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Realizing a Green Hydrogen Economy: An Examination of Influencing Factors

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***Abstract* – The significance of hydrogen in the context of the ongoing energy transition is growing noticeably. This study presents a review of the literature on the factors that influence the development of a hydrogen economy. Based on an analysis of relevant studies, we suggest the factors that drive the growth of a hydrogen economy. Unlike traditional sector-based analyses, our approach is a comprehensive examination of the hydrogen value chain, incorporating stakeholder perspectives that are frequently overlooked in technical and economic research. Drawing on recent International Energy Agency assessments and extensive desk research, we identify barriers and propose solutions critical to the successful implementation of a hydrogen economy. The study then introduces a conceptual causal loop diagram and an illustrative framework that visually depict the intricate interconnections between stakeholders and influencing factors. The findings emphasize the importance of increased political support, particularly for addressing concerns about technological immaturity and economic viability, and strategic collaborations between private companies, academia, and government institutions. The proposed solutions, which include research and development support and the formulation of national hydrogen strategies, highlight the critical role of a well-defined policy framework in advancing the green hydrogen economy. This study significantly enriches both academic understanding and practical decision-making by providing valuable insights for long-term hydrogen development.**

***Keywords* – Energy systems analysis; energy transition; hydrogen economy; influencing factors.**

1. INTRODUCTION

Fighting climate change is a contemporary challenge of the global society. Global temperatures have already reached half the allowed 2 °C temperature increase relative to pre-industrialized levels, which, scientists warn, is the threshold by the end of the century beyond which the climate and the environment will encounter dangerous, catastrophic consequences [1]. Transitioning toward climate neutrality [2] requires society to reduce carbon emissions in less than 30 years to an extent no sector has yet achieved.

Efforts to mitigate climate change should be improved, and hydrogen is one of the considered solutions [1]. Hydrogen pathways in clean energy transition are being actively explored in case studies of various scales, such as studies in China [2], Italy [3], and Europe [4] and a global study [5]. Hydrogen currently accounts for less than 2.5 % of the global energy consumption [6]–[8], but this proportion can increase to 12 % by 2050 [6]. The

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primary rationale for using hydrogen is to shift from the current linear energy systems to integrated energy systems, where energy flows between users and producers, reducing wasted resources and money [7]. Sustainable hydrogen provides energy storage, sector connectivity, and emission reduction [8].

However, despite the contribution of hydrogen to the achievement of decarbonization, several challenges hinder the development of hydrogen. Industry stakeholders raise significant barriers that the technology must overcome, such as high costs, availability of fuelling infrastructure, and lack of experience and knowledge [9]. Other authors have added such factors as lack of an integrated national strategy and roadmap, lack of private-sector participation, low willingness to use hydrogen, and high dependence on fossil fuel revenues [10] and safety issues [11]. These examples indicate the complexity of a hydrogen economy, highlighting the different stakeholders, interests, and time-varying factors determining the development of such an economy along its value chain [12].

This paper is a literature review on the factors that influence the development of a hydrogen economy. The introduction gives background information about the present consumption of hydrogen, future development prospects, and emerging trends based on a recent International Energy Agency (IEA) assessment [13]. Additionally, desk research is conducted on the variables influencing the growth of a hydrogen economy. This paper enriches the field in various ways. First, we take a holistic approach, examining the hydrogen value chain rather than specific phases or sectors, as has been described previously (such as [14]–[17]). Second, we incorporate stakeholder analysis, elucidating the practical perspective of implementers and gaining insights that are often overlooked in conventional technical or economic research. Furthermore, for the growth and advancement of a hydrogen economy, the significance of public attitudes and information distribution should be considered in addition to technical and economic factors. This involves the development of public policies and the establishment of collaborative efforts among research institutions and nations, drawing upon successful models of implementation. Such measures will facilitate the exchange of knowledge among relevant stakeholders [12]. Third, given our desk research findings, we propose a conceptual causal loop diagram that illustrates the linkages identified in the literature review between the various stakeholders in a hydrogen economy and their interactions. Clarifying the connections between the various components and participants of the economy can facilitate the prediction of system behaviour and its associated effects. This approach will then enable the formulation of highly informed decisions aimed at reducing the carbon dependency of domestic economies. It will also help deepen the comprehension of the intricate hydrogen economy. By summarizing existing knowledge about the elements affecting the green hydrogen economy from a holistic perspective and identifying gaps in the current understanding of the subject, this study is practically significant not only as a decision-making guide but also as an academic resource.

1.1. Background Information

The latest IEA Global Hydrogen Review 2023 [13] distinguishes five sectors of hydrogen consumption: industry, refining, transport, buildings, and electricity generation. Below, we briefly provide background information about the current hydrogen developments in these sectors and expected future trends.

1. Industry. The industry sector is the largest consumer of hydrogen globally, using 53 Mt of hydrogen in 2022. Hydrogen is used to produce three major industrial commodities: ammonia (60 % of hydrogen demand in 2022), methanol (30 % of hydrogen demand in 2022), and steel (10 % of hydrogen demand in 2022). Considering current trends and announced policies, the IEA projects that the demand for hydrogen

will rise by approximately 20 % by 2030 relative to the 2021 level [18]. Virtually all hydrogen used in the industry sector is obtained from unabated natural gas or coal, producing 630 Mt of direct CO_2 emissions on a net basis (or 7 % of industrial CO_2 emissions) in 2021. Considering current policies and announced projects, by 2030, low-emission hydrogen production in the industrial sector is expected to reach 3 Mt and the hydrogen demand for oil refining, ammonia and methanol production, high-temperature heating, and production of primary steel is projected to grow by 7 %, 31 %, 9 %, and up to 14 %, respectively [19].

2. Refining. The global hydrogen demand of the oil refining sector exceeded 41 Mt in 2022 [13]. This demand is mainly influenced by the consumption of oil products, as hydrogen is used to remove impurities and upgrade heavy oil fractions into lighter products. Almost all hydrogen used in refineries is obtained from fossil fuels, resulting in 240–380 Mt of CO_2 emissions in 2022. New sources of hydrogen demand in refineries may include biofuel upgrades, the production of low-emission synthetic hydrocarbon fuels (synfuels), or high-temperature heating for various processes.
3. Transport. Hydrogen consumption in the transportation sector is rapidly growing. The total hydrogen demand of this sector exceeded 30 kt in 2021 and increased by approximately 45 % in 2022. Nonetheless, hydrogen consumption accounts for an insignificant part of the total transport energy consumption. Given their high annual mileage, trucks and buses are the biggest consumers, although the largest fleet in terms of the number of units is passenger cars (approximately 50 thousand). In 2022, the first fuel cell train fleet started operating in Germany [20]. Hydrogen's role in rail transport is expected to rise in the near term, as it is a substitute for diesel rail lines where electrification is difficult and the distances are too long to be covered by battery electric trains. Global hydrogen demand is expected to reach 0.7 Mt by 2030 in the Stated Policies Scenario and 8 Mt in the Announced Pledges Scenario [18]. Industry announcements indicate that the market for hydrogen-powered vehicles is poised to expand over the next decade in all road segments. China and Korea have had the largest increase in the number of hydrogen refuelling stations in stock since 2020, with Korea accounting for approximately two-thirds of the increase in the number of fuel cell vehicles in 2022. In terms of infrastructure, approximately 1,100 hydrogen refuelling stations are operating globally as of June 2023, with hundreds more planned. Hydrogen technology development is also occurring in off-road transport, shipping, and aviation. Ports are particularly well-suited to become hydrogen hubs, and some are beginning to integrate hydrogen infrastructure to support heavy-duty trucks, cargo handling equipment, and other port equipment and maritime vessels. The European Union (EU) established the FuelEU Maritime regulation in July 2023 to encourage the use of low-carbon fuels in shipping, offering additional incentives for the use of nonbiological fuels, such as low-carbon hydrogen [21].
4. Buildings. Hydrogen accounts for a negligible share of energy demand of the building sector, with no significant increase from the previous years. Currently, hydrogen cannot compete with traditional low-carbon alternatives, such as electricity, district heat, and distributed renewables. Hydrogen consumption will exceed 1 Mt by 2030, accounting for only 0.14 % of the overall energy demand of the industry. The main reason for this is the low energy extraction efficiency of buildings. However, opportunities for hydrogen applications may exist in buildings that already have natural gas infrastructure and where energy use is difficult to decarbonize. Hydrogen can provide building heat supply in several possible ways. Blending hydrogen with natural gas (blending ratio of 5–20 %) using existing gas infrastructure and equipment

