

Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption across All Economic Sectors

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Abstract: This perspective article delves into the critical role of hydrogen as a sustainable energy carrier in the context of the ongoing global energy transition. Hydrogen, with its potential to decarbonize various sectors, has emerged as a key player in achieving decarbonization and energy sustainability goals. This article provides an overview of the current state of hydrogen technology, its production methods, and its applications across diverse industries. By exploring the challenges and opportunities associated with hydrogen integration, we aim to shed light on the pathways toward achieving a sustainable hydrogen economy. Additionally, the article underscores the need for collaborative efforts among policymakers, industries, and researchers to overcome existing hurdles and unlock the full potential of hydrogen in the transition to a low-carbon future. Through a balanced analysis of the present landscape and future prospects, this perspective article aims to contribute valuable insights to the discourse surrounding hydrogen's role in the global energy transition.

Keywords: hydrogen; energy storage; energy carrier; green hydrogen; blue hydrogen; decarbonization



Citation: Cheekatamarla, P. Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption across All Economic Sectors. *Energies* **2024**, *17*, 807. <https://doi.org/10.3390/en17040807>

Academic Editor: Alessia Arteconi

Received: 14 December 2023

Revised: 2 February 2024

Accepted: 6 February 2024

Published: 8 February 2024



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1. Introduction

Global decarbonization efforts are gaining momentum in response to the urgent need to address climate change and transition towards a sustainable, low/zero-carbon future. Reducing or eliminating carbon dioxide (CO₂) emissions from various sources, particularly those associated with human activities is key to sustainable decarbonization. Key strategies include renewable energy adoption, improvements in energy efficiency, electrification, carbon capture and storage, afforestation and reforestation, circular economy, policy, and regulation [1].

In this context, hydrogen stands out as a remarkably versatile energy carrier with the potential to revolutionize our global energy landscape [2]. Its adaptability lies in the fact that it can be produced from a variety of sources, both conventional and renewable. Once produced, hydrogen can be utilized in various sectors, serving as a clean fuel and chemical feedstock. This versatility positions hydrogen as a key pillar in the pursuit of decarbonization, offering a scalable and sustainable solution across diverse economic sectors. As we navigate the complexities of the global energy transition, hydrogen emerges as a key player, bridging sectors and serving as a catalyst for a more sustainable and resilient energy future.

Numerous studies were conducted on the subject of hydrogen's role in the energy transition. Kovac et al. recently reviewed the progress of hydrogen technologies and their application in both emerging and developed countries [3]. Similarly, Yue et al. conducted a

detailed review of the current progress of and outlook for hydrogen technologies, particularly related to power systems for generation and storage. Additionally, techno-economic analysis of such technologies was conducted to show the critical impact of cost, efficiency and durability [4]. Recent updates on the hydrogen economy were reviewed along with case studies of applying green hydrogen in transportation, industry, and power generation. The authors demonstrated that using green hydrogen in a combined cycle gas turbine power plant can result in significant CO₂ emission reductions [5]. Recent studies also provided a technological and geopolitical perspective on the role of green and blue hydrogen in the energy transition. The energy losses associated with the hydrogen supply chain and the significance of international standards and cost targets in enabling a hydrogen economy were emphasized [6,7]. A systematic review of the literature was recently reported, with a focus on the role of end users in the increased uptake of energy transition technologies [8]. Individual clean hydrogen case studies for different countries were also reported in which the authors provided prevalent scenarios and expected outcomes for different regions (Japan [9]; Africa and Europe [10,11]; China [12]; Germany [13]; Russia [14]; Australia [15]; the Global South [16]; Qatar [17]; South America [18]; the Middle East [19]; Mexico [20]; and Canada [21]). A number of review studies were also conducted on challenges and opportunities for innovation in hydrogen-related technologies [22–24], with particular focus on production [25–27], storage [28–30], distribution [31,32], grid integration [33,34], and utilization [35,36].

Most of the reported studies focused on technological advancements and opportunities for hydrogen as an energy transition medium; however, its complementary role as an enabling factor in realizing the full potential and deployment of renewable but intermittent solar and wind power has not been investigated. This aspect requires special attention since the current energy transition is not only driven by the typical energy security need but also by the critical energy sustainability and climate goals. Hence, one of the primary objectives of this paper is to shed light on the role of hydrogen in the energy transition landscape.

More specifically, the objectives are to (i) examine the synergy of energy demand growth, renewable energy scale projection, and the necessary storage capacities to explore hydrogen's potential role; (ii) review the 200-year historical energy transition for insights into factors relevant to the current energy transition; (iii) analyze the hydrogen production carbon intensity and its potential for carbon reduction across various sectors compared to conventional applications; (iv) review hydrogen's transformative role in the global energy landscape as a versatile and synergistic clean energy carrier; and (v) summarize key technological barriers and market dynamics critical for fostering widespread hydrogen adoption.

Section 2 provides a historical perspective on energy transformation while Sections 3–5 provide an overview of the role and significance of energy storage and how hydrogen can address some of the known energy transition challenges. Section 6 focuses on hydrogen production methods while Section 7 shows the value proposition of hydrogen in reducing the carbon footprints of different industries. One key limitation of this paper is the bibliometric review of individual hydrogen energy technologies since vast amount of literature has already been presented by numerous researchers, as discussed above. Additionally, given hydrogen's significance in the rapid transformation of the energy landscape, this article also provides a holistic overview of the role of hydrogen as an energy storage medium, conventional and emerging production sources, use cases and the impact of replacing fossil fuels, primary technology challenges and sustainability barriers, global investment scenarios, and recent success stories. Finally, an outlook for hydrogen's emergence as a key decarbonization pillar is provided.

2. Historical Energy Transitions

The historical energy transition over the past 200 years has been marked by significant shifts in primary energy sources and technological advancements [37]. The timeline below highlights key phases in this transition (Figure 1).

In the pre-industrial era (before 1800 A.D.), human societies relied predominantly on traditional biomass, such as wood and crop residues, for cooking, heating, and basic energy needs [38]. Water and wind power were occasionally utilized for mechanical processes. However, the advent of fossil fuels began in the 18th and 19th centuries. Particularly, the industrial revolution marked a major shift with the widespread use of coal as a primary energy source. Steam engines fueled by coal revolutionized transportation, manufacturing, and agriculture. Then, the rise of oil and gas began in late 19th century. The discovery of oil in the late 19th century and the subsequent development of the oil and gas industry led to a transition away from coal. The internal combustion engine transformed transportation, and oil and natural gas became key sources for heating and electricity generation [39].

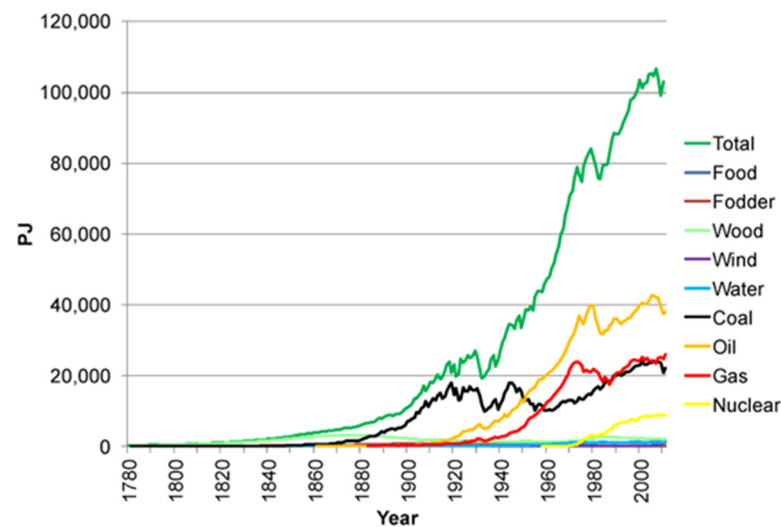


Figure 1. Historical global energy transitions [40]: Energy consumption profile of each primary energy resource from year 1780 to 2010.

