hydrogen

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Review

The Hydrogen Economy: Progress and Challenges to Future Growth

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Abstract

The rally to mitigate growing carbon emissions and climate change necessitates decarbonization strategies, with hydrogen emerging as a key candidate option across multiple sectors. This review examines the current state of the hydrogen economy, including production, implementation, and associated risks. Hydrogen's versatility in industry, transportation, and energy storage is highlighted, alongside the challenges of transitioning from fossil fuel-based production. It explores the current state of hydrogen technologies, differentiating between green, blue, and gray hydrogen production methods, and highlights advancements in production techniques like thermochemical water splitting. Key findings show that while green hydrogen offers the cleanest pathway, high production costs and infrastructure limitations remain significant barriers to widespread adoption. This study also addresses safety concerns and public perception, emphasizing the need for robust risk assessment methodologies and management approaches. Furthermore, this paper underscores the importance of technological innovations, such as high-temperature electrolysis and synergies with renewable energy sources, to enhance efficiency and sustainability. Policy recommendations include financial incentives, regulatory frameworks, and international cooperation to accelerate hydrogen adoption and balance its development with other low-carbon solutions.

Keywords: hydrogen economy; hydrogen production; green hydrogen; hydrogen storage; fuel cells; hydrogen infrastructure; energy transition; decarbonization; policy recommendations; sustainable future; risks; risk management

1. Introduction

There is a broad scientific consensus that the proliferation of carbon emissions, global warming, and climate change poses significant risks to ecosystems and human civilization [1]. Rising global temperatures, increased frequency of extreme weather events, and prolonged droughts signal an urgent need for action. In response, decarbonization has emerged as a fundamental strategy aimed at systematically reducing carbon dioxide (CO_2) emissions across all sectors of society. Hydrogen can serve as an important piece in decarbonizing multiple industries, including transportation, energy storage and delivery, and high-temperature process industries. The paradigm of hydrogen as a clean energy carrier serving multiple sectors of the economy and catalyzing widespread decarbonization and sustainable development is the "hydrogen economy" [2].

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The global decarbonization effort is driven by international agreements, such as the Paris Agreement, which seeks to limit global temperature rise to below 2 °C above pre-industrial levels, with an aspirational goal of 1.5 °C [3]. Governments, corporations, and financial institutions are aligning policies and investments toward low-carbon practices, emphasizing structural shifts in energy production, transportation, industry, and agriculture [4]. Key strategies include scaling renewable energy sources, such as wind, solar, and hydroelectric power, enhancing energy efficiency across sectors, and promoting the electrification of industrial processes and transportation [5]. These strategies are bolstered with economic instruments like carbon pricing to further incentivize emission reductions [6]. In light of the multidomain, transdisciplinary drive toward a hydrogen economy, this review takes a wide-ranging look at the present state of the industry, recent advancements, and opportunities for further improvement. Table 1 distinguishes this review from other recently published academic and industry reviews of hydrogen.

Table 1. Comparison of the present review versus selected alternatives.

Review	Scope & Key Themes	Limitations/Gaps	Novelty of the Present Review
Present Review	End-to-end view of hydrogen economy: Production, implementation, applications and risks at present. Cross-sector overview of recent progress, continuing challenges, and opportunities.	Reduced analysis on market and growth.	Novelty in integration of state-of-practice review integrated with technical literature. This review covers policy, economics, infrastructure readiness, risks, and long-term growth barriers.
Staffell et al., 2019 [7]	Production, storage, transport & applications in global energy with focus on power, heat and transport; strong emphasis on fuel cells and energy-system integration.	Focuses more on fuel cells; limited economic/policy depth	Th present review expands treatment of economic barriers, investment trends, and global policy frameworks.
IEA Annual Global Hydrogen Review [8]	Production, demand, policy, infrastructure	High-level focus on current industry environment	The present review synthesizes academic and industry literature to provide a scholarly, integrative, cross-sector review.
Singh et al., 2025 [9]	Structured assessment across technology, economics, environment, policy, and collaboration.	Limited perspective beyond green hydrogen production.	The present review generalizes to all hydrogen pathways and full scope of hydrogen value chain, adds sector-specific progress, and provides a more depth in risk and risk analysis.

The adoption of net-zero commitments by major economies and multinational corporations has accelerated investments in green technologies and sustainable infrastructure, including in the hydrogen economy [4]. In 2023, global investment in hydrogen supply projects reached $3.5 billion, with 80% directed toward electrolysis, mostly in China and Europe, and the rest toward CCUS-equipped production, led by North America; despite market challenges, hydrogen start-ups raised $3.7 billion in equity, and key innovations like AEM electrolysis and methane decomposition advanced to TRL 7 (prototype demonstration), though an estimated $50 billion in annual investment is still needed to meet net-zero goals [10]. While the transition presents significant challenges, particularly for carbon-intensive industries and fossil-fuel-dependent economies, developing efficient, decarbonized fuels helps balance the competing imperatives for economic growth, energy security, social equity, and global environmental stewardship. However, coordinated global action, technological advancements, and robust regulatory frameworks that promote both environmental sustainability and economic resilience are crucial to ensuring the success of this energy transition [11].

A key challenge in achieving net-zero emissions is identifying viable clean energy alternatives. Among the emerging options, hydrogen has gained attention as a potential transition fuel or even a dominant clean alternative. However, questions remain regarding its feasibility, scalability, and economic viability. This raises a critical question: Is hydrogen the energy source of the future, or just another fleeting trend? Hydrogen has developed into a multi-purpose energy carrier that can greatly reduce greenhouse gas (GHG) emissions in many different sectors. The relevance of hydrogen in the decarbonization effort also differs by sector, for example:

- **Industry:** Hydrogen may be a viable substitute for fossil fuels in the energy-intensive production of, e.g., steel, cement, chemicals, and other goods [12,13]. For example, Suntory has begun using hydrogen to decarbonize its production of whisky [14].
- **Transportation:** For transportation in general, hydrogen fuel cell vehicles (HFCVs) are gaining ground in long-range applications, particularly with refueling times just below 5 min in many cases, compared to a battery electric vehicle that potentially takes 30 min–20 h to fully charge battery electric options. In contrast to battery-powered vehicles, the refueling times for hydrogen vehicles range from 15 to 30 min, representing a significant adoption consideration [15]. While the economy is still nascent, several automakers, particularly in Europe and Asia, offer HFCV options, and their use is growing in commercial and public transit fleets [16].
- **Energy Storage:** Hydrogen is a major player in energy storage because of its capacity to efficiently store substantial amounts of energy, which can contribute to reducing the challenge of intermittency of renewable energy sources and supporting energy availability during periods of low production or high demand [17]. The integration of hydrogen with renewables can enhance grid stability and enable surplus energy storage, significantly contributing to carbon emission reduction, especially when it is produced by means of electrolysis using renewable energy sources [18]. For example, the United Arab Emirates is currently operating a large, solar-powered facility producing hydrogen as a peaking-power (demand-satisfying) fuel [19].

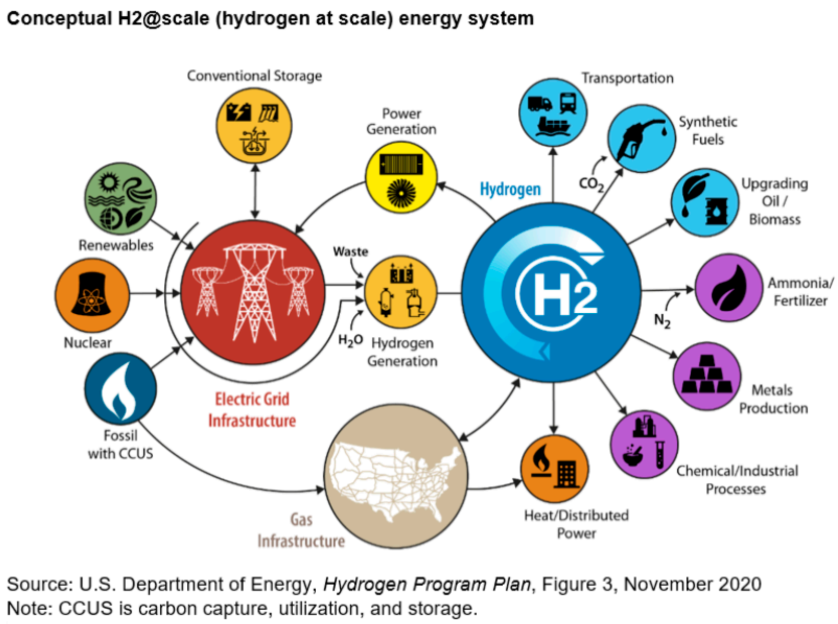

Figure 1. A conceptual hydrogen economy at scale [20].

