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Review

Advancing Hydrogen: A Closer Look at Implementation Factors, Current Status and Future Potential

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Abstract: This review article provides a comprehensive analysis of the hydrogen landscape, outlining the imperative for enhanced hydrogen production, implementation, and utilisation. It places the question of how to accelerate hydrogen adoption within the broader context of sustainable energy transitions and international commitments to reduce carbon emissions. It discusses influencing factors and policies for best practices in hydrogen energy application. Through an in-depth exploration of key factors affecting hydrogen implementation, this study provides insights into the complex interplay of both technical and logistical factors. It also discusses the challenges of planning, constructing infrastructure, and overcoming geographical constraints in the transition to hydrogen-based energy systems. The drive to achieve net-zero carbon emissions is contingent on accelerating clean hydrogen development, with blue and green hydrogen poised to complement traditional fuels. Public–private partnerships are emerging as catalysts for the commercialisation of hydrogen and fuel-cell technologies, fostering hydrogen demonstration projects worldwide. The anticipated integration of clean hydrogen into various sectors in the coming years signifies its importance as a complementary energy source, although specific applications across industries remain undefined. The paper provides a good reference on the gradual integration of hydrogen into the energy landscape, marking a significant step forward toward a cleaner, greener future.

Keywords: sustainable clean energy; renewable energy development; carbon emissions reduction; global energy transition; international energy policies; decarbonisation strategies; hydrogen policy framework

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1. Introduction

The future of the energy sector is marked by concerns about the security of supply and climate change, as well as the increasing prices of energy services. Hydrogen is becoming an increasingly important energy vector and a key component of the global energy revolution. It has the potential to drive transformative changes in energy and transportation and reduce emissions in sectors where electrification may not be a feasible solution [1,2]. However, despite the promising potential of hydrogen, the industry is uncommercialised due to the uncertainty of demand and the lack of reliable distribution systems and storage networks for hydrogen [3]. There is a need to consolidate an automated approach to hydrogen development that can be adapted to various constraining factors, levels of interest, and potential incentives [4–6]. To expedite hydrogen development, it is imperative to adopt a comprehensive policy approach and conduct a rigorous analysis of regulatory measures while drawing insights from existing projects. Advancing hydrogen energy has the potential to combat global warming and enhance energy security, particularly in nations with limited energy resources.

The major concerns for the energy sector's future are the security of the energy supply and addressing climate change. Hydrogen (H_2) is emerging as a viable and environmentally friendly energy carrier with the potential to have a significant impact on our global energy system thanks to renewable energy technologies. It has established itself as a candidate for a key place in our future energy environment since it can be used for both energy transportation and storage. In addition to concerns about energy supply security, climate change and local air pollution and the increasing prices of energy services impact policymaking around the world [7,8]. For these reasons, Ref. [9] employed Spearman's technique to analyse the national development of a hydrogen economy. Their study also aimed to assess environmental performance parameters to establish correlations between renewable energy's environmental, economic, and energy use factors. The significance of links between ecological factors and energy use has also been emphasised using Spearman's correlation to identify indicators of energy sustainability measurement [10–14]. Ref [15] reported that a remote generator will save almost 90% of its total costs due to the decrease in the cost of hydrogen fuel by 2030. Further research is needed to enhance the efficiency and dependability of fuel cells and other hydrogen-based technologies according to several studies [16–22]. Research by [23–26] discusses the main findings related to energy conversion efficiency and environmental impact, as well as the challenges in identifying the relative challenging factors in the hydrogen energy transition process.

This article provides an insightful review of hydrogen energy development systems, challenges in optimizing their deployment, and their implementations. It categorises the influential factors into technical and logistical, as depicted in Figure 1. Technical factors encompass hydrogen transportation, supply–demand dynamics, industrial use, technology advancements, environmental concerns, and supply chain intricacies. Logistical factors include regulatory policies, stakeholder roles, economic considerations, financial efficiency, and private sector involvement. It also addresses challenges in identifying prominent obstacles during the hydrogen energy transition.

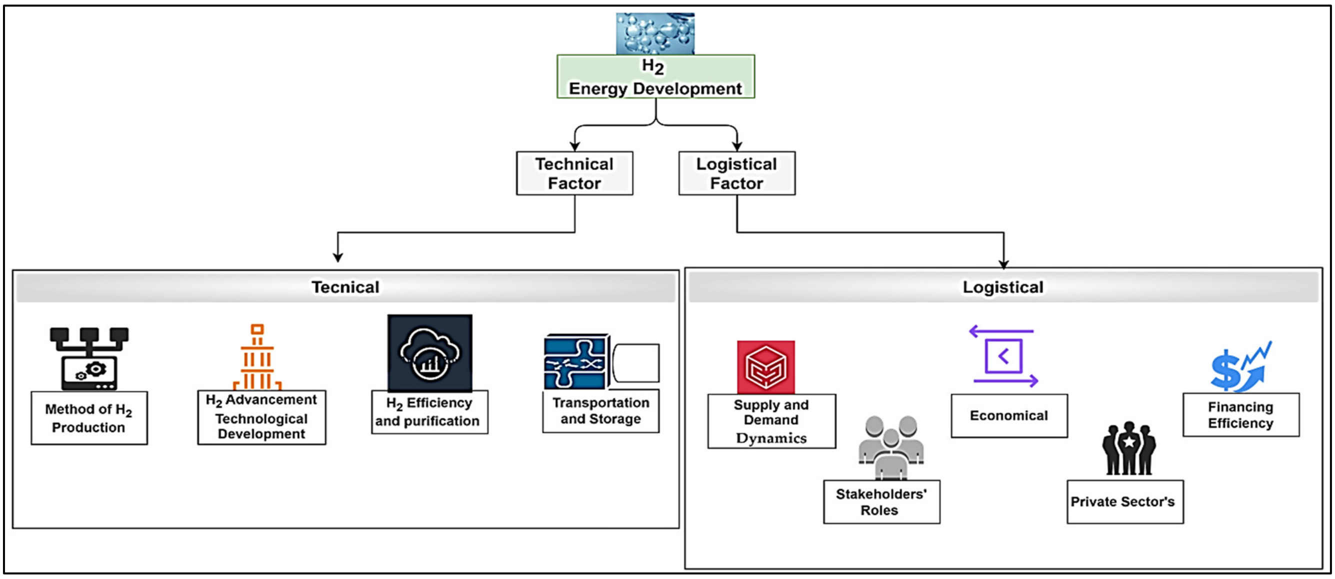

Figure 1. Hydrogen energy implementation factors.

2. Influencing Factors on Hydrogen Energy Transition

There is a recognised need for a streamlined approach to hydrogen development that can serve as a model for similar projects adaptable to varying factors and incentives, and a recognised absence of clear categories for these factors [27]. Hydrogen transportation development, industrial application and its expansion, and hydrogen energy utilisation and its environmental challenges are some of the technical aspects identified in this research. These contrast with factors that influence logistic strategy, which include the analysis of regulation and legislation policies, stakeholders' roles in hydrogen energy development, hydrogen economic factors, financial efficiency, and the role of the private sector in hydrogen energy development as an integral aspect of hydrogen development initiatives [24,28–32].

Recent studies show that all these factors have a significant impact on how the hydrogen sector grows. Furthermore, empirical findings reveal that distinct variables in each country influence the evolution of the vision of a hydrogen economy [33]. However, low-to-zero-carbon hydrogen generation faces a significant obstacle in the fact that it is still in development on a commercial scale. The following sections discuss the factors categorising them into technical and logistical factors.

2.1. Technical Factors

Technical considerations play a role in determining the feasibility and long-term sustainability of hydrogen. Ongoing research and development are focused on optimizing each of these factors with the goal of promoting the use of clean hydrogen as an ecofriendly energy source. Specifically, when it comes to producing zero-carbon hydrogen, various technical aspects come into play. These include selecting the method for hydrogen generation, continually advancing hydrogen technology, enhancing efficiency implementing purification techniques, and developing efficient transportation and storage solutions. These factors collectively determine the feasibility and sustainability of hydrogen generation and play a pivotal role in achieving low-to-zero-carbon clean hydrogen as a sustainable energy source. The following section discusses each of the technical factors.

2.1.1. Hydrogen Generation Method

Hydrogen is the simplest chemical element on Earth and has an atom composed of a single proton and a single electron. It can accumulate and provide energy, acting as an energy carrier [34]. It can be produced using several resources, such as fossil fuels (natural gas and coal), water, nuclear energy, and other renewable energy sources like biomass, wind, solar, and geothermal. Hydrogen can be produced at or near the point of use. Hydrogen can be produced using several different processes, which include thermal–chemical processes [35–37], photoelectric processes [38–40], and electrolytic processes [41–43]. Microorganisms such as bacteria and algae can also produce hydrogen through biological processes [44–46]. Figure 2 shows hydrogen energy production methods.

