



Original Article

Is hydrogen a silver bullet in fighting climate change and recent trends in hydrogen technologies

You-Zhi Tang¹

Abstract

This review article is not intended to audience that is specialized in the research and development as well as deployment of hydrogen technologies. Rather, it is for those who are in the fields of commercialization, investment and applications of new technologies, working in areas relevant to climate change and energy policies, as well as those who have a general interest in hydrogen energy. While hydrogen holds a bright future in reducing carbon emission and mitigating climate change, it is only one of the valid means among an integrated and diverse set of solutions. As part of the current effort for energy transition, hydrogen offers zero emission provided that the electricity used for generating hydrogen is from green sources. In the domain of producing green hydrogen, alkaline electrolysis (AE) currently dominates industrial applications thanks to its lower costs and reasonable efficiency, while it is expected proton exchange membrane (PEM) will pick up pace from 2030. Anion exchange membrane (AEM) is relatively new and may hopefully combine some of the advantages of both AE and AEM. However, each technology has its niche based on the application's specific requirements, such as cost sensitivity, purity needs, and operational flexibility. Producing hydrogen from biomass, including waste materials, is an area of active research and development and several technologies have been explored or under development for harnessing hydrogen from such resources. Manufacturing and applying more efficient and powerful electrolyzers at lower costs is the way to go. While storing and shipping hydrogen in containers with hydrogen in a compressed gaseous or cryogenic liquified form remain the primary ways, solid-state storage of hydrogen is getting more and more attention, with metal hydrides such as MgH_2 , $TiFeH_2$, $NaAlH_4$, etc. getting close to full commercial applications. Dissolving hydrogen in organic solvents or converting it into ammonia, is a direction of on-going research. With a proper way for safe and low-cost storage of hydrogen in large scale, hydrogen as an energy carrier is a great candidate for grid balance. Although hydrogen can be used as a fuel directly such as with an internal combustion engine (ICE) or gas turbine, as well as used as a chemical reagent such as a reductant in steel making or as feedstock in a variety of industrial processes, a lot of attentions is paid to the use of hydrogen with fuel cells (FC). Current focuses on FC are reducing costs, adapting to harsher working conditions, enhancing flexibility and durability, increasing fuel types, finding more applications and scaling up. It is expected that the hydrogen industry will continue to attract large capital inflows in 2025 and beyond to achieve a low-carbon transition for energy-intensive sectors. Hydrogen infrastructures are being developed all over the world, with China seemingly leading the way. Transporting hydrogen by pipeline is important for developing a hydrogen economy, and demonstration projects are currently underway in many countries.

Key words: hydrogen; a silver bullet; climate change; recent trends; hydrogen technologies; review

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1. Introduction

Climate science since its inception in the late 18th and early 19th centuries has evolved from rudimentary observations to empirical extrapolations or speculative predictions, further to a sophisticated understanding of Earth's climate systems. Today, climate science is a robust field characterized by advanced computational models, extensive datasets, and a high level of scientific consensus on climate change¹.

The IPCC's Sixth Assessment Report (AR6), highlight several critical aspects of current climate understanding, with the following two key points:

- **Global warming trends:** Average global temperatures have risen significantly, with 2020 being one of the hottest years on record. The past decade has been the warmest in the historical record².
- **Attribution of climate change:** There is a high level of confidence that human activities, particularly the burning of fossil fuels and deforestation, are the primary drivers of recent global warming. The IPCC AR6 report states that it is "unequivocal" that human influence has warmed the atmosphere, oceans, and land².

The AR6 Report further predicts the profound effects of climate change on ecosystems, human health, and economies, and calls for strategies and measures to mitigate climate change by reducing greenhouse gas emissions and adapting to its unavoidable impacts¹⁻². Transformation to renewable energy sources, enhancement in energy efficiency, and developing adaptive infrastructure are normally considered some of the most effective means and hydrogen is sometimes called the ultimate clean energy as it has zero emission of pollutants³⁻⁴.

Hydrogen is a chemical element with an atomic number of 1 and listed as the first on the Periodic Table of Elements. Therefore, it is called the Number 1 Element. Hydrogen is also an energy carrier that will certainly make an important and decisive contribution to the global energy transition and lead to a significant reduction in greenhouse gas (GHG) emissions over the coming decades. It is estimated that 60% of GHG emission reductions in the last phase of the energy transition could come from renewables, green hydrogen and electrification based on green energy development⁵.

Hydrogen can substantially contribute to global decarbonization efforts, especially in sectors difficult to electrify directly. It is considered a game-changer in fighting climate change as it possesses certain advantages with some of the examples listed below:

- **Zero emissions at point of use:** Hydrogen fuel cells emit only water, making them ideal for decarbonizing transport sectors such as heavy-duty vehicles, ships, and aircraft, where battery-electric solutions face limitations in range or payload⁶.
- **Energy storage and grid balancing:** Hydrogen as a flexible energy carrier is useful for storing surplus renewable energy and providing backup power for intermittent renewable sources. Hydrogen energy storage and grid integration are becoming important technologies for efficient energy generation and decarbonization, addressing the unpredictability of renewable sources like wind and solar⁷.
- **Industrial decarbonization:** It offers a viable pathway to reduce emissions from difficult-to-electrify industries such as steelmaking, chemical production, cement manufacturing and oil refinery⁶. Hydrogen can be used as fuel, feedstock and reagent in many industrial processes for decarbonization.