In spite of this promise, there are still challenges in hydrogen storage and deployment, high production costs, infrastructure needs, and safety concerns, all of which can limit widespread adoption [17,21]. Continued research into advanced storage materials like hydrides and cryogenic systems aims to overcome these barriers and unlock hydrogen's full potential as a clean, flexible energy carrier [22,23]. The use cases identified above collectively form parts of the "hydrogen economy," a cohesive and interdependent web of hydrogen production and utilization applications that span industries (see Figure 1). Hydrogen's versatility spans to other applications such as transportation, where fuel cells already offer zero-emission solutions, and various productive industries, including ammonia and steel production [18]. While it is clear that replacing traditional fossil fuels with hydrogen will greatly reduce overall GHG emissions, the production of hydrogen itself is not necessarily clean. Currently, 98% of hydrogen is produced from fossil fuel sources without CO_2 emission controls (i.e., black, brown, or gray hydrogen), which results in roughly 830 million tons of CO_2 every year [7,24]. The higher costs associated with cleaner production pathways have thus far precluded their widespread adoption, limiting its overall impact as a "clean" energy. Competitive clean hydrogen is included in the U.S. Department of Energy's Earthshots "Ambition" program [25].

Building an effective green hydrogen economy is increasingly important, as climate change, extraction (of fossil fuels) difficulty, and energy independence questions loom over the future of multiple industries. This paper reviews the current state of the hydrogen economy, including its production and implementation in various industries, to understand the state of practice and the need for further research and development. Section 2 reviews the current approaches to the production of hydrogen. Section 3 reviews the implementation of hydrogen across various domains and the challenges in its use. Section 4 outlines salient aspects of hydrogen risks and approaches to risk analysis and management. Section 5 outlines the technological and economic considerations for the future of the hydrogen economy. Section 6 discusses policy recommendations aimed at economic feasibility, technological and regulatory improvements, and international partnerships. Section 7 concludes with a short summary of the paper. Overall, this state-of-the-industry review provides a holistic, high-level picture of the hydrogen economy, the remaining challenges, and opportunities for innovation in research and implementation.

2. Current State of Hydrogen for Energy

2.1. Review Approach

This review is a wide-scope overview of the current status of hydrogen across domains, with a focus on risk and risk management, and an overview of the future of the hydrogen economy. As a "state of the industry" review, this paper draws on the academic literature, government and industry studies, and reputable news items regarding announced projects. Academic sources were found using Boolean search strings, including [("hydrogen economy" OR "hydrogen energy" OR "green hydrogen" OR "blue hydrogen" OR "hazards of hydrogen") AND ("production" OR "storage" OR "distribution" OR "market" OR "challenges" OR "progress")].

The search covered multiple databases, including Google Scholar, ScienceDirect, Oxford Academic, and the Libraries at Colorado State University. For academic sources, preference was given to open-access (freely available) sources published in hydrogen-relevant journals after 2020. Government and industry reports were sourced directly from the cognizant agencies, including the U.S. Department of Energy (DOE), World Bank, International Energy Agency (IEA), and the U.N. Intergovernmental Panel on Climate Change (IPCC). News items from reputable outlets and press releases regarding specific projects were sourced where appropriate to highlight current and announced initiatives. Papers were screened for relevance based on the title and abstract before a full text review.

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This paper follows a simplified PRISMA-style review process and pared down roughly 250 abstracts to 85 final studies. Using forwards-snowballing and continuous review of the new literature, additional sources were found, reviewed, and incorporated as necessary to provide adequate coverage of the topic scope, particularly for recent advances. Despite the semi-structured approach, this paper is thus not a full systematic review, but instead takes a broader lens that captures both industry and academic considerations for the hydrogen economy.

2.2. Current State of Hydrogen and Predominant Production Methods

As we examine the current state of hydrogen technologies and infrastructure, it is best characterized by consistent progress, particularly in production technologies, like electrolysis, that facilitate cleaner generation than competing methods, e.g., steam methane reforming [26]. Simultaneous advancements in hydrogen utilization and storage infrastructure, e.g., through proliferating hydrogen fueling stations for hydrogen-powered vehicles, evidence the full-scope nature of improvement across the hydrogen economy [27]. These advances lay the groundwork for a robust hydrogen economy and position hydrogen as a key component of future sustainable energy strategies.

Despite the advancement across multiple sectors of the nascent hydrogen economy, the adoption rates of hydrogen technology exhibit stark variability across different regions, largely influenced by local policies and investment capacities. Europe has emerged as a frontrunner due to its robust policy framework, encouraging substantial infrastructure development and technological implementation [28]. Conversely, adoption is slower in regions like Africa, where resource constraints and lack of investment hinder the establishment of necessary infrastructure. In the Asia–Pacific region, major economies such as Japan and South Korea are accelerating adoption with supportive government initiatives [29]. Hence, adoption rates reflect both economic priorities and policy environments, underscoring the need for tailored approaches to facilitate uniform hydrogen development globally [30]. Further, as discussed in the following subsection, the deployment of green hydrogen production remains limited.

Common hydrogen production methods include coal gasification, steam methane reforming (SMR), water electrolysis, and biomass gasification. At the time of this publication, carbon-intensive SMR is the dominant method [31] and is often implemented without emissions reduction technologies. SMR reacts methane with high-temperature steam to produce hydrogen and carbon monoxide. Thus, both the feedstock and byproduct of SMR hydrogen production contribute to a large carbon footprint. In addition to feedstocks and byproducts, the energy source for hydrogen production must also be considered for its environmental impact. Color codes are used to identify the carbon intensity of the production process for hydrogen based on the energy source (although this is somewhat correlated with the process). Table 2 and Figure 2 classify hydrogen production methods based on the cleanliness of their feedstocks and emissions due to production.

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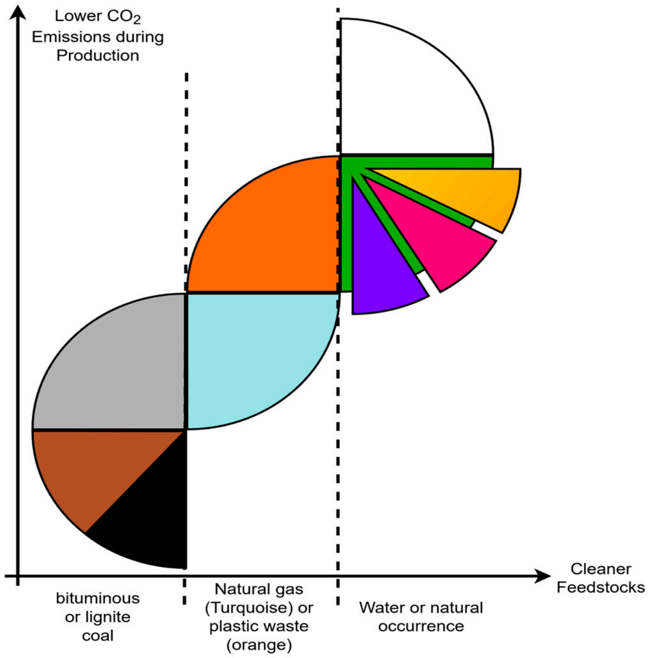

Figure 2. Colors of hydrogen illustrated with their respective feedstocks and production emissions.

Green Hydrogen: Green hydrogen uses renewable energy sources (e.g., solar and wind) to power the production process. Typically, green hydrogen production incorporates Polymer Electrolyte Membrane (PEM) electrolysis to separate hydrogen from water. Compared to traditional methods, renewable solar photovoltaic and wind electrolytic hydrogen production is estimated to emit 50–90% less GHG [13,32]. While dependent on the technology and feedstock, representative values of the "global warming potential" (GWP) for green production range from 0.03 to 3.00 kg CO_2 equivalent per kg H_2 produced [33].

