From Renewable Electricity to Green Hydrogen: Production and Storage Challenges for a Clean Energy Future

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Abstract :
Decentralized energy production without greenhouse gas emissions from renewable energy sources despite their advantage and environmental impact suffers from the problem of intermittent and fluctuating supply depending on weather conditions. To overcome this problem, energy storage is essential to enable reliable and continuous supply of the load. Hydrogen is one of the most promising energy storage solutions because it is easily transportable and can be used as fuel or as a raw material for the production of other chemicals.In this article, we will focus on hydrogen energy storage techniques using photovoltaic systems. We will review the different types of hydrogen storage structuresfor several applications, including residential and commercial buildings, as well as industry and transportation (electric vehicles using PEFMC fuel cells).

***Keywords**: Renewable energy, Electrolyser, hydrogen storage, fuel cell PEFMC cell.*

1. Introduction

The world's energy demand is largely dependent on fossil fuels such as petroleum, coal, and natural gas, which are rapidly depleting. Combustion of these fuels leads to the emission of carbon dioxide, a major contributor to global warming and a serious threat to life on earth. To mitigate this issue, renewable energy sources such as solar, wind, and biomass can be used as an alternative. Among these sources, the photovoltaic (PV) generator is widely used to convert solar radiation into electricity, especially in low power applications. PV generators are preferred due to their carbon-free and inexhaustible nature, noiseless operation, and size-independent electric conversion efficiency [FatihYilmazM. TolgaBaltaReşat Selba.2015 **].**

Major sources of renewable energy such as hydraulic, wind, and solar are known to be intermittent and unpredictable due to their dependence on climatic conditions. Unlike fossil or fissile energies, renewable energies require the maximum utilization of the available renewable deposit. While hydraulic energy can be stored in dams in its initial form, other renewable energies need to be immediately consumed or converted into a storable form. Hence, it is crucial to store the excess energy produced and distribute it when the energy demand is high. Hydrogen storage appears to be the most promising solution to store the electricity produced by renewable energies. Hydrogen presents itself as the fuel of the future due to its excellent energy density and the potential to become a highly developed energy carrier

[Juan P et Al .2023] ,[Jefferson A. et Al .2023],[Qusay H .2020], [J.O. Abe, et Al.2019]. Hydrogen has been a topic of discussion for powering the transportation sector since the 1970s, but high investment and production costs, as well as safety concerns surrounding hydrogen storage, have impeded its widespread adoption. Nevertheless, with the increasing need to reduce greenhouse gas emissions and search for cleaner fuels, hydrogen has resurfaced as a potential energy carrier that could contribute to decarbonizing different sectors. It is no longer just the transportation sector but also industries such as heating, chemicals, and steel, where emission reduction has historically been difficult. To help reduce emissions related to ammonia production, for example, electrolyzer and carbon capture and storage technologies have been proposed.

In addition to emission reduction, hydrogen can also improve the sustainability, reliability, and flexibility of energy systems. Hydrogen can complement the integration of renewable technologies into the electricity sector, allowing excess renewable energy to be stored for later use. Similarly, hydrogen can be produced in regions with high renewable energy potential and transported over long distances to countries with high energy demand and limited energy resources. In the gas sector, hydrogen can be blended with natural gas to produce cleaner fuels.

Despite its potential, only about 5% of hydrogen is currently produced from renewable sources, with the remaining 95% being produced from fossil fuels by steam methane reforming. The lack of renewable production facilities, coupled with high costs and insufficient infrastructure, remains a significant barrier to widespread adoption. However, ongoing research and development efforts aim to reduce production costs and increase the efficiency of hydrogen production from renewable sources.

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Several countries, including Japan, Germany, and South Korea, have begun preparing hydrogen strategies for the gradual deployment of new applications, infrastructure, hydrogen production techniques, and institutional and commercial rules. [METI. Basic hydrogen strategy. 2017], [IEA. Global hydrogen review 2021].