In the past 5 to 10 years, many governments around the world have been actively developing strategies and plans to promote hydrogen. Notably, EU published its hydrogen strategy in July

2020⁸, and Australia (first in 2019 and updated in 2024)⁹, Germany (first in 2020 and updated in 2023)¹⁰, Chile (November 2020)¹¹, Canada in December 2020 announced their National Hydrogen Strategy¹². Japan, South Korea, Saudi Arabia, and India are all among those having an aggressive hydrogen plan¹³. China is making remarkable progress and is emerging as a global leader in hydrogen technology and infrastructure. The country is placing significant strategic emphasis on hydrogen as part of its energy transition and decarbonization plans. Its aggressive push positions it not just to meet domestic energy transition needs but potentially to become a global hydrogen powerhouse, influencing technology standards and supply chains worldwide¹³⁻¹⁵. However, hydrogen should be viewed as part of an integrated and diverse set of solutions, rather than a single, ultimate solution to climate change, as there are challenges that limit the role of hydrogen:

- **Cost and infrastructure:** Production (in a green way), storage, transport and distribution of hydrogen is still costly, requiring substantial investments in electrolyzers, infrastructure, and renewable electricity generation¹³. The lack of hydrogen refueling stations is one of the examples of stumbling blocks in hydrogen applications in the transportation sector.
- **Energy efficiency concerns:** Hydrogen production and conversion involve energy losses; thus, direct electrification may be more efficient and economically sensible for many applications¹⁶.
- **Technology maturity and safety:** Technical challenges and safety issues around hydrogen storage and transportation remain, especially concerning large-scale adoption¹⁷.

In general, hydrogen technology holds significant promise in the fight against climate change but cannot be considered a Silver Bullet. The term "silver bullet" normally refers to a simple and seemingly magical solution to a complex or difficult problem. The expression originates from folklore, where a silver bullet is often the only weapon that can kill a werewolf or other mythical creatures, symbolizing a direct and effortless way to end a formidable challenge. Apparently, the climate issue has far more complexity and the challenge is much more overwhelming, and there is no quick fix. Hydrogen could only be one critical component in a broader strategy that must also include renewable energy, cleaning and decarbonization of primary energy, electrification, energy efficiency, smart grid, behavioral changes, adaptation, etc.

2. Major applications of hydrogen for carbon reduction

With its advantages of zero emission and high energy density, hydrogen energy is being widely used in transportation, industry, energy storage and low-altitude economy, effectively promoting the realization of carbon reduction goals.

Figure 1 provides a breakdown of the areas of hydrogen applications¹⁸. It includes both new and existing applications currently responsible for 60 per cent of the world's energy- and process-related emissions.

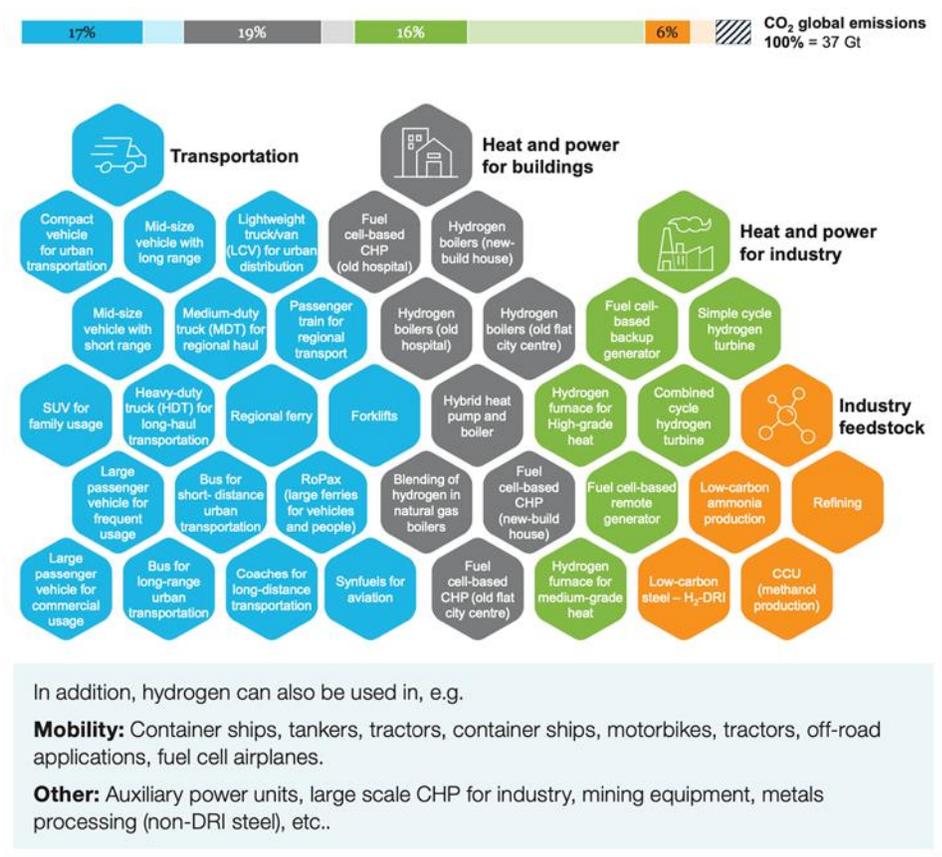


Figure 1. Overview of hydrogen applications¹⁸

For simplicity, our following discussion on using hydrogen for decarbonization will target on three sectors: transportation, industry, and energy storage and grid balance.