is a simple, cost-effective way to reduce emissions [22]. However, natural gas combustion releases emissions. Nonetheless, this type of hydrogen use will help scale-up hydrogen production, thus reducing hydrogen production costs [23]. For instance, from 2023, part of the gas network of the United Kingdom (UK) will be ready to use up to 20 % hydrogen blends [24]. According to IEA forecasts, the hydrogen consumption of buildings will account for 0.1–0.2 % of the sector's energy consumption in 2030. The following are other ways to provide building heat supply using hydrogen: methane production from pure hydrogen, direct use of pure hydrogen, and use of fuel cells and cogeneration.

5. Electricity generation. Hydrogen accounts for less than 0.2 % of global electricity generation. Gas turbines and reciprocating engines can use hydrogen. In the short run, co-firing with hydrogen or ammonia can lower emissions in current coal- and gas-fired power plants. The long-term flexibility or large-scale seasonal storage offered by hydrogen and ammonia-fired power plants can aid in the integration of changing renewable energy sources. The utilization of hydrogen in fuel cells and the co-firing of ammonia in coal-fired power plants will account for approximately 10 % and 6 %, respectively, of the project pipeline capacity by 2030 worldwide. Considering current trends, the demand for hydrogen for electricity generation is expected to remain quite low, approximately 0.3 Mt, until 2030. In the Announced Pledges Scenario, the hydrogen demand of the power sector will reach 5 Mt by 2030 [18]. According to project announcements, the capacity of hydrogen and ammonia-fired power generation may surpass 5800 MW by 2030, primarily from hydrogen co-fired in combined-cycle gas turbines.

2. METHODOLOGY

The methodology comprises two parts. First, desk research is conducted on the discussed topic. In this step, scientific sources are used, such as studies and publications from indexed databases of scientific articles, reports of independent organizations and industries, policy papers, and statistical data. The desk research is divided into two parts. First, the stakeholders engaged in the development of a hydrogen economy are identified in the context of barriers to hydrogen economy growth and potential solutions. Then, a systematic overview of the economic, political, technological, and social elements influencing a hydrogen economy is presented.

Second, we synthesize the findings of the literature review and visualize the relationships between stakeholders and the many factors affecting a hydrogen economy, ensuring that hydrogen technologies are adopted in a way that benefits society, the economy, and the environment while addressing the challenges and risks associated with their deployment. The research method is illustrated in Fig. 1.

Large amounts of material about ongoing work on hydrogen economy development, problems between different stakeholders, and factors impacting the continued growth of a hydrogen economy can be examined feasibly using the desk research approach. The literature review covers the years 2003–2023, but most of the scientific papers (>66 %) cover the years 2019–2023, especially 2022–2023.

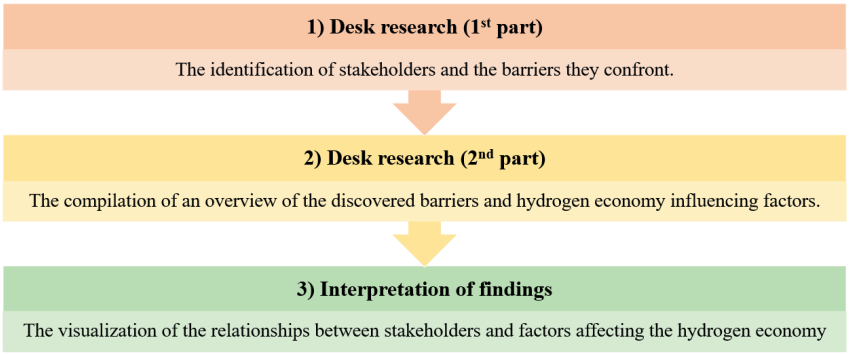


Fig. 1. Scheme of research method.

3. RESULTS

The introduction provides a brief overview of hydrogen use in several areas and potential developments. Based on the desk research results, this chapter provides a comprehensive, structured examination of the factors influencing hydrogen consumption.

3.1. Hydrogen Economy Stakeholders and Their Perception

Several studies have been published on the stakeholders involved in a hydrogen economy [25] and their different perspectives on the development of the hydrogen sector [9], [26], [27]. One of the most extensive studies on this subject was performed in Brazil. Chantre *et al.* distinguished five stakeholder groups: companies, public institutions, research centers, associations, and universities [9]. Based on a literature analysis and the results of interviews with 32 experts, they presented stakeholders' perspectives on the main barriers and needs of a hydrogen economy. Although opinions varied, economic viability was one of the most frequently mentioned barriers. The removal of hurdles for university and research centre stakeholders and the creation of incentives for scientific research were deemed critical. All respondents highlighted the significance of these institutions for generating knowledge and developing human resources. Interviewees from research centres and universities cited the absence of research and development (R&D) investments, political support, and incentives for infrastructure and market creation and enlargement as the main challenges in the development of a hydrogen economy. The study concludes that fostering a long-term policy framework will help increase the confidence of private investors. Furthermore, the maturity and market delivery of hydrogen technology can be accelerated by developing standards and regulations, increasing support for R&D, and removing barriers to market growth by creating dedicated funding programs [9].

Another stakeholder analysis through interviews was performed in Brazil by Aldara *et al.* [28]. They analysed the main routes and productive processes used in Brazil and the R&D of potential alternatives for fossil fuels, focusing on economic feasibility. The authors identified the following aspects of a hydrogen economy:

- Input and infrastructure (such as feedstock availability and infrastructure conditions for hydrogen storage and transport);
- Management (certification and standardization of products and processes involved in hydrogen production);

- Market and governance (the extent of the relationship of different hydrogen economy actors);
- Institutional environment (influence of sectoral policies), and technology (such as investments in R&D, technological maturity, and production costs).

Their results highlighted the value of funding R&D, innovation, and the spread of new technologies and the development of infrastructure for hydrogen production, distribution, storage, and transportation. Advances in the standardization and certification of hydrogen sectors and the initiation of relationships with established technology countries are required to build a national chain of component suppliers.

