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Examining dynamics of hydrogen supply chains

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ABSTRACT

Hydrogen is poised to play a pivotal role in achieving net-zero targets and advancing green economies. However, a range of complex operational challenges hinders its planning, production, delivery, and adoption. At the same time, numerous drivers within the hydrogen value chain present significant opportunities. This paper investigates the intricate relationships between these drivers and barriers associated with hydrogen supply chain (HSC). Utilising expert judgment in combination Grey-DEMATEL technique, we propose a framework to assess the interplay of HSC drivers and barriers. Gaining insight into these relationships not only improves access to hydrogen but also foster innovation in its development as a low-carbon resource. The use of prominence scores and net influence rankings for each driver and barrier in the framework provides a comprehensive understanding of their relative significance and impact. Our findings demonstrate that by identifying and accurately mapping these attributes, clear cause-and-effect relationships can be established, contributing to a more nuanced understanding of the HSC. These insights have broad implications across operational, policy, scholarly and social domains. For instance, this framework can aid stakeholders in recognizing the range of opportunities available by addressing key barriers to hydrogen adoption.

1. Introduction

Addressing climate change – one of most pressing challenges of our time - is a top priority for nations, corporations, and individuals alike. Actions taken in the next decade to significantly limit greenhouse gas emissions (GHGs) and to promote the robust expansion of renewable energy technologies will be crucial for a sustainable carbon-free future. In this sense, achieving global net-zero goals by establishing an affordable and effective zero-carbon energy system is imperative. Hydrogen is anticipated to play a pivotal role in decarbonization efforts and in meeting net-zero targets, while also contributing to the development of green, circular energy systems, sustainable economies, and a zero-emissions society (Shamsi et al., 2021; Fu et al., 2021). Hydrogen can be produced from a variety of renewable resources (e.g., solar, wind, biomass) or non-renewable energy resources (e.g., natural gas, nuclear power, coal) using different methods and technologies (e.g., photo fermentation, gasification, electrolysis, fermentation) (Acar and Dincer, 2019; Fu et al., 2021;Sharma, Verma et al., 2023). Hydrogen supply chain (HSC) encompasses the entire process of capturing this energy from its source to the end consumer (Dagdougui, 2012). Specifically, HSC refers to the network of companies, activities, and resources involved in the stages of hydrogen from production to storage and delivery to utilization (Felder and Meier, 2008; Peng et al., 2023).

A hydrogen value chain involves a series of stages, as depicted in Fig. 1, beginning with the selection of a suitable feedstock. Feedstock may include non-renewable sources, such as natural gas or water, as well as renewable energy sources, such as solar, wind, or geothermal energy. Hydrogen is subsequently produced from these feedstock using processes such as electrolysis or steam methane reforming. Once produced, hydrogen undergoes purification and compression before being transported to distribution points or end-users via pipelines, trucks, or ships. Finally, hydrogen serves as both a clean energy source and versatile feedstock, used in a variety of processes including manufacturing, power generation, heating, fuel for fuel cell vehicles, and as a key input in chemical and industrial applications. Effective management across this supply chain guarantees hydrogen's seamless integration into various industries, supporting the transition towards a low-carbon economy and sustainable energy future. To use hydrogen as a source of clean energy, it

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is necessary to monitor the supply chain of hydrogen carefully. Hydrogen, due to its versatility as an energy carrier, has the potential to significantly reduce GHGs across various sectors, including transportation, manufacturing, and power generation. An efficient HSC ensures that hydrogen is produced, transported, and stored optimally, facilitating its widespread application. By establishing an effective HSC, we can advance the integration of renewable energy sources, accelerate the transition to a sustainable energy future, and address critical environmental challenges.

As a clean energy technology, hydrogen is not a single technology. Hydrogen encompasses a range of processes, including production, compression, storage, transportation, and utilization in generators and various industrial applications (Dagdougui, 2012). Hydrogen holds immense potential due to its versatility across diverse applications. However, the current lack of comprehensive advancements in the HSC hinders the feasibility of expanding this technology to the necessary scale. Significant investments are needed to develop hydrogen-fuelling infrastructure, enhance fuel cell efficiency, and develop efficient hydrogen production techniques to facilitate its widespread adoption of fuel in industry (Browne et al., 2012). Consequently, the overall capital and operating costs associated with hydrogen remain prohibitively high, particularly when compared to low-cost and often subsidized fossil fuels (Sharma, Verma et al., 2023). The viability of HSCs is influence by various factors, including the cost as well as spatial distribution, storage technologies, transportation and distribution methods, and market penetration of hydrogen-based technologies, among others (Emonts et al., 2019). Therefore, identifying the drivers and barriers within the HSC is crucial for reducing GHGs and achieving more sustainable energy systems. This study aims to explore the potential of HSC in meeting net-zero targets by identifying its key drivers and barriers. To the best of our knowledge, comprehensive research has yet to be conducted to elucidate the drivers and barriers of HSC. In this context, this study seeks to fill a significant gap in the literature. The following research questions (RQs) will be addressed in this study:

RQ1: What are the drivers and barriers to be addressed in HSC?

RQ2: What are the interrelationships between these drivers and barriers in HSC?

In this study, a three-phase framework is employed to answer the aforementioned questions. First, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique is utilized in conjunction with experts' opinions to identify the drivers and barriers. Second, these drivers and barriers are validated using the DELPHI method. Third, the nexus among these factors is ranked in order of importance based on expert judgment through the Grey-Decision-Making Trial and Evaluation Laboratory (Grey-DEMATEL) approach.

The remainder of this paper is structured as follows: Section 2 provides the research background, followed by Section 3, which outlines the methodology, including the PRISMA, DELPHI, and Grey-DEMATEL techniques. Section 4 presents the results of the study, while Section 5 discusses the findings and their significant implications. Finally, Section 6 concludes the study by identifying its limitations and proposing direction for future research.

2. Research background

2.1. Hydrogen economy

With Hydrogen's global market valuation of USD 242.7 billion in 2023 and projected revenue reaching USD 410.6 billion by 2030 (Markets and Markets, 2023), the HSC is anticipated to undergo rapid transformation by the end of the decade. The pace of this transformation will be influenced by several key factors, including:

- Reduced cost of green hydrogen production/new efficient production techniques.
- Novel storage techniques with higher energy density and lower cost.