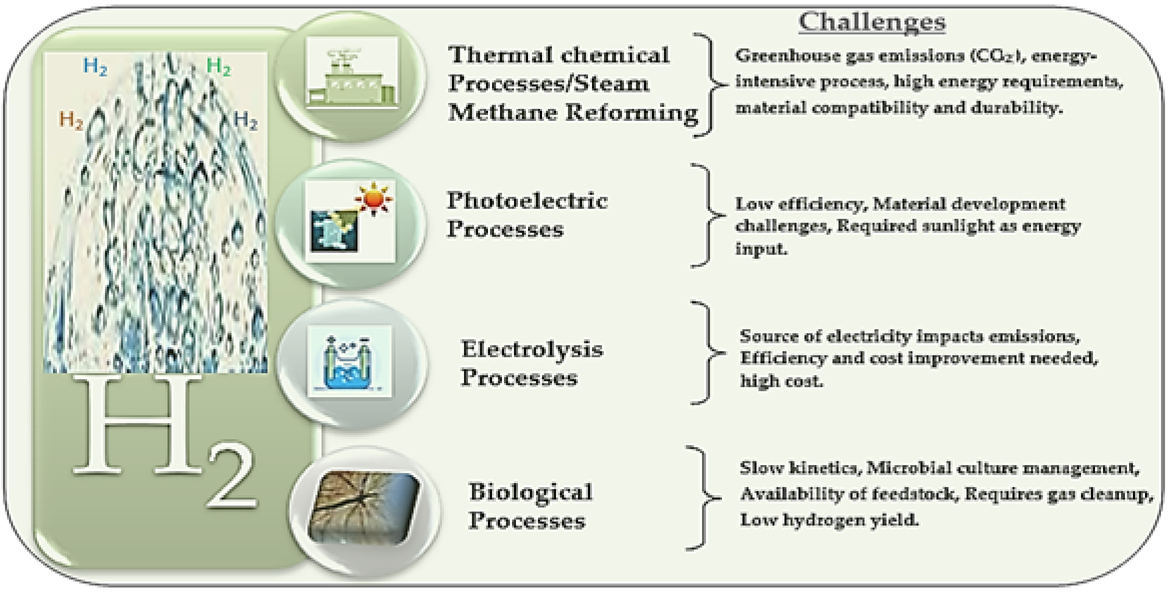

Figure 2. Hydrogen energy production methods and challenges.

Thermal–chemical processes use heat and chemical reactions to extract hydrogen from natural gas, coal, biomass, and even water. Natural gas contains methane that can be used to produce hydrogen by thermal–chemical processes like steam reforming and partial oxidation [35]. In steam reforming, methane and other hydrocarbons react with high-temperature steam under pressure, and, in the presence of a catalyst, the reaction is accelerated. The reaction products are hydrogen and carbon monoxide. Electrolytic processes used electricity to make chemical reactions. The most common process is the electrolysis of water, where water is split into hydrogen and oxygen using electricity [47]. This is a sustainable method for producing hydrogen because there would be no greenhouse emissions during production when integrated with renewables. Photoelectric chemical processes use sunlight energy to split water into hydrogen and oxygen. In a photoelectric chemical cell, the semiconductors are like those used in photovoltaic solar electricity generation. They are immersed in a water-based electrolyte where sunlight energises the water splitting process into hydrogen and oxygen, like in the electrolysis of water [38]. Biological processes include the microbial conversion of biomass, where microorganisms consume and digest biomass to release hydrogen [44–46]. This happens in fermentation-based systems where microorganisms such as bacteria break down organic matter to produce hydrogen. A global hydrogen production projection has been reported by [48] based on four scenarios, as shown in Figure 3.

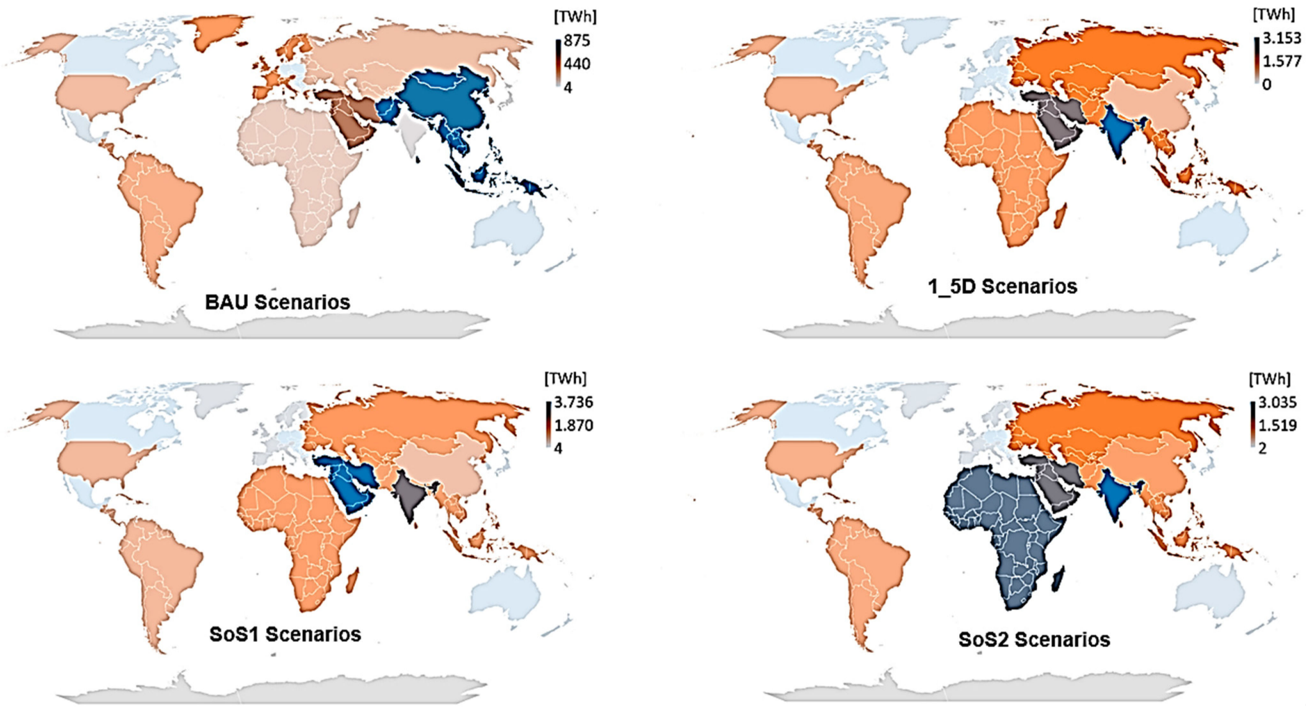

Figure 3. Global hydrogen production based on BAU, 1_5D, SoS1, and SoS2 scenarios [48].

Green hydrogen is produced from electrolysis integrated with renewable energy resources [49]. One key challenge in producing green hydrogen is the amount of electricity required from renewable energy resources. Improving production efficiency, lowering production costs, creating and scaling up hydrogen storage and transportation technologies, and current system integration are important technological considerations for expanding hydrogen energy.

2.1.2. Advancements in Hydrogen Technology Development

The development of hydrogen energy has the potential to reduce global warming and provide energy security for nations that do not currently have sufficient energy resources. Extensive research has shown that hydrogen, if successfully developed, might power vehicles and generate electricity [9,26,31–34,50]. The three pillars of the development of hydrogen energy are fuel-cell installation, hydrogen power plants/mass supply chains, and CO_2-free hydrogen, as shown in Figure 4. Technological influencing factors pertain to these three pillars of hydrogen development and assure economic efficiency [51]. The status of research and design projects' development has been outlined, projecting a global energy model to the year 2050 as reported in the following research [9,24,52].

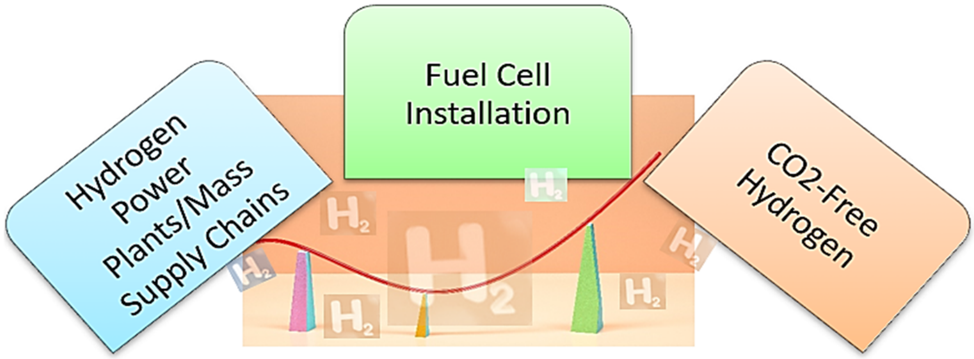

Figure 4. The three pillars of hydrogen advancement.

The goals of the technology development projects are to drastically expand the utilisation of hydrogen in the power generation field, to build the world's first full-scale hydrogen supply chain by approximately 2030, to establish flexibility in the energy supply system, and to contribute to ensuring energy security through the development and implementation of technologies [1,53]. The use of hydrogen technologies in renewable energy development and the stabilisation of electricity distribution networks would derive from both a comprehensive approach and strategic planning. Japan and Romania are setting up a global supply network as a top priority, as reported in [54,55]. For example, Japan's policy is to import fossil fuels from abroad and use them to make blue hydrogen by capturing carbon dioxide using carbon capture, utilisation, and storage (CCUS) technologies as well as establishing international hydrogen supply networks. Hence, the results from the associated hydrogen import verification tests are expected soon [3].

Fuel cells turn hydrogen-rich fuels into energy [56]. Fuel cell applications and integrated renewable power with hydrogen production systems are studied in technology validation projects to bring hydrogen and fuel cells to market [18,31,57–60]. Solutions to problems with weight and hydrogen compression and storage are required as reported by [6,17,61].

The use of fuel cells to power electric motors has many advantages. They are quiet and create no exhaust greenhouse gases [3,50,62]. Hydrogen fuel cells could replace lithium batteries in long-distance and heavy-duty vehicles, but hydrogen prices must be lowered [24]. Long distances and insufficient network use may not necessitate track electrification, making hydrogen-powered trains more viable for freight and rural/regional lines [63,64].