Stakeholder analysis related to a hydrogen economy was also conducted in Germany. In this study, 49 stakeholder groups were identified and analysed to determine the relationships, opportunities, and risks they perceive are crucial to a hydrogen market ramp-up. The paper also addresses the potential problems arising from the growth of a hydrogen economy in the fields of foreign policy, supply, consumption, and economics. The authors concluded that R&D, hydrogen technology providers, and electricity utilities are the most important stakeholder connections. R&D connects many otherwise unconnected groups and is therefore the most critical stakeholder group. Stakeholder groups from beyond the value chain, such as non-governmental organizations, energy service companies, public companies, and associations, can achieve a significant effect during market ramp-up [29]. Murray *et al.* also discussed the significance of R&D in the hydrogen field, concluding that a portfolio of demonstration projects should be created and that further obstacles are caused by a lack of demand for hydrogen in the end-use stage [30].

Denmark aims to foster a hydrogen economy by investing substantially in hydrogen research. Andreasen *et al.* identified Denmark's main stakeholders in a hydrogen economy and the conflicts between them [27]. They concluded that the path of hydrogen-related technologies toward maturity may be hindered by conflicts as stakeholders try to determine the direction of maturity [27]. Similar findings were obtained by a German study where approximately 30 % of respondents anticipated stakeholder conflict caused by technology preferences. One significant obstacle is a three-sided chicken-and-egg problem, which states that the future development of the hydrogen industry will be significantly slowed down by a lack of cooperation between the supply sector, customers, and infrastructure developers [29]. Nonetheless, Andreasen concluded that conflicts on the development of a hydrogen economy will compel stakeholders to find solutions that will satisfy all involved parties as much as possible, thus making the technology resilient and competitive [27].

The necessity of conducting various information campaigns that involve local officials, consumers, and other key stakeholders was covered by Gordon *et al.* [31]. They also discussed the importance of social acceptance challenges, such as the safety, cost, usability, convenience, and (thermal) comfort of hydrogen; the national and local contexts; the robustness of supply chains and skilled technicians; and the composition of stakeholder engagement. Additionally, the authors stated that investments in the R&D sector play a critical role in the scale-up of demonstration projects and that emerging supply chains are compromised by a lack of market confidence. Additionally, the paper underlines the necessity of public support and addresses society's lack of awareness regarding hydrogen technology.

3.2. Factors Influencing Hydrogen Demand

As the literature analysis reveals, the need for hydrogen varies by industry. Furthermore, hydrogen should be regarded not just as a feedstock for manufacturing and refining processes or as a transportation alternative to fossil fuels but also as an energy carrier in the context of

renewable energy storage (RES) power storage. The possibilities of energy accumulation using hydrogen are mostly related to energy transformation, which is closely related to the energy sector. Nevertheless, we highlight the possibility of using hydrogen separately, as the accumulated energy can be used in all sectors. Hydrogen is an efficient, cleanest, light fuel due to its high efficiency; thus, it is excellent for storing renewable energy, which is somewhat unpredictable due to seasonal or daily changes in solar and wind energies. Green hydrogen generation and utilization create RES prospects, hence broadening the use of renewable energy and boosting energy independence [32]. Hydrogen demand is important for determining not only future emission reduction but also the size of the necessary infrastructure and the required hydrogen supply volume [15].

Tao Ma *et al.* [15] were among the first to use system dynamics in the context of a hydrogen economy. Their developed model enables an analysis of China's medium- and long-term hydrogen demand against the economic sector's gross domestic product and energy consumption intensity. They concluded that the country's hydrogen demand is determined by factors that need to be studied besides the economic growth rate. In the second chapter of his book 'Solar Hydrogen Production', Benedetto Nastasi discusses the importance of the following deciding elements for the growth of a hydrogen economy [33]:

1. Market. Hydrogen price competitiveness is an important factor for demand increase. It may be influenced by demand stimulation, a higher CO_2 emission price, the development of hydrogen infrastructure, and assurance of long-term profitability, which can all be handled through political and regulatory initiatives;
2. R&D projects. The development of hydrogen alternatives, such as battery technology and technologies for large-scale storage, considerably influences the hydrogen demand potential. The growing market for renewable energy and the ability to accumulate the generated renewable (hydrogen) energy with relatively small losses are also vital. Thus, the rapid development of solar panels, wind power plants, and other renewable energy technologies also contributes to the demand for hydrogen [34]–[36];
3. Hydrogen policy. Large-scale energy system reforms require new hydrogen infrastructure and value chains, and regulation tools must be applied, such as government support and public funding [32], market-driven investments [37], confirmation of the origin of low-carbon hydrogen and evaluation of avoided carbon emissions [38], and limits for hydrogen blending in natural gas pipelines [39], [40].

The IEA-commissioned Global Hydrogen Review 2023 offers numerous ways to increase the demand for renewable hydrogen [13]. These options are divided into two categories; the first aims to increase the demand for existing hydrogen applications, and the second aims to create demand for new applications where other low-emission alternatives are limited and hydrogen can thus play a pivotal role in decarbonization. The review focuses on prices in the first category; it emphasizes the need to implement a carbon pricing market and supports the "polluter pays" concept and other support mechanisms that make the use of renewable hydrogen cheaper than the use of fossil hydrogen. This may be accomplished by promoting green hydrogen generation and raising taxes on fossil fuels, making ecologically friendly alternatives more competitive. About the use of hydrogen in new applications, the review underlines the importance of regulation, including the control of hydrogen use in new sectors and the development of standards. Moreover, it assesses the benefits of the rise of green hydrogen demand, which is affected by international collaboration and the establishment of national objectives [13].

In addition, the public's acceptance of hydrogen technology is an important variable in the growth of a hydrogen economy [41]. The following subsections cover the factors influencing hydrogen demand:

- Overall costs;
- Governmental institutions and their role in implementing hydrogen-related policies;
- Development of alternative technologies (primarily driven by the R&D industry);
- Level of public acceptability.

3.2.1. Cost Competitiveness

The most significant factor influencing hydrogen consumption is cost despite its wide-ranging ecological and social ramifications [31]. As hydrogen technologies become more cost competitive, so does the demand for hydrogen. The certainty of meeting the growing demand for hydrogen is based on many cost parameters, such as hydrogen technology costs (capital costs, operation and maintenance costs [OPEX], and raw material costs), infrastructure construction costs, the costs of other alternative fuels, fossil fuel prices, and CO_2 emission allowance prices [42]. The amount, source, and price of consumed electricity; the supply of photovoltaics and wind electricity; and investments in system components are the most crucial factors influencing the overall costs and environmental burdens of large-scale hydrogen production configurations [43]. The following subsections explain current costs in the hydrogen value chain and conclude with an overview of hydrogen cost competitiveness in the industries that contribute to hydrogen demand.

Hydrogen Production

The present costs of producing hydrogen using coal gasification and steam methane reformation are USD 0.90–2.11 and USD 0.75–3.49 per kilogram, respectively [44]. However, both methods do not produce hydrogen sustainably and require the use of carbon capture equipment. Some studies indicate that this technology raises the initial cost of hydrogen production by 7–18 %, but other studies indicate a price rise of up to 60 % [45], [46]. The capital cost of electrolysis technology, which can be used to produce renewable hydrogen, can vary significantly, ranging from USD 500 to USD 5,600 per kilowatt, depending on factors such as the electrolyser type and the associated installation expenses [13]. The primary factor influencing the production costs of green hydrogen is the substantial capital expenditure (CAPEX) related to the electrolyser, which entails a significant capital investment [31]. Therefore, the present cost of hydrogen production via electrolysis considerably varies, ranging from USD 0.98 to USD 23.27 per kilogram of H_2, with an average value of USD 6.62 per kilogram of H_2 [44].