Blue Hydrogen: Blue hydrogen is a lower-carbon alternative being produced through steam methane reforming (SMR) with carbon capture and storage (CCS), although this reduces CO_2 emissions compared to conventional SMR (without CCS); however, its environmental benefit depends on CCS efficiency and the risk of methane leakage from natural gas feedstocks [34]. Unlike green hydrogen, blue hydrogen relies on fossil fuels, making its sustainability subject to upstream emissions and capture rates. Dependent on the specific system, blue hydrogen production averages 3.70–7.14 kg CO_2 equivalent per kg H_2 produced [33].

Gray hydrogen: Gray hydrogen is produced through fossil fuel-powered SMR or coal gasification without CCS to offset emissions. Currently, over 95% of global hydrogen production comes from gray hydrogen, contributing approximately 830 million tons of CO_2 emissions annually [35,36]. This is roughly equivalent to 13% of annual U.S. carbon emissions. Depending on the system, gray hydrogen production has a GWP of 10.56–25.28 kgCO_2 equivalent per kg H_2 produced [33]. While this method and associated technology are well-established, it is not sustainable for achieving climate goals.

While gray, blue, and green are the most commonly defined colors of hydrogen, other colors have been developed to further delineate hydrogen production based on energy source, feedstock, and production process. These are shown in Table 2 and Figure 2. For thorough reviews of the lifecycle emissions and environmental impacts of various hydrogen production methods, readers are referred to [33,37].

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Table 2. Hydrogen color designations, adapted from [38].

Color	Energy Source	Feedstock	Process	CO_2 Emissions
Green	Renewable	Water	Electrolysis	No Direct GWP: 0.03–3.00 [33]
Blue	Fossil Fuel with CCS	Natural gas or Biomass	SMR	Low GWP: 3.70–7.14 [33]
Gray	Fossil Fuel without CCS	Natural gas	SMR	High GWP: 10.56–25.28 [33]
Black	Fossil Fuel without CCS	Bitumin	Coal gasification	High
Brown	Fossil Fuel without CCS	Lignite or Biomass	Coal gasification	High
Turqoise	Fossil Fuel with CCS	Natural gas	Pyrolysis	Low
Pink	Nuclear (electric)	Water	Electrolysis	No Direct
Purple	Nuclear (electric + heat)	Water	Electrolysis	No Direct
Red	Nuclear (heat)	Water	Thermolysis	No Direct
Yellow	Solar	Water	Thermolysis	No Direct
White	Dependent	Natural hydrogen	Collection	Minimum

As shown in Table 2, several additional colors of hydrogen have been proposed based on the energy source, feedstock, and process. While not as popular as blue, gray, or green hydrogen, these architectures are being explored. For more details, readers are referred to Incer-Valverde et al. (2023) [38]:

- **Orange:** Hydrogen produced through water electrolysis with electric power taken from the existing grid. As a result, the environmental impacts of orange hydrogen are entirely dependent on the energy mix of the existing grid.
- **Pink:** Hydrogen produced via water electrolysis with electric power supplied by a nuclear reactor would emit no direct CO_2 emissions.
- **Purple:** Purple hydrogen improves upon pink hydrogen by leveraging steam preheating of the water feedstock to improve the efficiency of the electrolysis process. Because electric power is provided (in addition to steam) from the nuclear reactor, this method emits no direct CO_2 emissions.
- **Red:** Red hydrogen uses high-temperature steam to drive thermolysis or thermochemical splitting of water, and thus emits no direct CO_2 emissions.
- **Yellow:** Yellow hydrogen, similar to red hydrogen, uses high temperatures to thermolyze or thermochemically split water. Powered by solar energy, yellow hydrogen would produce no direct CO_2 emissions.
- **Turquoise:** Similar to gray hydrogen, turquoise hydrogen employs electric power from natural gas (e.g., combined cycle) but employs carbon capture and storage to minimize CO_2 emissions.
- **Black and Brown:** Black and brown hydrogen both produce hydrogen via coal gasification, employing electricity produced from fossil fuels without carbon capture. The difference is the specific fuel (bituminous coal for black hydrogen; lignite for brown hydrogen).

Figure 2 visualizes the various colors of hydrogen based on feedstock and carbon emissions during production. Regardless of the production method, hydrogen production can require significant amounts of energy. The most common process (gray) produces significant CO_2 emissions, although various decarbonization technologies (e.g., CCS for blue hydrogen) and cleaner production processes (green, yellow, and pink/red/purple) are available to reduce emissions. As technology advances, it may be possible to leverage naturally occurring hydrogen sources such as "white hydrogen" [35].

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In 2023, the global hydrogen review publicized a new method of hydrogen production that could represent a significant technological breakthrough for the hydrogen economy. Thermochemical water splitting produces hydrogen through a series of high-temperature (500 °C or above) chemical reactions via multiple pathways. In general, thermochemical water splitting uses high-temperature heat (e.g., from concentrated solar or nuclear sources) to drive hydrogen-producing chemical reactions involving metal oxides. Two examples of thermochemical splitting include the cerium oxide two-step (reduction–oxidation) cycle and the copper chloride hybrid (dissociation–electrolysis–hydrolysis) cycle [39,40]. There is a significant body of research on thermochemical splitting for hydrogen production, including [41–44].

Thermochemical water splitting methods offer the potential for higher-efficiency and lower-cost hydrogen production. However, developing these methods for commercial-scale use requires more research and development. Other emerging production methods rely on connecting existing and emerging technologies to generate hydrogen, rather than demonstrating new reactions. These include nuclear heat and electricity [45], nuclear waste decay heat [46], and bio-energy methods, including water photolysis and photo-fermentation [47]. These approaches promise green hydrogen production with existing technologies, minimizing the need for novel processes or material developments and potentially accelerating deployment. However, thus far, the deployment of advanced hydrogen production techniques has been slow, as traditional production methods remain cost-efficient and (particularly compared to using nuclear power) free from excessive regulatory burden. For recent reviews of extant and emerging hydrogen production methods, readers are referred to [48–50]. Useful industry overviews of available and emerging technologies are available from the International Energy Agency [51,52], U.S. National Energy Technology Lab [53], and U.S. Department of Energy [54]. Table 3 provides a brief assessment of the predominant hydrogen production technologies in terms of energy consumption and cost (per kg of H_2 produced) and the maximum reported technological readiness level (TRL).

Table 3. Overview of economic considerations for selected production technologies.

Technology	Consumption (kWh/kg H_2)	Cost (\$/kgH_2)	Max Reported TRL [50]
SMR (No CCS)	50.89 [50]	1.38 [53]	9
SMR (CCS)	62.43–73.86 [50]	2.00 [53]	8
Coal Gasification (No CCS)	57.7 [52]	3.36 [53]	9
Coal Gasification (CCS)	60.00 [52]	3.80 [53]	8
Biomass gasification (no CCS)	31.94–50.00 [50]	2.34–7.89 [51]	9
Biomass gasification (CCS)	50.00–66.67 [50]	2.34–7.89 [51]	8
PEM	50.00–77.78 [50]	6.32–8.84 [54]	9
SOEC	45.83–51.11[50]	3.54–9.44 [50]	8
Biomethane pyrolysis	10.00–30.00 [50]	1.43–3.55 [50]	7

Note that, in Table 3, some sources provided ranges for values, while the NETL study provides mainly point values [53]. In cases where the technology was discussed with multiple power sources (e.g., PEM and SOEC), the range represents the minimum and maximum across technologies. Cost figures have been converted from the source value to 2026 (February) U.S. dollars using the Consumer Price Index inflation calculator from the U.S. Bureau of Labor Statistics.

2.3. Storage and Transportation Infrastructure

Storage and transportation of hydrogen are undisputably major challenges in the realization of a hydrogen economy. Current technologies for the storage of hydrogen include high-pressure compressed gas bottles (cylinders), cryogenic liquid storage tanks, high-pressure tube trailers for regional delivery, liquid organic hydrogen carriers (LOHC), and emerging solid-state materials like metal hydrides [55]. Table 4 provides a brief overview of the energy densities of various storage technologies, as well as the charge/discharge energy required (i.e., energy input to storage). For chemically bound storage technologies (i.e., LOHC and solid metal hydrides), the enthalpy of dehydrogenation—the energy required to release hydrogen—is reported in Table 4 as well. For thorough reviews of hydrogen storage technologies, readers are referred to [56–59].

