Potential of Portable Solar Powered Electrolysis System for Off-Grid Hydrogen Generation

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ABSTRACT

The growing interest in hydrogen as a clean fuel alternative stem from the adoption of sustainable and decentralized energy systems. Portable solar-powered hydrolysis systems show promise for off-grid hydrogen generation because they can serve emergency relief and rural electrification needs and mobile scientific missions. The research investigates theoretical capabilities of these systems through both literature-based analysis and performance modeling. Photovoltaic energy generation is part of the suggested system framework, which is followed by proton exchange membrane (PEM) electrolyzers for compact hydrogen storage and water electrolysis. The performance calculations use solar irradiance data together with electrolysis energy requirements. The research indicates that portable solar-hydrolysis systems have the potential to operate in low-power remote applications with zero emissions despite their current scalability and hydrogen storage challenges.

Keywords: Hydrogen generation, water electrolysis, portable solar-hydrolysis systems, solar energy, off-grid

1. Introduction

Hydrogen is becoming an important energy carrier through global transition to clean and sustainable energy systems. It has a high energy density [1] and can also be generated with zero-carbon emissions from renewable energy sources. However, existing approaches to generate hydrogen such as electrolysis, steam methane reforming and biomass [2] are carbon-inefficient and mostly limited to large centralized industrial plants. Renewable energy (primarily solar and wind) electrolysis provides a cleaner, more versatile alternative. Figure 1 shows an example of hydrogen generation system using solar power.

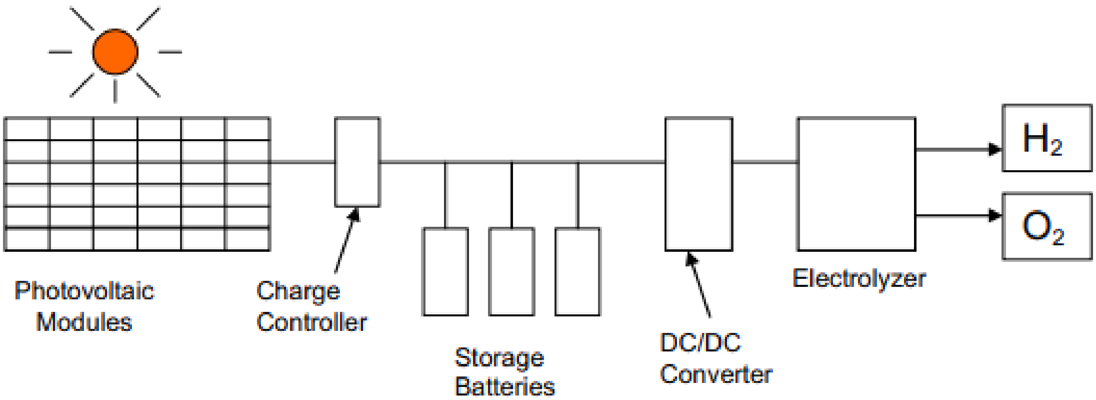

Figure 1. A conventional photovoltaic-electrolyzer hydrogen generation system [3]

Due to its flammable and explosive character [4], hydrogen itself is intrinsically hazardous though otherwise could be advantageous. The chemical reactivity of hydrogen means it must be handled and stored with great care, notably because of its reactivity with heat, and its pressure. Portable hydrogen applications can only increase the demands. Requirements for a portable system are therefore challenging, yet attainable. There is a requirement for such technology in portable hydrogen systems that fit storage, safety and light-weight material constraints.

Also, the electrolysis of water (e.g. to produce hydrogen) has a special difficulty. It's an energy-intensive process requiring the decomposition of water molecules into hydrogen and oxygen [5]. This aggravates the problems of mobile systems development, specifically when these systems can only be powered by renewable energy resources like solar energy.

Advances in photovoltaics (PV) technology, compact electrolyzer designs and portable power devices have led to novel prospects for decentralized hydrogen production. A scalable, lightweight portable solar-driven electrolysis system can adapt these advances to accomplish off-grid and clean generation of hydrogen with potential applications in the field under remote and mobile conditions. This paper attempts to evaluate the practicality, performance and possible applicability of such systems via literature review and theoretical modeling.