Raw material prices affect hydrogen production, and electricity prices account for 60–80 % of green hydrogen costs, thus increasing the market volatility and investment risks of hydrogen production [47]. However, the availability and prices of coal and natural gas and CO_2 allowance prices considerably impact the future use of grey hydrogen (derived from fossil fuels) and blue hydrogen (derived from fossil fuels and pared with carbon capture and storage (CCS) technologies). The competitiveness of green hydrogen depends on reductions in electrolysis and renewable electricity costs and the availability of green hydrogen against the hydrogen demand; blue hydrogen costs depend on natural gas prices, residual emissions, carbon pricing, methane leakage, capture rates, and permanent CO_2 storage [48]. The future of blue hydrogen in a climate-neutral setting depends on the extent to which residual emissions can be avoided or compensated for via CO_2 removal and geological CO_2 storage.

Storage

Storing hydrogen is a substantial challenge with associated financial consequences apart from the costs involved in the production process. A hydrogen storage system's cost is greatly

impacted by several variables, such as the particular storage technology used, the mode of storage (onboard or offboard), the storage capacity, and the system's production volume. A 2007 study in India demonstrated that the levelized cost of underground storage was lower than those of other storage technologies, with the order being as follows: underground, compressed hydrogen, liquid hydrogen, and metal hydride [49]. Underground storage incurs low expenses due to its small capital costs and ability to accommodate bigger gas storage volumes over extended durations, resulting in lower costs per day. According to another study, the daily cost of storing hydrogen in salt caverns is approximately USD 0.14 per kilogram of H_2 [50]. By contrast, the levelized cost of small-scale hydrogen storage in the form of pressurized gas for a brief duration is approximately USD 0.19 per kg of H_2. This amount escalates by up to 10 times for extensive volume storage over longer seasonal periods. The use of metal hydride [49] for hydrogen storage incurs costs ranging from USD 0.4 to USD 4.0 per kilogram of H_2.

Transportation

Various methods can be used to transport hydrogen, among which pipeline transport is widely regarded as the most cost-effective means of large-scale gaseous hydrogen transportation due to its low maintenance expenses. Transporting liquid hydrogen via trucks and railways is viable, depending on the availability of these modes of transport [44]. Trucks are more cost-effective than trains for transporting gaseous hydrogen over short distances (less than 300 km) but are more costly over longer distances (more than 300 km) [51]. Due to the large capacity of trains, liquid hydrogen delivery by rail may be less expensive than trucking for large quantities of hydrogen. The influence of transit distance on gaseous hydrogen transport via pipelines is negligible. However, when the hydrogen flow rate is raised from 5 kg H_2/h to 45.4 kg H_2/h, the cost per kilogram of H_2 decreases considerably from USD 320.4 to only USD 0.1 [51]. Thus, gas pipelines can transmit hydrogen efficiently across short and long distances at a high flow rate [44]. The transportation costs of hydrogen in the UK were predicted to be USD 0.1–1, USD 0.5–2, USD 0.3–0.5, and USD 1.8–2 per kilogram of H_2 per 100 km for gaseous hydrogen via pipelines and gaseous hydrogen via tube trailers, trucks, and ships, respectively [44].

Infrastructure

The transportation industry has a huge potential for hydrogen usage. Infrastructure such as filling stations and the expenditures related to buying hydrogen-fuelled cars are also necessary for the use of hydrogen in the transportation industry. A hydrogen refuelling station's capital cost can range from USD 0.84 million to USD 7.84 million, depending on the infrastructure and configuration of the station, the type of vehicles to be refuelled, capacity (the mass and number of vehicles to be refuelled and the number of tube trailer connection points), operation conditions (temperature and pressure of delivery), and the installation country. According to estimates [44], the capital costs of refuelling stations in Europe are approximately USD 1.34 million for 150 kg/day capacity stations and USD 2.05 million for 700–1000 kg/day capacity stations. Due to low vehicle production, the unit manufacturing cost of fuel cell stacks is approximately EUR 175 per kW, which may be reduced by three times by increasing production to 100,000 units/year. The typical maintenance cost, such as that of battery electric cars, is roughly EUR 0.018 per km.

Future Perspective on Hydrogen Cost Competitiveness

Fast industrial development will occur when the costs of hydrogen become equal to or lower than those of current alternatives. In 2020, the Hydrogen Council published a paper titled

'Path to Hydrogen Competitiveness: A Cost Perspective' [52]. The report encompasses projections for the time frame in which renewable hydrogen is expected to achieve cost competitiveness. Furthermore, it provides a comprehensive analysis of the prevailing pricing of hydrogen technologies, categorized by segment [52]:

- According to the paper, hydrogen is now utilized as a feedstock in several industries where it is cost competitive, such as refining and ammonia and methanol production. Furthermore, hydrogen is expected to achieve cost competitiveness in steel manufacturing by 2030;
- In emerging hydrogen applications, the use of hydrogen has achieved competitiveness in the context of backup generation. However, hydrogen will shortly also attain competitiveness in simple cycle turbine usage. The forecasted trend suggests that hydrogen will experience enhanced competition in the domain of mid-grade heating beyond 2035. The usage of hydrogen in combined-cycle turbines and high-grade heating is projected to become more competitive around 2050;
- The report's data indicate that the use of hydrogen for building heat and power and its application in current and future networks (such as blending) will become economically viable by about 2030. The use of combined heating plants is expected to follow suit shortly after 2030;
- The transportation sector is expected to emerge as a rewarding hydrogen application. The use of hydrogen in regional trains, coaches, and heavy- and medium-duty vehicles can become cost competitive by the mid-2020s. Soon, the competitiveness of hydrogen use in various transportation sectors will improve. This competitiveness will initially (approximately within 2027–2030) be observed in applications such as taxis, long-distance buses, large passenger vehicles, sports utility vehicles, small ferries, and mid-sized long-range vehicles. Subsequently, between 2030 and 2035, the cost competitiveness of hydrogen will extend to include applications such as urban delivery vans, short-distance urban buses, large ferries, mid-sized short-range vehicles, and even synthetic fuels for aviation.

The least competitive applications of hydrogen include its use in small urban automobiles within the transportation sector and its use in distant power production for industrial purposes within the heat and power industry. Both applications will not achieve cost competitiveness by the year 2050 [52].

The predicted price decline induced by scale-up will drive the future growth of the use of hydrogen technology. The development of hydrogen technologies will boost demand, hence increasing manufacturing plant capacities while decreasing the OPEX [48], [52]. Supply chain scale-up will reduce the cost of hydrogen use for non-transportation applications by 90 %, whereas the manufacturing scale-up of end-use equipment will account for up to 70 % of cost reductions in transportation applications [52]. In terms of future costs, the Hydrogen Council predicts that a scale-up within five to ten years can reduce renewable hydrogen costs to approximately USD 1.0–1.5 per kg at optimal locations and to approximately USD 2–3 per kg under average conditions due to significant reductions in the electrolyser CAPEX (approximately 70–80 %) and renewables' levelized cost of energy [47]. The price of hydrogen fuel may be reduced by 60 % by 2030 due to future technical advancements [47].

