Original Article: Hydrogen Production and Storage Systems

Mohammad Parsa

Department of Mechanical Engineering, Lorestan University, Lorestan, Iran

Use yor device to scan and read the article online

Citation *M Parsa.*, **Hydrogen production and storage systems,** *EJCMPR* . 2024; 3(1): 487-498

https://doi.org/10.5281/*EJCMPR*.20240413

Article info:

Received: 14 February 2024

Accepted: 05 May 2024

Available Online:

ID: EJCMPR-2405-1166

Checked for Plagiarism: Yes

Peer Reviewers Approved by:
Dr. Frank Rebout

Editor who Approved Publication:
Dr. Frank Rebout

Keywords:
Hydrogen, Storage, Tank, Hydrocarbon Fuel

ABSTRACT

In the present study, hydrogen production and storage systems have been investigated. Underground hydrogen storage is suitable for providing high voltage network energy storage for intermittent and periodic energy sources such as wind power, in addition to providing fuel for transportation, especially for use in ships and airplanes. Most of the research conducted in the field of hydrogen storage emphasizes the storage and maintenance of hydrogen as a dense, light and compact energy carrier for mobile applications. Liquid hydrogen requires cryogenic storage and boils at -252,882°C or -423,188°F. Therefore, its water content is subject to a large reduction and loss of energy. Tanks should also be installed well in order to prevent excessive boiling, but adding insulation or non-conductor will result in higher costs. Liquid hydrogen has a lower energy density in terms of volume and capacity compared to hydrocarbon fuel. Compressed and condensed hydrogen is stored in a completely different way. Hydrogen gas has a good energy density in terms of weight, but its energy density is low in terms of volume and capacity compared to hydrocarbons. Therefore, it requires a larger tank for storage. A large hydrogen tank will be heavier than a small hydrocarbon tank used to store the same amount of energy, all other factors remaining equal. Increasing gas pressure improves energy density in terms of volume and capacity, which favors smaller, though not lighter, tanks.

Introduction

The goals were set by Freedom Automotive in January 2002 between the United States Consul for Automotive Research (USCAR) and the US.DOE. The goals set in 2005 were not achieved. The 2009 targets were revised and re-examined to reflect new data on system efficiency obtained from the test vehicle fleet. The ultimate goal for volume storage is still superior to the theoretical density of liquid hydrogen [1]. It is important to note that the targets set and predicted are for the hydrogen storage system, not the hydrogen storage material. The capacities of the system are often about half of the material used. Hence, while a material may store about 6% by weight of H_2, an active system using the same material may store only 3% by weight when the reservoir weights, heat and temperature and the pressure control tool should be considered [2].

***Corresponding Author: Mohammad Parsa** (*mohammadparsa15@yahoo.com*)

In 2010, only two storage technologies were identified as likely to meet DOE's goals. MOF-177 exceeds the 2010 volume capacity goals, while cryogenically compressed H_2 exceeds the more restrictive 2015 goals for both volume capacity and weight capacity [3].

Metal hydride hydrogen storage

Metal hydrides such as $TiFeH_2$, $LaNi_5H_6$, LiH, $LiAlH_4$, $NaAlH_4$, MgH_2, and palladium hydride (a rare, silver-colored and malleable element from the platinum group) with different degrees of efficiency can be used as hydrogen storage tools, often Used and applied reversibly. Some of them are liquid and can be easily refueled at ambient pressure and temperature, and others are solid that can be converted into smaller molds [4]. These materials have favorable energy density by volume and capacity, although their energy net by weight is usually worse than that of major hydrocarbon fuels. Most metal hydrides bond strongly with hydrogen [5].

As a result, high temperatures of around 120℃ (248℉) and -200℃ (392℉) are needed to release their hydrogen content [6]. This energy cost can be reduced by using alloys that consist of the previous strong hydride and a weak hydride such as $NaBH_4$, $LiBH_4$, $LiNH_2$ [7]. They are able to form even weaker bundles. In this way, they need a lower amount of input or input to release the stored hydrogen, but if the interaction is too weak, the amount of pressure required to add water will be higher and will result in the loss of energy storage [8].

The prescribed targets for mobile hydrogen fuel systems are approximately 100℃ for release and 700 bar for refilling. An alternative method to reduce the heat and temperature brittleness is the initiator strengthening method [9], which has been successfully used for aluminum hydride, but the composite preparation is undesirable for most applications. Because it is easily refillable with hydrogen. Recently, the only hydrides capable of achieving the 2015 target of 9% by weight are limited to the main compounds of lithium, boron, and aluminum, and at least one of the first rows or AL must be added [10]. Research in the field of determining new compounds that can be used to achieve these needs is ongoing. The hydrides proposed for use in the hydrogen production structure include simple and non-complex hydrides of magnesium, or translucent metals, and complex and compound metal hydrides, typically including sodium, lithium, or calcium, and aluminum or boron [11]. Selected hydrides provide low reactivity and high hydrogen storage volume for storage applications. The main candidates are lithium hydride, sodium borohydride, lithium aluminum hydride and borane, ammonia [12].