2. System Concept Overview

A portable solar-hydrolysis system typically includes:

- Photovoltaic Panels – Lightweight or foldable solar modules providing DC electricity.
- Electrolyzer (PEM) – A compact unit for water electrolysis with high responsiveness and efficiency.
- Power Regulation – A DC-DC converter or MPPT controller ensures stable voltage and current to the electrolyzer.
- Hydrogen Storage – Stores produced hydrogen for later use, potentially via a metal hydride tank or low-pressure container.

Photovoltaic (PV) panels in a portable solar-hydrolysis system are used as the main energy source to convert sunlight directly to direct current (DC) electricity with a photovoltaic effect directly. Thin film solar panels are better suited to portable use, due to their flexibility, light weight and space-saving properties [6]. Thin film modules can be developed into foldable or rollable shapes with little performance compromise compared to traditionthinrittle crystalline silicon modules. All these features make them well suited to supply small-scale hydrogen production systems in off-grid or mobile settings. The electricity produced is fed directly to the electrolyzer, enabling hydrogen production without any dependence on legacy power supply.

The Proton Exchange Membrane (PEM) electrolyzer is a compact and efficient system used for the electrolysis [7]. Water electrolysis is a key technology for the sustainable production of hydrogen, which is based on the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2) gases upon the application of electrical energy. It takes place in a two-electrode electrolytic cell, anode and cathode, respectively. At the anode, the water molecules are oxidized to hydrogen ions (H^+) and oxygen gas (O_2) along with all the remaining electrons, which are passed by the anode into the external circuit as depicted in the half-reaction [7]:

$$H_2O \rightarrow H^+ + {}^1\!/_2\ O_2 + 2e^- \qquad (1)$$

The released electrons travel through an external circuit to the cathode, where the reduction reaction occurs. At the cathode, hydrogen ions gain electrons to form hydrogen gas according to the equation [7]:

$$2H^+ + 2e^- \rightarrow H_2 \qquad (2)$$

Thus, the overall reaction of water electrolysis can be formulated as [7]:

$$H_2O\ (l) \rightarrow H^+(g) + {}^1\!/_2\ O_2(g) \qquad (3)$$

This procedure needs not only to use purified water but also involves importation of a large amount of the energy to perform itself, which imported energy is usually supplied from an outer source such as photovoltaic system in which renewable procedures are trying to be used. The generated hydrogen can be stored and utilized as an environmental clean fuel, with oxygen being generally released as a byproduct.

The power regulation module of a portable solar water hydrolysis system can regulate and optimize the flow of electrical current from the photovoltaic modules to the electrolyzer [8]. Sunlight intensity, shading, panel position, etc. can affect solar energy generation and can influence the electricity output. To ensure stable and effective voltage and current to the electrolyzer the system includes DC-DC converters and Maximum Power Point Tracking (MPPT) controllers [9].

A DC-DC converter is working to convert the raw output current and voltage from the solar panels to operate the electrolyzer. This can avoid damage or loss in working efficiency depending on the input state. In the meantime, the MPPT controller continues to search for the solar panel's maximum power point, at the best voltage which the current ratio to which the panel generates a maximum power. The MPPT adjusts the electrical load so that the system would always extract the maximum available energy from the solar panels. These power control elements work together to not only stabilize the system, but to increase the energy consumption, and provide reliable hydrogen production under variable environmental factors. This integration is particularly important in portable systems where both the energy efficiency and reliability are very important for an off-grid application.

The hydrogen storage system is an essential part of a mobile solar-hydrolysis unit for the safe storage of hydrogen gases, evolved during electrolysis, until they are used. However, due to its gaseous and lightweight nature [10], hydrogen has a high diffusion coefficient and high flammability, and storage of hydrogen should be secured in a cost-effective and safe way, particularly in portable or off-grid applications for which space, weight, and safety considerations are critical.

There are a number of possible methods of hydrogen storage, but metal hydride tanks and low-pressure containers are among the only practical solutions for portable systems. Metal hydride storage works by chemically binding hydrogen to a metal alloy so that it can be absorbed and released in a reversible way [11]. This process provides high volumetric density, greater safety (lower pressure) and compact size suitable for a mobile or field deployable device. Also, such metal hydrides can deliver hydrogen at a moderate temperature that provides benefits in flow rate control for use in fuel cells.

Alternatively, low-pressure vessels can be employed to store hydrogen gas physically at low pressures which is considered as a safe and easy-handling approach than high-pressure tanks. Even though the size of storage may be small, it can be easy to connect in small-scale systems with small energy needs. In general, the hydrogen storage system allows the energy collected and converted from the solar input to be stored in chemical form until use, taking advantage of clean hydrogen energy on-demand in remote or mobile situations.