Future price decreases will be influenced by learning curves/rates, which reflect technical development as a function of experience with the adopted technology [50], [53]. The acquisition of technical expertise will lower the required CAPEX. For example, in 2020, the total investment in projects related to hydrogen fuel cell vehicles was approximately USD 1,500 million, which is expected to increase in the coming years [44]. Nonetheless, far more financial resources are required. The availability of refuelling and distribution networks and

the cost differential between fuel cell tanks, hydrogen tanks, and low-carbon alternatives globally need an additional investment of USD 30 billion to overcome the economic gap [52]. Moreover, the cost differential between hydrogen and natural gas and the expenditures needed to develop or convert the first gas pipeline networks for hydrogen will total USD 17 billion by 2030 for buildings and industries; a total of 70 GW of electrolyser capacity must be installed to produce competitively renewable hydrogen via electrolysis, implying a cumulative amount of USD 20 billion needed with grey production [52].

The Hydrogen Council predicts that a scale-up will shortly lead to electrolyser learning rates for alkaline and proton exchange membrane technology of approximately 9 % and 13 %, respectively, whereas fuel cell stacks for passenger vehicles will have a learning rate of approximately 17 % [52]. Commercial vehicles will have lower learning rates, approximately 11 %, due to the lower volume of cars compared with private vehicles but will still benefit from a scale-up in other segments, which will considerably cut equipment prices across the hydrogen value chain. The total expenses for big passenger vehicles should fall by approximately 45 % by 2030 because of three major factors: reduced vehicle CAPEX, cheaper hydrogen distribution and retail, and lower hydrogen generation. Hydrogen distribution and retail costs account for most of the cost of hydrogen incurred by big passenger vehicle end users, accounting for approximately 60 % of the outlay. A value chain scale-up can result in an 11 % reduction in the total cost of ownership of a major passenger car. For example, increasing the utilization of hydrogen refuelling stations from 60 % to 80 % will reduce these stations' cost contribution by approximately 25 %.

Expenses also have associated risks. Market ramp-up risks and first-mover risks are expected, such as slow market dynamics, a low learning curve, and cost regression effects; uncertainty regarding demand and supply volumes, which was considered a risk by every fourth respondent in the study of David Schlund *et al.*, can be particularly problematic for stakeholders during hydrogen market ramp-up [29]. According to the same study, 54 % of stakeholders feel that the national government and economy should bear the risks associated with becoming a first-mover nation, which entails significant investments in R&D, facilities, and infrastructure [29]. Cost sharing during market ramp-up has also been highlighted in publications. For example, a study conducted in Poland found that the costs of CCS are unknown and may add to the challenges of CCS. This is why zero-emission coal-based power plants are deemed challenging, according to M. Luke Murray *et al.* study. The authors also underscored the uncertainty around the parties that will be responsible for paying for the CCS process, estimated plant costs, and transportation and sequestration problems [30].

Cost data suggest that green hydrogen is not yet competitive relative to other fuels and grey hydrogen. Assistance is required to end the current reliance of hydrogen consumption on fossil raw materials (which will continuously increase CO_2) considering the price difference between green and fossil hydrogen. Decision-makers should consider whether fiscal and regulatory policy tools may be used to influence price difference as soon as possible to limit the development of fossil hydrogen capacity. Supporting the development and use of renewable hydrogen and outlining the position to utilize this form of hydrogen in the future will help reduce the fossil hydrogen production capacity and accelerate the transition to renewable fuels.

3.2.2. Strength of Policy

Considering the current inability of green hydrogen to compete with other alternatives in many sectors and directions of use, policies must be developed for hydrogen technologies to be adopted by the market. The IEA's 'The Future of Hydrogen' report identifies five policy initiatives that are required by 2030: establishing long-term signals to foster investor

confidence; stimulating commercial demand for hydrogen in multiple applications; helping mitigate salient risks, such as value chain complexity; promoting R&D and knowledge sharing; and harmonizing standards and removing barriers [19].

Solutions for policy implementation have been explored on regional and national scales. A total of 41 nations, accounting for roughly 80 % of worldwide energy-related CO_2 emissions, are already implementing hydrogen plans [13]. The following outlines the objectives that the United States (US), South Korea, Japan, and the EU have set for the development of hydrogen technology, demonstrating the global diversity of this field.

One such example is the hydrogen development program of the US and the 'Road Map to a US Hydrogen Economy', which identifies four stages of hydrogen economy development and realistic goals:

- The 'immediate next steps' (2020–2022), or the establishment of reliable, technology-neutral decarbonization targets;
- The 'early scale-up' phase (2023–2025), which calls for the development of large-scale hydrogen production, thus reducing costs;
- The 'diversification' phase (2026–2030), which focuses on extending hydrogen use across different applications;
- Widespread deployment throughout the US after 2030. This approach emphasizes that hydrogen technologies are not yet common enough and, similar to other technologies, will also have to undergo the Rogers innovation diffusion curve [45] and associated challenges.

In general, the adoption of a proper policy framework significantly influences the development of new technologies, particularly during the implementation of research prototypes and the early stages of commercialization [54]. The effective use of incurred expenditures necessitates the formulation of an appropriate policy (strategy) for the hydrogenation of the economy, which includes public administration support, assurance of stable investment conditions, and the necessary regulatory conditions in addition to precisely defined long-term objectives [54].

Despite the absence of domestic clean hydrogen production in South Korea, where all 220 000 metric tons generated in 2020 were derived from fossil fuels (grey hydrogen), the country has set an ambitious target of supplying 27.9 million metric tons of hydrogen per year by 2050 [55]. This objective will be achieved through the production of 3 million metric tons of green hydrogen per year and 2 million metric tons of blue hydrogen per year alongside the importation of 22.9 million metric tons per year of green hydrogen from international sources. Notably, South Korea's hydrogen supply will exclusively consist of green and blue hydrogen [55]. By implementing this strategy, South Korea aims to obtain approximately one-third of its energy from hydrogen by 2050, therefore establishing hydrogen as the predominant energy source in the country.

Japan has also proposed strategies for the establishment of a 'hydrogen society,' wherein hydrogen plays a prominent role in the nation's secondary energy infrastructure, as outlined in its Strategic Energy Plan [56]. Japan's 6th Strategic Energy Plan aims to decrease hydrogen costs from the current JPY 100 /Nm^3 to JPY 30/Nm^3 in 2030 and to no more than JPY 20/Nm^3 in 2050; it also aims to increase hydrogen supply from the current approximately 2 million tons/year to a maximum of 3 million tons/year in 2030 and to 20 million tons/year in 2050 [57]. To implement this plan, Japan intends to:

- Increase the use of hydrogen on the demand side (power, transportation, industry, and consumer sectors);
- In the power generation sector, the demonstration of co-firing/single-fuel firing will be promoted, an environment will be prepared for the appropriate assessment of non-

fossil value, and a 1 % hydrogen/ammonia power generation mix is planned for the fiscal year 2030;
- In the transportation sector, the demonstration of co-firing/single-fuel firing will be promoted, and an environment will be prepared for the appropriate assessment of non-fossil value;
- The large-scale diversion of manufacturing processes, such as hydrogen-reduced iron making, and the technology development of burners and large, highly functional hydrogen-fired boilers will be addressed based on combustion characteristics;
- Technology development toward the cost reduction and expansion of stationary fuel cells, including pure hydrogen fuel cells, will be addressed in the industry sector [57].