The adoption and utilisation of hydrogen-energy-powered automobiles can be achieved. The current position of fuel cells and fuel-cell vehicles has been widely accepted in Japan, as was reported in [54]. However, there is need for proposed regulations to improve top-level design, pilot demonstration, and hydrogen supply chain expansion for the transportation sector. The cost of hydrogen relative to fossil fuels, the difficulties of a loss of cargo space due to fuel storage, and the implementation of worldwide refuelling networks are also influencing factors. Nonetheless, to achieve financial success, it is necessary to fulfil the standards of cost, durability, and reliability. Figure 5 gives a summary of current advancements and challenges in hydrogen technology development in three stages: production, transportation, and storage.

2.1.3. Hydrogen Efficiency

The economic viability of hydrogen depends on the production process. Hydrogen is not a readily available energy source. It is usually stored in water, hydrocarbons such as methane, and other organic matter. The challenges of using hydrogen as an energy storage mechanism come from being able to efficiently extract it from these compounds.

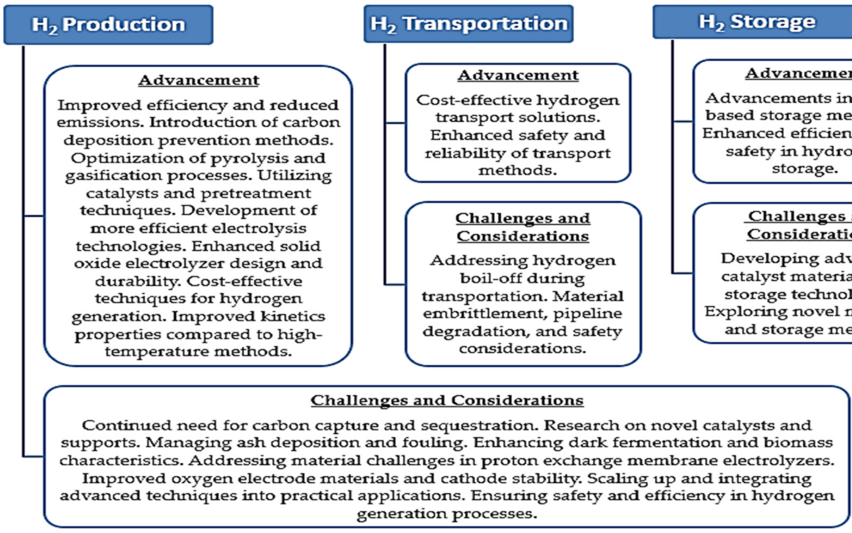

Figure 5. Advancements and challenges in hydrogen technology development.

Hydrogen is often considered for its potential in energy storage, particularly in power-to-gas systems where excess electricity is used to produce hydrogen through electrolysis [65]. This hydrogen can then be stored and later converted back to electricity when needed. However, this process is fraught with efficiency losses as reported in [66–69]. The efficiencies of hydrogen production have been reported in [70] as shown in Figure 6. Each conversion step from electricity to hydrogen and then back to electricity involves energy loss. These losses make the entire process less attractive compared with direct electrical energy storage methods like lithium-ion batteries. Furthermore, the efficiency loss becomes particularly significant when grid-scale energy storage is considered. The most employed method of hydrogen production is steam methane reforming (SMR), which involves high operating temperatures and pressures necessitating a large energy input. Though relatively efficient, the method also produces a significant amount of CO_2 as a byproduct, undermining the clean energy credentials of hydrogen.

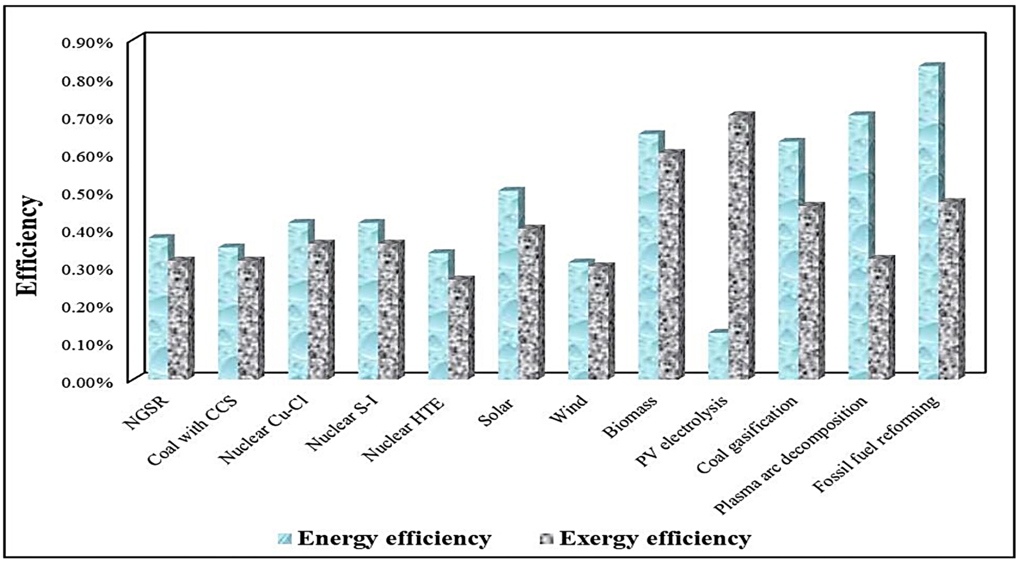

Figure 6. Hydrogen energy production efficiencies adapted from [70].

Hydrogen energy production efficiency has been reported in several studies. Water electrolysis, and more especially alkaline electrolysis, exhibits a wide range of energy efficiencies, ranging from 161% to 82% [71]. Electrophotolysis, which uses photo-electrochemical processes, has energy efficiencies ranging from 0.5% to 12% [72]. Energy efficiencies for photolysis and photosynthetic processes range from 1% to 3% and are less than 5% [73]. Ref. [74] reported that water thermolysis procedures have energy efficiencies of 20% to 55%, whereas Ref. [73] reported that chemical processes involving redox reactions had energy efficiencies of 3% to 5%. Additionally, steam methane reforming, which produces hydrogen from hydrocarbons like natural gas, often achieves energy efficiencies ranging from 74% to 85% [75]. Fossil-fuel partial oxidation technologies exhibit energy efficiencies between 60% and 75 [75]. The energy efficiencies of proton exchange membrane (PEM) technology, which is essential to water electrolysis, typically range from 67% to 84% [76]. These results demonstrate the variety of efficiencies in hydrogen generation techniques and the significance of choosing the most appropriate strategy based on energy effectiveness and purity. According to research by [77], microorganisms can attain energy efficiencies in "biolysis", or dark fermentation, that range from 60% to 80%. Ref. [74] reported that microalgae often display lower energy efficiencies, often less than 1%, with a range of 1% to 3%, with the "biophotolysis", or photofermentation, technique. According to a review [74], energy efficiencies of between 70% and 80% have been attained with "bioelectrolysis", or microbial electrolysis. Additionally, Ref. [78] reported that co-fermentation hydrolysis produced energy efficiencies of between 35% and 45%.

The concept of green hydrogen, which produces hydrogen through electrolysis using renewable energy, offers a more environmentally friendly alternative to SMR. However, challenges include the total energy requirement and availability of renewable sources of energy. While hydrogen holds promise as a medium for energy storage, challenges in terms of efficiency need to be addressed. Infrastructural development must be overcome for it to play a significant role in future energy systems.

2.1.4. Transportation and Storage

Storage and transportation have significantly impacted the cost effectiveness and practicality of using hydrogen in various industries. A viable hydrogen infrastructure requires that hydrogen be able to be delivered from where it is produced to the point of end use, such as a refuelling station. Delivering hydrogen from the point of production has an impact on the overall cost [79]. As shown in Figure 7, transportation can be categorised as semi-centralised, centralised, or intercontinental depending on distance, while storage can be liquefaction, compression, or physical or chemical bonding such as in NH_3, metals, and hydrides [79,80]. The major challenges faced while transporting hydrogen in liquefied form include maintaining a very low temperature, of about −250 °C, requiring high energy for storage [81]. Additionally, liquification consumes about 20 to 40% of the energy brought by hydrogen [82]. Other challenges include the risk of leakage, long-term storage and boil-off control. Until effective solutions for these challenges are found, hydrogen's adoption in the industrial sector will remain limited.

Safety concerns are of the utmost priority, and hydrogen poses risks [83,84]. Its flammability range is far wider than that of conventional fuel, meaning it can ignite in a wide range of concentrations. Furthermore, storing hydrogen requires either cryogenic temperatures or high pressures, both of which present the additional risk of leaks or other failures. As such, the safety systems around hydrogen storage and delivery need to be dependable, requiring redundant safety mechanisms that could add weight and complexity to the existing infrastructure design [85]. The use of hydrogen as an energy carrier must contend with various misconceptions and negative public perceptions, some of which date back to incidents like the Hindenburg disaster [86]. While technology has advanced significantly since then, the perception of hydrogen as a risky and complicated option persists. This notion can slow down the adoption of hydrogen technologies by causing hesitation among consumers and investors. Overcoming this barrier requires not just technical advancements but also concerted public relations efforts, education, and a proven safety record to change the narrative.

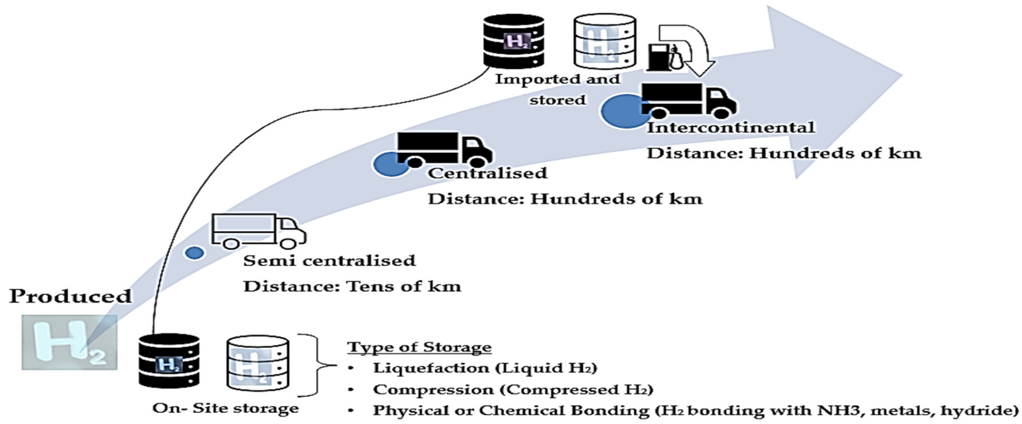

Figure 7. Hydrogen transportation and storage.