3. Methodology

This study uses a qualitative and quantitative framework to evaluate the potential of portable solar-hydrolysis systems. The approach consists of four steps:

3.1 Literature Review and Benchmarking

An extensive review of academic journals, technical reports, and commercial data sheets was conducted to understand current capabilities in:

- Solar-powered electrolysis (especially PEM-based)
- Portable energy systems
- Compact hydrogen storage solutions

The goal was to determine achievable energy outputs, portability trade-offs, and real-world examples.

3.2 Theoretical Performance Estimation

The theoretical hydrogen output was estimated based on standard assumptions for PEM electrolyzers and solar panels. Key assumptions include:

- Electrolysis energy requirement: ~50–60 kWh/kg H_2
- PV efficiency: 15–22%
- Solar irradiance: 1000 W/m²
- Daily sun hours: 4–6 hours

The following equations were used:

$$Daily\ PV\ ENergy\ (Wh) = Area\ (m^2)\ \times Irradiance\ (W/m^2)\ \times Efficiency\ \times Sun\ Hours \quad (4)$$

$$Hydrogen\ Output\ (g) = \frac{Daily\ PV\ Energy}{Energy\ per\ gram\ of\ H_2} \quad (5)$$

3.3 Application Analysis

Various practical as well as potential uses of the system were examined to study the places where solar-powered hydrogen technology can efficiently be implemented. Such applications were in disaster response and emergency lighting use cases in which speed of deployment and off-grid power was essential in off-grid areas such as rural communities, or on remote fieldwork stations where centralized energy infrastructure were unavailable and on mobile applications, such as educational tools and demonstration units, where portability and ease of setup were important.

This system integration with fuel-cell vehicles in the long term was also considered, as sustainable mobility is becoming increasingly important. As for the criteria for the two scenarios, three factors were considered to the best of our ability, namely the magnitude of the energy requirement for the application, the required portability, and how practical it would be to implement such a system in commercial use. Low-power applications, such as emergency lighting and sensor charging, were found to be feasible while high-power applications, such as onboard hydrogen production for fuel cell vehicle refueling, are difficult to accomplish due to the existing constraints of solar energy capture, storage, and conversion efficiencies. The assessment helps to identify near- term opportunities of deployment and can inform on-going improvements in the systematic design and energy efficiencies.

3.4 SWOT and Feasibility Analysis

A SWOT (strengths, weaknesses, opportunities, threats) analysis helped to evaluate the overall viability and commercialization potential of portable solar-driven hydrogen-generation systems [12]. This strategic analysis provides a full view of the strengths and weaknesses of the system (internally) and the opportunities and threats (externally) affecting the system [13]. Through identification of strengths, such as no emissions, site-independent operation and weaknesses, like limited hydrogen generation, reliance on pure water and sunlight, it shows where success of technology lies and in turn what is lacking.

It considers outside opportunities including employment of the technology in disaster relief and education as well as threats, including the threat posed by competition from batteries and concerns about regulation around hydrogen safety. In all, SWOT analysis would be very useful for assessing practically the use of the system and for testing the potential to extend the feasibility of the system to commercial applications and real-world applications.

4. Results and Discussion

4.1 Theoretical Hydrogen Output

For a 100 W solar panel with 18% efficiency under 5 peak sun hours:

Assumed,
100 W solar panel,
Efficiency = 18%
Sun Hours = 5 h

$$Daily\ PV\ ENergy\ (Wh) = 100\ W\ \times 5\ h = 500\ Wh = 0.5\ kWh$$

$$Hydrogen\ Output\ (g) = \frac{0.5\ kWh}{50\ kWh/kg} = 0.01\ kg = 10\ \ g/day$$

Based on a daily solar input scenario, a 100 W photovoltaic (PV) panel operating under average sunlight conditions for 5 hours per day would produce approximately 500 Wh, or 0.5 kWh, of electrical energy. This energy is then used to power the electrolysis process for hydrogen production. Given that the typical energy requirement to produce 1 kilogram of hydrogen via electrolysis is approximately 50 kWh, the system would yield a daily hydrogen output of about 0.01 kg, or 10 grams per day.