A regional policy is evident within the EU framework. The EU adopted the European Hydrogen Strategy in 2020 [58]. The strategy outlines 20 key actions, including financial (such as the Clean Hydrogen Alliance Investment Platform), regulatory (taxonomy regulation, Fit for 55 package incentives, and the REPowerEU Plan), and research (such as the European Clean Hydrogen Innovation Partnership) initiatives. The European objective regarding hydrogen involves constructing 17.5 GW of electrolyzers by 2025 to supply energy to the EU industry sector by producing 10 Mt of renewable hydrogen domestically and importing an additional 10 Mt by 2030. Furthermore, the EU objective entails developing a contemporary regulatory framework for hydrogen and constructing the required infrastructure, such as storage facilities and ports. Recently, the European Commission (EC) announced the creation of the European Hydrogen Bank, an EU public support measure designed to kickstart the hydrogen economy by acting as a major funding scheme to ramp-up the hydrogen value chain [59].

From a system perspective, the EU hydrogen policy is largely driven by the need to achieve climate neutrality and therefore can be described as based on the 'distance' between the desired goal and the current situation [59]. The greater the difference between the achieved and required CO_2 emission reduction (worse situation), the stronger the policy. The smaller the difference between the achieved and required CO_2 emission reduction, the weaker the policy. Policy strength affects several sectors, such as energy demand ([39], [40]), price drivers (including tax and CO_2 price increases and financial support in different stages of the hydrogen supply chain), infrastructure support policy, and additional investment in R&D.

Several researchers have analysed the hydrogen sector through system dynamics modelling, specifically for an analysis of policy support in the field of hydrogen. Li *et al.* found that greater support consisting of different mechanisms is necessary for the initial stages of hydrogen use to ensure rapid development, followed in subsequent years by dynamic policy adjustments and subsidy reductions in line with progress [32]. Jiayang Gao *et al.*, who based their analysis on California market data, presented a similar conclusion. Their article states that moderate public funding is required to establish the scale of application of on-site hydrogen production technology in the early stages of market development and provide a buffer time for technology upgrading; moreover, they explained that excessive subsidy amounts and durations will stagnate supply and increase demand [14].

Aside from providing a policy framework for national goals, fostering cross-national collaboration is critical to the establishment of a hydrogen economy [17]. The advancement of hydrogen technology will help form international collaborations between various countries, thus boosting the chances of establishing a hydrogen economy. The International Partnership for Hydrogen and Fuel Cells in the Economy is an example of such a collaboration [60]. This organization was established to aid in the transition to sustainable energy and hydrogen-based mobility systems. Australia, Canada, the EC, India, the Netherlands, Switzerland, Austria, Chile, France, Italy, Norway, the United Arab Emirates, Belgium,

China, Germany, Japan, the Republic of South Africa, the UK, Brazil, Costa Rica, Iceland, the Republic of Korea, Singapore, and the US are members of this organization.

3.2.3. Impact of R&D

Further study is required to further enhance the effectiveness of hydrogen generation techniques while addressing related issues, such as cost and scalability. A previous study highlights how crucial it is for governments, businesses, and academic institutions to cooperate to spur innovation and accelerate the switch to renewable hydrogen generation [61]. The introduction of hydrogen energy technologies requires increasing public expectations and establishing R&D networks [9], [15], [62], [63], as confirmed by our preceding stakeholder analysis. The establishment of a specific funding program can be a powerful tool to bind academia and industry together quickly and effectively through the creation of customized solutions for the hydrogen market [9]. Investments in hydrogen technologies are needed to foster energy-efficient solutions across diverse industries as fuel cells emerge as promising alternatives to internal combustion engines, with the total energy use significantly influencing the need for such financial support. The origin of such investments may encompass both governmental backing and private-sector initiatives. This was confirmed by Yoo and Park in their study, where they analysed the history of national R&D programs in the development and commercialization of hydrogen energy technologies by studying national hydrogen vehicle development projects in Korea over the last three decades and how they have evolved with changes in the country's technological and economic levels [62]. They concluded that after commercialization, government-funded R&D projects developed cooperative networks, which then became a value chain network.

The development of renewable energy supply chains is significant, as CO_2 emissions and hydrogen production have a strong synergy due to the wide use of fossil fuels for hydrogen production. Emission reductions across the full value chain of hydrogen technologies may be possible in the distant future, but environmental policy should encourage the use of low- and zero-emission technologies and fuels [64].

The amount of R&D investment in renewable energy technology will improve the renewable energy output, and higher renewable energy production will reduce the carbon emissions of the energy sector [65]. Lower carbon emissions will promote R&D investment, which will enhance the energy output of renewable sources [65]. Thus, investment in energy technology R&D for hydrogen and fuel cells is highly correlated with CO_2 emissions [64].

The prospect of future relative profitability also drives R&D investment in a certain powertrain. Any potential future penalties for failing to achieve emissions limits are utilized as an extra impetus for investment in powertrains that are most likely to cut emissions. Investment in such powertrains is further encouraged by potential future fines for failure to meet emissions targets [17]. This takes the form of a straightforward monetary increase in the potential value of R&D, weighted by the potential environmental improvement of the engine. Avoiding future fines means higher revenues for businesses; therefore, investing in components that contribute considerably to carbon reduction is consistent with the present stance of the European industry [17].

The impact of R&D-supporting activities may be quantified by assessing the quantity of newly granted patents. The basis of the market for inventions is provided by patents, which facilitate the market's establishment in several crucial ways, including by encouraging the financing of inventions and innovation. The development of new, improved techniques for producing hydrogen has become increasingly popular in recent years, and numerous businesses and researchers have filed relevant patents [61]. The data show a rising interest

and investment in the development of greener, more sustainable methods of producing hydrogen [61].

3.2.4. Social Acceptance

Social factors, such as public acceptance, are important for the implementation of any new technology. According to the theory of diffusion [66], potential users of a technology become aware of it, are convinced of its benefits, and then choose to adopt and buy it. In other words, public acceptance occurs over time in five distinct stages: knowledge, persuasion, decision, implementation, and confirmation. If customers are satisfied during the confirmation stage, they will continue using the technology; otherwise, they will reject it [67]. This demonstrates the value of knowledge, without which new technology cannot be introduced to the market. Thus, people's mistrust of the safety of hydrogen technologies is also a barrier that should be addressed [9], [68]. Such mistrust is mostly caused by a lack of knowledge. According to Kyoko Ono *et al.*, risk information increases the acceptability of hydrogen refuelling stations next to home hydrogen refuelling stations. They concluded that good risk communication should be implemented before the installation of a hydrogen refuelling station because receiving risk information about such stations alleviates people's dread or uncertainty [69]. Furthermore, pro-environmental education among the youth will positively influence the transition to renewable energy sources, help ensure planetary justice over the long run [70], and help develop renewable technologies and resilient energy systems in production companies [71].