2.1 Decarbonization of the transportation sector

Hydrogen has the potential to meaningfully reduce GHG emissions in the transportation sector. It can particularly offer benefits to the heavy-duty transportation sector applications (i.e., long-haul trucks, locomotives, ships, etc.) where current battery technology might not yet be suitable for certain transportation modes (e.g., the necessary battery weight would be too substantial). Hydrogen passenger vehicles, heavy-duty freight trucks, buses, and even hydrogen trains and drones have gradually moved from demonstration to large-scale application. However, integrating fueling infrastructure for hydrogen into current local and national roadways will take some time.

2.2 Key industrial applications of hydrogen

Hydrogen is increasingly recognized as a key player in reducing carbon emissions across various industrial sectors. Its applications are diverse, from traditional roles in refining and chemical

production to innovative uses in steelmaking and concrete production. The shift to low-carbon hydrogen, especially green hydrogen produced from renewable energy sources, offers significant potential to reduce industrial carbon emissions. This type of hydrogen does not produce carbon emissions at the point of use and can be integrated into existing industrial processes with minimal changes to infrastructure. Only a brief review is given in this paper on the industrial applications of hydrogen relevant to reducing carbon emission.

2.2.1 Steel making

Hydrogen can replace coal in steel making, where hydrogen is primarily being explored as a chemical reduction agent rather than just as a fuel. Traditionally, coal or coke is used in steel production to remove oxygen from iron ore, which is necessary to produce metallic iron. Hydrogen can perform this same function—when it reacts with iron oxides (FeO), it reduces them to iron metal and produces water as a byproduct instead of carbon dioxide, which is typically generated when carbon (coal/coke) is used.

The application of hydrogen as a reducing agent is a key part of creating what's termed “green steel.” This process significantly reduces carbon emissions associated with steel production, aligning with global efforts to decrease industrial carbon footprints and combat climate change. This innovative use of hydrogen could transform the steel industry and contribute significantly to decarbonization efforts. *The Future of Hydrogen* well describes the use of hydrogen for reducing carbon emissions from this sector⁴.

2.2.2 Cement and concrete production

Hydrogen is also being explored as a means to reduce emissions in the production of concrete. This process is traditionally very carbon-intensive due to the energy required. Using hydrogen as a part of the fuel mix can help decrease the carbon footprint of this essential building material.

2.2.3 Ammonia and methanol production

These are two of the largest industrial uses of hydrogen. Ammonia is crucial for fertilizer production, and methanol is used widely as a chemical feedstock. Both processes can benefit from using “green” hydrogen produced via renewable energy sources, reducing the carbon emissions associated with these industries.

2.2.4 Oil refining

Hydrogen is essential in refining processes, especially for removing sulfur from crude oil to make cleaner fuels. Some 38 MtH₂/yr, or 33% of the total global demand for hydrogen (in both pure and mixed forms), is consumed by refineries as feedstock, reagent and energy source⁴. Transitioning to hydrogen produced from low-carbon sources can further reduce emissions in this sector.

2.3 Energy storage and grid balance

Hydrogen can also store energy for long periods of time. As additional renewable electricity such as that wind and solar technologies is added to the grid, hydrogen could be used to help balance intermittent supply with varying demand. Being an energy storage medium, hydrogen energy can effectively absorb the surplus electricity of intermittent renewable energy, realize the decarbonization and stable operation of the power system through hydrogen energy storage technology.

2.4 Challenges and future prospects

These applications of hydrogen not only show the potential for hydrogen to significantly reduce carbon emissions but also highlight the ongoing need for investment and innovation in hydrogen technologies to make these opportunities viable at scale.

The main challenges for hydrogen use include the high costs of green hydrogen production and the need for significant infrastructure investments. However, with technological advancements and increased government and industry support, hydrogen is poised to play a crucial role in the global transition to a low-carbon economy. The report *Path to Hydrogen Competitiveness* provides a good analysis on the costs of producing, distributing and using hydrogen and the trends in reducing these costs¹⁸.

3. Recent trends in hydrogen technologies

As more favourable policies have been promoted or are being developed in various countries, investment into this industry is increasing and the industrial chain is constantly improving. Importantly, hydrogen energy technology is gradually maturing, and it is entering into the stage of large-scale commercial application. 2025 may become the turning point for the development of the global hydrogen energy industry¹³.

The hydrogen industrial chain is mainly consisted of 1) hydrogen production by various means; 2) hydrogen storage, transportation and distribution; and 3) hydrogen utilization / end uses. Figure 2 is an illustration covering the whole hydrogen value chain from production to application¹⁹.

From the viewpoints of the industry and investment community, the current hydrogen energy technology and market progress are mainly manifested in the following aspects.

3.1 Production (green, blue, grey, turquoise hydrogen)

There are different ways to produce hydrogen. Examples include production from renewable energies through electrolysis of water, steam reforming of biomethane and pyrolysis of biogenic feedstocks (green hydrogen) and natural gas through steam reforming with (blue hydrogen) and without (grey hydrogen) the sequestration and storage of CO₂ by CCUS - Carbon Capture, Utilization and Storage²⁰.