This output highlights the limited hydrogen production capacity of small-scale solar setups, especially when space and solar intensity are constrained. While sufficient for demonstration purposes or micro-scale applications, this level of production is currently insufficient for high demand uses such as refueling fuel cell vehicles, which typically require over 1 kg of hydrogen per refill. This analysis underscores the need for either larger PV systems, more efficient electrolysis units, or energy storage integration to make solar-driven hydrogen production viable at a larger scale.

4.2 Portability Potential

The proposed solar-powered hydrogen system demonstrates a strong potential for portability, making it well-suited for field deployment in remote or off-grid areas. The complete system which includes a photovoltaic (PV) panel, a Proton Exchange Membrane (PEM) electrolyzer and a small hydrogen storage tank can be integrated into a compact unit weighing approximately 10 to 15 kilograms. This relatively low weight allows for easy transport by a single person and fits within the logistics constraints of portable field equipment.

A key advantage lies in the use of foldable or flexible solar panels, which significantly reduce the system's volume during transport. These panels can be unfolded and set up quickly in the field, making the system ideal for rapid deployment scenarios such as disaster response or temporary scientific expeditions. Additionally, the incorporation of solid-state hydrogen storage as opposed to conventional pressurized gas tanks enhances safety, reduces system complexity, and minimizes the overall bulk. Solid-state storage typically involves metal hydrides or advanced sorbent materials that can store hydrogen at lower pressures and temperatures, which further supports safe handling in mobile contexts.

From a practical standpoint, the portability of this system increases its accessibility and usability in regions where conventional hydrogen infrastructure is unavailable or impractical. It also opens up opportunities for educational demonstrations, mobile research platforms, and emergency energy backup systems. However, it should be noted that while the system is highly portable, the hydrogen production rate remains limited due to the small size of the solar array and electrolyzer. Therefore, its use is best suited for low-power or small-scale hydrogen applications rather than for vehicle refueling or industrial-scale processes.

4.3 Application Scenarios

Table 1 shows the feasibility of using solar-powered systems for different applications varies significantly depending on the power or energy demand. For low-power use cases such as emergency lighting (5–20 W) and phone or sensor charging (5–20 W) [14], solar systems are feasible. These applications require minimal energy and can be easily supported by small-scale photovoltaic panels and basic energy storage solutions, making them ideal for off-grid, remote, or emergency scenarios.

However, for high-demand applications such as refueling fuel cell vehicles (FCVs), which typically require more than 1 kg of hydrogen per day [15], the use of onboard solar-powered electrolysis remains impractical with current technology. Producing 1 kg of hydrogen via electrolysis requires approximately 50–55 kWh of electricity, translating to a solar array of around 10 kW capacity or more. This would demand a large surface area, typically 50–70 m^2, which is not feasible on a vehicle’s roof. Therefore, while solar-powered systems are well-suited for small-scale energy needs, major technological advancements in high-efficiency photovoltaics and compact electrolysis systems are required before such systems can viably support the energy demands of FCV refueling.

Table 1. Feasibility of Solar-Powered Applications Based on Power Demand

Use Case	Power demand	Feasibility
Emergency lighting	5–20 W	Feasible
Phone/sensor charging	5–20 W	Feasible
FCV refueling	>1 kg/day	Not practical (yet)

5. SWOT Analysis

The SWOT analysis (Table 2) of the portable solar-assisted hydrogen production system reveals a promising yet challenging technological solution. Emission-free operation and off-grid functionality make it an environmentally friendly energy source and able to operate independently in remote or disaster-prone regions. Moreover, scalable and modular design allows it to play well with various cases, from small educational kits to use in fuel cell vehicles (FCVs). But the system also has a number of significant gaps. The limited output of hydrogen per day is due to low solar input and electrolysis efficiency which limits its use for high demand applications. Its performance is also highly dependent on solar energy, which will vary by weather and location, and it requires pure water for electrolysis, which affects its effectiveness, making further logistical considerations in some locations.

The technology has potential applications in disaster relief and humanitarian settings where dependable off-grid power is key. It also has potential as a powerful tool in STEM education to assist students in learning the hands-on aspect of renewable energy systems. In addition, the system could be expanded to be incorporated into fuel cell car kits, to facilitate innovation in low energy vehicle transportation. But the technology is also challenged, especially as it competes for market share with batteries and solar-powered storage solutions that are more cost-effective and efficient today. When it comes to safety regulations from a hydrogen storage perspective, that poses a huge additional challenge, especially for mobile or educational implementations. Additionally, the high initial price of the hardware (electrolyzers, solar panels, and hydrogen tanks) may limit widespread adoption. That said, although the system in question is a model of a new and innovative hydrogen production system for climate-friendly hydrogen production in a step toward sustainable hydrogen production, the technical and economic limitations will essential to be addressed in order for them to be implemented further.