Table 4. Overview of energy density and needs for various hydrogen storage technologies.

Phase	Technology	Energy Density MJ/m³	Charge/Discharge Energy Needed (kWh/kg) *Dehydrogenation Enthalpy (kJ/mol)*
	Gaseous: $500–$1000 per kg [59]		2/0 [56]
Gaseous H_2	Type I Cylinder	1200–2400 [57]	---
	Type II Cylinder	2400–3600 [57]	---
	Type III Cylinder	3600–4800 [57]	---
	Type IV Cylinder	3600–4800 [57]	---
	Liquids: $1500–$3000 per kg [59]		12–17/0 [56]
Liquid H_2	LH_2 @ 1 bar	6000–8500 [58]	---
	LH_2 @ 350 bar	9600 [58]	---
Liquid Organic	LOHC (toluenes)	5600–6700 [58]	*68–71* [57]
	LOHC (naphthalenes)	7500–10,400 [57]	*66.5* [58]
	Solids: $2000–$5000 per kg [59]		0/2–11 [56]
Physical Adsorption	Activated Carbons	2400–5000 [57,58]	---
	Zeolites	2400–5000 [57,58]	---
	MOF	3100 [57,58]	---
Metal Hydride	MgH_2	13,200 [58]	*75* [57]
	$FeTiH_2$	13,700 [58]	*28* [57]
	$NaAlH_4$	9600 [58]	*41* [58]

Italicized entries in righthand column indicate dehydrogenation enthalpy (kJ/mol). Non-italicized entries indicate charge/discharge energy (kWh/kg).

The advancements in hydrogen storage are not without their limitations, including unfavorable (slow) reaction kinetics for metal hydride storage, high energy input requirements for liquid storage, and poor energy density for gaseous hydrogen storage. Despite advancements, issues such as low volumetric energy density, high costs, and infrastructure limitations remain major constraints to efficient storage, while the current transportation methods such as pipelines, roads, and maritime transit each present trade-offs in terms of efficiency, scalability, and safety [57]. Currently, pipeline transport appears to be the most viable for large-scale distribution despite requiring substantial upfront investment [60]. Hydrogen can be injected into existing natural gas pipelines to form a "hythane" blend gas, producing the benefit of gaseous H_2 pipeline transportation (the cheapest transportation) without the requirement for new pipeline infrastructure [61]. Recent research emphasizes the potential of underground storage facilities such as salt caverns and nanomaterials to enhance capacity and safety, while integration with renewable energy sources could further optimize the hydrogen supply chain. A recent review of 81 papers identified 25 technical and 9 economic factors that directly influence hydrogen logistics costs, with capital expenditure (CAPEX), transportation distance, and storage capacities as dominating constraints [62]. For a detailed comparison of land transportation for hydrogen, readers are referred to [61].

3. Hydrogen Implementation

3.1. Worldwide Deployments

Where advances in the technology for hydrogen production, storage, and transportation infrastructure (Section 2) reveal the state-of-the-art, examining current hydrogen projects provides insight into the state-of-practice and the potential trajectory of the hydrogen economy. This section reports a spot check on hydrogen implementation to show its trending position as it is today. As mentioned previously, progress around the world is not uniform, and some economies are pursuing hydrogen more aggressively than others.

The pipeline for clean hydrogen projects across the world has expanded significantly in recent years. According to the Hydrogen Council's "Hydrogen Insights 2024" report, the number of clean hydrogen projects across the world rose from 228 in 2020 to 1572 by May 2024, representing a sevenfold growth. Additionally, the committed investment for projects that have reached final investment decisions (FIDs) grew from approximately USD 10 billion across 102 projects in 2020 to around USD 75 billion across 434 projects in 2024. The global project pipeline has also reached maturity, with focus shifting from proposals to execution. Data published in the report shows that publicly committed gross investments (up to 2030) rose by about 20% to USD 680 billion [63]. Two global hydrogen development frameworks, in the United Arab Emirates and Japan, are worth discussing as illustrative of recent hydrogen deployment successes.

In the United Arab Emirates, for instance, the country's commitment to hydrogen as a sustainable energy alternative is exemplified through its integrated adoption model, with local production facilities reducing dependency on conventional fossil fuels [64]. This initiative showcases the strategic importance of developing regional capabilities while addressing both economic and environmental goals. The UAE currently operates the first solar-driven hydrogen production in the Middle East/North Africa region, generating 400 kg of hydrogen per day [19]. Built as part of a $14 M (USD) public–private partnership, this project not only demonstrates the feasibility of solar hydrogen production but also the benefits of nontraditional funding mechanisms that can alleviate some of the capital expenditure burdens for emerging governments [65].

Meanwhile, Japan has demonstrated substantial progress through its advanced hydrogen infrastructure, marked by a network of refueling stations supporting widespread adoption of hydrogen-powered vehicles [64]. Japan has followed an evolving hydrogen strategy since 2017, announcing a $100 B (USD) investment plan with an emphasis on public–private and international partnerships in 2023 [66]. This approach facilitated Japan's largest project of green hydrogen production, a $122 M (USD) 16 MW facility supplying hydrogen (produced via proton exchange membrane (PEM) electrolysis) to partially decarbonize operations at the Suntory Distillery [14].

Diverse approaches across regions are shaping the global progression of the hydrogen economy, fostering innovation and adaptive strategies tailored to local contexts and infrastructure needs. Obviously, adopters will generally introduce systems that their current infrastructure can handle, as they look into the viability of scaling and committing to large-scale infrastructure spend. It is easy to see that policy has a major role to play, as will be discussed in Section 7.

3.1.1. Hydrogen in Transportation (Fuel Cell Vehicles, Trains, and Ships)

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Hydrogen is being studied across multiple sectors in transportation, with particular attention on commercial, industrial, and heavy-duty applications. HFCVs are of significant interest in these domains because of faster refueling times (less than 4 min) compared to battery electric vehicles (BEVs). Because of the possibility of building centralized refueling infrastructure, commercial applications of HFCVs (e.g., vehicle fleets) are less sensitive to a lack of distributed hydrogen refueling infrastructure than the consumer domain. This is critical in areas that have been slow to build out hydrogen refueling, such as the USA [67], where hydrogen fueling stations are mostly concentrated in California (West Coast). There are emerging deployments across the USA aimed at long-haul transportation applications of HFCVs [68]. Additionally, in maritime transportation, hydrogen fuel cells are becoming viable alternatives to marine fuels [69]. The railway sector is also exploring hydrogen as an alternative to diesel fuel in freight operations or cumbersome electric lines in passenger rail [70].

3.1.2. Industrial Applications (Steel Production and Chemical Manufacturing)

Hydrogen is being explored for diverse industrial applications, particularly within steel production and chemical manufacturing. In the steel industry, hydrogen represents a potential alternative to the carbon-based gases (e.g., carbon monoxide, CO) traditionally used in both blast furnace and direct reduction processes. Augmenting blast furnace steel production, hydrogen can substantially lower emissions, although carbon cannot be completely eliminated. However, hydrogen can replace CO (and is a better reductant) in direct reduction processes [71]. The transition to hydrogen (where feasible) is deemed crucial for the industry's sustainability efforts, as it can decrease the carbon footprint of steel production appreciably. In the same light, hydrogen is gaining ground in chemical manufacturing, where it is used as a feedstock for the synthesis of ammonia and methanol to support the production of fertilizers and other chemicals [72].

3.1.3. Power Generation and Grid Balancing

In power generation, hydrogen can serve as an effective energy storage and production medium, particularly as a means to integrate variable generation into the grid. The variability inherent in, e.g., solar and wind production, complicates grid balancing. However, because hydrogen can be stored (after, e.g., being produced during periods of low demand) and quickly redeployed (when demand rebounds), it can effectively stabilize the supply of energy from renewable sources [72].

3.2. Comparison with Other Low-Carbon Alternative Energy Sources

As an energy carrier, hydrogen is in competition with several alternatives being developed with the broader aim of decarbonization. As such, it is worth comparing hydrogen with other available low-carbon alternatives, such as biofuels and renewable energy, to understand the distinction in terms of efficiency, cost, and environmental impact. As a fuel, hydrogen must compete with lithium-ion batteries, biodiesel and renewable diesel, natural gas, and ethanol—all of which offer competitive advantages in terms of existing infrastructure and emissions reductions compared to traditional fuels. As a clean energy source, hydrogen further competes with solar, wind, and hydropower.

