Source at pH 9 with an Electrode Surface Area of 20cm^2.

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	1.98	0.76	33	18.06	300
5	2.49	0.59	34	17.63	300
5	2.41	0.60	27	17.35	300
5	1.71	1.15	35	23.60	300
5	2.32	1.02	26	28.40	300

Table 4. Results Using a Conventional Power Source at pH 9 with an Electrode Surface Area of 30cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.35	0.83	35	23.41	300
5	1.72	0.36	39	7.43	300
5	2.41	0.69	40	19.95	300
5	1.56	1.05	26	19.66	300
5	1.85	0.92	40	20.42	300

Table 5. Results Using Solar Panel at 30° Sunlight Angle, pH 7, and Electrode Surface Area of 20cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	1.95	1.0	26	23.4	300
5	2.21	0.36	34	9.55	300
5	1.98	0.95	35	22.57	300
5	2.16	0.85	40	22.03	300
5	1.80	0.75	40	16.2	300

Table 6. Results Using Solar Panel at 30° Sunlight Angle, pH 7, and Electrode Surface Area of 30 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.38	0.74	32	21.13	300
5	1.95	0.53	28	12.4	300
5	2.48	0.62	31	18.45	300
5	2.32	0.36	25	10.02	300
5	1.88	0.49	39	11.05	300

Table 7. Results using a solar panel at a sunlight angle of 30°, pH 9, and an electrode surface area of 20 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.24	0.31	32	8.33	300
5	1.58	1.13	39	21.42	300
5	2.18	0.69	29	18.05	300
5	1.87	0.53	39	11.89	300
5	1.74	0.91	31	19.00	300

Table 8. Results using a solar panel at a sunlight angle of 30°, pH 9, and an electrode surface area of 30 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	1.65	0.91	28	18.02	300
5	2.12	0.56	34	14.25	300
5	1.51	0.95	31	17.21	300
5	1.59	1.11	32	21.18	300
5	2.23	0.35	29	9.37	300

Table 9. Results Using Solar Panel at 45° Sunlight Angle, pH 7, and Electrode Surface Area of 20 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.16	1.15	32	29.81	300
5	2.21	0.44	28	11.67	300
5	1.97	0.58	32	13.71	300
5	2.32	1.0	38	27.84	300
5	1.84	0.54	29	11.92	300

Table 10. Results using a solar panel at a sunlight angle of 45°, pH 7, and electrode surface area of 30 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.47	0.53	32	15.71	300
5	2.32	0.74	25	20.60	300
5	2.26	0.75	26	20.34	300
5	2.22	0.82	27	21.84	300
5	1.56	0.61	33	11.42	300

Table 11. Results using a solar panel at a sunlight angle of 45°, pH 9, and electrode surface area of 20 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.25	0.45	32	12.15	300
5	1.70	0.33	39	6.73	300
5	2.09	0.62	34	15.55	300
5	2.09	0.75	35	18.81	300
5	1.51	1.16	35	21.02	300

Table 12.Results using a solar panel at a sunlight angle of 45°, pH 9, and electrode surface area of 30 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.13	0.37	32	9.46	300
5	2.41	0.53	39	15.33	300
5	2.18	0.35	28	9.16	300
5	2.30	0.82	30	22.63	300
5	1.87	1.06	33	23.79	300

Table 13. Results using a solar panel at a sunlight angle of 60°, pH 7, and electrode surface area of 20 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	1.65	1.19	26	23.56	300
5	2.25	1.18	37	31.86	300
5	2.39	0.85	31	24.38	300
5	2.32	0.36	29	10.02	300
5	1.94	0.52	35	12.11	300

Table 14. Results using a solar panel at a sunlight angle of 60°, pH 7, and electrode surface area of 30 cm².

Time (min)	Voltage (V)	Current (A)	Temperature (°C)	Hydrogen Volume (ml)	Duration (s)
5	2.07	0.90	35	22.36	300
5	2.34	0.73	35	20.50	300
5	1.64	0.35	26	6.89	300
5	1.98	0.81	30	19.25	300
5	2.23	1.08	29	28.90	300

4. Analysis of Results (Data Analysis)

5.1 Conventional Source vs. Solar Energy:

When comparing the two power sources, the conventional system demonstrated more stable hydrogen production. For example, at pH 7 with a 10 cm² electrode surface area, as was in the table, the hydrogen volume ranged between 11.31 and 31.2 ml, with relatively consistent current values of 0.38 to 1.19 A. In contrast, the solar panel system under the same conditions showed wider fluctuations, with hydrogen volumes varying from 9.55 to 23.4 ml depending on sunlight conditions. This confirms that the conventional power supply provides greater reliability, while the solar source is more sensitive to external environmental factors.