Shift towards cleaner energy sources began in the early to mid-20th century through the utilization of electrification and nuclear power. The early 20th century witnessed a surge in electrification. Hydroelectric power plants were built, and advancements in nuclear power technology led to the deployment of the first nuclear reactors for electricity generation [40]. Concerns about environmental impacts and finite fossil fuel resources prompted a renewed interest in renewable energy sources. The late 20th century saw increased investments in solar, wind, and biomass energy. Governments worldwide started implementing policies to promote cleaner energy. The digitalization and energy efficiency focus began in the late 20th century, when advances in digital technology and automation facilitated improvements in energy efficiency. Smart grids, energy management systems, and energy-efficient technologies became integral to modern energy systems [41,42].

The global focus on sustainability kicked off in the 21st century. A growing global emphasis on sustainability and the urgent need to address climate change triggered the acceleration and transition toward cleaner and more sustainable energy sources, with increased investments in solar and wind power, energy storage, electric vehicles, and a growing commitment to reducing greenhouse gas emissions [1].

Throughout this historical energy transition, societal, economic, and technological factors played critical roles. The transition of the primary energy resource has proceeded gradually. Throughout history, each shift involving the replacement of over 25% of the energy supply source has taken a minimum of 50 years [43].

Additionally, the capacity factor is a crucial metric that represents the actual electricity output of a power plant relative to its maximum potential output over a specific period, usually a year. A high capacity factor indicates that a power plant is operating efficiently and consistently, while a lower capacity factor suggests more intermittent or variable operation. This value varies for different primary energy sources and is influenced by factors such

as technology, geography, and operational characteristics, as shown in Figure 2 [44]. For instance, nuclear plants have a high capacity factor of >90%, while fossil fuel plants vary in the range of 40–65%. Most critically, renewable energy technologies typically operate at just 25–35% of the peak capacity.

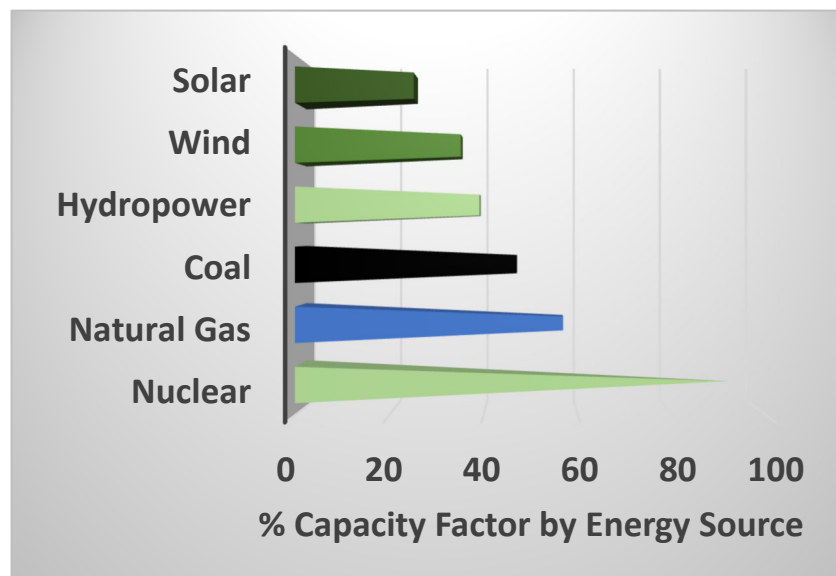


Figure 2. Capacity factors of different energy sources [45].

The capacity factor is a crucial metric in the context of energy transition, as it provides insights into the efficiency and reliability of energy sources. Understanding the significance of the capacity factor and its relationship with energy storage is key to building a resilient and sustainable energy system [46].

These transitions highlight the dynamic nature of the energy landscape, driven by evolving technologies, environmental concerns, and the need for more sustainable and resilient energy systems. The ongoing challenge is to balance energy security, affordability, and environmental sustainability in the quest for a cleaner and more sustainable energy future.

By studying past energy transitions, we can glean crucial insights for the future of the energy infrastructure. Just as the shift to fossil fuels required significant infrastructure investment and policy changes, so too will widespread adoption of a new energy supply. Lessons learned from past booms and busts can guide us in developing efficient production methods, robust storage solutions, and supportive regulations that incentivize innovation and market growth. Given the historical dependence of the energy transition on the critical capacity factor, hydrogen has emerged as a prominent energy storage medium in addressing the challenges mentioned above. The success factors implemented in each of the past energy transitions are still applicable in the current clean energy revolution.

3. Role of Hydrogen in Energy Transformation

Hydrogen has gained attention as a clean energy carrier in the 21st century, with a focus on its potential to decarbonize challenging sectors. Advanced technologies, including artificial intelligence, machine learning, and advanced materials, are being leveraged to optimize energy systems and enhance sustainability [47].

Hydrogen possesses unique properties that make it a promising candidate for energy storage in the context of renewable energy integration and grid resilience. Hydrogen has a high energy content (141.86 MJ/kg or 1478.6 Wh/L (@69 Mpa and 25 °C)) [48], making it an efficient energy carrier. This is particularly advantageous for applications where space or weight considerations are critical, such as in transportation or remote energy storage facilities. Hydrogen is versatile in its storage applications [49]. It can be stored

as a gas or liquid, and its energy can be converted back into electricity through various methods, including fuel cells and combustion, providing flexibility in how stored energy is utilized. Moreover, hydrogen has the potential for long-duration energy storage [50]. Unlike electrochemical battery technologies that may have limitations in terms of discharge time, hydrogen storage systems can store large quantities of energy for extended periods, making them suitable for addressing fluctuations in renewable energy generation, both daily and seasonally [51].

Hydrogen storage allows for the decoupling of energy production and consumption. Excess energy generated during periods of high renewable energy availability can be used to produce hydrogen through electrolysis, as shown in Figure 3. The dotted lines represent the intermittency associated with a renewable power grid, where excess energy is converted to and stored as hydrogen. This stored hydrogen can then be converted back to electricity when the energy demand is high (for instance, using fuel cells, turbines, etc.). Hydrogen storage systems can be designed to scale according to the energy storage needs of a particular application. This scalability makes hydrogen an adaptable solution for a range of energy storage requirements, from small-scale residential systems to large industrial facilities. Hydrogen storage systems can have relatively low energy losses during the storage and retrieval processes, especially when using advanced technologies such as solid oxide electrolysis cells (SOECs) and high-efficiency fuel cells.