3.2.1. Fuel Comparison

As a potential fuel, hydrogen is being considered alongside other decarbonized alternatives, particularly biodiesel and renewable diesel. While biofuels offer immediate advantages, including the ability to be immediately implemented and lower production costs, they do not produce the same decarbonizing benefits as hydrogen during use, particularly if compared to HFCVs [73]. Further, as a combustible fuel, hydrogen could be

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used to provide similar immediate benefits—efficiency gains (in dual-fuel engines) and use of existing infrastructure—as biofuels [74]. Moreover, the lifecycle impact of biofuels presents significant challenges, particularly concerning land and water use and resultant carbon emissions [75]. In economic terms, biofuels retain several advantages over hydrogen, with generally lower production and transportation costs. Similar factors emerge when considering hydrogen in relation to ethanol and natural gas, which are both technologically mature as vehicle fuels with robust existing infrastructure [76]. However, like biofuels, both ethanol and natural gas suffer from the decarbonizing potential of hydrogen.

Despite its challenges when compared with alternative "green" fuels, hydrogen's decarbonizing potential makes it an attractive option. As advancements continue to resolve its key challenges (namely, infrastructure), hydrogen is well-placed to serve as an effective tool for deep decarbonization of transportation. Further, these advancements can continue as hydrogen is leveraged as an immediate complement to the existing capacities of biofuels, ethanol, and natural gas.

3.2.2. Energy Comparison

In the energy sector, hydrogen competes with and complements solar, wind, and hydropower. As previously reviewed, while the current state of hydrogen production is far from environmentally friendly, clean hydrogen production is a viable pathway for zero-carbon energy [77]. However, the technological maturity of many green energy technologies (solar, wind, hydropower, and geothermal) is well-established, with declining costs making them exceedingly competitive. However, they are not without their own challenges. Both solar and wind face inherent challenges related to energy intermittency and storage capacity. Hydropower and geothermal energy offer consistent energy output but raise concerns related to ecological disruption and geographical dependency. In contrast, hydrogen stands out as an effective storage medium for surplus renewable energy, thereby addressing the intermittency issues of solar and wind [78,79]. Further, various hydrogen production technologies can resolve the environmental impact and geographical concerns associated with hydropower and geothermal. Consequently, while the initial capital investments for hydrogen infrastructure can be substantial, it offers a promising future as a low-carbon energy storage medium and source of dispatchable power. Table 5 compares the efficiency, emissions, and costs associated with competitive clean energy sources. Note that values for fuel cell systems are derived for different production techniques (green and gray) to demonstrate the wide variation of hydrogen emissions and costs. A standard assumption that 1 kg H_2 is equivalent to 33.33 kWh was used to derive lifecycle emissions and levelized cost data for hydrogen. Levelized costs were calculated from costs associated with PEM and SOEC reported in Table 3.

Table 5. Efficiency, emissions, and costs associated with various competitor technologies.

Energy	Efficiency (%)	Lifecycle Emissions (gCO_2/kWh)	Levelized Cost ($/MWh)
Natural gas turbine	60–65	430–550 [80]	48–109 [81]
H2 fuel cell (gray)	60 [82]	320–766 [33]	107–287 [50,54]
H2 fuel cell (green)	60 [82]	<100 [33]	107–287 [50,54]
Battery storage	70–85 [82]	9–135 [83]	126.20 [31]
Wind (onshore)	45 [82]	7–56 [80]	37–86 [81]
Wind (offshore)	45 [82]	7–56 [80]	70–157 [81]
Solar PV (Utility)	10–25 [82]	18–180 [80]	38–78 [81]
Hydro	90	0.11–54.7 [80]	58.54 [31]
Nuclear	33–37	3.7–64 [80]	34–228 [81]

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3.3. Overview of Challenges in Implementing Hydrogen

Hydrogen thus distinguishes itself as a potent and multi-use energy carrier, with high potential for emission reductions across the transportation and energy sectors. Beyond decarbonization, it can serve as a clean, resilient, and dispatchable energy storage and generation medium. However, high production costs and technological immaturity currently constrain its widespread adoption when compared to available alternatives such as biofuels in transportation or renewables in energy. Beyond the high production costs of clean hydrogen, there are also costs associated with implementing carbon capture mechanisms on currently feasible technologies (e.g., gray hydrogen) to minimize environmental impact [84]. Limitations around existing infrastructure (e.g., insufficient refueling and storage capabilities) deter rapid adoption in the transportation sector.

Thus, the dominant challenges with the hydrogen economy appear to be economic rather than technological. While technological advancements are undoubtedly needed, for instance, to improve the efficiency and affordability of hydrogen production, policy advances are critical to the wider adoption of hydrogen energy systems. Methodological improvements are also needed in the assessment and management of risks in hydrogen production, storage, and use, as will be discussed in the following section.

4. Risks and Risk Management

4.1. Safety Concerns and Public Perception

One of the dominant factors in technological adoption, including hydrogen, is the management and public perception of technological risk. Public reluctance to embrace hydrogen as a fuel is influenced by risk perception and safety concerns, and can escalate into opposition if not addressed through transparent risk management processes. According to Norazahar et al. (2023), the perceived safety of hydrogen technologies considerably influences public acceptance, particularly in regions emerging as potential adopters [85]. Public perception of any technology often hinges on the understanding of the technology and its safety implications, trust in the "gatekeepers" (i.e., the technology developers), and the transparency of, and perceived agency in, the deployment and adoption process [86]. Further, risk can become "socially amplified" when an adverse event like an accident occurs that receives wide (media) attention. The resulting information cascade can magnify the impact beyond immediate victims to influence broader perception and reduce trust in the technology [87]. Societal acceptance can also be impeded by historical misconceptions and the tangible risks associated with hydrogen storage and use, as well as highly visible incidents, necessitating comprehensive risk communication strategies [88].

Thus, despite the long and relatively safe operational history with hydrogen in industrial contexts, its broader adoption can be slowed down by visible and historic incidents that trigger enduring safety concerns, even including the Hindenburg disaster of 1937. This event gave rise to what some authors term the "Hindenburg syndrome," a reflexive fear rooted in public memory that continues to shape perceptions of hydrogen safety [89]. Transitioning hydrogen from industrial to public-facing applications introduces new challenges, requiring stricter safety criteria, regulatory oversight, and public education to build trust [87]. Thus, managing public perceptions is critical to improving the willingness to adopt and incentivizes a focus on safety by design, accident avoidance, and the production of social benefits.

However, risk is not just a matter of public perception, but a real factor that must be understood and addressed for system viability and safety. While the public perception of risk guides attention towards high-profile events such as large-scale explosions, the real risks of hydrogen may be more mundane. Groth and Al-Douri (2024) [90], among others, outline the safety concerns and hazards associated with hydrogen systems. These include:

(1) Hydrogen Release

The release of hydrogen, due to its small molecular size and low viscosity, is more likely than for other process chemicals [90]. The releasability and undetectability of hydrogen allow it to travel easily through systems, necessitating robust detection and mitigation mechanisms, including advanced sensors and automatic shutdowns [91]. Hydrogen release was the proximate cause of the explosions at the Fukushima-Daiichi Nuclear Power Plant following partial meltdown, bringing the necessity of hydrogen detection and mitigation into sharp relief.

(2) Hydrogen Ignition

Hydrogen is well-known to be highly flammable, with both a wide flammability range (4–77% volumetric concentration) and low ignition energy. While highly dispersant, its accumulation in enclosed and/or poorly ventilated areas presents a significant ignition concern, both as hydrogen escapes the system (immediate ignition) and as hydrogen accumulates in a space (delayed ignition) [92]. Because of its low ignition energy, hydrogen gas has several ignition mechanisms beyond the expected (e.g., flames, sparks, and hot surfaces)—frictional heating, compression, and the presence of catalytic materials (e.g., platinum) can ignite hydrogen [93]. For a thorough review of hydrogen ignition, readers are referred to Wen, Hecht, and Mevel (2025) [93].