A few researchers have also conducted reviews and modeling techniques for the deployment of a hydrogen supply chain, highlighting the structure and technical-economic inputs for hydrogen production. However, current hydrogen supply chains and additional model inputs such as hydrogen demand projections have yet to be fully explored. Collaborations between different disciplines are crucial to developing accurate and robust models that can facilitate the widespread adoption of hydrogen as an energy carrier.Hydrogen storage is one of the most challenging issues in today's energy sector due to its storage needs. Hydrogen can be stored in three forms, via compressed gas, as a cryogenic liquid, and by solid state storage. When stored as compressed gas, hydrogen needs to be in a highly pressurized tank which makes it ideal for hydrogen storage as a fuel source. Storage via cryogenic liquid requires high funding costs and issues of boiling over time. Solid state storage allows for adsorption and/or absorption onto the surface of metal hydride and or carbon nanostructured materials, which can be efficiently produced through the use of advanced manufacturing techniques.

In this context, hydrogen storage is focused on high-pressure gas storage, which requires highly pressurized tanks [LI Jian, ZHANG Lixin, LI Ruiyi, YANG Xiao, ZHANG Ting ,2021]. Compressed gas storage tanks are typically equipped with safety devices such as pressure relief valves, pressure regulators, and overpressure protection devices. This ensures safe and efficient use of hydrogen by minimizing the risks of leaks, explosions, or fires. However, it is important to note that safety remains a crucial aspect of hydrogen storage and any storage solution must undergo rigorous testing to ensure safe and responsible use of this energy source.

2. Hydrogen storage techniques

Hydrogen storage can be in gaseous, liquid or solid form. All three techniques have advantages and disadvantages and are suitable for different applications

2.1. Hydrogen gas storage

Hydrogen gas storage is the most common method of hydrogen storage. It is easy to produce and use, but its volumetric density is low, which means it requires a large volume to store a significant amount of hydrogen. In addition, the compression of hydrogen gas is expensive and energy-intensive.Hydrogen gas storage systems can be classified into two categories: high pressure systems and low-pressure systems. High-pressure systems store hydrogen at pressures greater than 10,000 psi (700 bar). Low pressure systems store hydrogen at pressures below 1000 psi (70 bar). High pressure systems are more compact but require expensive compression equipment. Low pressure systems are less expensive but require a larger volume to store the same amount of hydrogen.

2.2. Liquid hydrogen storage

Liquid hydrogen storage is a more efficient method of storage than gaseous hydrogen storage because the energy density is higher. However, the production, handling and storage of liquid hydrogen is more expensive and more complex than for gaseous hydrogen. In addition, liquid hydrogen must be kept at very low temperatures (about -253°C), which requires special storage equipment.

2.3. Solid hydrogen storage

Solid hydrogen storage is a relatively new method of storing hydrogen. Solid H_2storage systems use materials such as metal hydrides, organic materials or nanostructures to store hydrogen in solid form. The advantages of this method are its high energy density, storage flexibility and low storage cost. However, disadvantages include poor hydrogen absorption and desorption kinetics and the need to maintain high temperature to release stored H_2.

Besides, Hydrogen (H_2) storage applications by grid-connected photovoltaic systems can be divided into three categories:

- *Vehicle power supply:* The stored hydrogen can be used to power electric vehicles powered by hydrogen fuel cells. These vehicles are not seen as a proper alternative and more environmentally friendly gasoline-powered vehicles.
- *Industrial applications:* The hydrogen stock can be used in the industrial process to produce energy and heat. Factories can thus reduce their dependence on fossil energy sources and reduce their carbon footprint.
- *Natural gas networks:* The stored hydrogen must be injected into natural gas networks to improve gas quality and reduce CO_2 emissions.