A French company called MCPHY ENERGY is developing and producing the first industrial production based on magnesium hydride, which has been sold to some big customers such as ENEL and Iwatani. Arizona state university is researching hydrogen storage using a borohydride solution that is released when the solution flows through a catalyst made of ruthenium, a new scientist has admitted [13].

Non-metallic hydrides

Italian catalyst manufacturer Acta proposes the use of hydrazine as a substitute for hydrogen in fuel cells. Because hydrazine fuel is liquid at room temperature, it is much easier to store and use than hydrogen [14]. By storing it in a tank full of double bonds based on CO (carbonyl) carbon oxygen, it reacts and forms a hydrazone solid. Until the tank is filled with hot water, liquid hydrazine hydrate is released. Hydrazine inside the cell can be decomposed to form nitrogen and hydrogen, which bind with oxygen and thus release water [15].

Carbohydrates

Carbohydrates (polymeric $C_6H_{10}O_5$) release H_2 in a bio-organizer through the synthesis of enzymes of the metabolic synthetic pathway, free of cells and cells. It provides high hydrogen storage volume as a liquid for air pressure regulation (mild pressure) and cryogenic limitation (cryogenic), it is also able to be stored as a solid powder [16]. Carbon-rich carbohydrates are the world's most renewable bioresource. In May 2007, biochemical engineers from Virginia state university and Polytechnic Institute and biologists and chemists from Oakridge national Laboratory announced a method for producing pure hydrogen with high efficiency from water and starch. In 2009, they showed and proved the production of about 12 moles of hydrogen per unit of glucose from cellulose materials [17]. Due to the complete conversion and balanced action conditions, they propose the use of carbohydrates as hydrogen carriers with high energy volume with a weight density of 14.8%.

Synthesized hydrocarbons

There is an alternative to hydrides that uses hydrocarbon fuels as hydrogen carriers. A small hydrogen organizer then pulls the hydrogen out. Because it needs a fuel cell. However, this regulator is slow to react to the required changes and will cause an exponentially high cost in the vehicle's drivetrain. Methanol fuel cells do not need a regulator [18], but they contain less energy compared to traditional fuel cells [19]. However, this can be equated to a much better energy volume than ethanol and methanol in hydrogen. Alcohol fuel is a renewable resource. Oxide-solid fuel cells can be used in light hydrocarbons such as propane (heavy and colorless alkane with the formula C_3H_8) and methane (CH_4) without modifiers or added to the main and larger hydrocarbons with only minor modifications [20], but high temperature and the slow start-up time of these fuel cells is problematic for applications and uses related to motor vehicles [21].

Liquid Organic Hydrogen Carriers (LOHC)

Unsaturated organic compounds are able to store a large amount of hydrogen. These liquid organic hydrogen carriers (LOHC) are hydrogenated and then dehydrogenated for storage when hydrogen/energy is needed [22]. Cyclic compounds such as aromatic gasoline, whose molecules contain carbon, are considered the most appropriate option for this. The compound that is the focus of LOHC is N-ethyl carbazole, but there are others as well. For example, dibenzyl, toluene, which are now industrially used as water type or heat transfer fluid. By using $LOHC_2$, relatively high volume of propellant storage reaches about 6% of weight and overall energy efficiency is higher for other chemical storage options such as methane production from hydrogen. Amine and borane compounds Before 1980 [23], several compounds for hydrogen storage including complex borohydrides, or aluminohydrides and ammonium salts were under investigation. These hydrides have a high yield of limited theoretical hydrogen of about 8.5% by weight. Among the compounds that only contain H, N, B (positive and negative ions), typical cases include amine boranes, boron hydride with ammonia, borane hydrazine citrate, and ammonium octahydrate or tetrahydrates. Among these, amine boranes have been comprehensively and in detail researched as hydrogen carriers [14]. During the 1970s and 1980s, the US Navy and Army conducted efforts to develop deuterium/hydrogen gas production compounds for use in HCI, HF/DF chemical lasers, and gas dynamic lasers. Former hydrogen gas production formulations used amine boranes and their derivatives [19]. Combustion of borane amine forms boron nitride (BN) and hydrogen gas. In addition to ammonia borane (H_3BNH_3), other gas producers include diammonia diborane, $H_2B(NH_3)_2BH_4$.