(3) Fires and Explosions

The major operational concerns with hydrogen are, of course, fires and explosions caused by the release and ignition of gas. Except for large or contaminated fires, hydrogen flames are not visible to the naked eye, meaning a thermal hazard can be present with minimal indication. Different flame and explosion typologies are possible depending on the scenario, including jet fires (unidirectional flame), flash fires (omnidirectional flame), deflagrations (subsonic flames), and explosions (supersonic flames).

4.2. Risk Analysis Methodologies

To address the risks outlined above, many different risk assessment techniques, tools, and methodologies have been developed, adapted, or redesigned specifically to address hydrogen hazards. One prominent approach is Quantitative Risk Assessment (QRA); this is widely utilized due to its structured nature, allowing for a detailed evaluation of potential hazards associated with hydrogen technologies [94]. As a family of methods, including probabilistic risk assessment (PRA), QRA is well-established in other high-risk industries, including nuclear energy production [95] and spaceflight [96]. While demonstrably effective, quantitative approaches require significant data on the components in the system context, a potentially prohibitive requirement for developing technologies like hydrogen infrastructure [97]. Al-Douri and Groth (2024) identify significant roadblocks to enabling quantitative assessment of hydrogen systems, including the collection and dissemination of operation data, robust system descriptions and documentation, and the development of specific QRA standards [98].

For developing systems, qualitative approaches—including failure modes and effects analysis (FMEA) and preliminary hazard analysis (PHA)—can offer useful insights into system risk without the data burden that often accompanies quantitative methods, although these methods are not without their own challenges [99]. Qualitative methods have been applied to hydrogen systems with promising results, particularly for demonstrating risk acceptability and compliance with safety requirements [100]. Hybrid methods, which combine the model-based approaches common in qualitative approaches like FMEA with more robust analytics, have also been used to develop useful risk insights for hydrogen systems [101].

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Other approaches in hydrogen risk analysis are focused on developing bespoke tools rather than adapting existing methods to the new context, producing methodologies specifically created for hydrogen, each with its own strengths and challenges. These include the Hydrogen Risk Assessment Process proposed by Min et al. (2025), which aims to fuse first-principle theory, experimentation, and simulation, and risk assessment methodologies to improve analytical accuracy [102]. This approach, like other model-based assessment tools like HyRAM+ [103], relies on computational fluid dynamics (CFD) and simulations to understand and predict hydrogen behavior [104]. These methodologies, while robust, require continuous refinement and adaptation to ensure they remain relevant amidst evolving technological and environmental contexts.

One useful heuristic for visualizing the progression of root cause to system-level effect is the bow tie model, which also indicates how different barriers within the system can combine to prevent or mitigate a particular accident sequence. These qualitative models provide useful decision-making insights regarding the adequacy of preventative and mitigative system mechanisms and easily communicate system risk to stakeholders. For example, Figure 3 translates the risk characteristics of hydrogen systems—common causes and end-level effects—into a basic bow tie model.

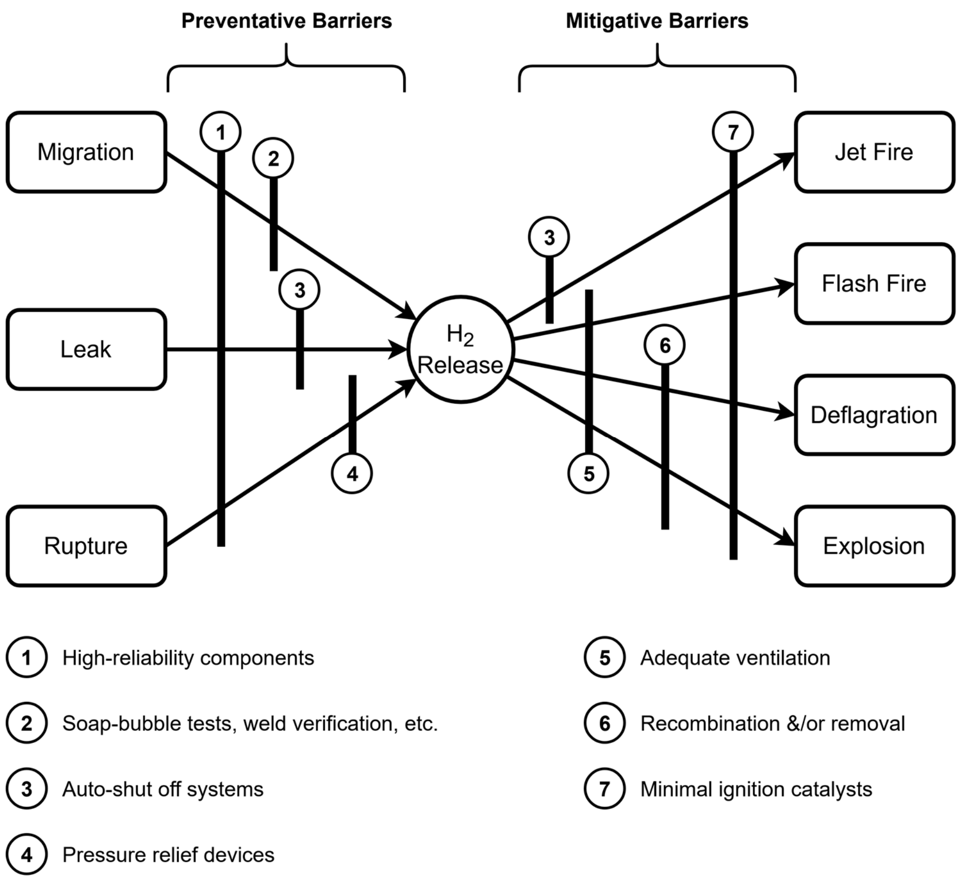

Figure 3. Basic bow tie model of hydrogen risks from Section 4.1.

4.3. Risk Mitigation and Management Approaches

Risk analysis—understanding the causes and effects—is a critical piece of system safety, but analysis alone does nothing to address the occurrence or impact of risks. Risk mitigation is the reduction of risk by reducing the probability of occurrence and/or the consequences of a risk event. In the nascent hydrogen industry, risk mitigation strategies generally rely on rigorous compliance with relevant codes and standards, such as NFPA 2 (Hydrogen Technologies Code) [105]. A compendium of codes and standards applicable to hydrogen is maintained by the Fuel Cell and Hydrogen Energy Association (FCHEA) [106]. While risk is not, and should not be treated as, a simple question of compliance with a standard, the consistent application of standards helps to ensure safety, and the standards themselves can highlight systems, components, and practices that need to be improved, as well as non-compliance-based risk mitigation measures. The development of inherently safer containments, sophisticated hydrogen detection systems, the enforcement of setback distances, and the use of regular inspections are all available and effective risk mitigation measures.

In some sense, hydrogen benefits from having relatively well-understood properties and risks, and thus can draw on a long history of risk management from other similar industries. For example, a primary hazard is hydrogen's high flammability, which can be effectively managed with rigorous safety protocols [84] and robust regulatory frameworks [28]. However, hydrogen's particular hazards necessitate safety through technological measures, not only risk management techniques. Comprehensive safety measures, such as inherently safer containment systems and robust sensor networks, help mitigate potential explosions either caused by leaks or other factors [29]. Pressure relief devices are essential in managing risks associated with the storage and use of pressurized hydrogen, but can come with their own risks [107]. Automatic shut-offs are necessary mechanisms to prevent unintended release, especially for dispensing (e.g., at refueling stations) [108]. As in many systems, diverse and redundant measures are critical for ensuring safety and managing risk.

4.4. Challenges in Risk Assessment and Management

Together, regulatory measures and technological improvements are instrumental in fostering a secure environment for the broader adoption of hydrogen, aligning with global safety standards and advancing the transition to a sustainable energy economy. However, several challenges—both technical and political—exist in the assessment and management of hydrogen risk. One of the primary hurdles is political—the lack of standardized risk assessments across different hydrogen technologies complicates comprehensive safety evaluations and sharing operational experience [109].

Hydrogen technologies are emerging with subtle differences in design and operation. The diversity of hydrogen applications and parallel development across domains and jurisdictions have resulted in fragmented approaches to risk management. Even attempts at standardization and codification—for example, NFPA 2—are complicated by questions about the proper application to optimize hazard mitigation. Other efforts aimed at warehousing available standards are useful for sharing operational experience, but have not yet produced a cohesive approach for all hydrogen applications. Further, continuing to pursue divergent risk management approaches across hydrogen technologies complicates the efforts to develop risk models and data infrastructure.