Ref. [62], a review, reported that the transportation of liquid hydrogen has an excessive cost compared with other approaches, such as compressed gaseous hydrogen and ammonia storage. When introducing a hydrogen fuel system, production at fuelling stations is the most cost-effective method, as centralised manufacturing requires expensive transport and distribution infrastructure [87]. For longer distances or with an increased need for storage, ammonia may be a better option. However, its cost components are ammonia synthesis and reforming. Furthermore, storing hydrogen requires either cryogenic temperatures or high pressures [88], both of which present additional risks of leaks or other failures. As such, the safety systems around hydrogen storage and delivery need to be extremely reliable, adding weight and complexity to the hydrogen system design. Design changes may not only be expensive but also require an extensive period of research and development (R&D) testing and certification. These challenges, along with those regarding selection of production methods, show that the storage and transportation chain depends on application and context. Currently, another challenge is that there no single solution that would be equally applicable in all hydrogen generation systems.

The cost of storage and transportation remains a challenge because hydrogen is extremely low-density as a gas and a liquid. A distributed hydrogen production system can be constructed for hydrogen storage and transportation. Key factors to consider for optimisation of hydrogen supply are distance, volume, fuelling station utilisation, demand for liquid hydrogen, energy prices, and regional fuelling station density. Hydrogen supply can be well planned so that production facilities will cut transport costs.

2.2. Logistical Factors

The economic feasibility and long-term sustainability of hydrogen implementation is dependent on logistical factors. The objective of ongoing research and development is to maximise and encourage the use of clean hydrogen as an environmentally beneficial energy source. Specifically, several logistical considerations apply when producing hydrogen. Regulations, stakeholder responsibilities, economic considerations, financial effectiveness, and private sector participation are all examples of logistical factors. The production and implementation of hydrogen presents several logistical challenges. This section discusses the logistical barriers in the shift to hydrogen energy.

2.2.1. Hydrogen Energy Supply and Demand Dynamics

The supply and demand of hydrogen energy is another influencing factor. Hydrogen's value as an energy carrier is determined by manufacturing costs and consumption. For example, in the Netherlands, hydrogen is generated by SMR without carbon capture for €1.50/kg [89]. If carbon emissions were taxed higher, grey hydrogen costs would be expected to grow [90]. However, currently, green hydrogen costs €5/kg, with power accounting for two-thirds and electrolysis for one-third of the costs, but this could drop to €2/kg by 2030. Hence, hydrogen production is feasible by 2030 if current plans are carried out, but supply and distribution must keep up [91]. However, demand for energy around the globe is forecast to increase steadily over the next few decades. Concerns about the reliability of the energy supply, global warming, and climate change all impact governments' decision-making, while concerns about the potential economic and geopolitical effects of oil supply disruptions have prompted the development of alternate fuels [92,93]. In an examination of research in [54], the projections for 2050 for both the supply and consumption of hydrogen vary widely. Figure 8a shows hydrogen global demand; it has been reported that, even with uncertainties, hydrogen demand increases according to [94] as shown Figure 8b.

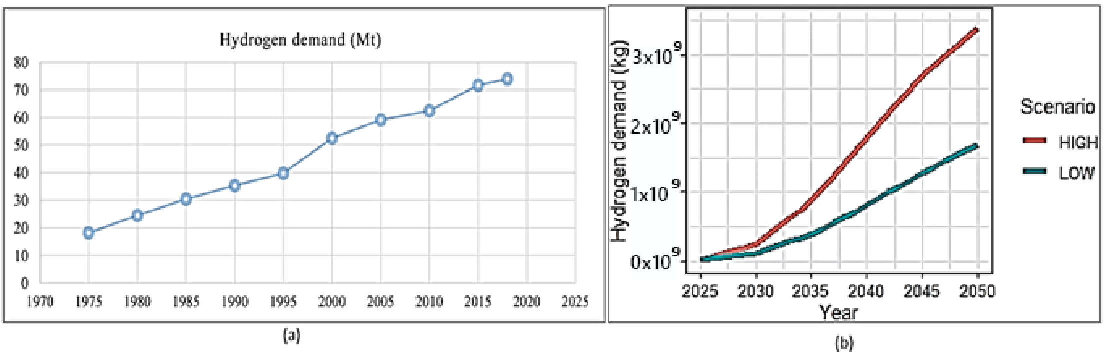

Figure 8. Hydrogen demand: (**a**) global demand according to [95]; (**b**) demand under uncertainty using the United States as a case study [94].

Research by [48] reported hydrogen energy demand using four scenarios. Their results show that the worldwide demand for hydrogen is high in the 1_5D scenario, standing at 2776 TWh, whereas the demand in SoS1 scenario is slightly lower, at 2055 TWh. Contrarily, the SoS2 scenario projects 2688 TWh of hydrogen demand. The findings indicate that hydrogen is utilised in the final energy consumption under the BAU scenario. Their research concludes that the scenario that places a priority on addressing climate change lacks a security of supply strategy, and that not all regions can produce hydrogen domestically by 2100. In Ref. [95], global supply based on trade by country is reported based on export and import as shown in Figure 9. This shows that about 40% of all hydrogen exports are made by the Netherlands, with Canada coming in second. About 15% of all hydrogen is sold in Belgium, the US, and Germany, which together account for 90% of all exports. Moreover, half of all hydrogen imports come from the top two importers, which are Belgium and the United States. France imports 8%, the Netherlands 5%, and Germany 5% of pure hydrogen, respectively. These nations contribute more than 80% of world imports.

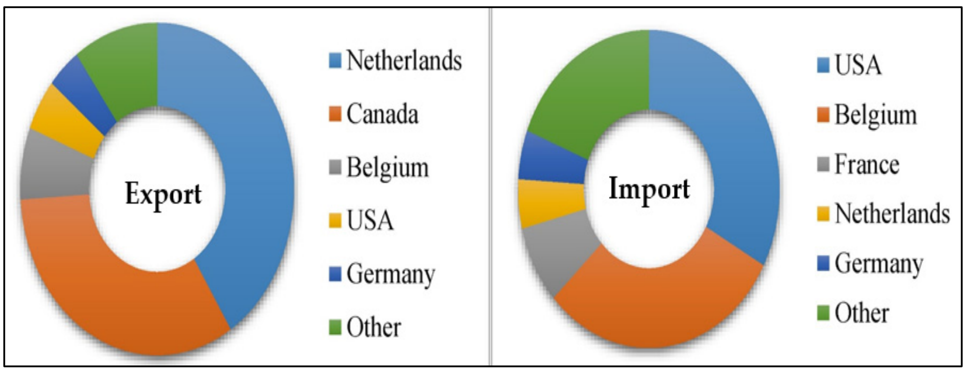

Figure 9. Hydrogen supply based on export and import trade according to [95].

Studies on the hydrogen supply chain are at an early stage. Current research on hydrogen supply chains focusses on how hydrogen relates to influencing factors regarding management of electricity and distribution networks that fuel renewable energy sources (RES). The concept of designing a hydrogen supply chain that differentiates the phases of supply, production, storage, and distribution of electricity is needed [13].

The use of hydrogen technologies in RES stabilisation may reduce the operational safety of electricity distribution networks. However, a comprehensive approach and strategic planning is needed. This strategic design should assist in approaching future global energy needs. It is important to have a good understanding of the types of environment and the existing literature to make rising RES share a future policy goal [96]. For instance, Japan may need to import hydrogen; thus, setting up strategic plans for a global supply network is a top priority [97]. To attain the economies of scale required to rapidly reduce affordable hydrogen, a significant expansion of upstream production, midstream transportation, and storage facilities for liquefied hydrogen, methylcyclohexane (MCH), and ammonia will be required [13]. Examples of some active initiatives are described [13,54,64]. Various pilot projects are being conducted in Japan to build a worldwide hydrogen supply chain. In Japan, current projects include hydrogen being transported in the form of (I) liquid hydrogen, MCH, and ammonia. As a result, Japan's domestic policy objective is to use surplus fossil fuels from abroad to make blue hydrogen by capturing carbon dioxide using CCUS technologies and establishing international supply networks. MCH is now employed as a fuel for thermal power plants and hydrogen is undergoing verification testing as an import [54,98,99]. Another project in Japan is ongoing as an attempt to extract hydrogen from brown coal, of which Australia has large reserves, and liquefy it for shipping to Japan by sea [17].

It has been reported that global oil demand is expected to rise by more than 30% by 2030, necessitating a doubling of present production levels. In addition, it has been highlighted that there may be a shortage of oil, necessitating the search for alternate sources of transportation fuel to meet expanding demand and restricted resource availability [7,98,100]. In the future, the cost of hydrogen will depend on its usage and production costs. Currently, hydrogen is mostly produced using SMR. There is a growing need for hydrogen that does not release carbon dioxide, and, if present plans are executed, the production of hydrogen energy might be deployed by 2030. Researchers typically utilise hypothetical settings to test ideas, and scenario-based studies often to look forward to the years 2030 and 2050. Based on the findings of hydrogen cross-sectoral research, supply and demand in the various markets operating will vary widely.