3. System description

The system of production and storage of hydrogen illustrated in figure 1, includes a photovoltaic (PV) array, an electrolyzer, a hydrogen storage tank, and a fuel cell. The PV array produces direct current (DC) electricity, which is regulated by a maximum power point tracker converter (MPPT) and then fed into the electrolyzerwhich splits water molecules into hydrogen and oxygen. The electrolyzer converts the electricity into hydrogen gas, which is then stored in storage tanks under high pressure (70 to 700 Bar). These tanks are designed to safely store and transport large amounts of hydrogen gas. They are typically made of high-strength materials such as carbon fiber, steel, or aluminum and are lined with special coatings to prevent hydrogen from permeating the tank walls.The stored hydrogen can be used in a fuel cell to produce electricity when needed. The fuel cell combines hydrogen with oxygen from the air to produce electricity, water, and heat. The electricity produced can be used to power various devices, such as electric vehicles or buildings and industrial applications.

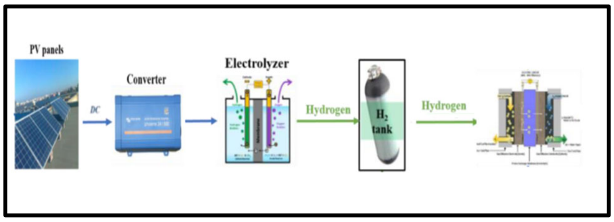

Figure 1 **:Architecture of the Hydrogen storage system**

3.1. The PV Array

Generally a PV panel of 0.3 m2 has an efficiency between 10% to 20%, a lifetime of 25 years and an output power between 100 to 500 W under a daily solar radiation between 500 and 1000 W/m2/day.
Table1 gives an example of PV parameters of theJinkoSolar JKM400M72L-V solar panel **[https://www.solarproof.com.au/products/JKM400M-72-V/]**

***Table 1*.PV module's characteristics.**

PV panel parameters	Values
Solar cell number per module	72 400
Maximum Power (w)	41.7
Maximum Power Point Voltage (Vmpp)(V)	9.6
Maximum Power Point Current (Impp) (A)	49.8
Open Circuit Voltage (Voc) (V)	10.36
Short Circuit Current (Isc)(A)	78.5*39.1*1.57
Dimensions (mm^3)	24.9
Weight (kg)	

3.2. The electrolyser PEM

A PEM (Proton Exchange Membrane) electrolyzer is a device that uses an acidic polymer membrane as an electrolyte to split water molecules into hydrogen and oxygen gases through an electrochemical process [**S. Shiva, V. Himabindu,2019**], [**F. Gallardo, and Al, 2022**]. The hydrogen gas is then collected at the cathode while the oxygen gas is produced at the anode. PEM electrolyzers are known for their high efficiency, producing high-purity hydrogen gas with minimal energy input. They are also relatively compact, lightweight, and safe to operate. PEM electrolyzers are widely used in various applications, such as fuel cell vehicles, renewable energy storage, and industrial gas production.

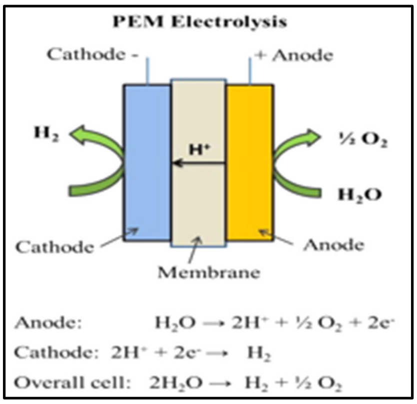

Figure 2 : PEM electrolyser

The used PEM electrolyzer, which had an operative power consumption of about 400 W and produced hydrogen with a purity of about 99.9% (as illustrated in **Table 2**),They are a promising technology for producing sustainable hydrogen gas as a fuel for transportation and power generation, helping to reduce greenhouse gas emissions and combat climate change.