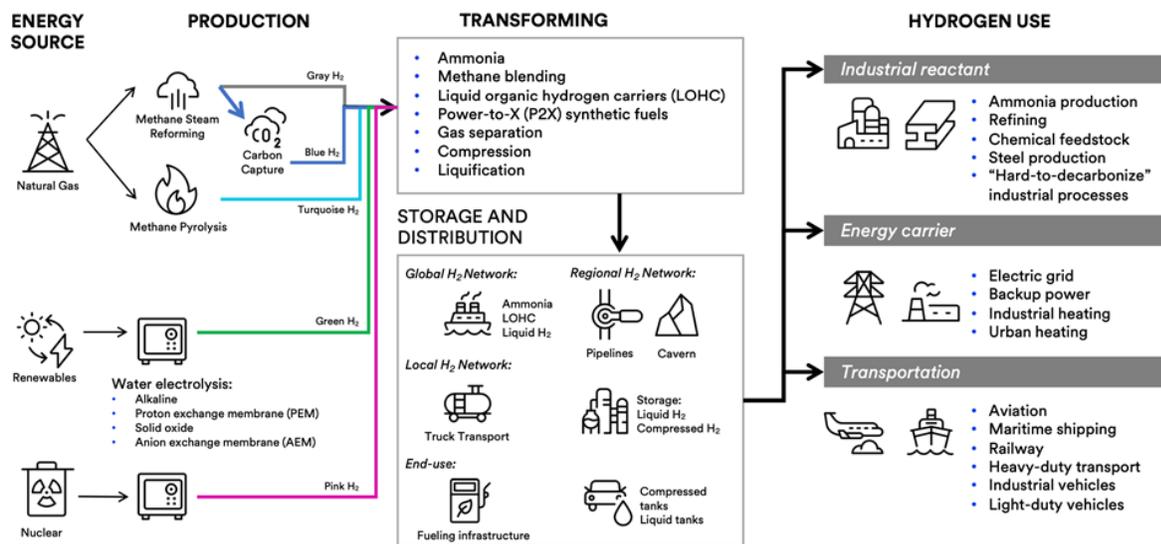


Figure 2. Hydrogen value chain¹⁹

According to Singh²¹, around 92% of hydrogen (by value) in 2022 was grey hydrogen, underlining global dependence on this carbon-intensive production process. It was expected by 2035 low to zero-carbon emitting blue and green hydrogen are to pick up pace and comprise about 22% of total hydrogen production.

It is obviously and necessarily that green hydrogen needs to gradually replace grey hydrogen (hydrogen produced from fossil fuels without removing CO₂). While the concept of making hydrogen from water by electrolysis has long been known, recent breakthroughs have been made in electrolysis efficiency, scale and cost control. In 2025, the market demand is trending towards higher power electrolyzers, and the requirements for the electro-hydrogen coupling performance of products will be significantly increased¹⁵.

In this review, discussion on the production of hydrogen from natural gas or methane by means of steam reforming²² and other ways of producing grey and blue hydrogen is not included. Rather, we will focus on green hydrogen production.

3.1.1 Electrolysis for green hydrogen production

Recent advancements in hydrogen production technologies, particularly the two conventional means, i.e. Alkaline Electrolysis (AE) and Proton Exchange Membrane (PEM) electrolysis, have focused on improving efficiency, reducing costs, and scaling up production to meet the growing demand for green hydrogen¹⁵.

- **Alkaline electrolysis (AE):** Alkaline electrolysis is a very well-established technology that uses two electrodes separated by a porous diaphragm and a liquid alkaline solution as the electrolyte²³⁻²⁴. The electrolyte solution allows hydroxide ions (OH⁻) to be transported

from the cathode to the anode with hydrogen being generated on the cathode side and oxygen produced on the anode.

The concept has been known for a long time, and many readers might have done such an experiment in a high school lab. In fact, AE systems have been commercially available for many years. This technology is considered as extremely efficient, reliable, and cost-effective. Capacity can stack in the MW range but drawbacks include using corrosive liquid electrolytes, operation at low current densities and low pressures as well as gas crossover. Traditional alkaline electrolyzers operate with efficiencies from 70% to 75%, with about 25% of the renewable energy for producing green hydrogen wasted.

- **Proton exchange membrane (PEM) electrolysis:** PEM electrolysis²³⁻²⁴ uses pure water and a solid polymer electrolyte instead of a liquid solution. The electricity splits the water into hydrogen and oxygen. Hydrogen protons pass through the membrane, combining with electrons to form H₂ gas on the cathode side.

PEM electrolyzers are well suited for use with volatile renewable energy sources thanks to their fast ramp-up/down capabilities and their wide dynamic operating range. No corrosive electrolyte is involved, and they operate at high current density which speeds up the breakdown of the water molecule, ultimately affecting production price. Finally, a small footprint and compact system design is a benefit for many on-site industrial applications.

- **Anion exchange membrane (AEM):** AEM electrolysis is an emerging technology for hydrogen production that utilizes a semipermeable membrane to conduct hydroxide ions (OH⁻), facilitating the electrolysis of water into hydrogen and oxygen gases²⁵. This method offers several advantages over traditional electrolysis techniques:
 - Cost-effective catalysts: Unlike Proton Exchange Membrane (PEM) electrolysis, which requires expensive noble metal catalysts like platinum and iridium, AEM electrolysis operates in an alkaline environment. This allows for the use of more abundant and affordable transition metal catalysts such as nickel, iron, cobalt, manganese, and copper.
 - Mild operating conditions: AEM electrolysis can function using pure water or mildly alkaline solutions (0.1–1M KOH/NaOH), reducing the risks associated with handling highly concentrated alkaline solutions required in traditional alkaline water electrolysis.
 - Reduced gas crossover: The membrane's selective ion conductivity minimizes the mixing of hydrogen and oxygen gases, enhancing both the efficiency and safety of the electrolysis process.