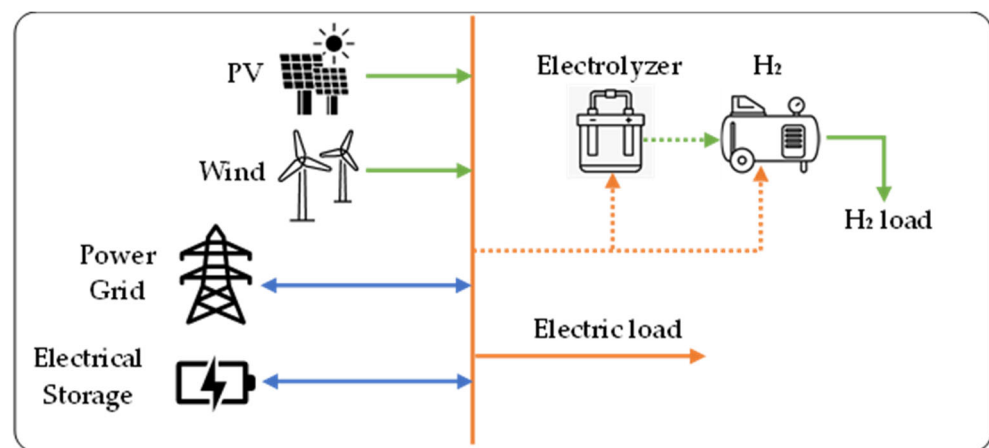


Figure 3. Grid stabilization and renewable source integration with hydrogen energy storage.

While hydrogen storage presents many advantages, it is essential to address challenges such as the cost of production, storage, and conversion technologies to maximize its potential as a widespread and cost-effective energy storage solution in the broader context of a sustainable energy transition [52].

4. Energy Storage Technologies

Recognizing energy storage as integral for mitigating climate change, it is crucial to note that only 3% of the global power capacity of 8.5 terawatts [53] is currently stored [54]. In order to cap global warming below 2 °C, the capacity for energy storage must triple by 2050. Achieving this ambitious goal necessitates exploring innovative approaches to expedite the development of viable cost and efficient energy storage technologies. The competition to identify the optimal energy storage solution is intensifying, with batteries and hydrogen emerging as primary contenders. The quest for clean energy storage solutions has thrust batteries and hydrogen into the spotlight. However, both technologies rely on critical materials, raising concerns about their long-term viability [55]. Navigating this complex landscape requires a nuanced understanding of the challenges and opportunities outlined below.

Those for batteries are as follows:

- Critical materials: lithium, cobalt, nickel, and rare earth elements like neodymium are essential for various battery types.
- Supply chain risks: geopolitical instabilities, environmental concerns surrounding mining, and limited recycling infrastructure threaten supply chain disruptions and price volatility.
- Innovation and diversification: research on new battery chemistries using less-critical materials, coupled with increased recycling and resource efficiency, is crucial for diversifying the supply chain and mitigating risks.
- Longevity and degradation: battery performance naturally declines over time, creating waste disposal challenges and requiring responsible end-of-life management.

Those for hydrogen are as follows:

- Critical materials: key elements such as platinum, iridium, nickel, and rare earth elements play a crucial role in the rollout of hydrogen production through electrolysis.
- Supply chain risks: these risks remain similar to those of batteries for certain low temperature electrolyzers; however, emerging high temperature electrolyzers use metals such as nickel, which have low supply chain risks.
- Cost and abundance: platinum's scarcity and high cost drive up the price of hydrogen production and utilization. However, alternative catalysts and electrolysis technologies are maturing to address this challenge.
- Infrastructure development: a large-scale hydrogen storage and transportation infrastructure requires significant investments, necessitating collaborative efforts from governments, industries, and investors.

Additionally, both technologies offer promising avenues for a clean and sustainable energy future, but each comes with its own strengths and weaknesses. Key distinguishing factors are discussed below:

a. Energy density: By weight, hydrogen offers higher energy density compared to lithium-ion batteries. This makes it ideal for applications where size and weight are significant factors, for instance, long-distance trucking, aviation, and portable power for remote areas.

b. Roundtrip efficiency: The current roundtrip efficiency of hydrogen technology hovers around 40%, compared to batteries' impressive 70–90% [56]. However, advancements in electrolysis and fuel cell technology are rapidly closing the gap. With continued research and development, hydrogen's efficiency is expected to rise significantly in the coming years.

c. Scalability and long-term storage: Batteries face a scaling challenge. Producing enough batteries to store the vast amount of energy needed for large-scale grid applications is resource intensive and expensive. In contrast, hydrogen can be easily stored in underground salt caverns or repurposed natural gas pipelines, offering virtually limitless storage potential. This makes it ideal for seasonal energy storage, where excess renewable energy generated in summer can be used to power homes in winter.

d. Environmental impact: Both hydrogen and batteries have their environmental upsides and downsides. While hydrogen production through electrolysis using renewable energy is clean, its current reliance on fossil fuels through steam methane reforming casts a shadow. However, with the rapid growth of renewable energy sources, this is becoming less of a concern. Batteries, on the other hand, contain critical minerals with environmentally damaging extraction processes [57]. Recycling and responsible sourcing are crucial for ensuring their sustainability.

Although hydrogen and batteries may appear to be competitors, the trajectory of energy storage's future is likely to be shaped by their synergistic collaboration, considering the aforementioned crucial parameters. The long-term viability of critical materials for batteries and hydrogen is not a matter of one vs. the other, but rather finding the right balance. Through constant innovation, responsible resource management, and collaborative efforts, it is totally possible to unlock the full potential of these clean energy storage solutions and pave the way for a sustainable future. Batteries demonstrate exceptional

performance in short-term, high-power applications, while hydrogen excels in long-term, large-scale storage. An integrated strategy optimally harnessing the unique strengths of each technology has a significant potential for laying the foundation for a clean and robust energy future. Hence, although batteries presently occupy the leading position, hydrogen's capacity for enduring and scalable energy storage positions it as a contender with substantial capabilities. In a more extensive framework, the aim is not to declare a single winner but to foster a synergistic interaction between these two leading players in the realm of clean energy. This approach ultimately contributes to the establishment of a sustainable energy future accessible to all.

5. Significance of Hydrogen

Hydrogen holds a substantial position in the context of the global transition toward a more sustainable and low-carbon energy future. Several key aspects underscore the significance of hydrogen, as detailed below.

Hydrogen is a versatile and clean energy carrier that can be produced without emitting greenhouse gases. When used in fuel cells or combustion processes, hydrogen produces energy with only water vapor as a byproduct, contributing to efforts to mitigate climate change. Hydrogen has the potential to play a crucial role in decarbonizing sectors that are challenging to electrify directly, such as heavy industry, shipping, and aviation. It offers a clean alternative to conventional fuels, helping reduce carbon emissions in these hard-to-abate sectors [58]. It can also serve as a form of energy storage, addressing the intermittency of renewable energy sources like wind and solar. Excess energy generated during periods of high renewable output can be used to produce hydrogen through electrolysis, which can then be stored and later converted back to electricity or used as a fuel [59]. Hydrogen is a key feedstock for various industrial processes, including the production of chemicals such as ammonia and methanol. Its versatility as one of the critical chemical building blocks in industrial applications makes it a fundamental element in many manufacturing processes [60]. Hydrogen can be used as a clean fuel for transportation, particularly in fuel cell vehicles. As an alternative to traditional gasoline or diesel, hydrogen-powered vehicles offer zero-emission mobility, contributing to efforts to reduce air pollution and dependence on fossil fuels [61]. Hydrogen can be produced from a variety of sources, including renewable energy and water. This diversity in production methods reduces dependence on specific fuels and geographic locations, enhancing energy security on a global scale [62]. The growing interest in hydrogen has spurred innovation and the development of new technologies. This, in turn, creates economic opportunities, driving job growth and fostering the emergence of a hydrogen-based industry.