Underground hydrogen storage

Underground hydrogen storage is a way of storing hydrogen in underground caves, salt anticlines and empty oil and gas fields [24]. Large amounts of gaseous hydrogen have been stored in underground caves and fissures by ICE over the years without any difficulties or problems. The storage of large amounts of underground liquid hydrogen can act as an energy storage network. The efficiency and efficiency of two-way travel (round trip) is about 40%.

Hydrogen storage solutions

The following solutions are proposed to solve the problem of hydrogen storage:

- ❖ The use of compressed tanks has been a suitable option that stores hydrogen at high pressure and low temperature.
- ❖ The up-to-date technology of biological cooling systems has also been effective in replacing electrolyzes and developing hydrogen transmission network models.

Challenges of hydrogen transfer

Hydrogen faces challenges for transportation due to its specific properties, such as being a gas and its tendency to leak. Designing hydrogen transfer systems that can prevent possible risks such as leakage and explosion is one of the basic challenges, and two solutions are proposed to solve these challenges:

1- The use of explosion-proof pipes and tanks with the ability to protect due to the lack of hydrogen leakage [24].

2- Using hydrazine technology as a new hydrogen carrier.

Different ways of hydrogen storage

High pressure hydrogen storage

1- High pressure tanks: In this method, hydrogen is stored in high pressure tanks. This method increases the energy density of hydrogen and its storage rate. In addition, in this method, there is also the possibility of energy transfer.

2- Hydrogen solidification: in this method, hydrogen is stored in a solid such as metal, fabric, alloys, nanotube structures. This method has high energy density and environmental systems [8].

B) Hydrogen storage in liquid form

1- Hydrogen soil vacuum: In this method, hydrogen is stored in a soil preparation with a special supplier in the form of a coordinate vacuum. This method is realized with the help of high technology in hydrogen storage.

2-Hydrogenable tapping: In this method, hydrogen is stored inside the metal and by using heat or pressure again, hydrogen is released [11].

Hydrogen storage using conductors

1- Nanoparticles: In this method, nanoparticles are used as conductors to transport hydrogen. This method has high energy density and high efficiency.

2- Hydrogen transportation systems: in this method, hydrogen is used as a conductor in gas distribution network systems, pipelines, etc.

Today, the issue of hydrogen storage and the use of renewable resources in its production is one of the important issues in the field of using clean fuel in energy production systems. Carbon nanotubes (CNT) are used in hydrogen storage due to their high specific surface area and unique structure, and are divided into single-walled (SWNT) and multi-walled (MWNT) categories. Hydrogen can be stored inside nanotubes by physical and chemical adsorption. Often, hydrogen is stored molecularly in pure carbon nanotubes [24]. In order to increase the absorption capacity, hydrogen can be examined atomically due to its stronger bond with carbon. Another important factor in the usefulness of nanotubes in hydrogen storage is the average ratio of stored hydrogen to carbon, which can be increased by improving purification methods. There are many evidences that prove that carbon nanotubes are a potential hydrogen storage [25]. However, it is still difficult to use carbon nanotubes due to the limitation of its mass production, and there are still obstacles that need to be solved by scientists. Hydrogen production from renewable sources by methods such as steam reforming, coal gasification and electrolysis were also used in the past years, but other methods such as photorefraction process still have a long way to commercialize. These methods have a high potential for sustainable hydrogen production without causing any environmental damage [25].

Hydrogen storage in vehicles

Hydrogen atom storage is difficult to store. Because it has a very low volumetric energy density. It is the simplest and lightest element, lighter than helium. Hydrogen energy has 2.3 times more energy than natural gas and 2,700 times less energy than gasoline. Hydrogen has 3.4 times more energy by weight than gasoline. Hydrogen must have a higher energy mass to be useful for transportation. There are three ways to do this. Hydrogen can be compressed, liquefied, or chemically combined [1].

Hydrogen can be stored in three ways

1- As compressed gas in high pressure tanks.
2- As a liquid in dewars or tanks [19].
3- As a solid or through absorption or reaction with metals or chemical compounds or stored in an alternative chemical form.

To meet the storage challenge, fundamental research is needed to identify new materials and address a series of related functions and systems. Problems include:

- ✓ Working pressure and temperature.
- ✓ Longevity of storage materials.
- ✓ Hydrogen purity requirements are enforced by the fuel cell.
- ✓ Reversibility of hydrogen absorption and release [17].
- ✓ The conditions of the amount and time of refueling.
- ✓ Hydrogen delivery pressure.
- ✓ Safety, toxicity and efficacy and overall cost of the system.