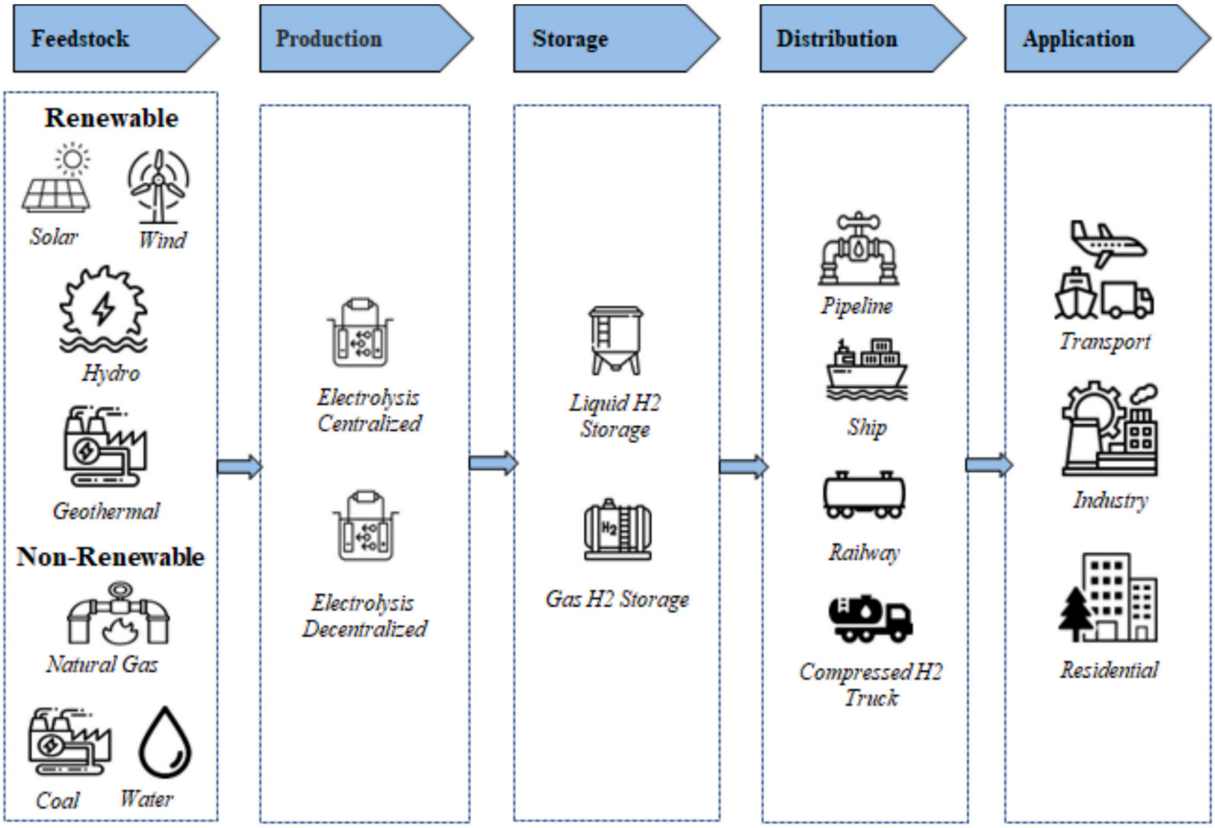

Fig. 1. A hydrogen supply chain.

- Increased adoption of fuel-cell vehicles.
- Intensified policy implementation on emissions reduction across industries. Those Regulations and oversights will forestall the potential for greenwashing.

While transition to hydrogen alongside other clean sources represents a major milestone in many countries, green hydrogen is the ultimate goal. This literature review focuses on two significant hydrogen production pathways: blue hydrogen and green hydrogen (Yu et al., 2021). Blue hydrogen is produced through the process of steam methane reforming (SMR) or auto-thermal reforming (ATR) in which natural gas is combined with steam to generate hydrogen and carbon dioxide (CO2) (Antonini et al., 2020; Oni et al., 2022). The CO2 generated during this process is subsequently captured and stored using carbon capture and storage (CCS) technologies which effectively preventing its release into the atmosphere (Al Ghafri et al., 2023; Wilberforce et al., 2021). This approach facilitates a transition from the existing natural gas infrastructure to a low-carbon future. In contrast, green hydrogen is produced through the process of water electrolysis, a method that separates water into hydrogen and oxygen using renewable energy sources such as solar, wind, or hydroelectric power (Chien et al., 2021; Ishaq et al., 2022) because it is entirely emissions-free and does not involve CO2 emissions (Novotny, 2023; Sharma et al., 2023a, 2023b).

2.2. *Hydrogen supply chain*

The development and implementation of a sustainable hydrogen economy are fundamentally dependent on the HSC. A crucial stage of HSC is storing hydrogen at depots and distributing them with proper safety procedures (Raeesi et al., 2024). In case of hydrogen storage, liquid hydrogen storage is accomplished by cooling hydrogen gas to cryogenic temperatures (−253 °C), where it condenses into a liquid (Aziz, 2021; Zhang et al., 2023). By significantly reducing the volume of hydrogen, this process makes it possible for extensive storage and transportation (H. Li et al., 2022). For the long-term distribution and storage of hydrogen, cryogenic liquid storage is frequently used, especially in sectors such as transportation, manufacturing or industries with a high demand for hydrogen (Razi and Dincer, 2022). Moreover, it is also possible to store hydrogen under high pressure (Tarhan and Çil, 2021). High-pressure hydrogen storage enables portable solutions for various applications such as automotive fuelling stations and portable cylinders for small-scale use. On the other hand, geological storage is a method for safely containing hydrogen, utilising natural underground formations (Tarkowski, 2019). One example of this kind of storage system is salt caverns (Williams et al., 2022). Salt caverns are particularly appealing due to their impermeability, which reduces the risk of hydrogen leakage (Raad et al., 2022). Injecting hydrogen into salt caverns during low demand and utilising it during high demand helps to maintain the supply and demand balance (Yue et al., 2021). Moreover, for the transportation, tankers are designed to maintain cryogenic temperatures which can transport hydrogen in liquid form (Liu et al., 2023; Ustolin et al., 2022). These tankers are commonly used for inter-regional and long-distance transportation, allowing large amounts of hydrogen to be delivered to various consumers (Borenstein and Kellogg, 2021). Furthermore, pipelines are an important component of the HSC, providing an efficient and cost-effective way of transporting hydrogen over long distances. The distribution of hydrogen to various end-users, such as industrial facilities and fuelling stations, is made possible by dedicated hydrogen pipelines or blending hydrogen into existing natural gas pipelines (Erdener et al., 2023). However, blending hydrogen into existing pipeline may be challenging due to (i) high level of purity required of industrial grade hydrogen; (ii) tendency to embrittlement of natural gas pipelines and potentially cause leaks. The implication of promoting blue and green hydrogen on supply chain includes that future hydrogen production could be achieved in multi-scale and decentralized manner at any point within the supply chain (including the consumer domain).

2.3. *Political perception of hydrogen supply chain*

A significant factor affecting the development and application of hydrogen as a clean energy solution is the HSC's political perception and maturity. This section examines the current political climate surrounding the HSC, including legislative initiatives, governmental programs, and cross-national partnerships.

Governments around the world recognize the potentials of hydrogen to help them achieve their energy transition goals and reduce GHGs (Dincer and Aydin, 2023). As a result, multiple countries have developed specific policies and strategies to aid in the development of the HSC. Examples of comprehensive roadmaps with concrete action plans include the “Basic Hydrogen Strategy” of Japan which include financial incentives and funding support for research and infrastructure projects (Fujii, 2023; Lux et al., 2022). The political environment of the HSC is also significantly shaped by international agreements and collaborations. Initiatives like the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and the Hydrogen Initiative under the Clean Energy Ministerial (CEM) promote international cooperation by promoting knowledge exchange, technology transfer, and standardization of hydrogen-related policies (Cames et al., 2021; Gabov and Lizikova, 2022; Sieler et al., 2021). These partnerships encourage international trade in hydrogen and establish a global framework for the development of the HSC.

However, despite the widespread enthusiasm for hydrogen, some political barriers still exist. The effectiveness of policies can vary, depending on how they are carried out, and political will power to translate them into practical actions.

2.4. *Legislations, regulations, and policies for hydrogen supply chain*

The HSC policies vary significantly from nation to nation, illustrating the various strategies and priorities of various countries in promoting hydrogen as a clean energy source. For example, Japan provided a thorough road map titled “Basic Hydrogen Strategy” for developing the HSC (Knüpfer et al., 2021; X. Ren et al., 2020). By strategically investing in technological advancement, infrastructure expansion, and international cooperation, the Japanese government anticipates creating a cost-competitive HSC by 2030 (Sgarbossa et al., 2023). Additionally, policy incentives like subsidies and tax breaks are offered to promote private sector involvement and investment in projects involving hydrogen (Styczynski and Hughes, 2019). Similarly, the “National Hydrogen Strategy” was established by Germany to accelerate the transition to a hydrogen-based economy (Burdon et al., 2019; Cuevas et al., 2021). The focus of the strategy is on developing an accessible and cost-effective HSC, with an emphasis on the industrial sector. To encourage growth in the HSC and foster innovation, the German government provides financial support for research, development, and infrastructure projects (Kovač et al., 2021). In addition, Australian governments agree that hydrogen presents an opportunity for the future and developed the “National Hydrogen Strategy” which aims to position the country as a global hydrogen leader (Hjeij et al., 2022; Lebrouhi et al., 2022; Scita et al., 2020). The goal of the strategy is to encourage domestic and international exports of hydrogen. To promote cooperation between business and academic institutions, policies include funding for infrastructure development, grants for pilot projects, and the creation of regional hydrogen hubs.