2.2.2. Regulatory and Legislative Policies

In certain countries, low-carbon hydrogen generation is already in use, although this is not widespread due to a lack of specific regulatory and legislative structures. As a result, certain parts of the hydrogen supply chain (including production, transport, storage, and distribution) are governed by separate sets of laws and regulations. However, if green hydrogen is to make the move from a niche player to a widespread power source, initial resistance to hydrogen development and the reaching of a minimum threshold for market penetration will require an integrated policy. National hydrogen plans, priority setting in policies, guarantees of origin, and enabling policies should form the backbone of this policy strategy. Nations can share risks, lessons learned, and best practices in the implementation of hydrogen-related solutions. By working together on safety and standards, nations can develop a common policy. Most agreements and regulations governing renewable energy systems in Europe could be adopted, depending on the possibilities and objectives set. A description of some directives of European (EU) committees is listed in Table 1 according to information collected from [20,91,101,102].

Table 1. Description of some examples of EU directives.

Directive	Description	Year	Area
(EU) 2018/2001	Renewable energy (RE) liquid and gaseous transport fuels of non-biological origin	2018	Renewable energy
2014/94/EU.	Alternative fuel infrastructure directive	2014	Hydrogen energy
98/70/EC	Fuel quality directive		Fuel directive
(EU) 2015/652	Greenhouse gas (GHG) council directive that sets the production of clean hydrogen, hydrogen from fossil fuels, and methane from hydrogen.	2015	Blue hydrogen energy
Horizon Europe EU research framework initiatives	Initiatives that fund hydrogen research and innovation projects (2021–2027)	Ongoing	Hydrogen energy
Fuel Cells and Hydrogen Joint (FCH JU)	The European Commission backing of a public-private collaboration	Ongoing	Hydrogen energy
EU	Important Project of Common European Interest (IPCEI)	Ongoing	Renewable energy
IPCEIs	Focus on microelectronics and batteries	2020	Energy
22 EU member states and Norway	Manifesto	Ongoing	Energy

Ref. [101] described the Chinese government as an example of an initiative to advance regulatory and legislative policies for hydrogen energy. Policies governing the hydrogen energy industry should be improved upon first-hand. Throughout the last few years, China's support for the hydrogen energy industry has increased [103], and local governments have issued hydrogen energy development plans and incentive policies [93]. However, each area's policy standards are fragmented and do not cohesively align. Hence, most hydrogen energy subsidy policies should be revised and improved considering ongoing advancements in this field.

An integrated policy strategy is required to overcome the initial resistance to hydrogen development and to satisfy a minimal threshold for market penetration. National hydrogen plans, priority setting in policies, origin assurances, and enabling policies should form the backbone of this approach. Global agreements and regulations for renewable energy systems should be implemented with reasonable targets in mind. Most importantly, more effective rules are required to regulate the hydrogen energy industry. Most industrialised countries have created incentive programmes and strategies to produce hydrogen energy to support the industry's rapid expansion. These policies might be utilised to shape ideas for policies that would bring about low-carbon status by 2030 and carbon neutrality by 2060, as reported in [21,101]. Table 2 suggests a convergence of directives and regulations based on some current regulations.

2.2.3. Intricacy of the Hydrogen Economical Factor

Hydrogen production relies on high-quality electrical energy, compression, liquefaction, transportation, transfer, and storage. It is in direct competition with utility-supplied power for stationary use, and liquid synthetic hydrocarbons have the potential to become the future's primary form of energy transport [17,52]. Hence, hydrogen prices need to be reduced to the lowest level feasible. In addition, the viability of the hydrogen economy hinges on its ability to make thermodynamic sense; otherwise, superior alternatives will quickly capture consumer demand. Furthermore, distribution networks already exist for most manufactured liquid hydrocarbons, but, as hydrogen needs a whole new network for energy production and distribution, systems will be drastically altered if the economy moves to be hydrogen-only. As a result, all factors involved in a hydrogen economy must be considered before making any financial investments. The following publications have discussed economic factors based on different case studies and scenarios [12,24,42,50,52,85,92,98,104].

Table 2. Proposed convergence of regulations and directives.

Regulation	Actions Required
The government	• Secure land. • Regulate the use of land. • Assess environmental impact.
Ministry of energy	• Deliver permits to build and operate pipelines for the transport of gaseous products.
Fluxes	• Transport natural gas from gas terminals to distribution system operators and large industrial consumers
Federal regulator	➢ Supervise transparency in the electricity and natural gas market in the following ways: • Approve the transmission tariffs of fluxes. • Watch over consumer interests. • Monitor whether the market situation is in the general interest and line with general energy policy. • Advise the authorities.
The Flemish Regulator of Electricity and Gas Market (VREG). Regional regulations: the Commission Wallonne Pour Energy (CWaPE) and the Brussels Energy Regulator (BRUGEL)	• Be responsible for the organisation and functioning of regional electricity and natural gas markets. • Advise the regional authorities and monitor the application of the law.

A comprehensive look into the energy requirements of a hydrogen economy can help answer some fundamental questions. Hydrogen economies must take into consideration the energy needed for the manufacturing, packaging, transportation, storage, and transfer of pure hydrogen. Refs. [12,60,105] have reported the need for comparing how energy output compares with the energy content of the delivered hydrogen. Fuel cell and hydrogen tank systems are expected to drop by as much as 70% by 2030, resulting in half of a backup generator's improved efficiency [10]. Generator systems are only slightly more efficient, but the cost of supplied hydrogen will decrease by 20–40%. Production cost reductions have less of an impact on total cost decreases, but remote generators will save almost 90% of their total costs due to a decrease in the price of hydrogen fuel [6,16].

To compete with conventional power sources, the cost-effectiveness of hydrogen generation must increase. It must abide by basic thermodynamic rules to succeed. Liquid hydrocarbons can be transported via existing networks, but transporting hydrogen calls for new infrastructure, which would significantly alter current energy systems. Numerous research must look at economic factors in this situation. It is critical to assess the energy requirements for a hydrogen-based economy. According to predictions, technologies like fuel cells and hydrogen tanks might be significantly more cost-effective by 2030, especially when it comes to enhancing backup generators. These emphasise the significance of cost reduction and energy efficiency for the viability of hydrogen-based energy systems.

2.2.4. Financing Efficiency

The internal and external financing environments are rarely considered simultaneously by scholars, and empirical studies do not consider the efficiency of financing costs and capital. For example, the hydrogen energy industry in China is still in its infancy and needs to improve its financing efficiency to develop to its full potential. This will help China achieve its long-term objective of transforming its economy into one based on high-quality sustainable development [20,101]. Seventy Chinese hydrogen energy firms were analysed in one study, with their funding efficiency between 2014 and 2020 evaluated using a Data Envelopment Analysis (DEA) model [21]. The following research explored the financing of hydrogen energy and the factors that affect it based on different case studies and scenarios [8,20–22,24–26]. The collective findings could be used as the basis for policy recommendations to aid the government in achieving its dual carbon target of peaking its carbon emissions by 2030 and being carbon neutral by 2060. The levelised cost of hydrogen (LCOH) with solar PV and electrolyser prices is shown in Figure 10a,b according to [106]. Currently, the cost of LCOH varies from 31€/MWhH_2, LHV (1.0€/kg H_2) in Atacama to 81€/MWhH_2, LHV (2.7€/kg H_2) in Helsinki. This is anticipated to decline by 33% by 2030 and by 67% by 2050. Notably, PV power prices already account for around 63% of LCOH and might reach 74% by 2050. This shows that electrolyser expenses will not have a significant impact on LCOH in the future. Additionally, it refutes the idea that inexpensive electrolysers are constrained by poor PV yield. Most high-priced electrolysers require high full load hours (FLHs).

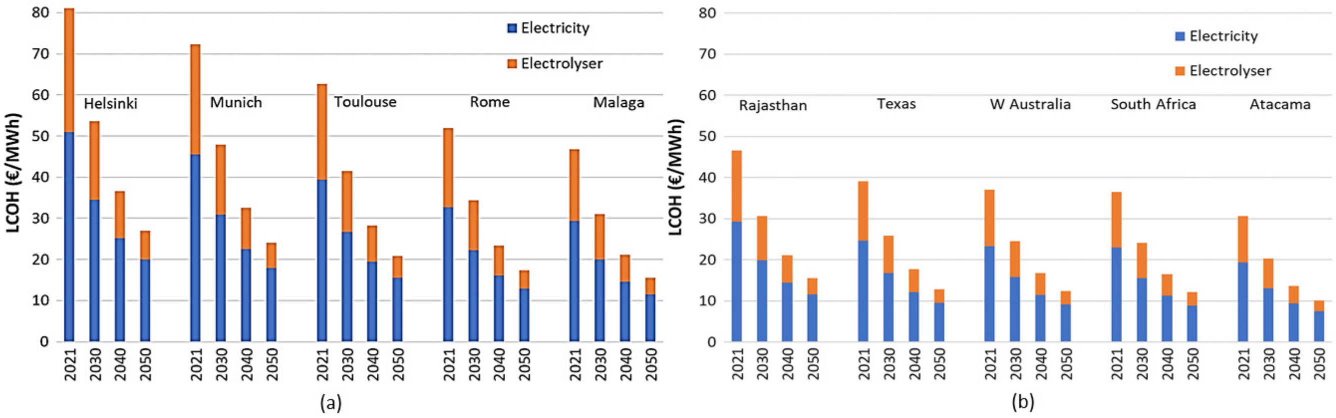

Figure 10. Financing cost of hydrogen: (**a**) based on some European locations [106]; (**b**) based on some non-European locations [106].