While AEM electrolysis presents significant advantages, challenges such as membrane durability and ionic conductivity remain. Ongoing research focuses on enhancing membrane stability at higher temperatures and in alkaline environments to extend the operational lifespan of AEM electrolyzers. Continued advancements in this field are expected to further reduce costs and improve the efficiency of green hydrogen production, contributing to global decarbonization efforts.

Overall comparison of AE, PEM and AEM: When comparing the advantages and disadvantages of Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM), and Anion Exchange Membrane (AEM) methods for green hydrogen production, several key factors like cost, efficiency, operational requirements, and application suitability come into play (Table 1)²⁶⁻²⁷.

Table 1 reflects general trends and performance metrics which can vary based on specific technological advancements and manufacturer-specific designs. Each technology has its niche based on the application's specific requirements, such as cost sensitivity, purity needs, and operational flexibility. However, AE will remain the dominant technology probably until 2030 due to its lower cost, and new technologies may pick pace from 2030.

Table 1. Comparison of AE, PEM and AEM

Feature	Alkaline Electrolysis (AE)	Proton Exchange Membrane (PEM)	Anion Exchange Membrane (AEM)
Cost of Equipment	Lower due to less expensive materials	Higher due to precious metal catalysts	Moderately low, uses cheaper materials
Operational Costs	Higher due to corrosion issues	Higher due to need for pure water	Lower than PEM, higher than AE
Efficiency	Moderate	High	Lower than PEM, but improving
Hydrogen Purity	High	Very high, suitable for sensitive applications	Lower than PEM, may not suit all applications
Ease of Use	Good, but handling of caustic electrolytes	Best, with rapid response to power changes	Good, less sensitive to impurities
Maturity	Most mature, widely used commercially	Commercially established, but less than AE	Emerging, with ongoing development
Durability	Good, but can be affected by corrosion	Lower due to membrane and catalyst degradation	Potentially better than PEM
Integration with Renewables	Moderate, less responsive to power fluctuations	Excellent, can handle rapid fluctuations	Good, improving with technology

3.1.2 Other emerging hydrogen production technologies

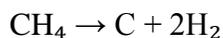
Producing hydrogen from biomass, including waste materials like garbage, is an area of active research and development, offering a sustainable alternative to fossil fuel-based hydrogen production. Several technologies have been explored to harness hydrogen from such resources.

- **Gasification:** Gasification involves thermochemically converting organic materials, such as biomass or municipal solid waste, into synthesis gas (syngas), a mixture primarily composed of hydrogen, carbon monoxide, and carbon dioxide. This process occurs at

high temperatures (typically above 700 °C) in an oxygen-limited environment. The resulting syngas can be further processed to separate hydrogen for use as a clean fuel or chemical feedstock. For example, Sierra Energy has developed the FastOx gasifier²⁸, which can convert nearly any type of waste into syngas without producing ash or other contaminants that need to be landfilled. This system operates at extremely high temperatures (around 2000 °C) and is modular, allowing for scalability.

- **Microbial electrolysis cells (MECs):** MECs utilize electrogenic microorganisms to decompose organic matter, releasing electrons and protons. By applying a small external voltage, these protons are reduced to form hydrogen gas²⁹. This bioelectrochemical approach allows for the conversion of waste biomass into hydrogen with higher energy efficiency compared to traditional water electrolysis. The efficiency of hydrogen production depends on the organic substrates used, with lactic and acetic acid achieving efficiencies of up to 82%.
- **Photofermentation:** Certain photosynthetic bacteria can convert organic substrates into hydrogen through photofermentation, a process that requires light³⁰. For instance, the bacterium *Rhodobacter sphaeroides* can transform small molecular fatty acids into hydrogen. This method leverages the metabolic pathways of these bacteria to produce hydrogen under illuminated conditions.
- **Plasmalysis:** Plasmalysis employs plasma technology to dissociate compounds like methane or wastewater into hydrogen and other byproducts³¹. For example, methane plasmalysis can efficiently produce hydrogen and elemental carbon without emitting carbon dioxide. Similarly, wastewater plasmalysis can recover hydrogen from pollutants such as ammonium or hydrocarbon compounds, simultaneously purifying the wastewater.
- **Turquoise hydrogen production:** Turquoise hydrogen refers to hydrogen produced through methane pyrolysis, a process that thermally decomposes methane (the primary component of natural gas) into hydrogen gas and solid carbon without emitting carbon dioxide (CO₂)³².

In methane pyrolysis, methane (CH₄) is subjected to high temperatures, typically around 900 °C, in the absence of oxygen. This thermal decomposition yields hydrogen gas (H₂) and solid carbon (C):



The solid carbon byproduct can be utilized in various industrial applications, such as manufacturing carbon black, which is used in products like tires, inks, and batteries.

Turquoise hydrogen production is considered environmentally favorable because it avoids CO₂ emissions associated with traditional hydrogen production methods, such as steam methane reforming. Additionally, the solid carbon produced can serve as a valuable industrial commodity, potentially offsetting production costs.

Several companies are advancing methane pyrolysis technologies to scale turquoise hydrogen production. However, challenges remain, including achieving energy efficiency, managing the solid carbon byproduct, and integrating renewable energy sources to heat the reactors.

In summary, turquoise hydrogen presents a promising pathway for low-emission hydrogen production, leveraging existing natural gas infrastructure while minimizing greenhouse gas emissions.

3.2 Advances in hydrogen storage and distribution

Traditionally, hydrogen is stored in compressed gaseous form in tanks or cylinders, or in a cryogenic liquified form. As hydrogen is very light, the former way requires very high pressure and / or a large volume. It is therefore bulky and less safe for storage and transportation. The latter means requires freezing hydrogen to $-253\text{ }^{\circ}\text{C}$ and keeping it at this extremely low temperature, creating challenges for handling³³.