These requirements are often contradictory and the need to address these issues simultaneously adds to the challenge. In fact, some of the needs of hydrogen storage with vehicles seem unattainable, especially with liquid and gaseous methods. Hydrogen storage in chemical compounds offers a wide range of possibilities to meet transportation needs, but no single material investigated to date exhibits all the necessary properties. The storage solution requires advances in material performance that can only come from innovative and fundamental research that goes beyond the materials considered to date [26]. Detailed demands on storage capacity, charge and discharge conditions, stability, and cost span the traditional domains of chemistry, physics, materials science, and engineering. The basic factors that control the bond strength, kinetics of desorption, degradation due to cycling and the role of nano size and nano structure in bonding and kinetics need to be researched and new materials should be found. Currently, only three systems for storing hydrogen for transportation are close to commercialization [7]. They compress gas at high pressures (5,000 to 10,000 psi in composite cylinders). Hydrogen is a liquid that requires a cryogenic temperature of -253 degrees Celsius, and the storage of materials is based on solid materials, which includes the use of metal hydrides, carbon-based materials, high-level absorbers, or chemical hydrogen storage [25].

Compressed hydrogen

Compressed hydrogen up to 800 atmospheres occupies 3 times more volume than gasoline for the same energy. It is necessary, if a vehicle is to carry enough hydrogen, it must reach this density. 800 bar pressure works up to 6 tons or 12,000 pounds per square inch. It is very difficult to contain such pressures in a light tank. A catastrophic tank failure releases energy equal to its weight in dynamite [11]. A tank made of high-strength steel weighs 100 times more than the hydrogen contained in it. A truck or car using a steel tank would be unusual. Because the tank weighs almost as much as the car. High-pressure hydrogen tanks made of carbon fiber may be one solution. Carbon fiber is a material used in airplanes and sports equipment. Currently, carbon fiber tanks are very expensive. A typical 18-wheel trailer carries two 90-gallon tanks and provides a range of 1,207 km. A typical 4-cylinder sedan has an 18-gallon fuel tank that has a range of 925 km. The diesel engine achieves 35% efficiency at cruise speeds [19]. Gasoline engine achieves 25% efficiency at cruising speed. Both vehicles can run on hydrogen fuel. Internal combustion engines (ICE) can be used resulting in 35% efficiency, or fuel cells can be used resulting in 45% efficiency. The space, weight and cost of steel tanks make them impractical. Any gains in energy efficiency are offset by losses in transporting very heavy tanks. Carbon fiber tanks of this size and performance do not exist. In contrast, gasoline only requires a small, low-tech tank [11].

Discussion

Hydrogen storage for future and subsequent uses and applications includes many approaches. Such as chemical, cryogenic and high-density compounds that reversibly emit H2 as a result of heating. Hydrogen storage is an important and fundamental challenge in the way of developing the use of hydrogen as an energy source [26]. One of the common methods is storing hydrogen in metal hydrides. Hydrogen in combination with metals produces metal hydrides and becomes solid, which can be stored much more easily and safely. Various metals have the ability to combine with hydrogen and produce hydride, each of which has advantages and disadvantages [13].

Various methods are used to store this gas, which include

1- Physical storage (compression or liquefaction).
2- Surface absorption.
3- Storage in hydrates [3].
4- Storage with the help of reversible metal hydrides by forming a chemical bond between hydrogen and metal.

Each of the mentioned methods has disadvantages. Apart from that, the safe and reliable transfer of hydrogen is not possible with conventional methods. As a cheap and lightweight metal alloy, FeTi has a good ability to hydride and store hydrogen. Although its surface activation before hydrogen storage has limited its application. This alloy has a mixture of nano and amorphous structures, which is produced using a mechanical alloying system, using Fe and Ti elements and using a ball mill method with a purity of 99.9%. In the ball mill, the balls are milled in a steel tank with a volume of 250 ml in an argon atmosphere from 5 to 100 hours and at a speed of 200 rpm. Single-layer carbon nanotubes (SWNT) are also produced by different Sol gel (gel formation) and chemical vapor deposition (CVD) methods [27]. Although there have been many laboratory investigations on the storage and absorption of hydrogen, the theory of its absorption on FeTi nanoparticles or carbon nanotubes is still unknown. Underground hydrogen storage is suitable for supplying and providing high pressure grid energy storage for intermittent and periodic energy sources such as wind energy, in addition to providing fuel for transportation, especially for use in ships and airplanes. Most of the researches conducted in the field of hydrogen storage emphasize the storage and maintenance of hydrogen as a dense, light and compact energy carrier for mobile applications [28]. Compressed and condensed hydrogen is stored in a completely different way. Hydrogen gas has a good energy density in terms of weight, but its energy density is low in terms of volume and capacity compared to hydrocarbons. Therefore, it needs a bigger tank for storage. A large hydrogen tank will be heavier than a small hydrocarbon tank used to store the same amount of energy, all other factors remaining equal.