Since the lack of financial resources is a major obstacle to a company's capacity and decision to obtain greater standards of environmental performance, a green hydrogen producer on a modest scale can be profitable. Hence, efforts to promote the extensive use of hydrogen technologies have some flexibility under the current policy framework. For instance, the 'Reward Instead of Subsidy' policy for fuel-cell vehicles has accelerated the planning and layout of China's hydrogen energy industry [10,107]. The Modigliani–Miller (MM) theorem can be applied to H_2 finances, and states that in a frictionless capital market, the value of a company is independent of its capital structure [108,109]. In 1963, the MM theorem was developed, and it states that an increase in liabilities could increase the value of a capital structure and enterprise value, but the Chinese domestic capital market is expanding due to market-oriented reforms and improved regulation [110]. According to [111], scaling up hydrogen usage not only reduces equipment costs but also enhances capital utilisation. For instance, when considering the total cost of ownership (TCO) for passenger cars, achieving cost reductions in fuel-cell vehicles necessitates scaling up component manufacturing and the hydrogen supply chain. Their report highlights that, by 2030, TCO for large passenger vehicles may decrease by around 45%, driven by lower vehicle capital expenditure, reduced hydrogen distribution and retail costs, and more cost-effective hydrogen production. These reductions are crucial for achieving cost parity with battery electric vehicles (BEVs). Table 3 gives a summary of the influencing indicators.

Table 3. Selected results of influencing indicators based on data from [111].

Influencing Indicators	Cost USD Cents/km	Percentage	Comment
As at year 2020	47.2	-	-
Scale-up of manufacturing Step 1	8.6	18%	Annual production of 200,000 vehicles
Scale-up of manufacturing Step 2	4.5	10%	Annual production of 700,000 vehicles
Green hydrogen production	5.3	11%	Transition to 2.5 larger HRS and 40 trucking capacity
Electrolysis deployment and transition to production systems	2.4	5%	~50 GW electrolysis deployment and transition to ~100 MW production systems
Parity with BEV	26.4	-	-

A techno-economic financial analysis of a system to sell green hydrogen and create feedstock and laboratories showed that a PV-based hydrogen generation facility on a modest scale can be profitable, demonstrating the benefits of hydrogen energy financing [112]. It has been reported that small-scale electrolysis units can generate greater economic and environmental benefits than larger facilities, as they can meet up to 14% of the potential demand for medical oxygen [112,113]. Ref. [112] reported the cash flow required to compute the levelised cost of hydrogen (LCH) and the net present value (NPV). Their outcome calculated the return on investment using NPV and considering all expenses and income. The NPV was negative for the first scenario (selling of hydrogen). The second scenario's NPV was positive at +228.7 kV (selling of coproduced oxygen and hydrogen). Both the internal rate of return (IRR) and the modified internal rate of return (MIRR) are higher than the weighted average cost of capital (WACC), 5.7%, at 9.8% and 7.3%, respectively. Table 4 shows the tax and financial parameters according to [112].

Table 4. Tax and financial parameters.

Parameter	Value
Equity rate of return	7.0%
Inflation rate	1.2%
Tax rate on earnings	30%
System degradation rate	0.5%/year

2.2.5. Stakeholders' Roles in Hydrogen Energy Development

Numerous sectors have already embraced hydrogen development, indicating a promising expansion of the hydrogen economy. This convergence engages companies across various sectors in collaborative efforts to develop and implement hydrogen-based solutions. These sectors encompass the automotive, chemical, energy, design, and financial industries. The wide array of sectors and regions participating in hydrogen development initiatives serves as evidence of hydrogen's significance in the shift toward a decarbonised economy. The diversity in both sectoral and geographical engagement underscores the pivotal role of hydrogen in the transition to a decarbonised economy [52]. These groups intend to collaborate to develop effective solutions and hasten the transition to sustainable energy [112,113]. This shows that the push to decarbonise the global economy is progressing, and hydrogen is a key component of that progress, as reported in [56]. The development and implementation of hydrogen solutions considering stakeholders' roles will play a fundamental role in building a clean and diversified energy system. As a result, hydrogen may make headway in the drive toward decarbonising the world's energy system.

A guaranteed alignment with key stakeholders' interests, such as industry, end users, academia, the investment community, and other government agencies has an impact. Countries like China, the United Kingdom, Japan, the United States, Germany, and South Korea are among the nations that have differentiated themselves in this field through their implementation strategies as reported in [114]. One of the key channels for this input is through requests for information and workshops to seek and incorporate input from a wide range of stakeholders into activity planning. These workshops would provide an open venue for discussing the status of technologies and the obstacles to their development and implementation.

Influencing factors in coordinating the priorities of various stakeholders go beyond national borders [115]. These include the need to develop a framework for seasonal and long-term hydrogen utilisation and use, set the role and pledging commitment in an exact time frame, and adhere to the regulation and policies of the strategy [116]. Large-scale implementation of hydrogen projects by the corporate sector requires commercial joint ventures, but the future of the hydrogen business hinges on technological advancements, so the importance of stakeholders and international cooperation are the backbone of hydrogen development. Stakeholders can benefit from events like workshops, roundtable discussions, delegations, and research trips, even when working on a global scale.

2.2.6. The Private Sector's Role in Hydrogen Energy Development

The influencing factors of the private sector have an impact on realising a hydrogen economy. It is expected that the private sector will lead the way in developing green hydrogen for applications in transportation and industry as well as hydrogen investment. Adding green hydrogen to the European Commission's hydrogen strategy is now under consideration [7,63].

A best-practices approach to hydrogen interactions is beginning to be applied to this in the private sector, with commission officials including hydrogen. Europe's 10 recommendations from June 2020 in the agency's overall hydrogen plan reported the role of low-carbon hydrogen in facilitating a seamless transition and emphasising the importance of technological neutrality. However, the World Water Forum (WWF) has spoken out against the Commission's strategy, claiming that it is incompatible with the EU's objective of being climate-neutral by 2030 because the Commission intends to continue generating low-carbon hydrogen using gas and carbon capture and storage (CCS) until 2030 [117]. The European Academies of Science and Arts Council (EASAC) has recommended new regulations to speed up the switch from fossil fuels to clean hydrogen in the chemical industries and steel production; as well as reconsidering carbon pricing and the elimination of fossil fuel subsidies, this would require scaling up hydrogen [117,118].

The Hydrogen Backbone Initiative was launched in July 2020 to build 6800 km of dedicated hydrogen transport infrastructure between hydrogen valleys by 2030. In February 2021, European energy regulators proposed a phased approach to hydrogen network regulation considering energy system integration [7]. The European committee has called for new regulations to expedite the transition from fossil fuels to clean hydrogen in the chemical industries and steel production, including a legal framework for market development and infrastructure and EU-wide sustainability classification [64].

2.3. Capital Availability

From 2001 to 2021, central banks across the world undertook unprecedented monetary easing. This dramatically improved capital availability and liquidity [119,120]. Such policies have a positive impact on the finances of green innovation firms, such as those in the low-emission hydrogen sector, by reducing borrowing costs and appreciating asset values. However, national governance factors and policy decisions on environmental regulation also have a significant effect in improving capital flows by reducing risk premiums [121]. However, the loose monetary policy produced inflationary pressures prompting central banks to increase interest rates and a reversal of the policy, reducing the overall availability of funds in all sectors including the hydrogen economy [119,122]. Major geopolitical events such as Brexit and US–China tensions have caused economic and regulatory policy uncertainties, negatively impacting capital flows. Refs. [123–125] focused on the impact on environmental sustainability in the presence of economic policy uncertainty and found a negative effect and recommended stable government policies to foster investment.

Due to an increase in awareness of the need for investment in green and sustainable technologies and projects, over the past three decades, ESG assets have increased ten times. ESG assets/investing involves including the environmental, social, and corporate governance benefits, performance, and behaviour of companies/firms in investment decisions [126]. The sustainability factor of green/low-emission hydrogen attracts capital in the ESG-conscious financial environment. Many investment institutions, including European investment banks, the International Finance Corporation, BlackRock, and Goldman Sachs have pledged billions of dollars of investment into hydrogen projects [127]. However, there are ongoing political and academic debates on the effectiveness of ESG-based investing and even hostile political action towards ESG-based investment: for example, the anti-ESG laws in Texas, USA, mandating disinvestment from ESG asset management companies [128]. Despite the authors of [128] not finding any significant economic effects, this remains a risk factor for the free flow of capital into the hydrogen economy [129].

3. Hydrogen Alignment with Fossil Fuels

There will always be considerable uncertainty concerning how much oil still exists in the world and how much can be recovered. Oil peak predictions have a lengthy history of being misleading, and previous experience has shown that reserves are often limited. However, there are convincing arguments for accepting modern forecasts as more reliable than previous predictions [7]. For example, since the 1980s, global production has exceeded the number of discoveries, while the magnitude of new discoveries has shrunk. However, the most recent world energy scenarios indicate that global oil demand will climb by more than a third through 2030. This forecast suggests that total oil production will need to double to keep up with increased demand [25]. However, analysis shows that if we continue to do business as usual, we will face shortages in the supply of oil in the next few decades due to a mismatch between growth forecasts and the remaining potential of conventional oil. Estimates indicate that the production of conventional oil will reach its peak between 2030 and 2050, leading to increased reliance on oil imports and the Organisation of the Petroleum-Exporting Countries. The time has come to diversify the transportation fuel market away from oil, as resource potential versus rising oil demand shows [60]. The hydrogen supply infrastructure can expand and have an impact on the energy transition from fossil fuels [79]. However, this depends on country-specific criteria like feedstock (such as renewable energies), population density, geographic factors, and legislative support; therefore, it must be analysed country-by-country.