5.2 Effect of pH

Alkaline conditions (pH = 9) consistently enhanced hydrogen output compared to neutral conditions (pH = 7). For instance, using a conventional source with a 15 cm² electrode surface, as was in the table, the hydrogen yield reached between 20.42 and 23.41 ml, whereas at neutral pH, the maximum was around 24.28 ml but with lower stability. Similarly, in solar-powered experiments, pH 9 produced hydrogen volumes up to 23.79 ml, which was significantly higher compared to neutral pH. This indicates that the presence of hydroxide ions (OH^-) in alkaline media improves conductivity and accelerates the reaction rate.

5.3 Effect of Electrode Surface Area:

Increasing the electrode surface area from 10 cm² to 20 cm², as reflected in the data, led to clear improvements. For example, at pH 7 with a solar angle of 45°, hydrogen production increased from a maximum of 21.84 ml (scaled from the 10 cm² data) to 29.81 ml. Similarly, at pH 9, production rose from 21.02 ml to 23.79 ml. This demonstrates that larger electrode surfaces provide more active sites for the reactions, thereby enhancing hydrogen generation.

5. Discussion of Differences and Similarities in Electrolysis Systems

Electrolysis systems for hydrogen production, whether conventional or solar-powered, share fundamental principles but differ significantly in performance, environmental impact, and operational challenges.

Similarities: Both systems rely on the core principle that optimal radiation or electrical conditions enhance hydrogen production. The radiation intensity and its angle are crucial in solar systems, affecting how effectively sunlight is absorbed. Similarly, increasing the pH level in the electrolyte enhances electrical conductivity, thereby improving electrolysis efficiency in both setups. Additionally, larger electrode surface areas are beneficial across the board, as they provide more contact between water and the electric current, facilitating better separation of hydrogen and oxygen gases. Temperature also plays a vital role; slight increases in solution temperature can boost electrolysis performance, but careful monitoring is necessary to prevent overheating and associated performance decline.

Differences: While conventional electrolysis systems generally exhibit higher efficiency and stability under controlled laboratory conditions, solar energy-based systems are more environmentally friendly and potentially more cost-effective in the long run. The performance of solar systems is heavily influenced by external factors such as weather conditions and solar radiation fluctuations, which can cause variability in hydrogen production. To mitigate these issues, techniques like solar tracking systems can be employed to maximize radiation reception. Moreover, advancements such as developing catalytic electrode materials or nanoscale coatings are specific to solar systems to enhance electrolysis activity. Temperature management also differs; solar systems require effective cooling systems to prevent temperature-related efficiency losses during large-scale operations, a concern less prominent in traditional setups.

6.1 Proposed Improvements:

Future experiments could explore different pH levels, test various electrode materials like carbon or metals, and study factors such as temperature, electrolyte concentration, and light quality. Additionally, redesigning the cell to minimize losses and improve hydrogen collection is recommended

CONCLUSION

This study examined how the performance of a solar-powered electrochemical cell for hydrogen production was impacted by the electrolyte pH, electrode surface area, and sunlight incidence angle.

The findings demonstrated that these operational factors have a significant impact on hydrogen output. In particular, alkaline settings (pH = 9) boosted conductivity and reaction rates in comparison to neutral conditions (pH = 7), while increasing the electrode surface area greatly increased hydrogen generation.

45° showed the best balance between solar radiation collection and electrochemical performance among the evaluated sunshine angles, producing the most hydrogen.

When solar panels and a traditional power source were compared, it was found that the conventional system offered more stability, but the solar system caused fluctuations because of variations in sun radiation. However, the solar-powered system showed promise as an economical, clean, and renewable substitute for sustainable hydrogen production.

Recommendation

Based on the findings of the study, it is advised to investigate higher alkalinity levels, such as pH 10 or 11, while evaluating electrode stability, improve electrode design with porous or catalytic coatings to increase efficiency, and investigate automatic solar tracking systems to maintain ideal panel angles. Performance can be further optimized under a variety of weather circumstances by employing high-quality solar panels and developing cooling systems. Promising directions also include enabling off-grid operation for rural areas and merging the system with hydrogen storage alternatives.

The sustainable development and application of solar hydrogen technologies will be aided by carrying out thorough environmental and economic analyses and encouraging cooperation between academia and industry.

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