Moreover, the “Hydrogen Energy Earthshot” initiative in the US seeks to lower the price of clean hydrogen production to encourage its wide availability (Lewis and Shultz, 2021; Miller, 2022). Projects involving the HSCs that are related to research, development, and demonstration receive funding from the US government. Furthermore, states like California have developed their own regulations, such as the “Low-Carbon Fuel Standard” (Mazzone et al., 2021; Romanak and

Dixon, 2022), which promotes the use of low-carbon hydrogen in transportation. Further, China's "Hydrogen Energy Development Plan" places a strong emphasis on incorporating hydrogen into its overall energy system (Song et al., 2020; WEI et al., 2021; Q. Zhang et al., 2022). The Chinese government makes substantial investments in hydrogen infrastructure development and provides financial support for pilot projects in strategic areas (Lebrouhi et al., 2022; Meng et al., 2022). Partnerships between the public and private sectors are essential to achieving China's lofty hydrogen goals (Sharma, Tiwari et al., 2023). Also, in South Korea, the "Hydrogen Economy Roadmap" lays out ambitious targets for hydrogen use, such as creating a national HSC (Chu et al., 2022; Hong et al., 2023). The Korean government actively encourages the use of fuel cell cars and provides subsidies for hydrogen distribution, production, and consumption (Kim et al., 2023; Park et al., 2023). Partnerships with business leaders are encouraged to accelerate the HSC's expansion. The goal of the EU's hydrogen strategy is to become carbon neutral by 2050 (Seck et al., 2022). The strategy prioritizes industries such as transportation and energy while concentrating on green and low-carbon hydrogen production (Chege, 2023). Further, with a domestic hydrogen industry, the UK's hydrogen strategy seeks to achieve net zero emissions by 2050 (Agarwal, 2022; Vella, 2021). Hydrogen that is both green and low-carbon will be created in order to decarbonize transportation, electricity, industry, and heating. From industrial development point of view, the foundational industries are by far the most challenging to decarbonize. With the recent breakthrough in fossil-free Hydrogen Breakthrough Ironmaking Technology (HYBRIT) process (Vattenfall, 2024), one of the biggest future beneficiaries of low-cost green hydrogen is the iron and steel industries. Sweden is already exploiting the HYBRIT technique.

Legislation and regulation play a critical role in shaping the development of the HSC. Legal frameworks establish essential guidelines for the green production, transportation, storage, and distribution of hydrogen, while regulations specify the requirements necessary to mitigate environmental impacts and uphold organizational protocols. Recent legislative and regulatory actions have significantly advanced the HSC. For instance, the European Union has introduced its hydrogen strategy to set targets for producing green hydrogen as part of its goal for a climate-neutral Europe, supported by the Renewable Energy Directive (RED II) (Vivanco-Martín and Iranzo, 2023). Similarly, the United States enacted the Bipartisan Infrastructure Law in 2021 to enhance funding for hydrogen projects and establish clear standards for developing a hydrogen economy (Bade and Tomomewo, 2024). Additionally, organizations such as the International Organization for Standardization (ISO) are actively working to update and ensure compliance with safety and environmental regulations for hydrogen transportation and storage facilities (Salehi et al., 2022).

In conclusion, this literature review underscores the significant impact of various national policies on the HSC. Each country tailors its strategy to align with its unique energy requirements, technological capabilities, and long-term sustainability objectives.

2.5. Research gap

The current rise in hydrogen demand necessitates an effective HSC that can successfully satisfy this expanding need (Ratnakar et al., 2021). To do this, it is crucial to pinpoint the barriers that interfere with or hinder the HSC's efficient operation. Additionally, creating an effective HSC is crucial for meeting demand as well as reducing the negative effects on the environment (Ishimoto et al., 2020; Yue et al., 2021). The production, distribution, and use of hydrogen sustainably can be embedded in a well-designed supply chain (Rai et al., 2022), which can help lower GHGs and improve the sustainability of hydrogen. Again, to highlight the HSC's potential advantages, it is crucial to identify its primary driving factors (Ralston and Blackhurst, 2020; Saeed and Kersten, 2019). Understanding these factors highlights the strategic importance of an effective HSC and encourages additional investments in its growth. At the same time, it's critical to remove the barriers preventing the HSC from progressing (Yao et al., 2020). Even though there have been many studies on hydrogen production, storage techniques, and policy-making, there is still a significant research gap when it comes to the effective transfer of hydrogen from the production stage to consumers through a reliable supply chain (Dawood et al., 2020; Falcone et al., 2021; Xie et al., 2020). Although, some studies have investigated particular aspects of the hydrogen domain, such as the work by Yousefi et al. (2019) focusing on hydrogen storage materials and that of Nishiyama et al. (2021) presenting a solar-driven hydrogen production framework, few thoroughly address the efficient journey of hydrogen through a well-structured supply chain. In conclusion, a resilient, effective, and sustainable hydrogen economy depends on an understanding of the drivers, barriers, and overall dynamics of the HSC. Thus, this study aims to identify the drivers of HSC and barriers that the HSC faces. Thus, this study aims to identify the drivers of HSC and the barriers it faces.

In this regard, the contribution of this study can be summarized as follows:

1. It compiles a comprehensive list of drivers and barriers of HSC.
2. The Grey-DEMATEL approach is proposed to identify, analyse, and rank the critical drivers and barriers.
3. The Grey-DEMATEL approach is again applied to identify the interrelationship among the prominent drivers and barriers.
4. Identified drivers and barriers from this study can facilitate the HSC to fulfil consumer demands.

3. Methodology

This study follows a three-phase framework, as illustrated in Fig. 2. In Phase 1, systematic review of existing literature is conducted in accordance with PRISMA guidelines to identify the primary drivers and barriers of HSC. Subsequently, experts are selected for the DELPHI and Grey-DEMATEL methods to validate and analyse the identified factors. In Phase 2, the identified drivers and barriers are validated using the DELPHI method, based on expert opinions, providing detailed insights into the final set of factors. Finally, in Phase 3, the Grey-DEMATEL technique is employed to analyse the causal relationships between the validated drivers and barriers based on expert evaluations.

3.1. Systematic identification of HSC drivers and barriers using PRISMA

The primary objective of this study is to identify the key drivers and barriers within the HSC. To accomplish this, we employed the PRISMA technique to systematically extract relevant drivers and barriers from existing literature. PRISMA is a widely recognised and reliable method for gathering information from previous studies in a clear and, structured manner (Page et al., 2021). The PRISMA technique utilized in this study is presented in Fig. 3.

3.1.1. Search strategies

A comprehensive search was conducted across electronic databases (Scopus and Web of Science) following the search protocols outlined in Fig. 3 to identify drivers and barriers separately. Additionally, an extensive search was performed using various search engines (e.g., Google) in line with the protocol in Fig. 3 to access grey literature, thereby gathering supplementary information on ongoing initiatives, debates, and other relevant developments. The search protocol established in this study is designed to capture a wide range of the drivers and barriers within the HSC. For instance, incorporating keyword variations such as "driver*", "opportunity*", "critical factor*" facilitates the extraction of all pertinent drivers from the literature. Furthermore, the inclusion of a search protocol for grey literature expands the scope, ensuring comprehensive coverage of all relevant documents.