In summary, the significance of hydrogen lies in its potential to address climate change, promote energy security, and drive innovation across various sectors, ultimately contributing to a more sustainable and resilient global energy system in achieving 2050 climate goals.

6. Hydrogen Production

Hydrogen production involves various methods, each with its own set of advantages and challenges [63]. Additionally, ongoing research and technological advancements continue to shape the landscape of hydrogen production.

Conventional hydrogen production methods include utilization of fossil fuels such as natural gas and coal. Today, the majority of hydrogen production is accomplished via one of these methods, with steam methane reforming (SMR) being the dominant resource. Gray hydrogen refers to hydrogen produced through methods that involve the use of fossil fuels, primarily natural gas, without implementing carbon capture and storage (CCS) technologies.

The production processes associated with gray hydrogen typically result in the release of carbon dioxide (CO₂) into the atmosphere. The term "gray" is used to denote the environmental impact of the production method, as it is associated with higher carbon emissions. The primary production methods for gray hydrogen include Steam Methane

Reforming (SMR), the most common method for gray hydrogen production, involving the reaction of natural gas with steam to produce hydrogen and carbon dioxide. Partial Oxidation (POX) is another method that utilizes natural gas, reacting it with a controlled amount of oxygen to produce hydrogen and carbon monoxide. Autothermal Reforming (ATR) combines the SMR and POX processes to attain thermal neutrality by producing higher concentrations of hydrogen than POX but lower than SMR [64]. In cases where coal is used as the feedstock, gasification processes can be employed to convert coal into syngas, from which hydrogen is extracted. This process also emits carbon (Figure 4).

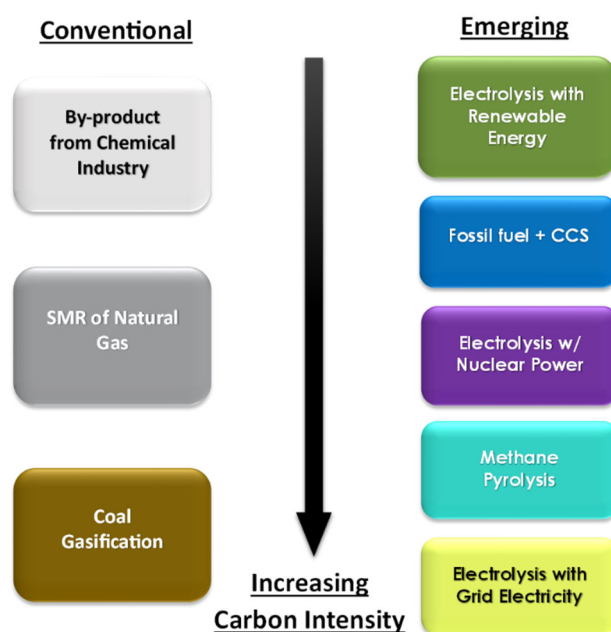


Figure 4. Hydrogen production methods and relative carbon footprint. Color-coded nomenclature for different production methods [64–66].

Additionally, current hydrogen sources include byproduct streams from multiple industrial processes such as petroleum refining, chemical manufacturing, chlor-alkali production, steel production, waste treatment, etc.

The environmental impact of gray hydrogen has led to an increased emphasis on developing and adopting cleaner and more sustainable methods of hydrogen production to align with global efforts to reduce carbon footprints and address climate change. As technologies advance, there is a growing focus on transitioning towards low-carbon and renewable hydrogen production methods. While gray hydrogen is widely produced due to its economic viability, it is considered less environmentally friendly compared to “green” or “blue” hydrogen [65]. Green hydrogen is produced through electrolysis powered by renewable energy sources, while purple hydrogen utilizes electricity produced with a nuclear-powered grid. Blue hydrogen, on the other hand, still involves the use of fossil fuels but incorporates carbon capture and storage to reduce emissions. Turquoise hydrogen involves pyrolysis and is a versatile method that can use different feedstocks, contributing to the utilization of methane, biomass and waste materials [66].

“Geologic hydrogen” typically refers to hydrogen that is naturally occurring within the Earth’s subsurface, often found in geological formations or reservoirs. Unlike hydrogen produced through industrial processes, geologic hydrogen has its origins in natural geological processes. It is important to note that while geologic hydrogen exists, it is not always readily accessible or commercially viable for extraction and use [67]. Extracting hydrogen from geological formations involves challenges related to technical feasibility, economic viability, and environmental considerations [68]. The study of geologic hydrogen contributes to our understanding of Earth’s subsurface processes, and it has implications

for various scientific and industrial applications, including energy exploration, storage, and potential future hydrogen resources.

The exciting new hydrogen production methods listed below are also paving the way for a sustainable future:

1. Photoelectrochemical water splitting: inspired by nature's photosynthesis, this method uses sunlight and specially designed semiconductors to directly split water into hydrogen and oxygen.
2. Biomass gasification: instead of fossil fuels, this method uses organic materials like wood chips or agricultural waste to produce syngas, a mixture of hydrogen and other gases.
3. Supercritical water gasification: this cutting-edge technique uses high-pressure and high-temperature water to convert almost any organic material, from seaweed to plastic waste, into hydrogen and valuable carbon byproducts.
4. Biological hydrogen production: Microorganisms such as algae and bacteria are being employed as hydrogen producers, utilizing their natural metabolic processes to generate clean hydrogen by converting organic matter or wastewater.

These new methods offer several advantages over traditional fossil fuel-based hydrogen production:

- Reduced carbon footprint: by using renewable resources like sunlight, biomass, or even waste, these methods significantly reduce greenhouse gas emissions compared to the conventional and some of the emerging clean methods.
- Scalability: many new methods can be implemented in small-scale or modular systems, making them suitable for distributed energy production and for applications in remote areas.

While challenges remain in the areas of energy efficiency and production scaleup, the future of hydrogen is bright. By embracing these innovative methods, we can unlock the potential of this versatile fuel and accelerate the transition to a clean and sustainable energy future. As research and development continues, we can expect even more breakthroughs that will further solidify hydrogen's role in powering a clean energy future.

7. Hydrogen Use Cases

Hydrogen plays a vital role in various industrial processes across sectors. Primary uses of hydrogen today (displayed in Figure 5) include refining, chemical production, direct reduced iron (DRI) production, and heat generation. In refining operations, hydrogen is used for manufacturing ammonia and methanol and in hydrogenation reactions [69].