Justice is another important social factor that needs to be considered when developing a hydrogen economy. Dillman *et al.* assessed the inequity in the hydrogen value chain that may arise during the implementation of a hydrogen economy [72]. They found potential injustice in several areas, including unjust decision-making, socially irresponsible development, and poor distribution of misfortunes and benefits in the field of consumption. The authors emphasized the role of hydrogen in creating a green future and the resulting need for a hydrogen economy to experience a rapid rise in the coming years. Nonetheless, they explained that although a ‘move fast and break things’ mentality may be necessary for this rapid scale-up, decision-makers should question not only the green-ness of planned strategies but also their social fairness by evaluating the potential social pitfalls of a hydrogen transition. Recognizing and reducing these inequities during the development of a hydrogen economy should encourage public support for its spread.

A strengths–weaknesses–opportunities–threats study by Youhyun Lee *et al.* analyses the public acceptance of H_2 stations. Interviews with 20 experts highlighted such strengths as driver convenience, reduction of fine dust, and a positive response to climate change. The authors identified the safety of this technology as the biggest hindrance to the wide implementation of hydrogen technology [11]. In this regard, Crowl and Jo compared hydrogen and methane [73]. Hydrogen has an increased flammability range, a lower ignition energy, and a higher deflagration index; based on physical properties alone, primarily due to the increased probability of ignition, these characteristics pose an increased risk compared with gasoline and methane. The study also mentions the safety risks associated with the use of hydrogen, particularly its colourless (and thus difficult to detect) flame and its self-heating properties when it leaks from a high-pressure source. Many studies state that the safety of the use of hydrogen technology should be improved by implementing political decisions that will organize this industry, such as technical and safety standards (particularly for hydrogen transport and storage [38], as well as improved hydrogen safety [68], and human resource training [9]), provide risk management, and establish clear permitting processes [19], [74].

Another issue is that such policy decisions, which society does not understand and/or is not ready to implement, can cause a pushback effect, which is a type of information feedback to the government about the public's acceptance of its governance. The amount of pushback is determined by the balance between the strength of the policy push and the difficulty for actors to comply with the policy. Public opposition to unpopular policies should be considered because an increase in societal pushback to such policies may delay the achievement of targets by 10 years; the target can even be missed altogether if such opposition were combined with a higher-than-expected difficulty of executing critical measures [75], [76]. The implementation difficulty of a measure implies that adopting an overly ambitious policy in a short time generates challenges in execution, but this difficulty will diminish as society's experience grows.

4. DISCUSSION AND CONCLUSIONS

The increasing academic interest, political efforts, and industry developments in the field of hydrogen indicate the emerging role of hydrogen in energy transition and decarbonization. However, green hydrogen still encounters many challenges across the value chain, including hydrogen production, storage, infrastructure, and application. In addition to technological and economic issues, social and communication challenges must be resolved.

Here, we conduct desk research on the factors influencing the development of a hydrogen economy to understand existing barriers, identify stakeholders, and determine development directions. This section summarizes the most important conclusions, offers a visualization of our results, and discusses future research directions.

Fig. 2 schematically illustrates the interconnections among the stakeholders and emphasizes the outlined barriers in the desk research, their corresponding solutions, and the specific stakeholder groups accountable for implementing such solutions. The results show that all stakeholder groups emphasize, in addition to technological maturity, the necessity of increased political support for the successful implementation of a hydrogen economy, particularly concerning its barriers. For instance, for the companies accountable for ensuring the accessibility of hydrogen to end users, the primary concerns are economic viability, which can be addressed through investments in R&D initiatives, and the formation of partnerships between private companies and academic institutions. From the proposed solutions, we can distinguish support for and investment in the R&D sector, collaboration between private companies and academia, and the formulation of national hydrogen strategies; many studies (such as [9], [39], [53], [54], and [77]) state that the implementation of a proper policy framework has a major impact on the development of new technologies.

Fig. 3 illustrates the links between the stakeholders and influencing factors within the context of the green hydrogen economy considering the barriers in Fig. 2. The yellow, red, purple, blue, and green boxes in Fig. 3 denote parameters linked to hydrogen demand, policy, R&D, the economy, and the social component, respectively. Several stakeholders also appear in this figure; *public institutions* are responsible for the support of other stakeholders and, with the influence of university representatives, the formulation of policies. *Companies' stakeholder* interests appear in the production and use of hydrogen, which in turn are influenced by the interests of *society*, whereas the *R&D sector* affects cost reductions and the preparation of human resources.

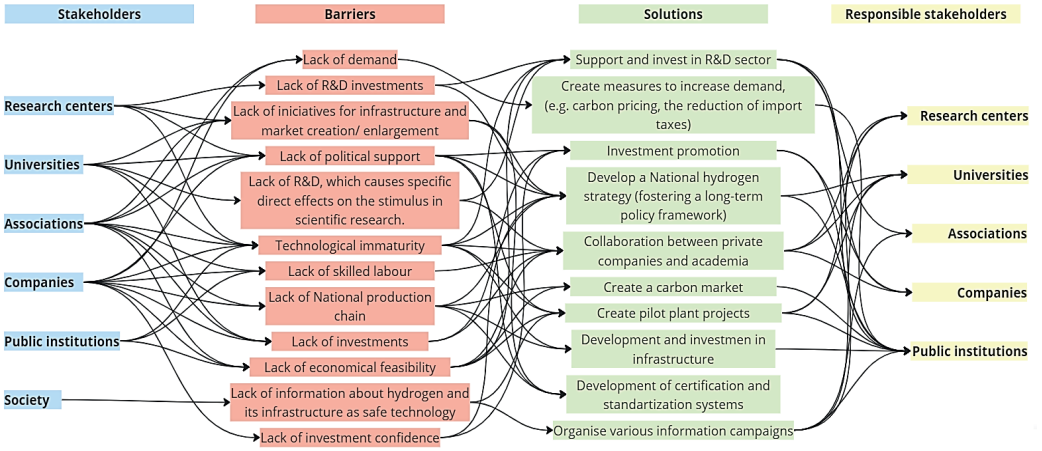


Fig. 2. Diagram of hydrogen economy barriers and stakeholder relationships.

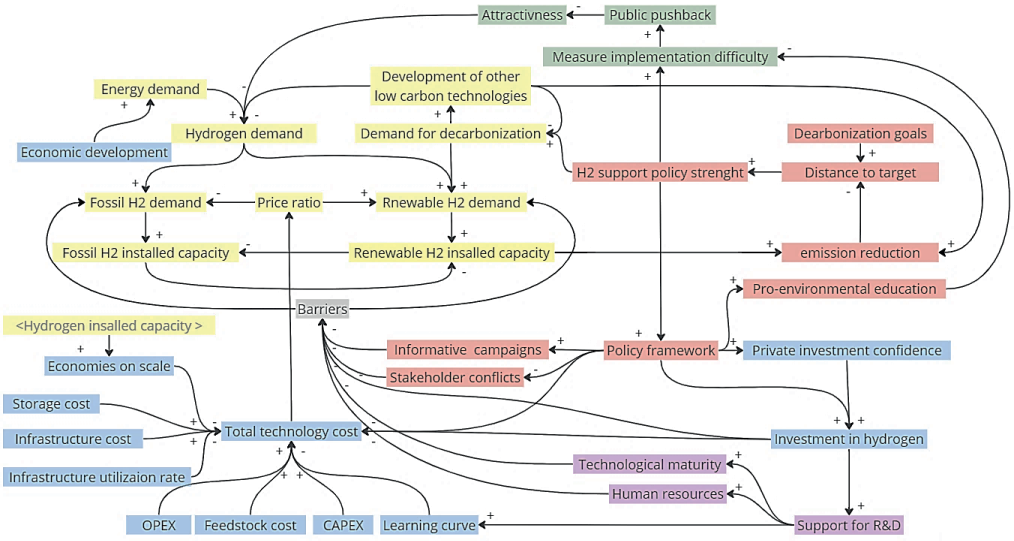


Fig. 3. Causal loop diagram of simplified system dynamic model structure. The parameters in the yellow, red, purple, blue, and green boxes are linked to hydrogen demand, policy, R&D, the economy, and the social component, respectively.