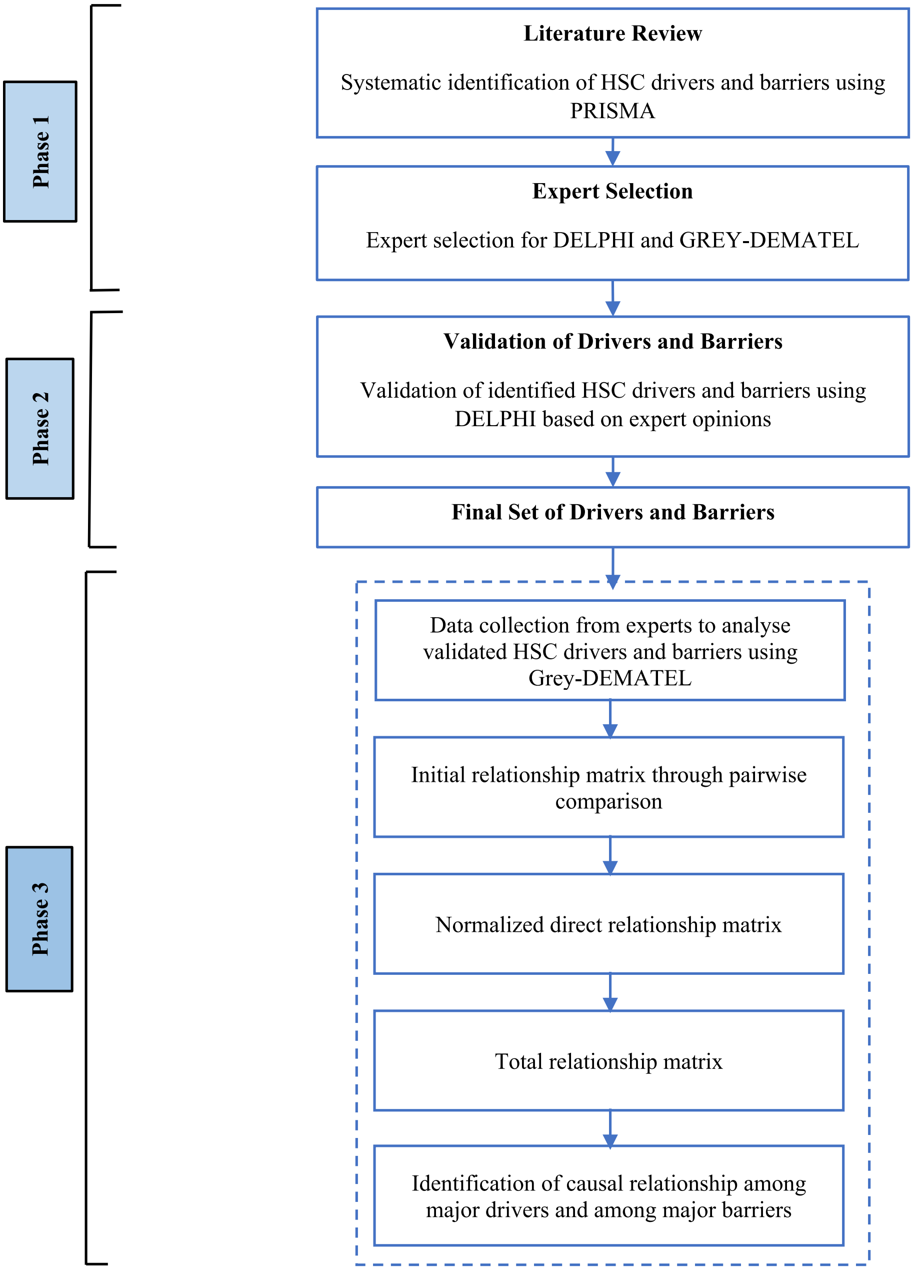

Fig. 2. Methodology of proposed framework.

3.1.2. *Grey literature*

The term “grey literature” refers to research and information that is not published through traditional academic channels, such as peer-reviewed journals (Gul et al., 2021; Kamei et al., 2021; Kayikci and Kabadurmus, 2022). This category includes reports, working papers, technical documents, government publications, and other materials that contribute significantly to the research landscape. In this study, using the search protocol outlined in Fig. 3, we conducted searches across various search engines, including Google. Initially, a total of thirty-four articles covering HSC content were identified. Following a thorough screening process, four articles were deemed directly relevant to our study.

3.1.3. *Inclusion and exclusion criteria*

This study includes only literature that specifically addresses the drivers and barriers within the HSC. Additionally, studies focusing solely on hydrogen, hydrogen production, the hydrogen economy, or traditional supply chain management were considered during the initial screening phase. Furthermore, to ensure comprehensive coverage, no restrictions were applied regarding article type, publication year, or country of origin. However, non-English articles and those not focused on relevant outcomes were excluded from consideration.

3.1.4. *Articles content review*

The initial screening using keywords yielded a total of 155 articles on drivers and 397 articles on barriers from academic databases (Scopus and Web of Science). Additionally, 34 relevant articles on the HSC were retrieved from grey literature sources. After excluding non-relevant and duplicate articles, the pool was reduced to 59 articles on drivers and 106 on barriers. Among these, 39 articles ($n_1 = 12$ for drivers, $n_2 = 27$ for barriers) were excluded because they were non-English, not research articles, or did not focus on relevant outcomes.

Following that, the remaining articles were then downloaded for a detailed review of titles, abstracts, and introductions. Finally, only

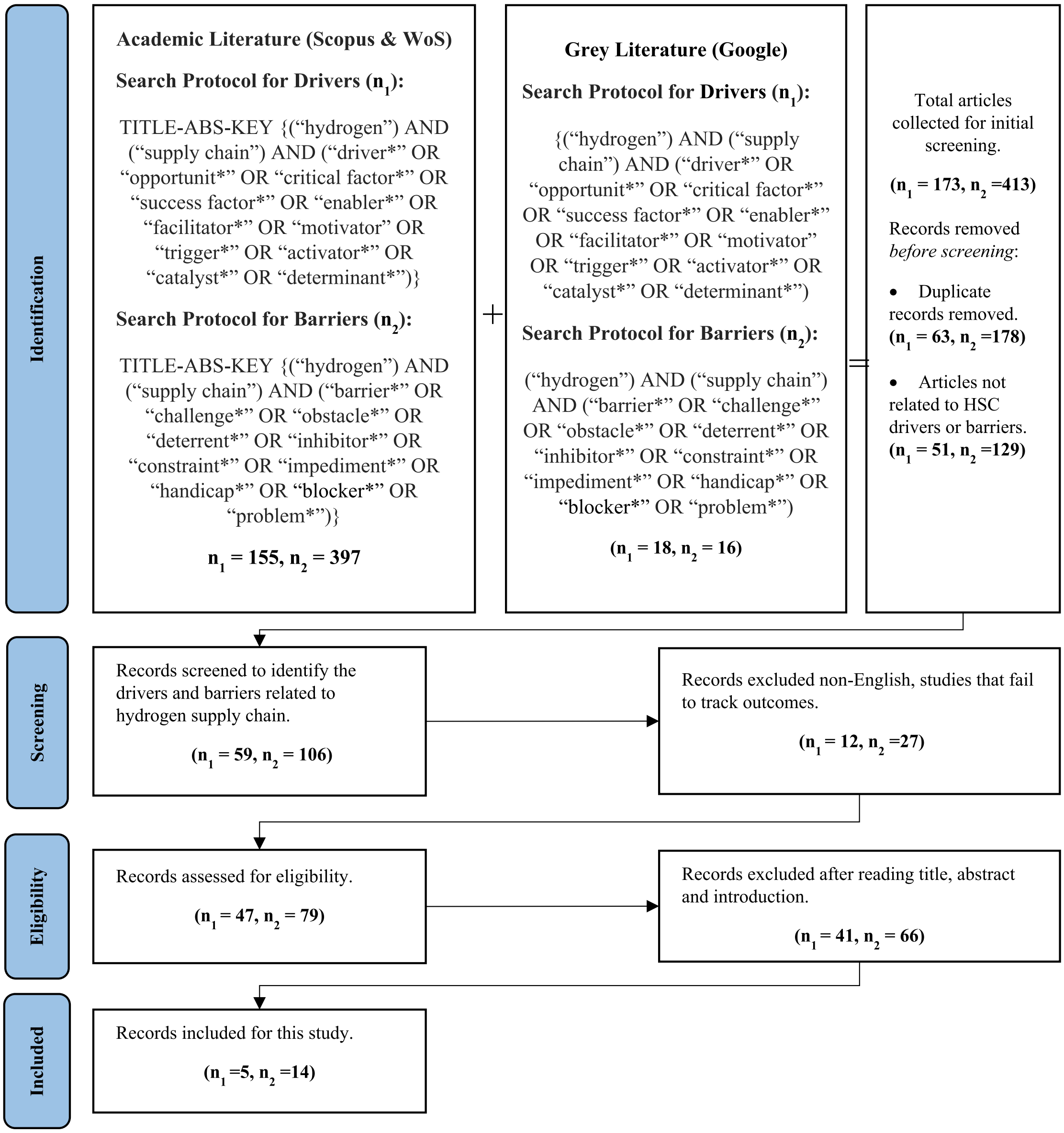

Fig. 3. Literature search following PRISMA technique.

nineteen articles were directly relevant to our study: five focused on HSC drivers, and fourteen on HSC barriers. As a result, the identified drivers and barriers are illustrated in Fig. 4. To strengthen the findings, Section 3.3 further validates the selected drivers and barriers.