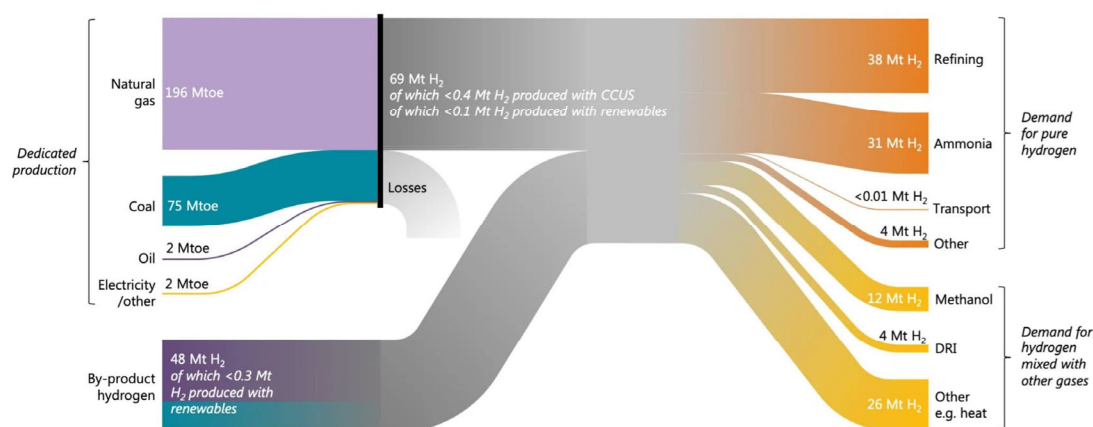


Figure 5. Hydrogen value chains in today's world [69]. Mtoe—million tonnes of oil equivalent. Mt—million tonnes. Source: IEA (2019) The Future of Hydrogen, <https://www.iea.org/reports/the-future-of-hydrogen> (accessed on 21 October 2023).

More specifically, hydrogen is extensively used in the refining industry for hydrocracking processes, where it helps break down large hydrocarbons into smaller, more valuable

products, such as diesel and other refined fuels. It is employed in desulfurization processes to remove sulfur impurities from crude oil, resulting in cleaner and environmentally friendly fuels. One of the major applications of hydrogen is in the production of ammonia, a key precursor for fertilizers and various chemicals.

Additionally, it is a crucial feedstock for the production of methanol, which is used in various chemical processes and as a fuel. Hydrogen is also used in various hydrogenation reactions, where it is added to unsaturated compounds to produce saturated compounds. This is common in the production of edible oils, for instance.

The projected use cases for hydrogen have been evolving as countries and industries increasingly focus on decarbonization and the transition to cleaner energy sources. Some anticipated use cases for hydrogen in the coming years are transportation, mid-grade and high-grade heating, power generation, combined heat and power, maritime applications, and hydrogen blending with natural gas for consumption in all economic sectors. New use cases include transportation fuel in both fuel cell vehicles and internal combustion engines; industrial heating and drying; production of carbon-free chemicals such as ammonia and methanol; steel production; power generation via fuel cells, turbines, and engines; and aviation and maritime applications via fuel cell power generation. The cost competitiveness of hydrogen applications and its evolution over time suggests hydrogen's entry into all sectors of the economy, including transportation, buildings, and industry [70].

Within all economic sectors, hydrogen is anticipated to find significant adoption rates in industrial applications first. Industry represents 30% of U.S. primary energy-related CO₂ emissions, or 1360 million metric tons (MMT) of CO₂ (2020). The generation and use of heat is the most significant end use of energy in the industrial sector [71], accounting for more than half of the total energy consumed. Process heaters and dryers are widely used on an industrial scale. For instance, process drying accounts for 10–15% [72] of total industrial energy use. Friedmann et al. [73] found hydrogen to be a feasible substitute for fossil fuels.

Replacing natural gas and coal with hydrogen combustion would reduce emissions by 7 kg of CO₂ per kg of H₂ and 12 kg of CO₂ per kg of H₂, respectively [74]. Blending hydrogen generated with different carbon intensities and at different energy-based concentrations with natural gas (i.e., % energy delivered by individual fuels) can influence the overall carbon emission reduction capability, as shown in Figure 6. Blending of hydrogen with different carbon footprints in the range of 0–100 g of CO_{2e} emissions per kilowatt-hour of energy utilized will yield different levels of carbon reduction potential compared to natural gas utilization.

The dependency of the carbon intensity of the hydrogen, its blending fraction on the basis of energy rather than molar concentration, is not easily found and needs to be calculated for specific scenarios. Figure 6 allows all hydrogen stakeholders to quickly assess the carbon emission reduction capability of multiple shades of hydrogen blends over the 0–100% range, independent of the end-use application being investigated. As shown, the carbon intensity of the fuel and the blend concentration influence the overall carbon reduction potential in the end-use application. For instance, green hydrogen represented by hydrogen with a carbon intensity of zero can lower the carbon equivalent emissions by the same blend concentration with primary energy. However, blue hydrogen represented by a carbon intensity of 30 g of carbon dioxide per kilowatt-hour of energy can only lower the carbon equivalent emissions by approximately 80% when completely replaced with a fossil fuel. It has to be noted that the baseline primary energy source is considered to be natural gas but since the analysis was conducted on a unit energy basis, the estimated carbon reduction percentages are valid for all the primary energy sources of interest—whether it be a building or industrial heating equipment using fossil fuels or an internal combustion engine of a vehicle or a turbine generating electric power.

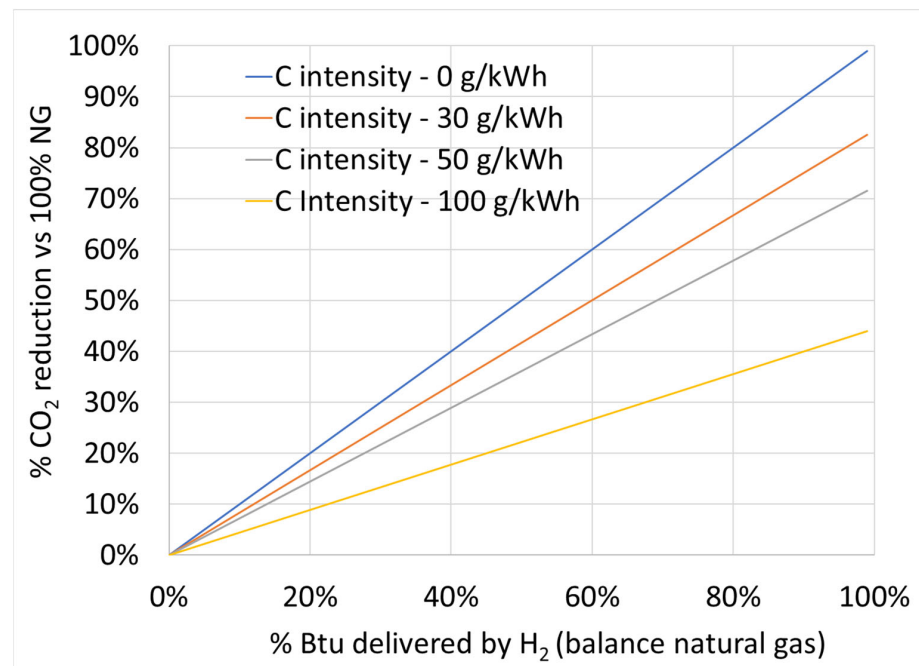


Figure 6. Impact of hydrogen concentration (on an energy basis) and its carbon footprint on CO₂ reduction capacity.

Thus, efficient utilization of low- or zero-carbon fuel as the primary energy resource in supporting current and future industrial energy needs targeting energy and environmental security via hydrogen is a highly attractive sustainable decarbonization pathway.