Advancements in materials and methods led to some new technologies in hydrogen storage. This article will not discuss the two conventional ways for hydrogen storage, i.e. in compressed gaseous and cryogenic liquified forms, and will try to look into the relatively new means for storage.

3.2.1 Solid-state storage of hydrogen

Solid-state hydrogen storage technologies have been the focus of extensive research due to their potential to safely and efficiently store hydrogen for various applications³⁴⁻³⁵. These technologies primarily involve the absorption or adsorption of hydrogen onto or into solid materials, offering advantages over conventional gas or liquid storage methods. Followed is an overview of the key solid-state hydrogen storage technologies.

- **Metal hydrides**

Metal hydrides are compounds formed by the reaction of hydrogen with metals, resulting in materials capable of reversibly storing hydrogen³⁶. They are categorized into three main classes:

- **Intermetallic hydrides:** These hydrides, such as LaNi_5H_6 and TiFeH_2 , exhibit fast kinetics and moderate hydrogen storage capacities. They are often used in stationary storage and fuel cell applications.
- **Complex hydrides:** Examples include sodium alanate (NaAlH_4) and lithium borohydride (LiBH_4), which offer higher hydrogen storage capacities but typically require catalysts to facilitate hydrogen release.
- **Lightweight hydrides:** Materials like magnesium hydride (MgH_2) provide high gravimetric hydrogen storage but require high temperatures for hydrogen desorption. For instance, MgH_2 contains 7.6 wt% hydrogen but requires temperatures above $300\text{ }^{\circ}\text{C}$ for hydrogen release.

Magnesium hydride has garnered attention due to its high hydrogen storage capacity (7.6 wt% theoretically). However, its practical application is limited by the high desorption temperature required to release hydrogen. Research efforts are focused on reducing this temperature through methods such as nanostructuring and doping with catalysts. For example, nano-engineered Mg-Ti-V composites have demonstrated reduced desorption temperatures, enhancing their suitability for fuel cell vehicles.

Alanes, such as lithium alanate (LiAlH_4) and sodium alanate (NaAlH_4), are complex hydrides that have been extensively studied for hydrogen storage. LiAlH_4 , for instance, has a theoretical hydrogen capacity of 10.5 wt% and undergoes dehydrogenation in multiple steps. While these materials offer high hydrogen content, challenges remain in achieving practical desorption temperatures and kinetics. Strategies like ball-milling and catalyst addition have been employed to enhance their performance.

Palladium can absorb hydrogen at room temperature, forming palladium hydride (PdH_x). This material can absorb up to 900 times its own volume of hydrogen, making it a subject of interest for hydrogen storage. However, the high cost of palladium limits its widespread application.

Sodium silicide (NaSi) reacts exothermically with water to produce hydrogen gas and sodium silicate. This reaction has been utilized in hydrogen generation technologies, offering a method for on-demand hydrogen production. However, practical challenges, such as handling and reaction control, need to be addressed for widespread application.

Hydrogen spillover refers to the migration of dissociated hydrogen atoms from a metal catalyst to a support material, enhancing hydrogen storage in materials like metal-organic frameworks (MOFs) and carbon-based materials. This mechanism has been explored to improve the hydrogen storage capacity of various materials, although the exact mechanisms and efficiency are subjects of further research.

In summary, solid-state hydrogen storage technologies encompass a variety of materials and mechanisms, each with its own set of advantages and challenges. Ongoing research aims to optimize these materials to achieve practical hydrogen storage solutions suitable for various applications.

3.2.2 Others

- **Formic acid as a hydrogen carrier:** Formic acid has been established as an effective hydrogen storage medium³⁷. Its liquid state at room temperature and non-toxic properties makes it ideal for safe storage and transportation.
- **Mechanochemical storage solutions:** Innovations in mechanochemical processes have led to the development of hydrogen storage using readily available salts. This method offers a potential solution to the challenges of hydrogen storage, providing a safe and efficient means of storing hydrogen in powder form³⁸.
- **Advancements in LOHC technology:** Liquid organic hydrogen carriers (LOHCs) are organic compounds that can absorb and release hydrogen through chemical reactions, serving as storage media for hydrogen³⁹. In 2020, Japan established the world's first international hydrogen supply chain between Brunei and Kawasaki City utilizing toluene-based LOHC technology. Additionally, Hyundai Motor has invested in developing stationary and on-board LOHC systems, indicating a growing interest in this storage method.
- **Ammonia:** Ammonia has long been a chemical associated with hydrogen. It is in the recent years viewed as a viable option for hydrogen storage and transport, especially for long-distance transport where direct hydrogen methods face challenges⁴⁰. However, the overall sustainability and efficiency of using ammonia as a hydrogen carrier depend on overcoming the challenges associated with its production, handling, and dissociation. Ammonia as a hydrogen-rich molecule

is also finding direct applications as a fuel or precursory material of hydrogen in some scenarios of hydrogen utilization. These topics seem worthy of a separate article to discuss.

3.2.3 Transporting hydrogen by pipeline

In addition to transporting/shipping hydrogen in a storage tank, either as compressed gas, liquid, solid-state or in one of the forms discussed in the previous section, use of pipeline offers the best economy for large scale and long-range transport of hydrogen⁴¹⁻⁴².