3.2. Experts selection

This study employs the DELPHI method to validate the identified drivers and barriers, while the Grey-DEMATEL method is used to determine the most critical factors and analyse their interrelationships. The accuracy and reliability of both methods rely heavily on expert contributions; therefore, a rigorous selection process was undertaken to ensure the inclusion of highly qualified professionals. For the DELPHI method, a panel of five experts participated in the validation of the identified drivers and barriers related to the HSC. Their demographic details are provided in Table A.1 (Appendix I). For the Grey-DEMATEL analysis, an initial outreach was made to 24 experts, of whom 19 agreed to participate. Each selected expert possesses in-depth knowledge and practical experience in areas such as hydrogen production, storage, transportation, and supply chain management, as well as in energy policy and renewable energy systems. This selection process was designed to minimize potential biases associated with the Grey-DEMATEL method and ensure the high quality and reliability of expert input. The professional composition of the respondents included: 7 CEOs, 8 Managers, 2 Professors and 2 additional experts in research or related supply chain positions. The study also ensured diverse regional representation, with 10 experts from Asia and 9 from Europe. A detailed demographic breakdown is provided in Table A.2 (Appendix I). Overall, the study benefited from the contributions of experts from industry, academia, and policymaking, representing various stages of the hydrogen value chain across Asia and Europe. Given that the Grey-DEMATEL method heavily relies on expert judgments, the careful selection of a diverse, well-qualified expert panel enhances the credibility, robustness, and practical relevance of the research findings.

3.3. Validation of HSC drivers and barriers using DELPHI

The DELPHI method is an organized method of communication that can be utilized to obtain feedback from a panel of experts (Hung et al., 2019; Lu et al., 2020; Romero-Collado, 2021). It was established in the

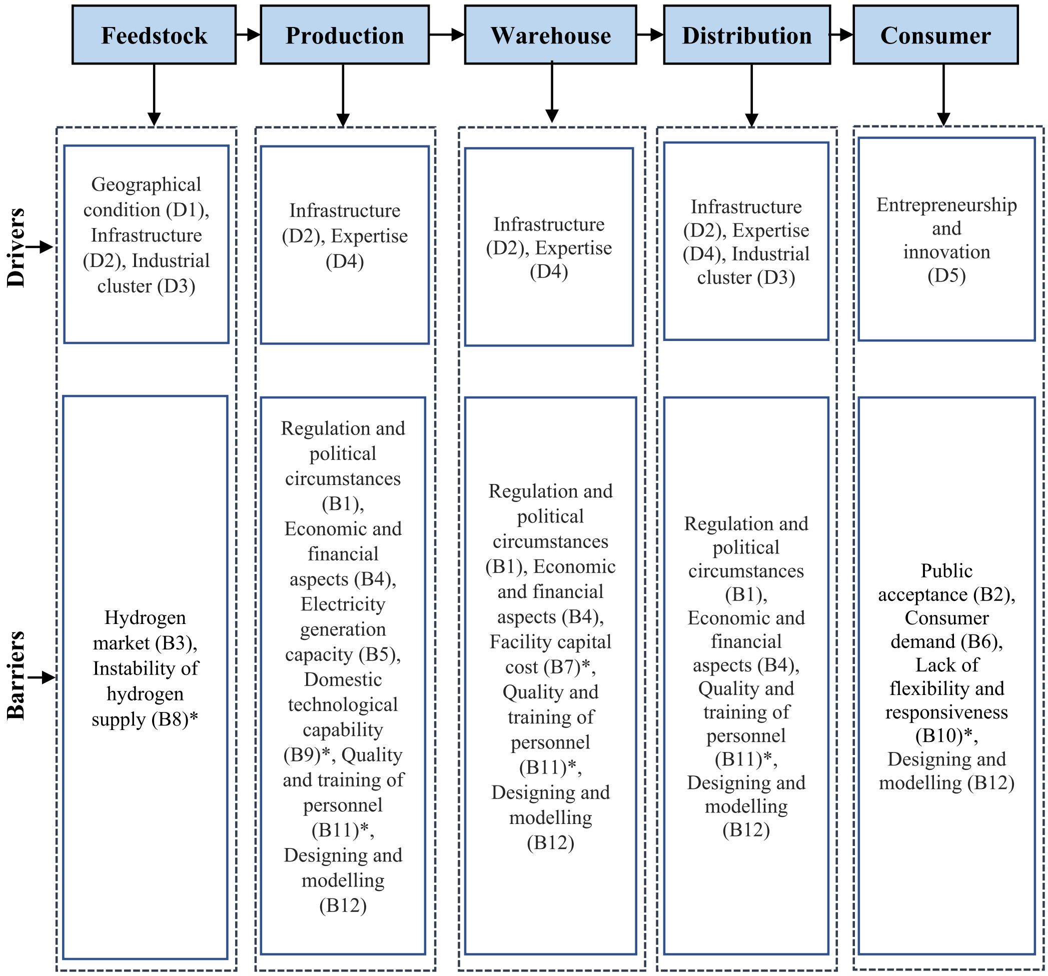

Fig. 4. Structure of Hydrogen Supply Chain along with its drivers and barriers.

1950s by Olaf Helmer and Norman Dalkey of the RAND Corporation (Neo, 2021). The method entails a series of questionnaires or rounds in which experts anonymously provide their opinions. For this, a facilitator needs to compile and summarize the responses, which are then presented back to the panel in subsequent rounds (Khanduja et al., 2023). This iterative process aids in the development of a consensus or agreement on a specific topic. In addition, the DELPHI method is useful for validating factors such as drivers or barriers because it allows for the exploration of multiple viewpoints, reduces biases, and promotes collective intelligence (Rampasso et al., 2021; Rezaei et al., 2021; Tengan and Aigbavboa, 2021; Almaraz et al., 2024). Hence, this study selected this method to validate the identified drivers and barriers effectively, and this complete method proceed according to the following steps:

1. Step 1 – Selection of the facilitator: At first, a facilitator or expert is needed in the DELPHI method to explain the mutual objective of this study to a group of people to take their decision appropriately.
2. Step 2 – Identification of the experts: We selected experts from various industries involved in hydrogen production, distribution, and utilization based on their willingness to participate, accessibility of information, and extensive experience in HSC operations. Their involvement helped us perform the task effectively and meet industry standards.
3. Step 3 – Definition of the problem: The main goal of this study is presented to the experts. Then, the description of drivers and barriers is given to the experts.
4. Step 4 – Round questions: In this step, at first general questions (i.e., what is HSC? why HSC is crucial? What stage of HSC is critical or challenging? What is HSC's level of maturity) asked experts to understand their perspective about HSC. After that, a questionnaire was provided to take decisions about the drivers and barriers of HSC. A survey used in this study is provided in the Appendix II to collect drivers and barriers according to expert opinions.
5. Step 5 – Action: After obtaining the results, we analysed the decisions of the experts using different parameters such as mean, median, percentage of agreement calculation.