For instance, Figure 7 displays the impact of displacing fossil fuels in sector specific applications with zero-carbon, green hydrogen. As shown, each kilogram of green hydrogen has the potential to eliminate 7–12 kg of CO₂ in fossil fuel powered industrial heating equipment. Similarly, 13–14 kg of carbon dioxide emissions can be eliminated per every kilogram of hydrogen utilized in replacing fossil fuel consumption in the transportation sector. The steel industry has the potential to reduce carbon emissions by as much as 32 kg of CO₂ equivalent per kilogram of hydrogen employed in the steel processing phase [75].

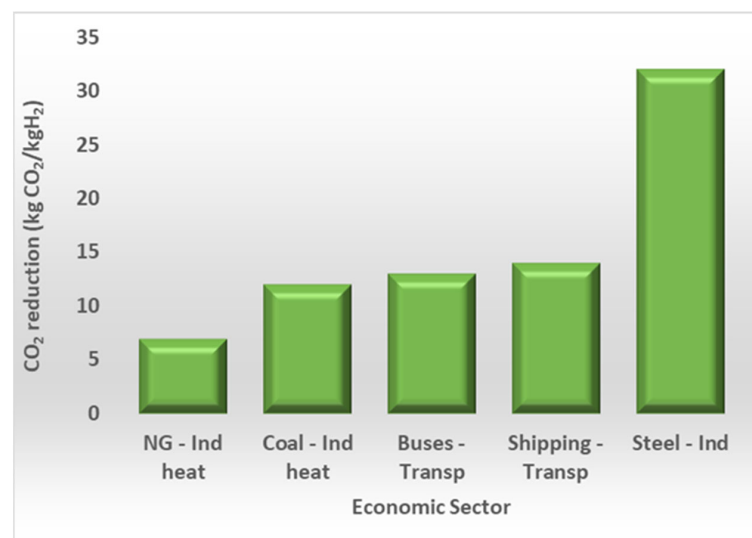


Figure 7. Impact of replacing fossil fuel with hydrogen: CO₂ reduction capacity per kilogram of H₂ utilized in industrial heating, buses, shipping, and steel manufacturing industries [69]. NG—natural gas, Ind—industrial, Transp—transportation.

Hydrogen's true potential as a clean fuel hinges on prioritizing clean production methods. Ignoring carbon intensity will ultimately fuel the problem, where the negative perceptions will slow the technology investments, innovation, and adoption. In summary, careful consideration of the hydrogen's carbon intensity is pivotal for aligning hydrogen production with environmental and climate goals. By prioritizing low-carbon or carbon-free production methods, we can harness the full potential of hydrogen as a clean and sustainable energy carrier, contributing to a more environmentally friendly and resilient future.

8. Barriers to Hydrogen Growth and Adoption

The growth and adoption of hydrogen as a clean energy carrier face several barriers, ranging from technological and economic challenges to policy and public perception issues.

The cost of hydrogen can vary depending on the production method used [75]. Three prominent hydrogen production pathways are generally considered to be the gray, blue, and green shades. Reported costs [76] for gray hydrogen range between \$1 and \$2 per kilogram whereas blue hydrogen varies between \$1.2 and \$2.9 per kilogram. Conversely, green hydrogen costs vary in a wide range from \$2.2 to \$8.1 per kilogram. It is important to note that the cost landscape for hydrogen is dynamic, and ongoing advancements in technology, economies of scale, and policy support can influence production costs. Additionally, the industry is moving towards a focus on green hydrogen produced through electrolysis with renewable energy, as it aligns with sustainability goals and addresses environmental concerns associated with gray hydrogen production. The cost competitiveness of hydrogen is one of the critical factors in its adoption and integration into various sectors of the economy. Multiple studies have shown the viability and sustainability of hydrogen as a broad energy carrier in the cost range of \$0.5–\$1 per kilogram [77].

The carbon intensity of the hydrogen production method described in Figure 8 refers to the amount of carbon dioxide emissions formed during the production of one kilogram of hydrogen. Different hydrogen production methods have different levels of the carbon intensity factor [78]. As shown in Figure 8, the conventional gray shade hydrogen generated via natural gas reforming carries a relatively moderate carbon intensity of 10 kg of carbon dioxide per kilogram of hydrogen. The blue shade of hydrogen produced from natural gas and combined with carbon capture and storage typically yields carbon intensities in the range of 1–5 kg of carbon dioxide per kilogram of hydrogen. Coal gasification and utilization of the US power grid on the other hand produces hydrogen with very high carbon intensities in the range of 19–21 kg of carbon dioxide emissions per kilogram of hydrogen. Green hydrogen generated via electrolysis and utilizing renewable electricity is the cleanest technology of all, with a negligible carbon intensity. As discussed in Section 6, this carbon intensity value of hydrogen is a crucial factor in assessing the environmental sustainability of hydrogen as an energy carrier.

An insufficient infrastructure, including hydrogen production facilities, storage, and distribution networks, hinders the widespread availability and accessibility of hydrogen. The development of a comprehensive hydrogen infrastructure faces multifaceted challenges that span technical, economic, and regulatory domains. One of the foremost hurdles is the limited number of hydrogen refueling stations, hindering the widespread adoption of hydrogen fuel cell vehicles. Establishing a robust infrastructure involves substantial upfront costs, encompassing the construction of production facilities, storage systems, and distribution networks.

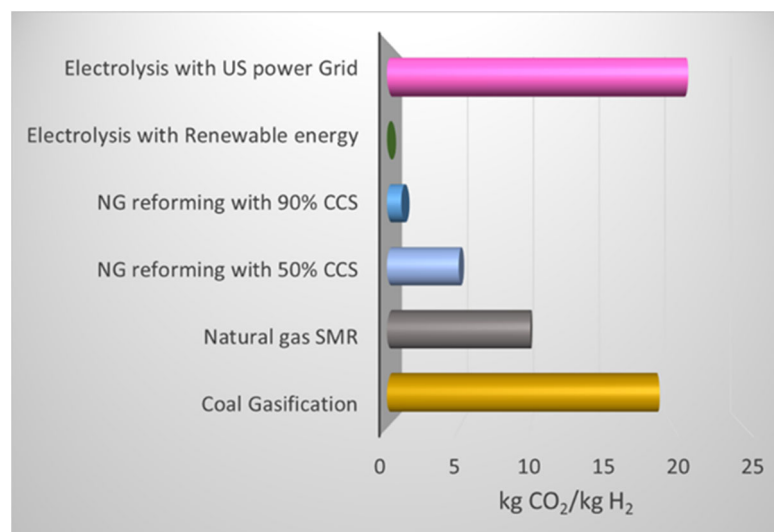


Figure 8. Carbon dioxide footprints of different hydrogen production methods [73].

Transportation and storage challenges arise due to hydrogen's low volumetric energy density, necessitating the development of efficient and cost-effective storage solutions. High-density hydrogen storage solutions play a pivotal role in overcoming this challenge. One notable approach is liquid hydrogen storage, where hydrogen is maintained in liquid form at extremely low temperatures, offering a higher energy density. Metal hydrides represent another avenue, forming compounds with metals that can absorb and release hydrogen efficiently. Chemical hydrogen storage involves storing hydrogen in chemical compounds like ammonia, providing a stable and high-density storage medium. Advanced carbon-based materials, such as carbon nanotubes and graphene, with their porous structures, enable the adsorption of hydrogen molecules, contributing to high-density storage. Additionally, composite materials, like high-strength carbon fiber composites, and advanced porous materials like metal-organic frameworks (MOFs) and porous coordination polymers (PCPs), offer solutions for both gaseous and reversible hydrogen storage with increased densities. Each of these high-density storage technologies addresses specific application needs, contributing to the advancement and diversification of hydrogen storage methods for various industries, including the transportation and energy sectors. Continued research and innovation in these areas aim to enhance efficiency, safety, and overall viability, accelerating the integration of hydrogen as a clean energy solution.