The main effects and benefits of hydrogen energy storage

1- Renewable energy integration: One of the main advantages of hydrogen energy storage is the ability to store excess energy produced by renewable sources such as wind and solar during times of low demand. This stored energy can be used when power generation is low, helping to offset renewable energy outages and increase grid reliability [16].

2- Grid stability and reliability: Hydrogen storage can contribute to grid stability by providing a dispatchable energy source. It can be used to meet peak power demand, stabilize frequency and provide backup power during grid outages, reducing the risk of outages and improving grid reliability [18].

3- Decentralized energy systems: hydrogen energy storage can be used in different scales. From small distributed systems to large centralized installations. This flexibility supports the development of decentralized energy systems by reducing the need for extensive transmission and distribution infrastructure [29].

4- Diversification in the energy sector: Hydrogen storage adds versatility to the energy range and complements other energy storage technologies such as batteries. Such diversity can improve the sustainability of the energy system and provide different options for solving energy problems.

Conclusion

With the increase in the level of prosperity and economic development of societies, sustainable energy supply as a driving engine for growth has become one of the basic challenges of mankind. In recent decades, excessive consumption of fossil fuels has raised concerns about energy security and climate change. Therefore, the use of renewable and sustainable energy sources has been prioritized. One of the renewable energy sources that has high conversion efficiency is hydrogen and fuel cell technology. Electric energy production from other renewable sources such as wind, sun, hydroelectricity and geothermal energy have many limitations due to dependence on environmental and climatic conditions. Among the introduced green options, hydrogen has become an option in accordance with the components of sustainable development for energy production and storage due to the abundance and variety of production sources. Hydrogen is an attractive energy carrier for electric power generation and transportation applications due to its high potential energy efficiency and low pollutant production. Currently, most of the required hydrogen is produced from hydrocarbon sources. The global demand for hydrogen consumption is about 70 million tons, of which more than 93% is spent on refining fossil fuels and producing chemicals. Hydrogen is a potentially carbon-free alternative fuel with a very high specific energy content of about 140.4 MJ/kg. The energy obtained from one kilogram of hydrogen is equal to the energy obtained from one gallon of gasoline. Hydrogen can be produced using renewable and non-renewable sources. Existing technologies for hydrogen production include: natural gas reforming, coal and biomass conversion to gas, water splitting by electrolysis, photo electrolysis, photobiological production, thermochemical water splitting ring at high temperature.

Steam reforming of methane is the most common and least expensive way to produce hydrogen, but about 2.5 tons of carbon dioxide is released into the atmosphere for every ton of hydrogen produced from reforming hydrocarbons. Electrolysis has the potential to be a successful and sustainable large-scale process for hydrogen production in the medium term. The efficiency of water electrolysis is favorable, but its production cost is several times higher than that of fossil fuels. The process of water decomposition, when done by burning fossil fuels, leads to huge emissions of carbon dioxide. The US Department of Energy has announced that electrolysis of water through sunlight could be a long-term carbon dioxide-free way to mass produce hydrogen. The process of thermochemical decomposition of water is also among the interesting methods of hydrogen production, which requires high temperatures. The inclusion of sulfuric acid in thermochemical cycles can reduce the operating temperature to 900 and 400 degrees Celsius, respectively. Electricity from renewable sources such as wind and solar may produce hydrogen locally, but it certainly will not meet the global demand for hydrogen. Therefore, we still have to rely on fossil fuels to produce hydrogen for various purposes.

Large-scale and long-term storage of hydrogen is one of the main challenges in the development of hydrogen as a fuel for widespread applications.

One of the methods of storing hydrogen in the form of gas is underground storage, and natural geological structures such as salt domes and underground aquifers or engineered rock caves can be used for this purpose. Mass underground storage is a normal operation in the natural gas industry, and having such a technological capability can be very useful in hydrogen storage as well. Compressed hydrogen tank and liquid hydrogen are two popular hydrogen storage methods for current industrial use. For their use as a hydrogen vehicle, there are similar challenges such as tank design and material requirements, reducing the energy cost in the compression and liquefaction process, and thus reducing the total cost. Hydrogen demand reached 90 million tons in 2020, most of which is for refining and industrial purposes and is exclusively produced from fossil fuels. The production of these 90 million tons of hydrogen was combined with the production of 900 million tons of carbon dioxide.