Currently, transporting hydrogen via pipeline is an evolving area in the field of energy infrastructure, with developments primarily aimed at creating a more sustainable and efficient energy system. Here are some key updates on the progress:

- **Infrastructure conversion and expansion:** Some existing natural gas pipelines are being tested and modified to transport hydrogen. This includes blending hydrogen with natural gas to leverage existing infrastructure while reducing carbon emissions. In Europe, for instance, several projects are underway to test the feasibility of converting natural gas pipelines to hydrogen⁴³. China's Hydrogen into Ten Thousand Homes project is another good example⁴⁴.
- **Dedicated hydrogen pipelines:** New projects are also focusing on building dedicated hydrogen pipelines, especially in regions heavily invested in hydrogen as a key part of their energy transition. For example, the European Hydrogen Backbone (EHB) proposes a hydrogen network spanning several countries, aimed to be operational by 2040⁴⁵.
- **Technological and material advances:** Research continues into improving the materials used in pipelines to handle hydrogen's unique properties, such as its propensity to cause embrittlement in traditional steel and welds. New alloys and composite materials are being developed to improve safety and efficiency.
- **Regulatory and safety standards:** There is ongoing development in regulatory frameworks to ensure safety, efficiency, and interoperability of hydrogen transport via pipelines. This includes setting standards for purity, pressure, and mixture ratios when blended with natural gas.
- **Economic and policy support:** Governments in potential hydrogen hubs like the European Union, Australia, and parts of the US are supporting these initiatives through subsidies and policy frameworks to encourage investment in hydrogen infrastructure.

These efforts are part of a broader strategy to integrate hydrogen as a major component of a low-carbon energy system, facilitating large-scale storage and distribution of renewable energy.

3.3 Fuel cell advancements and cost-reduction trends

Hydrogen fuel cell technology has seen considerable progress in recent years, driven by both industry and academia seeking cleaner and more efficient power generation. It has further matured, and the performance, reliability, and durability have been significantly improved, leading to the rapid expansion of hydrogen energy vehicles and commercial applications⁴⁶. Below are some key areas of advancement and notable trends.

3.3.1 Improved catalysts and reduced platinum usage

- Lower platinum-group metals (PGM) content: One of the main cost drivers of Proton Exchange Membrane (PEM) fuel cells is the platinum catalyst. Research efforts have focused on reducing or even replacing platinum—through alloyed catalysts (e.g., platinum-cobalt) or entirely platinum-free options (e.g., iron-nitrogen-carbon catalysts) - to lower costs and increase production feasibility⁴⁷.
- **Durability enhancements:** New catalyst formulations are engineered to be more resistant to oxidation and degradation, extending the overall lifetime of the cell and improving performance under a wide range of operating conditions⁴⁸.

3.3.2 Advances in membrane and materials science

- **High-temperature PEM fuel cells:** Traditional PEM cells operate efficiently in the 60–80 °C range. New high-temperature PEM fuel cells (operating up to ~120 °C) improve tolerance to carbon monoxide (CO) and reduce the complexity of cooling systems⁴⁹.
- **Ion-exchange membranes:** Ongoing development of membranes that offer higher proton conductivity at lower humidity helps maintain performance even in challenging environments. Improved polymers (such as perfluorinated sulfonic acids with modified structures) increase both efficiency and durability⁵⁰.

3.3.3 Solid oxide fuel cells (SOFCs) gains

- **Lower-temperature SOFCs:** While SOFCs typically operate at 600-1000 °C, there is a push to develop “intermediate” temperature versions (~500-700 °C). These lower operating temperatures reduce thermal stress, allow for cheaper materials, and facilitate faster start-up times⁵¹.
- **Flexible fuel options:** SOFCs can use various fuels—natural gas, biogas, hydrogen, or even ammonia-making them attractive for stationary power applications. Recent demonstrations have shown robust operation on ammonia, a potential carbon-free fuel for shipping or backup power^{15, 52-53}.

3.3.4 Scale-up and manufacturing innovations

- **Mass production of PEM stacks:** Automotive manufacturers (e.g., Toyota, Hyundai) continue to refine production lines to produce fuel cell stacks at higher volumes and lower cost. Standardized designs and automated processes are lowering the per-kilowatt cost^{15 & 54}.
- **Modular and compact systems:** Companies are introducing smaller, more modular PEM fuel cell units aimed at logistics applications (like forklifts, warehouse vehicles) and at backup-power markets for data centers and telecommunications¹⁵. While SOFCs typically operate at 600-1000 °C, there is a push

3.3.5 Market expansion to heavier transport and infrastructure

- **Trucks and buses:** Fuel cell electric trucks and buses are increasingly on the roads in Asia, Europe, and North America. Improved cell performance and hydrogen storage systems are helping address driving-range and refueling-time constraints⁵⁵.
- **Maritime trial:** Projects exploring hydrogen or ammonia fuel cells for ships and ferries, especially for short-sea shipping or inland waterways, are ongoing. Zero-emission vessels are being designed around solid oxide or PEM-based powertrains^{15 & 56}.
- **Aviation trial:** While batteries dominate small electric aircraft, companies are experimenting with hydrogen fuel cell powertrains for regional aircraft, with the aim of balancing weight, range, and refueling considerations^{15 & 57}.

3.3.6 Hydrogen infrastructure and policy support

- **Green hydrogen boom:** Rapid expansion of electrolyser capacity (for green hydrogen generation) and policies supporting hydrogen infrastructure bolster fuel cell deployment in both mobility and stationary power^{8-13, 34 & 45}.
- **Refueling infrastructure growth:** Countries like China, Germany, Japan, the U.S., and South Korea are investing heavily in hydrogen stations to support fuel cell electric vehicles - pushing technological improvements in hydrogen compression, storage, and dispensing^{6, 18 & 58}.