The efficiency of electrolysis, a key method for green hydrogen production, needs improvement to enhance the overall viability of the process. One significant challenge is the overall efficiency of the electrolysis process. Traditional electrolyzers often experience energy losses during various stages, including the conversion of electrical energy into chemical energy and the subsequent separation of hydrogen and oxygen. These inefficiencies reduce the overall effectiveness of green hydrogen production and contribute to higher costs. Overcoming these efficiency challenges is crucial for making green hydrogen production more competitive and accelerating its role in a sustainable energy transition.

Hydrogen, while offering numerous benefits as a clean energy carrier, presents safety considerations that must be addressed to ensure widespread acceptance and deployment. One key barrier to hydrogen safety is its high flammability and wide flammability range in the air. This characteristic requires stringent safety measures to prevent and mitigate the risk of fire or explosion. Hydrogen's low ignition energy and flame visibility pose challenges in detecting leaks promptly. Moreover, the colorless and odorless nature of hydrogen makes it imperceptible to human senses, necessitating effective leak detection systems. The high-pressure storage and transportation of hydrogen also require robust infrastructure and safety protocols to prevent accidents.

Additionally, inconsistent or unclear policies and regulations across regions can also hinder investment and impede the growth of the hydrogen sector. As hydrogen often involves cross-border trade and collaboration, the lack of global standards and cooperation can further impede its growth. Similarly, limited public awareness and understanding of hydrogen technologies can also lead to skepticism and resistance towards the adoption of hydrogen enabled energy technologies.

Although the road to a hydrogen-powered future is fraught with challenges, the potential rewards are immense. By tackling the existing hurdles and capitalizing on the accelerating progress, we can unlock the power of hydrogen and build a cleaner, more sustainable future for generations to come. Addressing all these barriers requires a coordinated effort from governments, industries, and researchers to invest in research and development, incentivize adoption, and establish supportive policies. The hydrogen industry is dynamic, and ongoing efforts aim to overcome these barriers and unlock the full potential of hydrogen as a clean energy carrier.

9. Global Investments

Global hydrogen investments have witnessed a significant upswing as countries and industries increasingly recognize the pivotal role of hydrogen in achieving sustainable energy goals. Governments worldwide are committing substantial funds to support hydrogen-related projects, encompassing research, development, and infrastructure initiatives. In Europe, the European Clean Hydrogen Alliance and Horizon Europe program are driving considerable investments. Asian nations, particularly Japan and South Korea, have allocated substantial public funds to advance hydrogen technologies, with Japan fostering a “hydrogen society” and South Korea focusing on green hydrogen. In the United States, the Department of Energy has been investing in hydrogen R&D through various programs. The private sector, including major corporations and venture capital firms, is actively contributing to hydrogen investments. These funds are directed towards innovative solutions, infrastructure development, and collaborative efforts such as the Hydrogen Council, fostering a global commitment to advancing hydrogen technologies. The dynamic landscape of global hydrogen investments underscores the growing importance of hydrogen as a key player in the transition to a sustainable and low-carbon energy future. Governments, private companies, and international organizations have been allocating substantial funds to support research, development, and deployment of hydrogen technologies. A comprehensive report on the state of the global hydrogen economy was recently published [79]. The report claims more than 1000 hydrogen project proposals, with a majority of them to be fully deployed by 2030. According to this report, a total budget of \$570 billion with a production capacity of 38 million tonnes of hydrogen per year has been planned, with a majority of them located in Europe, North America, and the Far East.

Global investments in hydrogen are surging, driven by the pursuit of a cleaner energy future and the versatile potential of this abundant element. As countries and companies strive to decarbonize their economies, hydrogen is increasingly seen as a key player in sectors like power generation, transportation, and industry.

A summary of the investment boom is as follows:

- In 2023, global announced investments in clean hydrogen projects reached over \$570 billion, representing a 35% increase compared to the beginning of the year.
- The electrolysis capacity, the crucial technology for producing hydrogen from water using renewable electricity, saw impressive growth as well, with over 1 GW deployed globally in 2023 alone.
- This investment boom is fueled by various factors, including falling renewable energy costs, supportive government policies, and growing corporate interest in hydrogen solutions.

A summary of the investment landscape is as follows:

- Renewable and low-carbon hydrogen production currently attracts the majority of investments, accounting for roughly 65% of the total. This includes green hydrogen

produced using renewable electricity and blue hydrogen produced from natural gas with carbon capture and storage.

- The transmission, distribution, and storage infrastructure also receives significant investment, with around \$40 billion allocated to this sector. Building this infrastructure is crucial for enabling large-scale hydrogen deployment and utilization.

A summary of the regional breakdown is as follows:

- Europe remains the leading region in terms of hydrogen investments, followed by Asia and North America.
- Countries like Japan, Germany, and China are leading the charge with ambitious hydrogen strategies and significant financial backing.

Global hydrogen investments are just the beginning of the transformative journey. As we embrace the potential of this versatile fuel, we can pave the way for a cleaner, more sustainable future for generations to come.

10. Hydrogen Success Stories

Recent successes in the hydrogen sector span various categories, showcasing the growing prominence and viability of hydrogen across the energy landscape.

In transportation end-use applications, the deployment of hydrogen fuel cell vehicles, such as the Toyota Mirai and Hyundai Nexo, marked milestones in achieving cleaner transportation. Seven million kilometers were driven by 120 hydrogen taxis deployed by Zero Emission Fleet Vehicles for European Rollout (ZEFER) in Paris and London [80]. In South Africa, Anglo American, a leading global mining company is currently exploring the potential for a hydrogen valley that will cluster several industrial and research initiatives to carry out pilot projects across the complete hydrogen value chain [81]. As part of this effort, the group launched the world's largest and lightest 510-ton hydrogen-powered vehicle. Similarly, hydrogen-enabled zero-emission aviation has witnessed notable successes, marking a transformative shift toward more sustainable air travel. Aircraft manufacturers such as Airbus have been at the forefront of innovation with projects like the zero emission (ZEROe) aircraft concept.

Green hydrogen production gained momentum with notable projects like Australia's Murchison Renewable Hydrogen Project, utilizing wind and solar power for large-scale production. Similarly, the GrInHy 2.0 electrolyzer (Salcos, Salzgitter, Germany), a 720 kW Solid Oxide Electrolyzer Cell technology (SOEC), produced 170 NM³ of green hydrogen per hour using waste heat from a steel plant at a 84% electrical efficiency in Germany [82]. Another prominent success in the space of blue hydrogen is the Shell Blue Hydrogen Process (SBHP) in greenfield projects, capturing 99% of carbon emissions and achieving up to 25% lower costs [83].

The integration of hydrogen in industrial processes, particularly in steel production projects like Hydrogen Breakthrough Ironmaking Technology (HYBRIT) in Sweden and H2 Green Steel in Norway, demonstrated progress toward decarbonizing heavy industries.