Table2 **:PEM Electrolyzer characteristics**

Electrolyzer Characteristics	Values
Purety hydrogen	99.9 %
Max hydrogen flow rate	40 NL/hour
Max outlet pressure:	30 bars (435 psi)
Operative power consumption:	400 W 420 W
Max power consumption:	5-40°C
Operating temperature:	1-2 liters
Water tank volume:	0.8-1.2 liters/hour
Max water consumption	400 x 250 x 350 mm
Dimensions	
Weight	g

3.3. Hydrogen Storage tank

A hydrogen storage tank is a specialized vessel designed to store hydrogen gas under high pressure or cryogenic conditions for various applications. Hydrogen is a very light and low-density gas, so to store it efficiently, it needs to be compressed to high pressures or cooled to cryogenic temperatures.A hydrogen storage tank with a volume of 30 liters and a pressure rating of 700 bar is commonly used for storing hydrogen in fuel cell vehicles and other applications[Table3 below]. The tank has a capacity of 4.2 kg of hydrogen and typically weighs between 25-30 kg, which includes the weight of the tank and any attached component [Shichun Mu and Shuyuan

Wu, **2016**],[H. S. Kumar, S. M. Shah and S. S. Sundareshan , **2019**]. The characteristics of the hydrogen gas stored in the tank depend on the purity of the hydrogen produced by the electrolyzer and any additional purification steps taken before the gas is stored in the tank.

Figure3: **Hydrogen tank**

Table3: **Hydrogen tank characteristics**

Hydrogen tank caracteristics	Values
Volume	30 liters
Pressure Rating	700 bar
Capacity	4.2 kg
Weight:	25-30 kg.

a. The Fuel Cell

A Proton Exchange Membrane fuel cell is consisting of an anode and a cathode separated by a polymer electrolyte membrane. The hydrogen molecules are split into protons and electrons at the anode. At the cathode, the protons and electrons combine with oxygen to form water as the only byproduct[NorikoHikosaka Behling, in Fuel Cells, **2013**],[Antonio José Martín , AitorHornés , Arturo Martínez-Arias , Loreto Daza ,**2013**].Fuel cell durability refers to the ability of a fuel cell to maintain its performance over an extended period of time. The durability of a fuel cell is an important consideration in its design and operation because it directly affects the cost and reliability of the fuel cell system [Huu Linh Nguyen and al,**2021**].PEM fuel cells have several advantages over other types of fuel cells, including fast start-up times, low operating temperatures, and high-power density. However, they also have some disadvantages, such as sensitivity to impurities in the hydrogen fuel and limited durability compared to other types of fuel cells.

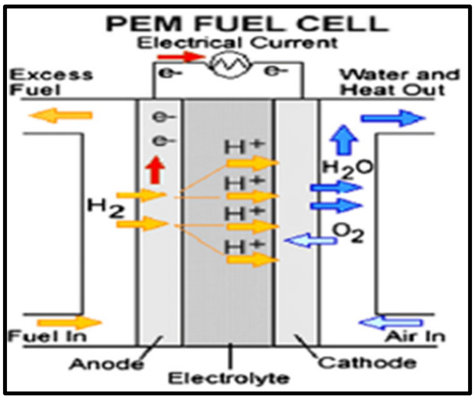

Figure 4 :**PEM Fuel Cell**

The electricity produced by a fuel cell is a clean and efficient form of energy, with the only byproducts being water and heat.It is characterized by the specifications oftable 4.

Table 4 : **Fuel Cell's Characteristics**

Fuel Cell's Characteristics	Values
Rated output	400W
Output voltage	12V or 24V DC:
Rated current	33.3A at 12V or 16.7A at 24V
Hydrogenconsumption	0.05-0.1 kg/kWh
Dimensions	50 cm x 40 cm x 20 cm
Weight	20-30 g.

4. System modeling

This paragraph details the modeling and simulation process of the system, which comprises various components such as PV panels, converters, hydrogen PEM electrolyzer, hydrogen tanks, and PEM fuel cell. These components were interconnected to construct the system's model, which was then simulated using MATLAB, with experimental conditions like solar irradiation and ambient temperature being considered.