3.4. Final set of HSC drivers and barriers

Fig. 4 presents a structured summary of the finalised set of drivers and barriers in the HSC, categorized according to its underlying framework. These factors were systematically identified through the DELPHI process, as detailed in Section 3.3. A total of five key drivers and twelve barriers were derived from an extensive literature review and expert consultations. The validity of all identified factors was further confirmed through expert consensus using the DELPHI method. Factors marked with an asterisk (*) in Fig. 4 denote those specifically identified through expert input as part of the DELPHI process. The final set of HSC drivers and barriers, as established by the DELPHI output, is presented in Table A.3. in Appendix I. A comprehensive overview of these drivers and barriers is outlined below:

3.4.1. Geographical condition (D1)

Geographical conditions encompass both natural and artificial elements that affect hydrogen availability, accessibility, and transportation within regions (Ebrahimi and Bagheri, 2022). These conditions include factors such as terrain, weather patterns, proximity to water sources, infrastructure availability, and regulatory requirements. In the HSC, geographical conditions are a critical driver, as they directly influence the cost, efficiency, and sustainability of operations (Gegesi-Kiss, 2021). For instance, the location and accessibility of hydrogen production facilities impact both the cost and supply readiness of hydrogen. Likewise, the logistics of hydrogen delivery are influenced by the distance between production and consumption sites as well as the availability of transportation infrastructure. Importantly, geographical conditions (D1) also drive the availability and cost-effectiveness of feedstock, a fundamental factor for HSC success. Thus, understanding and addressing the impact of geographical conditions on feedstock availability and accessibility are essential for optimizing HSC efficiency and sustainability (S&P Global, 2023).

3.4.2. *Infrastructure (D2)*

Infrastructure refers to the physical facilities and structures necessary for hydrogen production, storage, and transportation (Bique and Zondervan, 2018; De Blasio, 2024). This includes essential machinery such as electrolysers, pipelines, storage tanks, compressors, pumps, and dispensers along with auxiliary systems like power supplies and control systems. Infrastructure is a key driver of the HSC, as it significantly impacts the cost, efficiency, and reliability of operations (Gegesi-Kiss, 2021). For instance, the cost-effectiveness and efficiency of hydrogen production and transportation are closely tied to the capacity and quality of the available infrastructure. Additionally, the design and utilization of infrastructure can influence the safety and environmental impact of the HSC. Infrastructure supports various processes, including raw material delivery to production facilities, hydrogen storage, transportation, and delivery to end-users. Furthermore, the effectiveness, reliability, and cost of hydrogen distribution are directly affected by the design and management of infrastructure (Kurtz et al., 2019; Moradi and Groth, 2019).

3.4.3. *Industrial cluster (D3)*

In the HSC, an industrial cluster refers to a geographical concentration of interconnected companies, institutions, and facilities engaged in the production, distribution, storage, and utilization of hydrogen feedstock (van der Spek et al., 2022). Industrial clusters are designed to generate synergies and economies of scale that can reduce costs, enhance efficiency, and accelerate the commercialisation of hydrogen technologies. By bringing together businesses, research institutions, and other stakeholders within a shared environment, industrial clusters facilitate the exchange of knowledge, ideas, and expertise that can drive advancements in the HSC. For instance, clustering hydrogen producers and storage suppliers in specific regions can ensure a consistent and reliable supply of hydrogen to end-users, such as hydrogen refuelling stations and industrial customers. Consequently, industrial clusters represent a significant driver of the HSC (Gegesi-Kiss, 2021). Moreover, this clustering effect can create a positive feedback loop, attracting additional businesses and professionals to the development of new technologies.

3.4.4. *Expertise (D4)*

Professional experience and expertise in managing the HSC are essential for its advancement (Gegesi-Kiss, 2021). First, specialized knowledge is crucial in the production stage, whether hydrogen is generated through electrolysis or other methods, to ensure that production is efficient and minimizes environmental impacts (Osman et al., 2022; Younas et al., 2022). Second, due to hydrogen's highly flammable nature, expertise is necessary for designing safe storage and transportation systems. This knowledge is vital for ensuring that hydrogen is stored and transported safely, thereby preventing any harmful incidents. Third, proficiency is also required for the effective distribution and utilization of hydrogen (Younas et al., 2022), facilitating the establishment of an optimized distribution network within the HSC. Fourth, expertise in regulatory compliance is critical for navigating the complex regulatory landscape to ensure that the HSC adheres to all applicable laws and regulations. Additionally, relevant skills are needed to maintain the infrastructure and ensure its optimal and reliable operation. Overall, with the right expertise in place, the HSC can become a pivotal component of a sustainable energy future.

3.4.5. *Entrepreneurship and innovation (D5)*

Entrepreneurship and innovation are pivotal in creating new business opportunities within the hydrogen sector (Xu et al., 2023), such as the implementation of novel hydrogen production technologies or design of advanced hydrogen fuel cell systems for diverse applications. Moreover, entrepreneurship can facilitate the identification of emerging hydrogen markets (Trapp et al., 2022), including sectors such as fuel for heavy-duty vehicles. Entrepreneurs play a crucial role in advancing the HSC by developing innovative technologies that enhance the efficiency, cost-effectiveness, and environmental sustainability of hydrogen production, storage, and utilization (Gegesi-Kiss, 2021). Additionally, they can contribute to the establishment of new markets for hydrogen by devising innovative business models and fostering collaborations that promote the widespread adoption of hydrogen-based technologies. For instance, partnerships with manufacturers can facilitate the integration of hydrogen fuel cells into their products, while collaborations with utility companies can lead to the development of hydrogen-based energy storage solutions. Furthermore, hydrogen energy can be harnessed to power manufacturing plants, thereby expanding its application. Thus, entrepreneurship and innovation can be recognised as a significant driver of the HSC.

3.4.6. *Regulation and political circumstances (B1)*

Regulation and political circumstances can pose a significant barrier to the operation of the HSC in various ways (Gegesi-Kiss, 2021). For instance, regulatory measures may limit the volume of hydrogen that can be transported by pipeline or impose costly security requirements on hydrogen storage facilities (Moradi and Groth, 2019). Although these regulations are often established with the best intentions, they can inadvertently result in increased costs and delays for companies. Furthermore, political conditions can influence the availability of funding and support for hydrogen infrastructure development (Gordon et al., 2023; De Blasio, 2024). Political circumstances also play a crucial role in shaping the demand for hydrogen, which is vital for the success of any HSC. For example, if governments do not provide incentives for hydrogen adoption or fail to support the development of hydrogen-powered vehicles, the market for hydrogen may remain limited, thereby constraining the practical applications of HSC technologies. Additionally, as highlighted in discussions on the transition to a green hydrogen economy, certain laws and regulations governing hydrogen production can create bottlenecks within the supply chain, as stringent enforcement may hinder production rates (EPW, 2023).

3.4.7. *Public acceptance (B2)*

Public acceptance represents a significant barrier to the efficient and smooth operation of HSC (Gegesi-Kiss, 2021). The success of HSCs is heavily influenced by public perceptions of hydrogen as a fuel source. Given that hydrogen is relatively unfamiliar to most individuals (W. Li et al., 2020), concerns regarding its reliability and safety may arise. Additionally, there are apprehensions related to the environmental impact of hydrogen production and its usage. The lack of knowledge and education about hydrogen may further contribute to public resistance to its adoption as a fuel (Beasy et al., 2023). This ignorance can lead to misunderstandings and misconceptions about the reliability and safety of hydrogen as a viable energy source. Consequently, these uncertainties may pose challenges for businesses in securing investments necessary for developing the infrastructure that supports HSC. Thus, public acceptance can be viewed as a critical barrier to the advancement of HSCs.

3.4.8. *Hydrogen market (B3)*

The hydrogen market itself presents challenges that can hinder the development of HSC. In certain sectors or industries, the demand for hydrogen as a fuel remains constrained (Weimann et al., 2021). This limited demand may stem from a lack of hydrogen-powered vehicles or insufficient industrial applications for hydrogen. Furthermore, the production and distribution of hydrogen can be costly (Mah et al., 2019), particularly during the initial phases of market development. Consequently, hydrogen may struggle to compete on price with more established fuels. Although technologies used for hydrogen production, such as electrolysers for renewable hydrogen generation and fuel cells for electricity production, are continuously evolving, technological advancements require time to mature. The current state of these technologies may not adequately meet all market needs, which can hinder the scalability and cost-effectiveness of hydrogen solutions, thereby impeding the overall growth of the hydrogen market (Gegesi-Kiss, 2021).