Advances in safety were witnessed through ongoing research and innovations in leak detection systems, addressing concerns associated with hydrogen's flammability. Infrastructure development saw expansions in hydrogen refueling networks, enhancing accessibility for fuel cell vehicles. A total of 19 recommendations were formulated by Prenormative Research for the Safe Use of Liquid Hydrogen (PRESHLy) [84] on regulations, codes and standards to anticipate and mitigate accidents related to the hydrogen supply chain.

Hydrogen storage success stories highlight pivotal advancements in overcoming one of the key challenges in harnessing hydrogen as a clean energy carrier. The construction of the first green hydrogen storage demonstrator in a salt cavern is underway in France [85]. Similarly, the world's first liquefied hydrogen carrier, a 1250 cubic-meter tank, completed a 9000 km voyage [86].

These are just a few examples of how hydrogen is making waves across the globe. From everyday transportation to heavy industry, clean fuel solutions are gaining traction,

demonstrating the potential of hydrogen to reshape our energy landscape. Beyond these success stories, several exciting developments are emerging:

- Advances in electrolysis technology are making hydrogen production from renewable electricity more efficient and affordable.
- Innovation in hydrogen storage and transportation is expanding the reach and potential applications of this versatile fuel.
- Growing government support and corporate investments are creating a thriving hydrogen ecosystem, paving the way for wider adoption.

Collaborations and strategic partnerships between major energy companies, technology providers, and governments underscore the global commitment to advancing hydrogen technologies. In sum, recent successes across end-use applications, production, safety, storage, and distribution underscore the multifaceted growth and potential of hydrogen as a key player in the transition to a sustainable and low-carbon energy future. As the cost of hydrogen technology continues to decrease and the infrastructure expands, we can expect to see even more success stories emerge in the coming years. The future of hydrogen is bright, and its potential to power a cleaner, more sustainable world is undeniable.

11. Conclusions

The outlook for hydrogen is characterized by an increasingly central role in the global effort to transition towards a sustainable and low-carbon energy future. As nations intensify their commitments to decarbonization, hydrogen emerges as a versatile and clean energy carrier, capable of addressing challenges across diverse sectors and providing energy independence. Ultimately, the success of hydrogen as a clean energy solution hinges on our ability to learn from the past, harness its versatility, and navigate the challenges of implementation. By acknowledging the historical context of energy transitions and applying those lessons to the present, we can pave the way for a future powered by clean, sustainable hydrogen, ensuring a brighter tomorrow for generations to come. In the landscape of global energy, the transition towards hydrogen as a significant player requires careful consideration of multiple factors to ensure successful growth, widespread adoption, and a positive outlook for the future. Technological advancements stand as a cornerstone in this endeavor. Continuous research and innovation are imperative to enhance the efficiency and cost effectiveness of hydrogen production, storage, and utilization technologies.

Green hydrogen, produced through electrolysis powered by renewable energy, is gaining prominence as a key player in this transition. Technological advancements and declining costs in electrolysis processes, especially in proton exchange membrane and alkaline electrolyzers, are contributing to the economic feasibility of green hydrogen production. Blue hydrogen, produced from natural gas with carbon capture and storage, continues to play a transitional role, offering a pathway to decarbonization while the infrastructure and technology for green hydrogen mature. Additionally, the development of technologies in the field of solid oxide electrolyzers, including reversible solid oxide cells, is an area of ongoing research and innovation. What makes reversible solid oxide cells particularly noteworthy is their ability to operate in reverse, functioning as fuel cells that generate electricity from hydrogen. This dual functionality enhances flexibility in the hydrogen production and utilization cycle, contributing to the development of a sustainable and adaptable hydrogen infrastructure. As the world seeks cleaner energy alternatives, low cost, reliable, and energy-efficient electrolyzers emerge as a key technology facilitating the growth of hydrogen in a way that aligns with the goals of a greener and more sustainable energy landscape.

In transportation, hydrogen fuel cell vehicles are becoming more viable, providing zero-emission mobility solutions. Industries such as steel manufacturing are exploring hydrogen as a cleaner alternative, showcasing the potential to significantly reduce carbon emissions. The integration of hydrogen into power generation, both as a direct fuel and through power-to-gas applications, adds flexibility to renewable energy systems. Moreover, hydrogen is gaining traction as an energy storage solution, contributing to grid stability

and addressing the intermittency of renewable sources—a much needed solution to achieve global net zero emission targets.

Infrastructure development plays a crucial role in facilitating the adoption of hydrogen as an energy carrier. A robust network of production, distribution, and refueling facilities is essential to meet the growing demand across various sectors. Collaborative efforts between governments, industries, and research institutions are essential in creating the necessary infrastructure and overcoming the challenges associated with scaling up hydrogen technologies. Policy support is a linchpin for the successful transition to hydrogen. Governments worldwide need to implement supportive policies that incentivize the development and adoption of hydrogen technologies. This includes financial incentives, regulatory frameworks, and strategic investments to stimulate research and development. For instance, the “Hydrogen Shot” initiative by the U.S. Department of Energy (DOE) is part of the broader goal to advance hydrogen as a clean and sustainable energy source. The Hydrogen Shot initiative aims to significantly reduce the cost of clean hydrogen production to \$1 per 1 kg in one decade. The objective is to accelerate the development and deployment of hydrogen technologies, supporting the U.S. in achieving its clean energy goals. The private sector is actively investing in hydrogen technologies, and governments worldwide are formulating comprehensive hydrogen strategies and committing substantial funds to support research, development, and infrastructure projects. Collaborative initiatives, such as the Hydrogen Council, are fostering cross-industry partnerships to accelerate the deployment of hydrogen technologies globally. Incentives for green hydrogen generation and utilization are key tools to stimulate demand.

While the outlook is optimistic, challenges remain, including the need for further cost reductions, infrastructure development, and addressing technical and safety considerations. The evolving regulatory landscape and international collaboration will play crucial roles in shaping the trajectory of hydrogen adoption.

Industry collaboration is another key consideration. To achieve a comprehensive hydrogen ecosystem, various industries must work together. This involves partnerships between energy producers, manufacturers, transportation entities, and end users. Shared knowledge and resources can accelerate the deployment of hydrogen technologies across different sectors, fostering a more sustainable and interconnected energy landscape. Cost competitiveness is paramount for the widespread adoption of hydrogen. As production costs decrease, hydrogen becomes more economically viable, making it an attractive option for diverse applications. Continued research and development efforts are essential to bring down costs and improve the overall competitiveness of hydrogen in the energy market. Public awareness and acceptance are critical components of a successful energy transition. Educating the public about the benefits of hydrogen, dispelling myths, and showcasing real-world applications can garner support and enthusiasm for adopting hydrogen technologies. Public backing, in turn, can influence policymakers and drive further investments in the hydrogen infrastructure.

The ongoing efforts to overcome these challenges, coupled with the demonstrated successes and increasing momentum, position hydrogen as a key enabler in achieving a sustainable and resilient energy future. The coming years are poised to witness significant advancements, market expansion, and the establishment of hydrogen as a mainstream primary energy component.

In summary, a successful hydrogen energy transition requires a holistic approach that considers technological advancements, infrastructure development, policy support, industry collaboration, cost competitiveness, and public awareness. By addressing these considerations, the global community can pave the way for a sustainable and resilient energy future with hydrogen playing a crucial role in the global energy mix.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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