4.1. PV model

We can assign a designation to our photovoltaic module by[**Elibrahimi,2018**], [**Sofia Boulmrharj and al,2020**] :

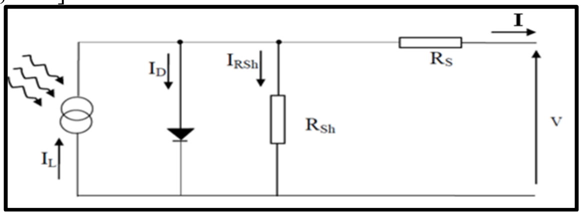

Figure6 :The PV cell's single-diode equivalent

Based on the photovoltaic module circuit, we apply the node law to find the relationship between current and voltage**[KHERIDLA Y ,KHINECHE K,2014],[Vinod , R Kumar , S.K. Singh ,2018].**

$$I = I_L - I_D - I_{RSh} \quad (1)$$

$$I = N_P\, I_L - N_P\, I_S \left[\exp\left(\frac{q\,(\frac{V}{N_S} + \frac{I_{Rs}}{N_P})}{nKT}\right) - 1\right] - \frac{\frac{N_P V}{N_S} + IR_s}{R_{sh}} \quad (2)$$

The parameters used in the equations include
Is : (diode saturation current),
Q : (electron charge),
Ns : (number of series cells),
Np : (number of parallel cells),
N : (diode ideality factor),
K : (Boltzmann constant),
T : (module temperature).

4.2.*Hydrogen PEM Electrolyzer model*

The PEM electrolyzer is a widely utilized system, in many applications, due to its many advantages over other electrolyzers. These include a compact design, swift response time, dynamic operation, hight efficiency, and the production of highly pure hydrogen.Itiscomposed of a cathode, anode, and solid polymer membrane, the PEM electrolyzer uses an electrochemical process to generate both hydrogen and oxygen from water and electricity. This involves introducing water into the anode electrode, where it separates into hydrogen proton (H+) and oxygen (O_2). The hydrogen proton then travels through the electrolyte to the cathode electrode, where it combines with electrons via DC current to produce hydrogen gas (H_2).There are various alternatives for modelling a PEM electrolyzer in the literature. Typically, the response of an electrolyzer model is evaluated based on two crucial parameters: the polarization curve (i.e. the variation of voltage with current in the electrolyzer) and the hydrogen production. While other factors such as temperature and pressure in the anode, cathode or membrane are also relevant to understanding the performance of the device, they are sometimes neglected in the model to simplify it.

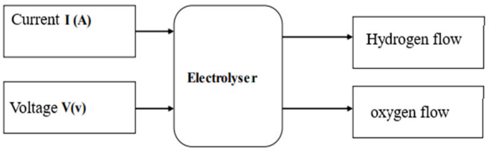

***Figure7*: The main inputs and outputs of an electrolyser**

The production Hydrogen's rate is given in the equation (3) based on the law of ideal gases:

$$V_{H_2} = \frac{nRT}{P} = \frac{n_{cRI_{elTt}}}{zPF} \quad (3)$$

With $n = \frac{It}{zF}$ (4)

The expression includes several variables, where n_c refers to the number of cells within the electrolyzer, z represents the number of electrons involved in the reaction (2 for hydrogen and 4 for oxygen), R is the gas constant (8.3145 J/mol·K), P denotes the working pressure of the electrolyzer (in Pascals), Iez represents the current applied to a single cell of the electrolyzer (in Amperes), F stands for the Faraday constant (96485.33 C/mol), T is the temperature at which the electrolyzer is operating (in Kelvin), and finally t represents the duration of the electrolysis process (in seconds).