Hydrogen infrastructure can deliver significant solutions and cross-national composite reliability for energy security including in the transportation sector. Nonetheless, this requires fuel-cell vehicles to be cost-competitive with conventional automobiles and problems regarding fuel cells and hydrogen storage to be solved [55]. However, hydrogen introduction is comprised of two phases, infrastructure build-up (2015–2030) and hydrogen technology diffusion (2030–2050). Early implementation (2015–2020) and transition (2025–present) make up the initial phase (2020–2030). Scenario results reported tend to converge after the transition phase when the initial infrastructure is created [12]. Hydrogen utilisation will start in heavily populated regions with beneficial support policies and will expand into rural areas during the transition phase. Buses and fleet vehicles like delivery vans operate locally, run on short, regular routes, and return to a central depot for refuelling and maintenance, making them perfect candidates for the early adoption of hydrogen [64]. Zero-emissions requirements and financial incentives are needed to accelerate hydrogen car adoption. Hydrogen internal combustion engine (ICE) vehicles with bi-fuel conversions may eliminate the need for a nationwide network of refuelling facilities in the early stages.

To go deeper, feedstock price assumptions, which impact production costs, are more vulnerable in longer-term hydrogen supply cost estimates. Overcapacity in supply and refuelling infrastructure is a major factor in the high initial prices for hydrogen. While energy and CO_2 certificates are predicted to increase in price, the cost of the hydrogen supply is expected to remain stable for decades [130]. As the price of fossil fuels reaches a certain threshold, the cost of producing renewable hydrogen will decrease, allowing the two sources to compete on price [2]. Between 60% and 80% of overall supply costs are related to hydrogen production, which is a sizeable component. With 10% going to transportation and liquefaction, the remaining 1% is given to petrol outlets. Once crude oil prices pass the range of $80 to $100 per barrel over the long run, hydrogen is positioned to become cost-competitive, excluding taxes and vehicle-related expenditures. Notably, using hydrogen to produce electricity from fossil fuels in centrally located facilities and combining it with carbon capture and storage might result in considerable reductions in carbon dioxide emissions.

3.1. Hydrogen Energy Utilisation and Implementation

Setting long-term greenhouse gas (GHG) emission reduction targets cannot be achieve by energy efficiency alone; supporting green hydrogen could help governments combine CO_2 emission goals with carbon trading programmes. These would allow corporations to sell excess emissions to higher-emitting companies [131] However, green hydrogen policies should work with carbon-capture policies to address fair international competition, implementation ease, and windfall profits [102]. In addition, grey hydrogen produces methanol and ammonia and can be created without updating equipment or technology [29,98] Governments and companies should boost global competitiveness. If some countries control industrial emissions, production could be relocated to countries with fewer rules and higher GHG emissions. Alternative methods could use renewable energy and green hydrogen.

The rising demand for hydrogen will have a significant impact on the cost of distribution and final consumption. By 2030, improvements in vehicle capital investment, hydrogen delivery and retail, and hydrogen generation could reduce the total cost of ownership (TCO) by as much as 45%. To make fuel-cell cars more affordable, production needs to be ramped up, and high-capacity logistics need to be implemented. High infrastructure utilisation and quick cost reduction are two outcomes that can be expedited in hydrogen energy transition based on demand-driven design. Boosting fuel cell and hydrogen storage tank output can save expenses by 70%, but achieving net-zero emissions is more important than making small improvements [132] Cost, investor confidence, competition, lack of legislative attention, lack of large-scale proof, and lack of knowledge are key factors in green hydrogen's industrial usage. However, R&D and legislative assistance can help overcome these obstacles [8]

The incorporation of green hydrogen into the ammonia industry and fertiliser production brings about substantial economic benefits and positive environmental impacts [133]. Reduction of harmful emissions from traditional methods of ammonia production contributes to biodiversity protection, safeguarding ecosystems near production facilities [134,135]. Several studies have reported that the economic viability of green hydrogen positively influences the overall cost structure of ammonia production [136–138]. This minimises the environmental impact associated with industrial activities, promoting a more harmonious coexistence between industry and nature. Overcoming challenges and investing in technological advancements are essential for realizing the full potential of green hydrogen in these critical sectors [133,134,138]. The use of green hydrogen in ammonia production should be emphasised due to its considerable financial advantages, favourable effects on the environment, and ability to establish green ammonia as a more sustainable and cleaner substitute in the ammonia sector. Realising these advantages in the creation of green ammonia will depend on overcoming obstacles and developing technologies. The impact of green hydrogen on ammonia is summarised in Table 5.

Table 5. Impact analysis of green hydrogen in the ammonia industry and fertiliser production.

Factors	Impact	Details
Economic	Cost Reduction, Market Growth and Efficiency	• Green hydrogen (G-H_2) can reduce the costs of ammonia production, making the process more economically viable. • Energy efficiency improvements in electrolysis can contribute to economic viability and enhance the competitiveness of G-H_2 compared with conventional steam methane reforming (SMR). • G-H_2 can encourage market expansion and employment opportunities, especially in the areas of renewable energy technology. • Opportunities for employment exist in R&D, infrastructure, and manufacturing, which supports the development of a skilled labour force.
	Diversification of Energy Sources	• Improves energy security and resilience in the manufacture of fertiliser and ammonia by reducing reliance on fossil resources. • Helps to promote sustainable production methods by lowering exposure to the price volatility of conventional energy sources.
	International Trade Opportunities	• G-H_2 adoption in ammonia production positions countries with surplus renewable resources to emerge as major key players in the global green ammonia trade. • International cooperation and the advancement of global sustainability goals can be facilitated by the export of green hydrogen and its byproducts, such as green ammonia.
Environmental	Carbon Emission Reduction	• In contrast to conventional processes for ammonia, G-H_2, in powering the synthesis of ammonia, significantly reduces carbon emissions, positioning green ammonia as a cleaner alternative. • The shift towards green hydrogen aligns with global efforts to mitigate climate change and achieve sustainability goals.
	Air and Water Quality Improvement	• Pollution from conventional methods is reduced, improving the quality of the air and water, which benefits nearby ecosystems and populations. • Since the emissions of dangerous compounds like carbon dioxide and nitrogen oxides are reduced, positive effects on public health are projected.
Challenges with G-H_2 in green ammonia production	Initial Investment Costs	• Development of financial incentives and policies between governments and industries to reduce the initial investment costs of establishing green hydrogen and green ammonia infrastructure.
	Intermittency of Renewable Energy	• Development of regulations and financial incentives between governments and businesses to reduce the initial costs associated with setting up green hydrogen infrastructure.
	Technology Development	• To make electrolysis technologies more effective and affordable for the large-scale generation of green hydrogen, continue to invest in research and development.

3.2. Role of Hydrogen

The production of hydrogen from waste refineries is a viable path towards developing a clean and renewable energy source. Techniques like gasification and steam reformation may convert organic waste components into useful hydrogen gas, offering a clean fuel choice for a variety of uses. Combining hydrogen production with waste refineries maximises the use of waste materials while lowering greenhouse gas emissions. The significance of H_2 availability is emphasised in relation to refineries' capacity to adjust to new biomass feedstocks. The development of biorefineries, and more especially the hydrotreatment of bio-oil, is a crucial step towards the integration of oils obtained from biomass into the petrochemical industry. The economic viability of noble metal catalysts in the bio-oil processes is hampered, nonetheless. Furthermore, the availability of green H_2 is necessary for catalytic processes that transform CO_2 into methanol, dimethyl ether, and other fuels. The direct synthesis of clean fuels from CO_2 and hydrogen, in which catalysts play a critical role, is one promising breakthrough. Additionally, systems that combine steam-dry reforming with bio-oil and sorption-enhanced steam reforming have promise for producing sustainable syngas from biomass and CO_2. All things considered, these developments highlight how crucial sustainable hydrogen generation is for a variety of uses, including the creation of biofuel and waste processing. Table 6 below summaries the future roles of H_2.

Table 6. Other roles for hydrogen.

Role of H_2	Details	Reference
Hydrogen Production from Waste Refineries	• Waste refineries can potentially produce valuable hydrogen through conversion operations. • Synthesis of hydrogen from waste materials, using methods like steam reforming or gasification, can transform organic elements in waste into hydrogen gas. • Hydrogen generated by waste refineries can serve as a clean fuel option for power production, transportation, and industrial uses. • Combining waste refineries with hydrogen generation contributes to reducing greenhouse gas emissions and maximizing the use of waste resources.	[139,140]
Biorefinery Development	• The availability of H_2 is essential for refineries transitioning to new feeds made of biomass. • An important step in biorefinery development is the hydrotreatment of bio-oil, enabling the incorporation of oils obtained from biomass into the petrochemical sector. • Sulphide transition metal catalysts, such as CoMoS and MoP, have shown effectiveness in the hydrodeoxygenation of bio-oil, demonstrating high selectivity for hydrogenated molecules. • Noble metal catalysts like PtPd bimetallic catalysts, while effective, may pose economic feasibility challenges due to their high cost and increased H_2 consumption.	[141,142]

Table 6. *Cont.*

Role of H_2	Details	Reference
CO_2 Conversion and Catalytic Processes	• The viability of catalytic processes for converting CO_2 into methanol, dimethyl ether, automobile fuels, and chemicals depends on the availability of green H_2. • Studies show that H_2 costs and CO_2 taxation impact the profitability of green methanol synthesis, requiring renewable energy for economical manufacturing. • Direct synthesis of dimethyl ether (DME) from CO_2 and syngas involves bifunctional catalysts, facilitating the conversion of hydrogen into DME. • Direct synthesis of gasoline from CO_2 and hydrogen is a promising approach for producing clean fuel, with various catalysts including nano-metal oxides and zeolites, playing a crucial role in the conversion process.	[143–146]
Bio-oil Combined Steam-Dry Reforming (CSDR)	• CSDR is explored as a viable method for producing syngas from biomass and CO_2. • Research indicates promising developments for bio-oil CSDR technology, combining decarbonisation with sustainable syngas generation. • The H_2/CO ratio in syngas from CSDR may vary based on specific operating conditions and feed composition.	[147]
Sorption Enhanced Steam Reforming (SESR)	• SESR is examined in terms of raw bio-oil, with the combination of dolomite and Ni/Al2O3 catalyst reported to lead to a gas stream with a high percentage of H_2 during hydrogen production.	[148]

4. Hydrogen Alignment with Hydropower

Hydroelectricity is the largest source of renewable power, and its total share is bigger than all other sources combined worldwide. Apart from hydrogen energy systems' alignment with RES for stabilisation, there is potential for green hydrogen production using cheap hydropower in hydropower-rich nations such as Brazil, China, Norway, etc. A case study noted that Nepal, which has surplus hydropower which may be curtailed due to low demand, can use green hydrogen production to add value [149,150]. Another study looked at the potential for hydropower in Brazil and concluded that the cheap availability of renewable power, especially excess hydropower, makes it economically viable to produce hydrogen at a lower LCOH [150]. Various historic and new projects are deployed or planned in various nations that are aligned with hydropower [151]. Both studies highlight the potential for generating cheaper green hydrogen with excess hydropower, especially when the water inflow is high, or the power demand is low.