3.4.9. *Economic and financial aspects (B4)*

Economic and financial factors can significantly impede the development of HSCs (Gegesi-Kiss, 2021). Establishing an HSC requires substantial initial investments, which encompass the construction or renovation of manufacturing facilities, storage pipelines, transportation systems, and distribution networks. The capital costs associated with these infrastructure components can be considerable (Delgado et al., 2019), particularly during the early stages of the hydrogen market's development. Such high initial expenses may discourage potential investors and impede the timely construction of essential infrastructure (Nissen, 2022). Moreover, the absence of a clear and predictable market can deter private-sector investment, as highlighted in the context of Southern Africa's hydrogen economy, which faces both opportunities and challenges related to financial viability (African Review, 2023). Additionally, the lack of favourable financial incentives can hinder HSC growth. For example, the economic viability of hydrogen projects may be jeopardized without government incentives such as subsidies or tax exemptions. These financial supports can help offset the higher costs associated with hydrogen production, distribution, and infrastructure development, thereby promoting the adoption of hydrogen technologies, as discussed in the exploration of shifting to a green hydrogen economy by 2030 (EPW, 2023).

3.4.10. *Electricity generation capacity (B5)*

The “electricity generation capacity” could potentially inhibit the growth of HSC (Gegesi-Kiss, 2021). Hydrogen production requires a substantial and continuous supply of electricity (Osman et al., 2022), particularly when utilising electrolysis. If the existing electricity generation capacity is insufficient to meet the demands of the electrolysis process for significant hydrogen production, allocating additional power for hydrogen production becomes challenging, especially when the electrical grid is operating at full capacity. This situation poses a risk to the stability and reliability of the grid. Moreover, the production of low-carbon or green hydrogen relies heavily on the widespread adoption of renewable energy sources such as wind and solar (Mohideen et al., 2021; Yu et al., 2021). The intermittent nature of these renewable sources can introduce complications in maintaining a steady supply of electricity. Additionally, competition for available electricity generation capacity among various sectors, including transportation, residential, commercial, and industrial, can further restrict the electricity allocated for hydrogen production. High demand for electricity in these sectors can significantly limit the availability of power for hydrogen production, thereby constraining the growth of the HSC. This multifaceted interplay between electricity generation capacity and hydrogen production underscores the need for integrated energy planning and investment in renewable infrastructure to support the hydrogen economy.

3.4.11. *Consumer demand (B6)*

Consumer demand represents a significant barrier to the establishment of HSCs, as any supply chain fundamentally relies on demand (Gegesi-Kiss, 2021). The success of the HSC is, therefore, heavily contingent upon consumer interest in hydrogen-powered products and services. For instance, if demand for hydrogen fuel cell vehicles remains low, this will subsequently diminish the necessity for hydrogen refuelling stations, which are critical components of the HSC. Moreover, consumer preferences and behaviours significantly influence market demand (Sheth, 2020). The adoption of hydrogen-powered technologies may face challenges if consumers prefer conventional fossil fuel-based vehicles or lack awareness of the benefits associated with hydrogen as a fuel source. Additionally, the relative pricing of hydrogen-based products compared to alternatives can impact consumer demand; if hydrogen-electric vehicles or appliances are considerably more expensive than existing options, consumer interest in transitioning to these technologies may wane. As highlighted in recent reports, addressing these consumer demand challenges is crucial for the growth of the hydrogen economy, particularly in light of the evolving market dynamics and ambitions for a sustainable energy future (S&P Global, 2023).

3.4.12. *Facility capital cost (B7)*

The initial investment required to establish infrastructure for hydrogen production, storage, distribution, and utilization is referred to as facility capital cost (Ren et al., 2013). This cost can significantly impede the growth of HSC in various ways. For example, the construction and refurbishment of facilities for hydrogen production, storage, and distribution necessitate substantial capital expenditures, including land acquisition, construction, and the purchase and installation of equipment.

High initial investment requirements can deter potential investors and project developers, particularly in the early stages of the hydrogen industry, where economies of scale have not yet been realized. Economies of scale are crucial in determining facility capital costs in any supply chain (Kazancoglu et al., 2020). Typically, large-scale production facilities benefit from lower costs per unit of hydrogen produced compared to smaller counterparts. However, during the initial phases of the hydrogen market, insufficient demand may hinder the viability of large-scale facilities, ultimately limiting project development and growth potential. Thus, addressing the challenge of facility capital costs is essential for fostering a robust hydrogen economy and ensuring the successful establishment of HSCs.

3.4.13. *Instability of hydrogen supply (B8)*

The instability of hydrogen supply poses a significant barrier to the HSC (Nissen, 2022). Hydrogen production relies on feedstocks such as natural gas, biomass, or water, and the availability and accessibility of these resources are crucial for the stability of the HSC (Ren et al., 2013). If the availability of these feedstocks is limited or subject to fluctuations, it can disrupt hydrogen production and compromise the overall stability of the supply chain (Shen and Sun, 2023).

Moreover, geopolitical and international trade factors can further impact the HSC, especially in regions that heavily depend on hydrogen imports. This import dependency introduces various risks, including international conflicts, supply disruptions, and price volatility, all of which can jeopardize the stability and security of hydrogen supply (Lindner, 2023).

Supportive policy and regulatory frameworks also play a critical role in influencing the stability of the HSC. Clear and consistent policies that encourage investment in hydrogen infrastructure can contribute to long-term stability. In contrast, inconsistent policy frameworks may create uncertainty, thereby hindering the development of a stable supply chain (Chenet et al., 2021). Therefore, addressing these factors is essential for enhancing the resilience and reliability of HSCs.

3.4.14. *Domestic technological capability (B9)*

Domestic technological capability refers to a country's capacity to develop and apply technology within its borders (Razzaq et al., 2021). In the context of the HSC, this capability encompasses a nation's ability to devise and implement technologies related to hydrogen storage, transportation, and utilization (Ren et al., 2013). Limited domestic technological capability can serve as a significant barrier to the HSC, constraining a country's ability to develop the necessary technologies and infrastructure for hydrogen-related activities. This limitation hampers the growth and efficiency of the hydrogen sector (Nissen, 2022; Alsaba et al., 2023; Erdener et al., 2023; Lagioia et al., 2023).

Moreover, countries lacking sufficient domestic capabilities often find themselves dependent on importing technology or expertise, which can be both costly and foster a pattern of dependency (Yang et al., 2022). The absence of adequate technological expertise also inhibits effective infrastructure design and construction, thereby diminishing the establishment of a robust and credible supply chain network (Montecchi et al., 2019). Furthermore, the shift towards a green hydrogen economy, as outlined in recent analyses, underscores the importance of developing local technological capacities to mitigate reliance on external sources and promote sustainability (EPW, 2023; Energy Council, 2023). In conclusion, limited domestic technological capacity significantly undermines the HSC's potential as a widely utilized and sustainable energy solution.

3.4.15. *Lack of flexibility and responsiveness (B10)*

Flexibility and responsiveness refer to the capacity to quickly and effectively adapt to changes in demand or circumstances (Gligor et al., 2019; Klein and Todesco, 2021). In the context of the HSC, these qualities are critical for the system's ability to respond swiftly to fluctuations in demand, technological advancements, and evolving market dynamics. This involves adjusting infrastructure, operations, and production processes to ensure a stable and efficient HSC, as identified by Ren et al. (2013) as a key criterion for success. However, a lack of flexibility and responsiveness can pose significant barriers to the effective operation of the HSC.

Rigid supply chains that cannot adapt to changing conditions may lead to inefficiencies, ineffective resource utilization, and challenges in meeting dynamic demand. For example, if the infrastructure and production capacities are fixed and cannot be easily scaled up or down, it becomes challenging to respond to shifts in hydrogen demand. Additionally, a failure to adapt to technological innovations may hinder the integration of more effective or economical processes (Hoang and Nguyen, 2021; Kapsalis et al., 2019). Overall, insufficient flexibility and responsiveness can impede the agility and resilience necessary for a dynamic and effective HSC.