The central component of the system is the (yellow) transition from conventional hydrogen production methods, which rely on fossil fuels, to green hydrogen, which is generated via electrolysis and the use of renewable energy sources. The production of fossil hydrogen is currently a source of CO_2 emissions. The anticipated increase in the hydrogen consumption of the industry, refining, and transportation sectors will enhance the total amount of CO_2 emissions, making the transition to green hydrogen critical. The greater (smaller) the installed capacity of green hydrogen production, the smaller (higher) the required installed capacity of fossil hydrogen. Several important factors influence this transition.

First is the issue of cost, which can be characterized by the cost ratio of fossil and green hydrogen. One of the most frequently mentioned barriers to the development of a hydrogen

economy is economic viability. The price-related components are in the blue boxes in Fig. 3. The diagram depicts not only the elements determining the two hydrogen technology costs (renewable and fossil) but also the factors influencing their reduction. The feedstock prices, CAPEX, and OPEX of hydrogen production technologies contribute to the overall cost of hydrogen production. The total technology cost is influenced by storage and infrastructure costs, which include hydrogen transportation and distribution costs, besides production costs. As shown by the schematic illustration, the total technology cost encompasses a range of expenditures related to storage, infrastructure, and renewable and fossil hydrogen production (including the CAPEX, OPEX, storage, and feedstock costs). This comprehensive perspective corresponds to the subsequent correlation for each type of hydrogen with the price ratio. For example, the term 'feedstock cost' describes changes in the availability of resources for hydrogen generation, implying changes in feedstock pricing. The raw elements required to manufacture green hydrogen, such as renewable electricity and water, are considered in the defined model. The sun, hydropower plants, and wind energy are deemed primary sources of renewable electricity generation. Natural gas is the primary raw material used to manufacture grey hydrogen.

As discussed, fossil hydrogen is currently cheaper than green hydrogen; therefore, considering the price difference between green and fossil hydrogen, existing hydrogen consumption will continue to be based on fossil raw materials, thus contributing to an increase in emissions, unless policy support is provided. Fiscal and regulatory policy tools must be implemented as soon as possible to limit the expansion of the required fossil hydrogen capacity. In Fig. 3, the policy sector, which is responsible for the implementation of support measures, is colour coded red.

The starting point of the policy objective, that is, the reasons for using hydrogen, shows that the price ratio between green and fossil hydrogen may not be the first determining factor of hydrogen use. If hydrogen use were encouraged through decarbonization policies (such as in difficult-to-decarbonize sectors), a higher price would be acceptable because fossil hydrogen will fail to meet targets. Thus, the strength of policies promoting the use of green hydrogen for the decarbonization of economic sectors is critical.

However, hydrogen competes with other zero-emission energy resources and technologies in the context of decarbonization, and this circumstance acts as a balancing loop. Therefore, green hydrogen will likely be a niche product in certain industries [74]. The hydrogen demand sectors and the determinants within them that may influence hydrogen demand should then be explored in detail. For example, in the transportation sector, hydrogen technology is tightly competing with electric transport. Even though both are emission-free technologies, using hydrogen has higher technical and socioeconomic barriers, so it cannot be assumed to develop at the same rate as other green technologies in situations with policy-supported green technologies. It competes not only with fossil alternatives but also with green alternatives that are cheaper and easier to use. Therefore, hydrogen may be relevant in certain niche markets that need to be affected by specific policy instruments that are not included in the loop diagram (such as support for the production of e-fuels or low-emission heavy commercial transport). Furthermore, according to Gunther Glenk *et al.*, the observed learning curves for specific clean energy technologies reinforce each other in accelerating the transition to a decarbonized energy sector [78].

Policy now focuses on measures to build a common hydrogen policy framework, remove existing barriers, and boost private investment rather than on the fact that hydrogen is obtained from renewable energy sources. Hence, additional research on the function of green hydrogen in supporting regional development, in addition to the benefits of decarbonization, is required to demonstrate the necessity of green hydrogen development. Further study will

also help policymakers identify the sectors that should be prioritized to enhance the role of green hydrogen.

The literature analysis shows that the introduction of renewable hydrogen in the market entails the formulation of a long-term policy framework for determining national goals, standards, regulations, and support mechanisms for the production and further use of renewable hydrogen. This action of public institution stakeholders will allow them to increase the confidence of private investors, which represents the interests of private companies' stakeholders. Consequently, this will improve investments in hydrogen technologies and support for the R&D sector by assisting stakeholders from research centres. This action will contribute to future cost reduction. Prices are influenced by policy support, which affects costs through taxes; fossil hydrogen can be made less competitive through CO_2 allowance prices and other taxes, and renewable hydrogen production can be supported through tax incentives. Policy support can also be used to improve investment in technology development and create a safe environment that encourages independent companies to invest heavily in hydrogen technologies and related R&D (purple in Fig. 3). Government and corporate R&D investments are critical because they accelerate learning, which leads to additional price reductions [78], [79]. In particular settings, sustained significant learning curves imply a significantly faster hydrogen cost drop than the 80 % price reduction caused by further learning curve [78]. Moreover, the R&D industry contributes significantly to human resource preparation [9]. Furthermore, a price reduction is impacted by variables such as economies of scale, which are mostly driven by capacity development [80], [81] and may be achieved by strengthening regulations, eliminating current barriers (Fig. 2), and lowering the renewable/fossil hydrogen price ratio.

One of the barriers to green hydrogen generation and consumption is social acceptability, which is heavily influenced by governmental decisions (green in Fig. 3). Knowledge is extremely valuable because people doubt new technologies without it. This, along with overly strict, unpopular policies, may result in a pushback effect, delaying the achievement of national targets [75], [76]. The implementation difficulty of measures implies that adopting an overly ambitious policy in a short period creates execution challenges; however, as society's experience grows, these difficulties decrease. In the development of a policy framework, pro-environmental education programs must be included to increase citizens' understanding of new technologies [70].

This paper provides a comprehensive literature review on the factors influencing a hydrogen economy, presents a diagram of the barriers to such an economy and the relationships between its stakeholders (Fig. 2), and shows a causal loop diagram (Fig. 3) of the interconnections among the stakeholders and influencing factors. This study emphasizes the critical need for increased political support, particularly in addressing stakeholder concerns about technological immaturity and economic viability. The proposed solutions, which include R&D funding, collaboration between private companies and academia, and the development of national hydrogen strategies, highlight the critical role of a well-defined policy framework in advancing a green hydrogen economy. These findings contribute to a comprehensive understanding of the complex hydrogen value chain, providing valuable insights for both academics and policymakers seeking informed strategies for long-term hydrogen development. One potential future research direction is an in-depth examination of the numerous factors that lead to social acceptance in the context of green hydrogen.

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