The limited availability of viable sites and other environmental concerns, large capital investment requirements, and the lengthy planning and development process for large-scale hydro projects have slowed their expansion. Also, existing hydro power plants in many developed economies are ageing rapidly. This poses a risk to their long-term viability. Their dependence on seasonal water availability and occurrence of droughts also poses risks [152].

5. Discussion

Despite its contributions, this study poses limitations that present challenging questions for future research in hydrogen development. Understanding of all the factors and parties involved in the hydrogen industry will lead towards more effective management and will pave the way for the development of comprehensive strategic plans and suitable computational industrial systems. Therefore, the consideration of all factors of influence will reflect positively on what we aim to achieve in this preliminary study. This paper may help to make decisions for hydrogen energy markets to be penetrated by 2030 and 2050. Furthermore, it will provide a more comprehensive view of the purpose and strategic plan for hydrogen utilisation, including decisions surrounding the location of hydrogen plants, considering infrastructure costs and distance to the end user, supply chain constraints, and the availability of alternative energy sources.

A comprehensive understanding of the factors affecting the development of hydrogen energy projects, including all the challenges facing the developers, is shown in Figure 11. The influencing factors are related and can sometimes include sub-factors related to each factor and their interdependence based on the project capabilities. Without rules and legislation to assure the rights of developers and investors, the success of an international hydrogen energy plan may not be realised.

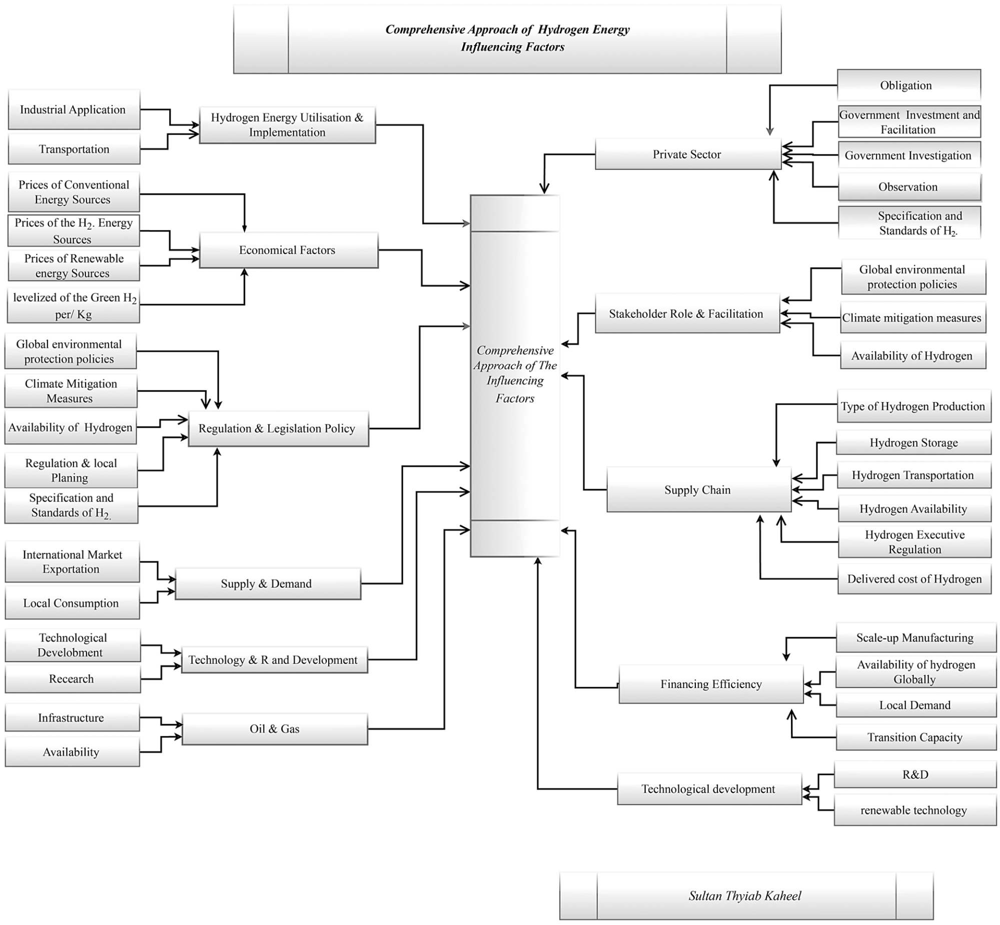

Figure 11. The comprehensiveness of Hydrogen-energy-influencing factors.

A summary of the influencing factors in hydrogen energy development is compiled below in Table 7. Difficulties in existing hydrogen energy transition strategies related to the key factors are indicated.

Table 7. Summarise of hydrogen-influencing factors.

Factor		Summary
Logistical	Policies	Inclusive policy strategies, enacted through regulation and legislation, are vital to overcoming scepticism and fostering market entry. Collaborative efforts among nations to share risks, lessons, and best practices are crucial.
	Supply and Demand of Hydrogen Energy	Achieving hydrogen production by 2030 hinges on executing current plans. Future hydrogen pricing is influenced by production expenses and expected demand. Increases in the price of grey hydrogen are expected with heavier carbon emission taxation under systems like the ETS.
	Energy Supply Chain	Infrastructure and technology availability supporting sustainable demand, storage, and distribution is crucial for long-term supply success. Establishing a global supply network and expanding upstream production are high priorities.
	Role of Stakeholders	The involvement of diverse sectors in hydrogen development underscores its importance in the transition to a decarbonised global economy. The expansion of the hydrogen economy signifies progress in decarbonisation efforts.
	Private Sectors	Private sector involvement is expected to accelerate green hydrogen adoption. The desire for quick financial gains drives the private sector to seek rapid improvements in hydrogen energy technologies, including production, transportation, and storage. Collaborative roles between industry sectors are vital in facilitating the sector's development and progress.
Technical	Production	
	Transportation and Storage	Hydrogen transportation presents logistical challenges. Hydrogen fuel cells could potentially replace lithium batteries in long-distance and heavy-duty vehicles, but this depends on reducing hydrogen prices. Hydrogen-powered trains are considered for freight and rural/regional lines, particularly in maritime and aviation, but solutions for weight and storage issues are needed.
	Hydrogen Technology	Technology development indicates that hydrogen fuel costs are expected to decline due to falling hydrogen prices, impacting energy production and distribution. Hydrogen directly competes with utility-supplied power for stationary use, necessitating a well-planned strategy for using hydrogen technologies in renewable energy sources. The integration of the Internet of Things (IoT) devices aids effective data collection.
	Utilisation and Implementation	Establishing large-scale hydrogen demand and achieving a hydrogen supply cost below $10/ton are essential for demonstrating the decarbonisation of basic chemicals and thermal demand. By 2030, large passenger vehicle ownership costs may decrease by as much as 45%.
Hydrogen Alignment with Fossil Fuels		Hydrogen supply infrastructure has the potential to diversify the transportation fuel market away from oil, dependent on feedstock, population density, geographic factors, and legislative support. Significant investments are required (estimated at $150–190 million per gigajoule) with potential reductions in carbon dioxide emissions.

6. Conclusions

This paper conducts a thorough analysis of hydrogen energy focusing on influencing factors for expanding hydrogen production. It has discussed both technical and logistical factors, including policies, and highlighted the need to incorporate key elements affecting hydrogen production. Currently, hydrogen applications are not fully realised on a large scale due to the absence of comprehensive strategic and economic plans, in both developed and developing countries. Recognising hydrogen as a clean energy alternative entails substantial planning, construction, operation, and overcoming of challenges, particularly depending on region. Efforts to achieve zero net carbon emissions involve speeding up the development of clean hydrogen, which is expected to gain prominence in the near-to-medium term, alongside traditional fuels. This transition is supported by public–private partnerships that facilitate the commercialisation of hydrogen and fuel-cell technologies. Clean hydrogen is poised to be integrated into various sectors in the coming years, complementing existing fuels, although specific applications in different industries remain undefined. The progress of hydrogen development needs to align with global commitments to achieve domestic and international net-zero carbon targets. Nonetheless, hydrogen's adoption is anticipated to increase gradually in the short-to-medium term, alongside conventional fuels and other decarbonisation technologies, though it will encounter various challenges despite its potential to overcome many fundamental obstacles.

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