Beyond the political challenges associated with disparate codes and standards, data availability is perhaps the primary technical challenge for hydrogen risk management. The lack of empirical data hampers the development of effective risk analysis and undermines effective decision-making [104]. Several approaches are being taken to provide models and data infrastructure for use in quantitative risk assessments. Modeling software like HyRAM+ [103] is in development to fuse first-principles approaches with a growing body of empirical data and produce more accurate risk assessments. Testing of hydrogen components and systems is a global effort that produces valuable data for operations and risk analysts alike, but dissemination can be complicated by a lack of standardization. As data becomes available from varied implementations, it is critical that it be widely usable. HyCReD, the Hydrogen Component Reliability Database [97], seeks to standardize the collection and storage of safety-relevant data for hydrogen components.

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These efforts ensure that data remains useful as the breadth of hydrogen implementation continues to increase.

Risk assessment and management methodologies for hydrogen systems are continuously evolving, and yet, no single method has come to the forefront as the most applicable or most beneficial. The regulatory application of risk analysis approaches, as a result, is similarly challenged with significant methodological differences [110]. Thus, significant research is needed to enable more robust assessment and management of risk. This is a key requirement in building the future of the hydrogen economy.

5. The Future Hydrogen Economy: Technological Innovations and Economic Considerations

5.1. Technological Innovations

Several technological improvements are under development that can impact the feasibility, economics, and environmental impact of the hydrogen economy. Continued innovation and improvement in production throughput and safety, and the introduction of cleaner power sources such as solar, wind, hydropower, and nuclear, will have significant impacts on the development of a viable hydrogen economy. Section 3 discussed two recent hydrogen projects in the UAE and Japan. In the USA, Chevron announced a 5-megawatt solar-powered hydrogen production project in California [111], continuing the drive to decarbonized production. Beyond production via renewables, nuclear-powered hydrogen is also gaining attention, both as a means to decarbonize production and improve the economics of nuclear power [112].

The combination of innovative technologies in nuclear-powered hydrogen production could catalyze efficient, eco-friendly generation with existing reactors and improve the economics of deploying advanced nuclear reactors. While existing reactors can supply electricity to power low-temperature electrolysis, the high temperatures produced by advanced nuclear reactors could further improve the economics of clean hydrogen production. Further afield, the prospect of fusion energy holds similar promises for hydrogen production.

Beyond the power source underlying production, improvements in production technology are also poised to significantly improve the economic feasibility and outlook of the hydrogen economy. Innovations in electrolysis based on high-temperature steam processes have shown significant opportunities for increasing the efficiency of hydrogen production [113]. This method promises to eliminate the constant problems of exorbitant hydrogen production costs and efficiency, with higher temperatures enabling energy efficiency increases of 9–12% and cost reductions of over 20%, depending on the specific system architecture [114]. Biohydrogen production through methods that involve the use of cyanobacteria is economically promising and ecologically safe [27]. Multiple approaches to biohydrogen production are being studied, including the use of organic waste as a feedstock [115]; hydrogen production as a byproduct of a necessary municipal function could improve the economics of these approaches. The use of advanced materials and catalysts has improved the feasibility and efficiency of photoelectrochemical production of hydrogen with solar energy [116]. For a recent review of hydrogen production methods based on patent filings, readers are referred to Arsad et al. (2024) [117].

The prospects of breakthroughs in the fields of electrolysis and fuel cell technology demonstrate that there are opportunities for significant progress in improving the efficiency of both hydrogen generation and its consumption. Novel catalysts and materials have had a positive impact on the efficiency and durability of fuel cells, making them a more cost-effective option for the production and use of hydrogen [117].

5.2. Economic Considerations

5.2.1. Workforce

Beyond technological improvements, the growth of the hydrogen economy is dependent on workforce training and education, including the workforce. According to the U.S. Department of Energy's National Energy Technology Laboratory [118], employment opportunities span the entire hydrogen value chain from production and storage to transportation and end-use applications. The hydrogen economy will require both conventional energy skills and specialized training in hydrogen technologies. To meet this demand, regional initiatives are launching workforce programs. The University of Toledo, for instance, is leading a $3 million federally funded initiative to prepare workers for hydrogen-related roles [119], while the University of Houston is targeting underserved communities in the Gulf Coast with tailored training programs [120]. These efforts are exemplars of the multifaceted, public-oriented initiatives necessary to build the hydrogen workforce and ensure the hydrogen economy benefits the public.

Economically, the hydrogen industry is poised to generate substantial growth. In the Gulf Coast of the USA alone, it is projected to create up to 180,000 jobs and contribute $100 billion to GDP by 2050 [121]; across the U.S., approximately 700,000 jobs are anticipated by 2030 through clean hydrogen investments [122]. Globally, countries like Australia are investing in purpose-built training centers—such as a $15 million facility in Townsville—to cultivate a highly skilled hydrogen workforce [123]. In addition to providing direct jobs in the hydrogen economy, the proliferation of hydrogen technology will provide employment opportunities in the manufacturing, transportation, and renewables sectors at and beyond hydrogen installations [124].

The hydrogen energy sector employment forecasts reflect a promising outlook. The hydrogen economy will deliver job opportunities across multiple sectors as hydrogen demand increases [125]. The growth in hydrogen infrastructure requires trained employees adapting to new technologies, a demand that can be satisfied with workforce-investment programs like those briefly introduced here. These programs are as critical to realizing the hydrogen economy as technological improvements, making the establishment of education and training programs a critical driver of hydrogen growth.

5.2.2. Production Costs

As discussed, production costs remain a key factor in the commercialization of clean hydrogen. The cost of production and cost to consumers must be competitive compared to conventional fuels to incentivize the shift towards hydrogen. A 2023 study by the Belfer Center highlights the present cost disparity in production costs between leading approaches, with green hydrogen between $4.50 and $12.00 (USD) per kilogram, and blue hydrogen between $1.80 and $4.70 per kilogram, where 1 kg of hydrogen is the equivalent of 1 gallon of gasoline [126]. Thus, as highlighted throughout, there is a substantial economic barrier to green hydrogen adoption. To rectify this, the U.S. Department of Energy is operating the "Hydrogen Shot" initiative, which aims at reducing the cost of clean hydrogen by 80% to $1 per kilogram in 1 decade ("1 1 1") [127].

The green hydrogen costs are a major hurdle to scalability and competitiveness. However, as the climate crisis continues to come into sharper relief, the role of hydrogen in meeting climate goals may spur continued technological advancements and catalyze new economic incentives for widespread adoption. Green hydrogen costs are high in large part because the cost of renewable electricity itself is higher than conventional sources; a reduction in these prices has already been witnessed and is likely to continue as part of the broader drive to decarbonize. However, externalities, including inflation, supply chain issues, and the continued use of much cheaper alternatives (e.g., steam methane

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reforming), complicate the ability for green hydrogen to be competitive in the near term [128].

Accordingly, government incentives and subsidies have a substantial role in increasing the financial viability of hydrogen technology by reducing the barrier to entry, or the investment needed to adopt hydrogen technology. Nyangon and Darekar indicated that subsidies could reduce the levelized cost and allow hydrogen to serve as an economically viable energy alternative [129]. Subsidies help to de-risk hydrogen technologies and allow smaller or less fiscally liquid companies to invest in hydrogen, enabling further cost decreases through increased competition. The Inflation Reduction Act, for example, incentivized clean hydrogen production and resulted in reduced costs and emissions of several hydrogen production technologies [130]. In addition to incentivizing technology adoption, subsidies also spur research investment to improve hydrogen technology and economic competitiveness. China created targeted subsidy policies that resulted in improved electrolysis efficiency, contributing to decreased electricity prices and increasing the attractiveness of hydrogen technologies [131].

The examples described above serve as evidence of how targeted incentive policies can help the development of the hydrogen market, improving both economic and technological capabilities. Financial incentives promote investment in hydrogen technologies across domains and spur the transition to cleaner energy while remaining competitive with traditional energy, thus limiting consumer burden. The policy allocation suggests that funding would allow stakeholders to further pursue the development of hydrogen technologies and reduce emissions.