Every year, refineries consume nearly 40 million tons of hydrogen as a raw material or as an energy source. The demand in the industrial sector is somewhat higher, where chemical production accounts for about 45 million tons of hydrogen demand, and almost three quarters of it is dedicated to ammonia production and one quarter to methanol. Over the past 5 years, the global capacity of electrolysis to produce hydrogen has doubled and reached more than 300 megawatts by mid-2021. By 2030, according to the defined projects, the electricity capacity allocated for 350 electrolysis projects will reach 54 GW, and

40 projects with a capacity of 35 GW are also in the early stages of development. All this, if realized, will produce about 8 million tons of hydrogen, which is far from the 80 million tons of capacity required according to the Net Zero Roadmap by 2050.

16 projects to produce hydrogen from fossil fuel with CCUS have been operated with an annual production of less than 700,000 tons. 50 projects are under development, which are generally located in the United States and Canada, and will reach a production capacity of 9 million tons by 2030. The cost of car fuel cells has decreased by about 70% since 2008 due to the advancement of technology and the growing sales of fuel cell electric vehicles. Achieving zero carbon goals by 2050 requires an investment of one trillion and 200 billion dollars in the hydrogen sector.

References

[1]Kumar, P.; Kannaiah, S.K.; Choudhury, S.R.; Rajasekar, N. Genetic Algorithm-based Modeling of PEM Fuel Cells Suitable for Integration in DC Microgrids. Electr. Power Compon. Syst. **2017**, 45, 1152–1160. [Google Scholar] [CrossRef]

[2]Lee, W.-S.; Kim, J.-H.; Lee, J.-Y.; Lee, I.-O. Design of an Isolated DC/DC Topology with High Efficiency of Over 97% for EV Fast Chargers. IEEE Trans. Veh. Technol. **2019**, 68, 11725–11737. [Google Scholar] [CrossRef]

[3]M. Asgari Bajgirani, et al., Boosting hydrogen storage capacity in modified-graphdiyne structures: A comprehensive density functional study, Materials Today Communications 39 (2024) 10878 [Google Scholar], [Publisher]Mahdinia, S.; Rezaie, M.; Elveny, M.; Ghadimi, N.; Razmjooy, N. Optimization of PEMFC Model Parameters Using Meta-Heuristics. Sustainability **2021**, 13, 12771. [Google Scholar] [CrossRef]

[4]Maheshwari, A.; Nageswari, S. Real-time state of charge estimation for electric vehicle power batteries using optimized filter. Energy **2022**, 254, 124328. [Google Scholar] [CrossRef]

[5]Mamouri, L.; Mesbahi, T.; Bartholomeus, P.; Paul, T. Design of a DC/DC Power Converter for Li-ion Battery/Supercapacitor Hybrid Energy Storage System in Electric Vehicles. In Proceedings of the 2020 IEEE Vehicle Power and Propulsion Conference (VPPC), Gijon, Spain, 18 November–16 December 2020; pp. 1–5. [Google Scholar]

[6]MB Sadr, A Samimi, Advanced Journal of Chemistry, Section B: Natural Products and Medical Chemistry, **2022**, 4(3), 174-183 [Google Scholar], [Publisher], [Crossref]Okundamiya, M. Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. Int. J. Hydrogen Energy **2021**, 46, 30539–30546. [Google Scholar] [CrossRef]

[7]N Motamedi, et al., Journal of Nuclear Medicine June **2023**, 64 (supplement 1) P1179; [Google Scholar], [Publisher]

[8]Özdemir, M.T. Optimal parameter estimation of polymer electrolyte membrane fuel cells model with chaos embedded particle swarm optimization. Int. J. Hydrogen Energy **2021**, 46, 16465–16480. [Google Scholar] [CrossRef]

[9]Pavanan, V.; Varadharajan, L. Optimization of various parameters for the performance enhancement of PEM Fuel Cell. Indian J. Sci. Technol. **2018**, 11, 1–7. [Google Scholar] [CrossRef]

[10] Restrepo, J.C.; Izidoro, D.L.; Násner, A.M.L.; Venturini, O.J.; Lora, E.E.S. Techno-economical evaluation of renewable hydrogen production through concentrated solar energy. Energy Convers. Manag. **2022**, 258, 115372. [Google Scholar] [CrossRef]

[11] Rezaei, M.; Akimov, A.; Gray, E.M. Economics of renewable hydrogen production using wind and solar energy: A case study for