4.3. Hydrogen storage tanke model

The hydrogen produced by electrolysis is stored in a high-pressure tank. A hydrogen tank model is used to collect and quantify the amount of stored hydrogen and the internal pressure. It is assumed that the tank is initially empty and the generated hydrogen is filled into the storage tank at the desired pressure. The flow rate of the hydrogen is then calculated at the operating pressure. The pressure within the hydrogen tank can be determined using a calculation.

$$P = z\frac{N_{H_2}\, R_u Ttank}{Vtank} + P_{initial} = \frac{nRT}{V - n_b} - a\frac{n^2}{V^2} \quad (5)$$

The variables used in the equation are as follows **[S.Boulmrharjet Al,2020]**: P for gas pressure in pascals (Pa), n for the number of moles in mol, R for the gas constant equal to 8.314 J/K·mol, T for the absolute temperature of the gas in Kelvin (K), V for the gas volume in cubic meters (m^3), b for the occupied volume by hydrogen molecules which is 2.661×10^{-5} m^3/mol, and a for the dipole interaction or repulsion constant which is

2.476×10^{-2} $m^6 \cdot Pa/mol^2$, z is compressibility factor and it is approximately 1 forhydrogen (**Tevfik Y, et Al,2016**).

4.4. PEM Fuel Cell model

A proton exchange membrane (PEM) fuel cell is an electrochemical device that converts the chemical energy stored in a fuel, typically hydrogen, into electrical energy through an electrochemical reaction.Various models and software tools have been created and documented in the literature for estimating and predicting the current/voltage relationship and evaluating the behavior of PEM fuel cells under diverse conditions. These models include analytical, mechanistic, and empirical models, as well as software tools **[T.Lajnef, et Al,2013],[Cheddie, D.; Munroe, N.2005],[J. J. Hwang, et Al,2008**].

The electrical model of a PEM fuel cell can be represented by the following circuit diagram:

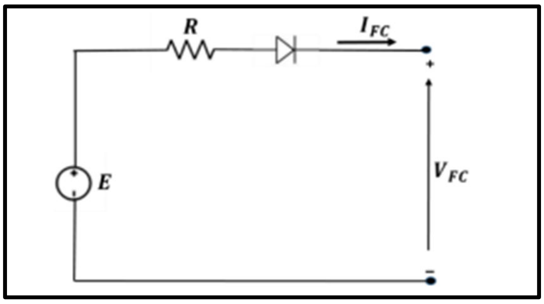

Figure8 : Equivalent circuit of PEM Fuel Cell

the fuel cell's stack voltage (VFC) iscomputed using Equation (6):

$$V_{FC} = E - RI_{FC} \tag{6}$$

The fuel cell output voltage is obtained also from the sumof three effects [7,8], the Nernst potential, the cathode andanode activation overvoltage, and the ohmic overvoltage dueto internal resistance:

$$V_{FC} = E + \eta_{act} + \eta_{ohmic} \tag{7}$$

The Nernst voltage in terms of gas molarities may be expressed as:

$$E = N_0 \left[E_0 + \frac{RT}{2F} \log\left[P_{H_2} P_{O_2}{}^{0.5} \right] + \right] \tag{8}$$

To meet power demand, the FC system utilizes hydrogen sourced from the high-pressure tanks . **[TourkiaLajnef, Slim Abid, and Anis Ammous,2013**].

The quality of hydrogen found from the hydrogen tank isgiven by equation (9):

$$Q_{H_2} = \frac{N_0 \, N_s}{2FU} \tag{9}$$

5. Simulations and discussion

The PV/Electrolyzer/Tank/FC system is an energy system that uses photovoltaic solar energy (PV) to produce hydrogen through water electrolysis. The produced hydrogen is stored in a tank and can be later used to generate electricity through a fuel cell (FC)[Deng, Q., Hu, J., Huang, Y., & Wang, K. (2021)][M.A. Aminudin , et Al.(2023)]. This system offers a long-term renewable energy storage solution, which can be used when solar energy is not available, such as during nighttime or cloudy days. In this discussion, we will explore simulations and performance of the system to evaluate its efficiency and viability as a renewable energy source.