5.2.3. Recent Trends and Future Projections

The recent trends in costs associated with hydrogen are best characterized as, *ceteris paribus*, significant reductions driven by technological improvements across technologies [132]. These trends are expected to continue, with projections of a levelized cost of hydrogen (LCOH) under 5 USD per kg by 2030, even when including green hydrogen production technologies (wind and solar) [132,133]. This decrease is driven by both hydrogen technology development and the general decrease in electricity prices from renewable sources. Production costs are expected to reach these levels across regions, including the Middle East and North Africa (MENA) [133], indicating the potential to realize the expected “energy democratization” through hydrogen. Electrolyzer technology is a key driver of further cost decreases [134], with some studies projecting 44–79% cost reductions due to research and development, scale-up, and operational experience in the coming decades [132].

A similar trend of decreasing costs over time is not observed for hydrogen transportation across the literature surveyed. This is understandable considering the relative technological maturity of hydrogen transportation compared to hydrogen production and even storage technology. That is, pipeline, trailer, and barge transportation continue to dominate. However, studies have noted that costs of transport increase with distance at different rates, with three identifiable regimes of cost-effectiveness for hydrogen transportation. Figure 4 depicts the optimal transport modality for different distances [135].

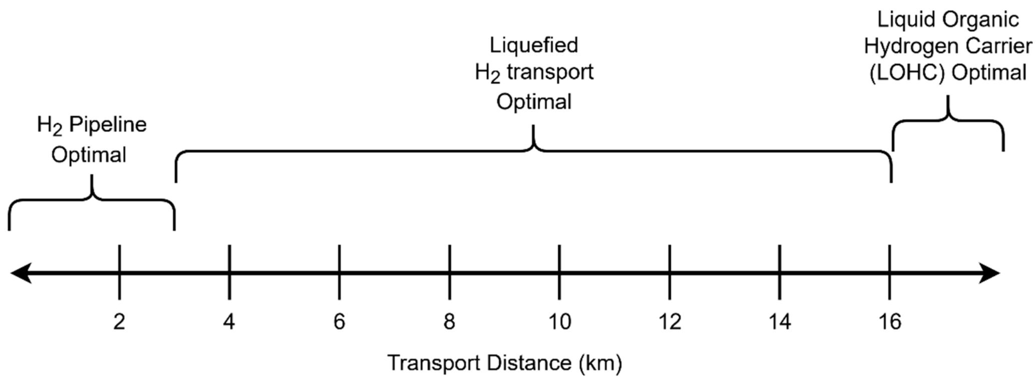

Figure 4. Cost-effectiveness of H_2 transport modalities.

6. Policy Recommendations

Effective policy measures are clearly instrumental in fostering the growth and integration of the hydrogen economy. While economic incentives are important, policy needs span, while reducing the burdens of technology and infrastructure development on stakeholders and consumers

6.1. Economics

As discussed throughout, alleviating the socioeconomic burdens of the transition to a hydrogen economy is a paramount consideration [136]. Targeted incentives that promote the adoption of particular technologies (e.g., subsidies) spur the short-term adoption of available technologies. For example, while HFCV sales in the USA fell by 70% in 1Q 2024 compared to the previous year [137], California remains a hydrogen-friendly state largely due to policy commitments and public awareness. California's strong policies and regulatory support, including production and use incentives [138,139], have helped create a supportive regional ecosystem. California remains the only state in the USA to seriously pursue hydrogen infrastructure. Other governments should pursue similar strategies to support the nascent hydrogen economy, incentivizing the adoption of available alternatives through, e.g., subsidies and tax credits, while also spurring development with investment frameworks, public–private partnership programs, and grants. These mechanisms are crucial to alleviating the high costs associated with hydrogen production and developing new technologies [136].

6.2. Regulation, Technology, and Education

Beyond economic incentives, strong policies are needed to spur the development and adoption of robust regulatory frameworks that standardize safety and environmental protocols. An established regulatory environment will reassure both investors and the public, promoting broader acceptance and utilization of hydrogen technologies [140]. Establishing sensible, but concrete, regulations fosters the development of technology with a lower risk of rejection and enables effective collaboration and knowledge-sharing across technological domains and regulatory jurisdictions. Governments and industry organizations should work in concert to develop effective regulations incorporating best practices from similar industries, operational experience with hydrogen, and relevant research.

To enhance technological synergy, governments should facilitate partnerships between research institutions and industry stakeholders to foster innovations in hydrogen technologies and applications [140]. These long-term research projects can also be supported through competitive grant programs and investments in education. Programs like the U.S. DOE's Hydrogen Shot exemplify the type of cross-cutting collaboration that should be fostered in research, development, and deployment of advanced hydrogen technologies. Lastly, investing in educational campaigns to raise awareness about the environmental and economic benefits of hydrogen can help address public skepticism and stimulate adoption. A concerted effort to integrate educational campaigns will also enhance public understanding and acceptance, address societal reluctance, and promote widespread adoption of hydrogen technologies.

6.3. International Cooperation and Balanced Development

International collaboration is central to advancing hydrogen technologies and establishing a global hydrogen economy. The global climate challenge demands a global solution, which is not possible with disparate and imbalanced approaches. A great example of the type of international collaboration necessary is the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). IPHE serves as a platform for over 26 member countries to share information, align policies, and develop common codes and standards for hydrogen utilization and safety [141]. This partnership fosters joint research and development efforts, leveraging global expertise to address challenges in hydrogen production, storage, and distribution. In addition, bilateral and multilateral agreements, such as those coordinated by the International Energy Agency (IEA), play a crucial role in harmonizing regulations and promoting the widespread adoption of hydrogen technologies [8]. Global cooperation will also help drive technological and regulatory standardization, further enabling the global development of hydrogen technology. Development of, and participation in, these types of international partnerships is a necessity for any government interested in starting or furthering the development of hydrogen in its jurisdiction.

The global development of hydrogen must be balanced with other low-carbon solutions to achieve comprehensive decarbonization. A study by the MIT Energy Initiative emphasizes the need for holistic optimization of electric power and hydrogen supply chains to maximize emission reductions and minimize infrastructure costs. Hydrogen's potential to complement variable renewable energy sources, such as wind and solar, makes it a valuable component of a diversified energy portfolio [142]. Integrating hydrogen with other technologies, including battery storage and carbon capture, to create a resilient and sustainable energy system will be a welcome idea, and this is already being required in some parts of the EU by the Renewable Energy Directive (RED) [143]. This type of technological balance not only incentivizes the early-stage adoption of existing hydrogen technology but also opens new avenues for hydrogen development. Significant care and collaboration across industries and domains (government, industry, and academia) should be exercised to design economic and regulatory policies that spur a balanced approach without inadvertently constraining any stakeholders.

7. Conclusions

In conclusion, the hydrogen economy presents a promising pathway toward decarbonization, offering versatile applications across various sectors, including industry, transportation, and energy storage. The transition to a hydrogen-based energy system is driven by international agreements and the adoption of net-zero commitments, spurring significant investments in green technologies. While advancements in hydrogen production, storage, and implementation are evident, the journey is not without its hurdles. As this paper concludes, there are significant challenges to the development of the hydrogen economy, but also ample opportunities for innovation.

This paper highlighted the current state of hydrogen technologies, emphasizing the need for cleaner production methods, such as green hydrogen, to minimize environmental impact. It also explored the challenges associated with hydrogen implementation, including high production costs, infrastructure limitations, and safety concerns.

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Technological innovations, such as advancements in electrolysis and fuel cell technology, are crucial for enhancing efficiency and reducing costs, as are methodological improvements in risk analysis that can be unlocked with further collection and sharing of valuable operations and testing data. Furthermore, effective policy measures, including financial incentives and robust regulatory frameworks, are essential for accelerating hydrogen adoption. International cooperation and standardization efforts are also vital for establishing a global hydrogen economy.

The most significant and lingering challenge to the hydrogen economy remains the high production cost of clean hydrogen. Addressing the barriers to deployment through technological advancements, government subsidies, and strategic policy interventions is necessary. In general, overcoming the cost constraint alongside continued efforts to address safety concerns and improve infrastructure is likely to pave a smoother way for a more rapid and successful transition to a sustainable hydrogen economy.

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