Table 2. SWOT Analysis of a Portable Solar-Powered Hydrogen Generation System

Strengths	**Weaknesses**
Emission-free operation	Low H_2 output per day
Off-grid	Dependent on sunlight availability
Scalable/modular design	Requires pure water input
Opportunities	**Threats**
Disaster relief and aid	Competition with batteries/solar
Educational STEM kits	Safety regulations for H_2 storage
Integration into FCV kits	High upfront cost for components

6. Conclusions

This paper explored the feasibility of portable solar-powered hydrolysis systems as off-grid hydrogen generators. Theoretical modeling indicates that such systems can generate up to 10–20 grams of hydrogen daily under standard conditions, sufficient for low-power applications. While limitations exist in hydrogen storage, purification, and scalability, the potential for mobile, clean energy generation remains promising, particularly in educational, emergencies, and remote scenarios. Further work is recommended to prototype the system and validate performance in field conditions. Innovations in micro-electrolyzers and safer hydrogen storage will be key to commercialization.

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References

[1] W. Lubitz and W. Tumas, "Hydrogen: an overview," *Chemical reviews 107,* vol. 10, pp. 3900-3903, 2007.

[2] P. Nikolaidis and A. Poullikkas, "A comparative overview of hydrogen production processes," *Renewable and sustainable energy reviews 67* , pp. 597-611, 2017.

[3] T. L. Gibson and N. A. Kelly, "Predicting efficiency of solar powered hydrogen generation using photovoltaic-electrolysis devices," *International journal of hydrogen energy,* vol. 35, no. 3, pp. 900-911, 2010.

[4] Y. S. Najjar, "Hydrogen safety: The road toward green technology," *International Journal of Hydrogen Energy 38,* vol. 25, pp. 10716-10728, 2013.

[5] G. Chisholm, T. Zhao and L. Cronin, "Hydrogen from water electrolysis," *Elsevier,* pp. 559-591, 2022.

[6] K. L. Chopra, P. D. Paulson and V. Dutta, "Thin-film solar cells: an overview," *Progress in Photovoltaics: Research and applications 12,* no. no. 2-3, pp. 69-92, 2004.

[7] Ö. F. Selamet, F. Becerikli, M. D. Mat and Y. Kaplan, "Development and testing of a highly efficient proton

exchange membrane (PEM) electrolyzer stack," *International Journal of hydrogen energy 36,* no. no.17, pp. 11480-11487, 2011.

[8] S. Dahbi, R. Aboutni, A. Aziz, N. Benazzi, M. Elhafyani and K. Kassmi, "Optimised hydrogen production by a photovoltaic-electrolysis system DC/DC converter and water flow controller," *International Journal of Hydrogen Energy 41*, no. no.45, pp. 20858-20866, 2016.

[9] M. E. Şahin, "A photovoltaic powered electrolysis converter system with maximum power point tracking control,"*International Journal of Hydrogen Energy 45*, no. no. 16 , pp. 9293-9304, 2020.

[10] A. Züttel, "Hydrogen storage methods," *Naturwissenschaften 91* , pp. 157-172, 2004.

[11] N. Klopčič, I. Grimmer, F. Winkler, M. Sartory and A. Trattner, "A review on metal hydride materials for hydrogen storage," *Journal of Energy Storage 72*, p. 108456, 2023.

[12] M. A. Benzaghta, A. Elwalda, M. M. Mousa, I. Erkan and M. Rahman, "SWOT analysis applications: An integrative literature review," *Journal of Global Business Insights 6*, no. no. 1 , pp. 54-72, 2021.

[13] C. Namugenyi, S. L. Nimmagadda and T. Reiners, "Design of a SWOT analysis model and its evaluation in diverse digital business ecosystem contexts," *Procedia Computer Science 159,* no. n0.22, pp. 1145-1154, 2019.

[14] J. Marsh, "Energysage," EnergySage Inc, 26 November 2024. [Online]. Available: https://www.energysage.com/electricity/house-watts/how-many-watts-does-a-phone-charger-use/..

[15] "Toyota," 2025 Toyota Motor Sales U.S.A. Inc, [Online]. Available: https://www.toyota.com/mirai/.