5.1. Simulation Results : PV power supply

Regarding the PV system's model, which is presented previously, it was implemented intoMATLAB. Then, it was simulated under the same experimental conditions, namely, the solar irradiationand the ambient temperature, in order to assess the performance of the system. Besides, Figure 9 presents the simulation and theexperimental results of the power generated by the PV and the electrolyzer system during 24 h.The simulation results of the daily profile of PV power and electrolyzer power have confirmed a close correlation with the daily sunlight profile. This is consistent with the fundamental principles of converting solar energy into electrical energy, where PV power production is directly linked to the amount of solar radiation received. As a result, when light intensity is high, electrical energy production is also high, which is then transmitted to hydrogen production through the electrolyzer. The results confirm the effectiveness of using solar energy for hydrogen production through electrolysis, particularly when combined with energy storage devices to ensure availability of the electrical energy produced.

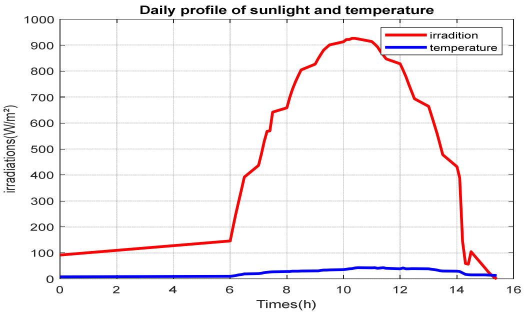

Fig 9: Daily profile of sunlight and temperature

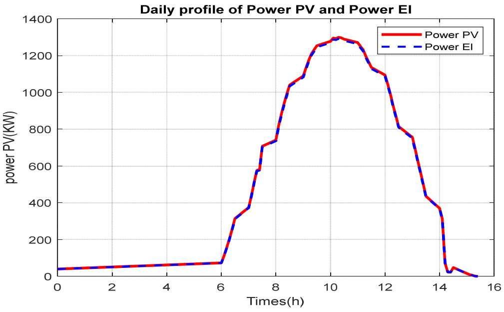

Figure 10 : Daily profile of power PV and electrolyser

This sentence describes how the power curves of PV solar panels and electrolyzers are linked to daily sunlight. Solar radiation is an important factor for solar energy production, as solar panels work by converting sunlight into electricity.In summary, the power curves of PV solar panels and electrolyzers follow the daily sunlight profile, gradually increasing in the morning, reaching a peak at solar noon, and gradually decreasing in the afternoon until sunset.The daily power curve of the PV panels and electrolyzers is directly linked to the amount of available sunlight, which affects hydrogen production. Optimizing hydrogen production based on solar energy production is crucial to maximize efficiency and minimize costs.

5.2.Simulation of the H_2 production

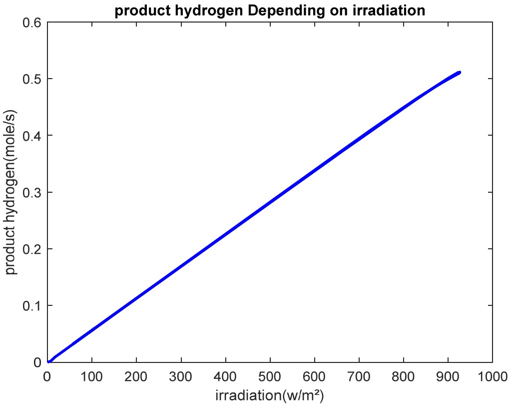

Fig11 : Product hydrogen depending on irradiation

The evolution of the hydrogen production curve in relation to irradiation as an increasing line is that hydrogen production increases as irradiation increases. This may be due to an increase in the amount of energy available to decompose water into hydrogen and oxygen, or an increase in the efficiency of the decomposition process in the presence of higher irradiation.This may have significant implications for large-scale hydrogen production, as it suggests that an increase in irradiation could significantly increase hydrogen production. However, it should be noted that this increase may be limited by other factors such as water availability and the ability of hydrogen production systems to handle higher levels of irradiation.