3.3.7 Digital optimization and system integration

- **Real-time monitoring and control:** Advances in sensors and data analytics help optimize fuel cell operation. Software-based “virtual sensors” and digital twins improve performance predictability, system longevity, and maintenance scheduling¹⁵.
- **Hybrid systems:** Fuel cells are increasingly being paired with battery systems to balance peak loads, handle transient power demands, and optimize overall efficiency. Such hybrid configurations are now common in bus fleets and certain industrial applications⁵⁹.

In summary, recent fuel cell technology developments revolve around reducing material costs (particularly platinum), improving durability, scaling manufacturing, and adapting to new fuels (like ammonia). Policy momentum toward decarbonization and green hydrogen production is accelerating fuel cell adoption in both transportation (trucks, buses, ships, and potentially aircraft) and stationary power (backup power, microgrids). As more countries commit to hydrogen infrastructure, we can expect further cost reductions, performance gains, and commercial deployments in the near future.

3.4 Hydrogen infrastructure

The construction of hydrogen refueling stations, hydrogen pipelines, hydrogen storage facilities and other infrastructure has been accelerated, effectively solving the bottleneck of hydrogen energy utilization. China’s boom in the promotion of hydrogen fuel cell vehicles is generating increasing demand for hydrogen refueling stations (HRS), which has resulted in them being included in government plans and regulations. According to Interact Analysis, 30 provinces and

municipal cities across China issued government policies and plans covering the development of HRS. Of these, 29 local governments outlined 2025 targets for the construction of HRS, totaling more than 1,200 sites, which is more than the current global total⁶⁰.

Also, China's "Hydrogen into Ten Thousand Homes" project has achieved remarkable progress. It is a significant national project designed to integrate hydrogen energy into daily life and industrial use across the country. The initiative, launched by China's Ministry of Science and Technology in collaboration with the Shandong provincial government, aims to demonstrate the comprehensive use of hydrogen energy in industrial parks, community buildings, and transportation systems, thereby fostering a hydrogen-powered society⁴⁴.

A key component of this initiative involves blending hydrogen with natural gas to supply energy via pipelines to residential, commercial, and industrial users. This showcases the versatility of hydrogen as an alternative energy source that can be integrated into existing energy infrastructures. The initiative also includes the construction of hydrogen fueling stations, such as the one built by Air Products in Shandong Province, which supports the refueling of buses and trucks and signifies a move towards green transportation solutions⁶¹.

Hygreen Energy, a global leader in hydrogen technology and electrolyser manufacturing, has announced the successful delivery of a 25-megawatt electrolyser system to Huadian Weifang Power Generation Co., Ltd., comprising five 5-megawatt electrolyser stacks, each capable of producing high-purity hydrogen at 99.999% levels. This marks the largest hydrogen production initiative in the region to date. The system represents a significant step in scaling up hydrogen production and integrating green hydrogen into power and industrial applications⁶².

The project underscores China's commitment to reducing carbon emissions and promoting renewable energy use, aligning with the country's broader environmental goals, including the 14th Five-Year Plan and the '30•60' decarbonization targets, i.e. carbon emission peaking by 2030 and reaching carbon neutral by 2060. The integration of hydrogen technologies in Shandong, recognized for its strategic hydrogen roadmap and development plan, exemplifies the region's leading role in hydrogen energy innovation within China⁴⁴.

4. Discussion

In the area of green hydrogen production, AE and PEM remain the major tools while AEM is emerging. R&D and innovation of other means for producing hydrogen from organic matter is current underway with promising results. Larger and more efficient electrolysers and better coupling with renewable energy will lower the cost of green hydrogen.

Storage and transport of hydrogen seems to present more challenges to the industry, but new developments in solid-state storage using metal hydride as well as progress in hydrogen pipelines provide encouragements to the hydrogen community.

Fuel cell technologies are improving steadily and finding more and more scenarios of applications.

In the author's opinion, the hydrogen industry is turning matured particularly in producing and utilizing hydrogen, while in the areas of storage and transportation/shipping of hydrogen more improvements and innovations are required.

In the eyes of the investment community, hydrogen energy is an important strategic investment area in the global energy transition, and the market potential is huge. KPMG's Energy Transition Investment Outlook notes that hydrogen technology has become one of the key areas attracting large amounts of capital¹³. With policy promotion and technological maturity, it is expected that the hydrogen industry will continue to attract large capital inflows in 2025 and beyond to achieve a low-carbon transition for energy-intensive enterprises.

Despite the rapid development of the hydrogen energy industry, it still faces many challenges such as cost control, technological competition, and fierce market competition. In the future, the hydrogen energy industry needs to further reduce the cost of hydrogen production, improve the reliability and safety of technology, build a reasonable business model, and truly achieve stable growth and long-term sustainable development of commercial scale.

6. Conclusions

As an important path for energy transition and carbon reduction, hydrogen energy technology has made remarkable technological progress, expanded application scenarios, and continued to grow the industry and market scale. However, it also faces many challenges in terms of technology, cost and market. The industry and investment institutions are actively participating in the layout, and the prospects of the hydrogen energy industry are worth looking forward to. Before artificial, controlled nuclear fusion for power generation becomes a commercial reality, hydrogen remains a strong option in our package for energy transition and combating climate change.

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Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.