Queensland, Australia. J. Clean. Prod. **2023**, 435, 140476. [Google Scholar] [CrossRef]
[12] Khare, V.; Khare, C.J.; Bhuiyan, M.A. Design, optimization, and data analysis of solar-tidal hybrid renewable energy system for Hurawalhi, Maldives. Clean. Energy Syst. **2023**, 6, 100088. [Google Scholar] [CrossRef]
[13] Karthikeyan, P.; Mahadevan, K. Investigation on the effects of SiC particle addition in the weld zone during friction stir welding of Al 6351 alloy. Int. J. Adv. Manuf. Technol. **2015**, 80, 1919–1926. [Google Scholar] [CrossRef]
[14] Karthikeyan, B.; Sundararaju, K.; Palanisamy, R. A variable step size fuzzy logic controller based maximum power point tracking controller for proton exchange membrane fuel cell powered resonant pulse width modulation high step up converter with multicarrier sinusoidal pulse width modulation inverter fed induction motor. Int. Trans. Electr. Energy Syst. **2021**, 31, e13093. [Google Scholar] [CrossRef]
[15] Ji, M.M.; Zhang, W.; Xu, Y.F.; Liao, Q.; Klemeš, J.J.; Wang, B.H. Optimisation of multi-period renewable energy systems with hydrogen and battery energy storage: A P-graph approach. Energy Convers. Manag. **2023**, 281, 116826. [Google Scholar] [CrossRef]
[16] Ishaq, H.; Dincer, I. Comparative assessment of renewable energy-based hydrogen production methods. Renew. Sustain. Energy Rev. **2021**, 135, 110192. [Google Scholar] [CrossRef]
[17] Ibrahim, N.F.; Ardjoun, S.A.E.M.; Alharbi, M.; Alkuhayli, A.; Abuagreb, M.; Khaled, U.; Mahmoud, M.M. Multiport Converter Utility Interface with a High-Frequency Link for Interfacing Clean Energy Sources (PV\Wind\Fuel Cell) and Battery to the Power System: Application of the HHA Algorithm. Sustainability **2023**, 15, 13716. [Google Scholar] [CrossRef]
[18] Human, G.; Schoor, G.V.; Uren, K.R. Power Management and Sizing Optimisation of Renewable Energy Hydrogen Production Systems. Sustain. Energy Technol. **2019**, 31, 155–166. [Google Scholar] [CrossRef]
[19] Hu, W.; Chen, C.; Sun, J.; Zhang, N.; Zhao, J.; Liu, Y.; Ling, Z.; Li, W.; Liu, W. Three-body aggregation of guest molecules as a key step in methane hydrate nucleation and growth. Commun. Chem. **2022**, 5, 33. [Google Scholar] [CrossRef]
[20] Hu, R.; Zeng, J.; Liu, J.; Yang, J. Double-input DC-DC converter for applications with wide-input-voltage-ranges. J. Power Electron. **2018**, 18, 1619–1626. [Google Scholar]
[21] He, Y.; Guo, S.; Dong, P.X.; Lv, D.Q.; Zhou, J.X. Feasibility analysis of decarbonizing coal-fired power plants with 100% renewable energy and flexible green hydrogen production. Energy Convers. Manag. **2023**, 290, 117232. [Google Scholar] [CrossRef]
[22] He, H.; Huang, Y.; Nakadomari, A.; Masrur, H.; Krishnan, N.; Hemeida, A.M.; Mikhaylov, A.; Senjyu, T. Potential and economic viability of green hydrogen production from seawater electrolysis using renewable energy in remote Japanese islands. Renew. Energy **2023**, 202, 1436–1447. [Google Scholar] [CrossRef]
[23] HassanzadehFard, H.; Tooryan, F.; Collins, E.R.; Jin, S.; Ramezani, B. Design and optimum energy management of a hybrid renewable energy system based on efficient various hydrogen production. Int. J. Hydrogen Energy **2020**, 45, 30113–30128. [Google Scholar] [CrossRef]
[24] Guo, X.; Ghadimi, N. Optimal Design of the Proton-Exchange Membrane Fuel Cell Connected to the Network Utilizing an Improved Version of the Metaheuristic Algorithm. Sustainability **2023**, 15, 13877. [Google Scholar] [CrossRef]
[25] Guo, C.; Lu, J.; Tian, Z.; Guo, W.; Darvishan, A. Optimization of critical parameters of PEM