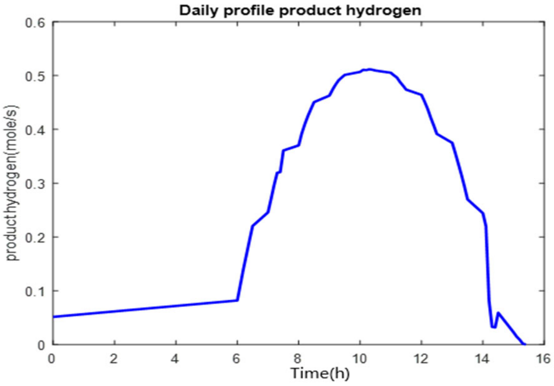

Fig 12.Daily profile of hydrogen production

It is plausible that the daily profile of hydrogen production follows the daily profile of sunlight, because hydrogen production from solar energy directly depends on the amount of solar energy available. Hydrogen production through electrolysis of water using a solar energy source requires exposure to sunlight to provide energy for water decomposition. Therefore, if sunlight is high during the day, hydrogen production may be higher during that period. However, it should be noted that other factors can also influence hydrogen production, such as the ability of hydrogen production systems to manage production fluctuations, water availability, and demand levels. Therefore, although hydrogen production may follow the daily profile of sunlight, additional factors may also affect hydrogen production.

5.3.Storage simulation

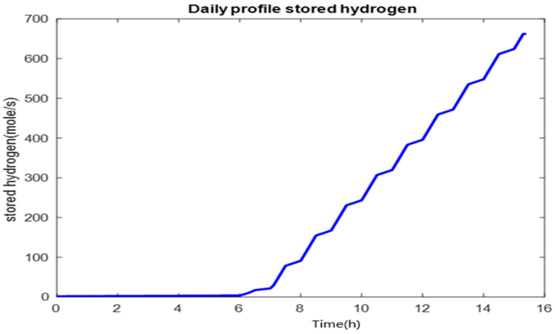

Fig12 : daily profile of hydrogen storage

The period from 0 to 6 hours corresponds to hydrogen production by the electrolyzer powered by the photovoltaic energy source, followed by a period of hydrogen storage that evolves in a staircase-like pattern. This curve may indicate that the electrolyzer and hydrogen storage system is designed to maximize the use of photovoltaic solar energy by producing hydrogen during the peak production period of the energy source and storing it for later use.

6. Conclusion

The use of renewable energies, such as photovoltaics, for electricity production is rapidly growing. To ensure continuous production, these systems can be hybridized with other energy sources, such as hydrogen. Hydrogen is a practical energy carrier that can be used to store and transport energy produced by renewable sources. It is produced by electrolysis, stored, and reused by a fuel cell to generate electricity. Hydrogen is a non-polluting source of energy. Electrolysis of water is the cleanest way to obtain it.This is an efficient way to store energy, and it is used in various applications, such as powering buses and cars in the transportation sector and in industrial processes, such as ammonia production. The daily simulation of PV power, electrolyzer output, and hydrogen production shows a strong correlation with daily sunlight. The results indicate that photovoltaic-electrolyzer hybrid systems are capable of producing hydrogen continuously and reliably, using solar energy as the primary energy source. This demonstrates the ability of renewable energy sources to meet current energy needs while reducing greenhouse gas emissions and minimizing environmental impact. These results encourage the development of photovoltaic-electrolyzer hybrid systems to meet the growing demand for sustainable and renewable energy.

Gaseous hydrogen storage is crucial for the energy transition and the environment because it enables the storage of energy produced from intermittent renewable sources such as solar power. Hydrogen stored in gaseous form can be used to produce electricity, heat, and fuel for fuel cell vehicles, thus reducing greenhouse gas emissions and promoting a greener and more sustainable economy. Additionally, gaseous hydrogen storage allows for the storage of large quantities of hydrogen in a small space and facilitates the distribution of hydrogen on a large scale.

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