fuel cell using TLBO-DE based on Elman neural network. Energy Convers. Manag. **2019**, 183, 149–158. [Google Scholar] [CrossRef]
[26] Gul, E.; Baldinelli, G.; Farooqui, A.; Bartocci, P.; Shamim, T. AEM-electrolyzer based hydrogen integrated renewable energy system optimisation model for distributed communities. Energy Convers. Manag. **2023**, 285, 117025. [Google Scholar] [CrossRef]
[27] Gokcek, M.; Kale, C. Techno-Economical Evaluation of a Hydrogen Refuelling Station Powered by Wind-PV Hybrid Power System: A Case Study for İzmir-çeşme. Int. J. Hydrogen Energy **2018**, 43, 10615–10625. [Google Scholar] [CrossRef]
[28] Ghandehariun, S.; Ghandehariun, A.M.; Ziabari, N.B. Performance prediction and optimization of a hybrid renewable-energy-based multigeneration system using machine learning. Energy **2023**, 282, 128908. [Google Scholar] [CrossRef]
[29] F Rebout, A Samimi, Progress in Chemical and Biochemical Research, **2022** 5 (2), 196-217 [Google Scholar], [Publisher], [Crossref]
[30] Ding, R.; Zhang, S.; Chen, Y.; Rui, Z.; Hua, K.; Wu, Y.; Li, X.; Duan, X.; Wang, X.; Li, J.; et al. Application of Machine Learning in Optimizing Proton Exchange Membrane Fuel Cells: A Review. Energy AI **2022**, 9, 100170. [Google Scholar] [CrossRef]
[31] Di Micco, S.; Romano, F.; Jannelli, E.; Perna, A.; Minutillo, M. Techno-economic analysis of a multi-energy system for the co-production of green hydrogen, renewable electricity and heat. Int. J. Hydrogen Energy **2023**, 48, 31457–31467. [Google Scholar] [CrossRef]
[32] Danoune, M.; Djafour, A.; Wang, Y.; Gougui, A. The Whale Optimization Algorithm for efficient PEM fuel cells modeling. Int. J. Hydrogen Energy **2021**, 46, 37599–37611. [Google Scholar] [CrossRef]
[33] Chen, Z.; Zuo, W.; Zhou, K.; Li, Q.; Huang, Y.; Jiaqiang, E. Multi-objective optimization of proton exchange membrane fuel cells by RSM and NSGA-II. Energy Convers. Manag. **2023**, 277, 116691. [Google Scholar] [CrossRef]
[34] Baque Billah, S.M.; Kabir, K.M.; Islam, M.O. Hydrogen Energy Storage Based Green Power Plant in Seashore of Bangladesh: Design and Optimal Cost Analysis. In Proceedings of the International Conference on Innovations in Green Energy and Healthcare Technologies (IGEHT), Coimbatore, India, 16–18 March 2017. [Google Scholar]
[35] Babatunde, O.; Munda, J.; Hamam, Y. Hybridized off-grid fuel cell/wind/solar PV/battery for energy generation in a small household: A multi-criteria perspective. Int. J. Hydrogen Energy **2022**, 47, 6437–6452. [Google Scholar] [CrossRef]
[36] Aziz, A.S.; Tajuddin, M.F.N.; Adzman, M.R.; Azmi, A.; Ramli, M.A. Optimization and Sensitivity Analysis of Standalone Hybrid Energy Systems for Rural Electrification: A Case Study of Iraq. Renew. Energy **2019**, 138, 775–792. [Google Scholar] [CrossRef]
[37] Amrollahi, M.H.; Bathaee, S.M.T. Techno-economic Optimization of Hybrid Photovoltaic/Wind Generation Together with Energy Storage System in a Stand-alone Micro-Grid Subjected to Demand Response. Appl. Energy **2017**, 202, 66–77. [Google Scholar] [CrossRef]
[38] Samimi, A., Risk Management in the Laboratory based on the 17025 Standards, Journal of Exploratory Studies in Law and Management, **2020**, 7 (3), 114-119 [Google Scholar], [Publisher]
[39] Samimi, A., Micro-organisms of cooling tower problems and how to manage them, International Journal of Basic and Applied science, Indonesia, 2013, 705-715 [Crossref], [Google Scholar], [Publisher]
[40] Johnson, A., et al., Progress in Chemical and Biochemical Res, **2022**, 5 (2), 218-228 [Google Scholar], [Publisher], [Crossref]

[41] Aljarajreh, H.; Lu, D.D.C.; Siwakoti, Y.P.; Tse, C.K.; See, K.W. Synthesis and Analysis of Three-Port DC/DC Converters with Two Bidirectional Ports Based on Power Flow Graph Technique. Energies **2021**, 14, 5751. [Google Scholar] [CrossRef]

[42] Adaikkappan, M.; Sathiyamoorthy, N. Modeling, state of charge estimation, and charging of lithium-ion battery in electric vehicle: A review. Int. J. Energy Res. **2022**, 46, 2141–2165. [Google Scholar] [CrossRef]

[43] A Samimi, Study an Analysis and Suggest new Mechanism of 3 layer polyethylene coating corrosion cooling water pipeline in oil refinery in Iran, International Journal of Innovation and Applied Studies, **2012**, 1 (2), 216-225 [Google Scholar], [Publisher]