3.4.16. *Quality and training of personnel (B11)*

“Quality and training of personnel” refers to the level of education, knowledge, skills, expertise, and training of the workforce within a specific industry or organization (Fachrunnisa and Hussain, 2020). This encompasses the qualifications, competence, and capabilities of individuals working in various roles and functions (J. Ren et al., 2013). The quality of staff and their training are critical for ensuring efficient operations, effective decision-making, innovation, and the overall success of the hydrogen sector (Nisar et al., 2021). However, insufficient quality and training personnel can present significant barriers to the HSC in multiple ways. For instance, if the workforce lacks essential knowledge, skills, and training related to hydrogen technologies and processes, it may hinder the efficient operation and maintenance of hydrogen storage and distribution facilities. Moreover, inadequate education and training can lead to a shortage of qualified personnel, which is vital for supporting the growth and development of the hydrogen sector (Joshi et al., 2021). Additionally, a lack of expertise may obstruct innovation and the adoption of best practices (Gupta et al., 2020), ultimately resulting in subpar performance and diminished competitiveness within the industry.

3.4.17. *Designing and modelling (B12)*

The process of designing and modelling encompasses the creation and conceptualization of the structure, layout, and operation of various components and systems within a specific context or industry (Franco, 2019; Vom Brocke and Maedche, 2019). In the HSC, designing and modelling involve developing plans, blueprints, and simulations to optimize the design, configuration, and operation of hydrogen production facilities, storage infrastructure, transportation systems, and related processes. This process may utilize computer-aided design (CAD), modelling software, and simulation tools to assess performance metrics, predict behaviour, and inform decision-making, thereby ensuring a profitable HSC. However, challenges or constraints within these processes can present barriers to the HSC (Almansoori and Shah, 2009). For example, a lack of resources to effectively design and model the components and systems of the supply chain may hinder the efficient and optimal planning of infrastructure, manufacturing facilities, storage systems, and distribution networks. Furthermore, the absence of standardized design guidelines for modelling could impede the overall effectiveness of the HSC, resulting in inconsistencies and inefficiencies in operations.

3.5. *Grey-DEMATEL*

A grey system theory-based DEMATEL method is a variation of the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method (Deepu and Ravi, 2021; Liu et al., 2021; Singh et al., 2023). In particular, it was established to address uncertainties related to decision-making processes (Akter et al., 2022; Ciptomulyono et al., 2022). Grey-DEMATEL assists in the analysis of complex relationships and dependencies among factors by considering qualitative as well as quantitative information. Its advantages include improved decision quality and better understanding of complex systems. As an example, Khan et al. (2022) effectively identified cause-and-effect relationships between drivers and barriers of circular economy implementation as well as ranking according to their importance level with the help of Grey-DEMATEL approach. In addition, Garg (2021) stated Grey-DEMATEL as an efficient method for assessing factors such as driver, barriers, etc. Furthermore, Konstantinou and Gkritza (2023) explored the barriers related to electric truck adoption using Grey-DEMATEL. Based on the above discussion, it can be stated that the Grey-DEMATEL methodology is an effective and efficient approach for identifying and analyzing the drivers and barriers of HSC, as well as revealing the causal relationships among the critical factors. The steps of the Grey-DEMATEL methodology in this study are as follows:

Step 1: This step involves developing a fuzzy direct relationship matrix using linguistic scales of five points, as Table 1.

We developed an initial direct relationship matrix for the drivers and barriers ($d_i, i = 1, 2, 3, \ldots n; b_i, i = 1, 2, 3, \ldots n$) to HSC with the help of D experts using pair-wise comparison and the grey number (Table 1). This replaces this matrix's linguistic terms. N number of $V^1, V^2, V^3, \ldots V^D$ direct relationship grey matrix is obtained from the experts. Combining all grey direct-relationship metrics using eq. (1) resulted in an overall grey-relationship matrix.

Table 1
Linguistic Terms and Their Corresponding Greyscales.

Linguistic Terms	*Grey numbers*
No influence(N)	[0,0]
Very low influence (VL)	[0,0.25]
Low influence (L)	[0.25, 0.5]
High influence (H)	[0.5, 0.75]
Very high influence (VH)	[0.75, 1]

$$V = \frac{\sum_{i=1}^{D} \left(V^{D}\right)}{D} \tag{1}$$

*Step 2:*In this step, the overall grey-relationship matrix converted into normalized direct relation matrix N using the eq. (2) and (3)

$$N = sV \tag{2}$$

$$S = \frac{1}{\underset{1 \le i \le n}{maxX}\, V_{ij}} \tag{3}$$

Step 3: In this step, the total relationship matrix "T" is determined based on eq. (4) where I represent the identity matrix.

$$T = \sum_{i=1}^{\infty} N^{i} = N\,(I - N)^{-1} \tag{4}$$

Step 4: This step determines the net and causal effects of drivers and barriers of HSC using eqs. (6)–(8)

$$R_i = \sum_{j=1}^{n} t_{ij} \forall_i \tag{5}$$

$$C_j = \sum_{j=1}^{n} t_{ij} \forall_j \tag{6}$$

$$P_i = \left\{R_i + C_j \mid i = j\right\} \tag{7}$$

$$E_i = \left\{R_i + C_j \mid i = j\right\} \tag{8}$$

Step 5: In this step, the cause-and-effect relationship digraph will be plotted using$\left(R_i + C_j\right), \left(R_i - C_j\right)$, threshold, and the total relationship matrix (T). $\left(R_i - C_j\right)$ will be represented on the vertical axis of digraph, while $\left(R_i + C_j\right)$ will be on the horizontal axis. In addition, the positive value of E_i represent the net effect (cause) on the system, while the negative value represents the net effect on the system (Yazdi et al., 2024).

4. Results

4.1. DELPHI application for validating HSC drivers and barriers

The DELPHI technique was applied from January 2023 to June 2023 using the secure online survey tool, for survey creation and distribution, enabling real-time data access and comprehensive analytics. One of the authors acted as the facilitator, recruiting experts, communicating objectives, delivering surveys, and collecting data. The expert panel comprised individuals experienced with various sectors relevant to the HSC. We contacted 11 experts, of which 5 agreed to participate in both rounds. Following Khan et al. (2023), Ziglio (1996) and Linestone and Turoff (1975), this number is adequate for reliable results. Surveys were constructed to validate the drivers and barriers of the HSC. The surveys included background questions and questions for rating the importance of drivers and barriers on a five-point Likert scale.

The first survey, distributed on February 8, 2023, received responses from all 5 participating experts. Experts rated the importance of each driver and barrier for implementing HSC in relevant industries. Based on first-round responses, a second survey was sent out on March 7, 2023, incorporating additional barriers suggested by the experts, including facility capital cost (B7), instability of hydrogen supply (B8), domestic technological capability (B9), lack of flexibility and responsiveness (B10), and quality and training of personnel (B11). Five experts responded again, showing increased consensus and less deviation. Online survey tool ensured anonymity and only facilitators had access to responses.

Responses were analysed using a five-point Likert scale to generate mean and median values, indicating increased agreement and consensus. Agreement criteria were set at 70 % or greater, in accordance with guidelines mentioned by Anderson and Tyldesley (2019), Önaç and Birişçi (2019). After validation, we identified five drivers and twelve barriers, which are described and detailed in Section 3.4. All validated drivers and barriers qualified for use in the next phase, Grey-DEMATEL.

4.2. Ranking and cause-and-effect grouping of drivers and barriers

The Grey-DEMATEL analysis was run for drivers and barriers according to the steps described in Section 3.5. The data was collected from the experts to analyse drivers and barriers. We sent them two surveys, one for the drivers and second for the barriers for pairwise comparison using linguistics terms. The direct relationship matrix, normalized matrix, and total relation matrices for drivers and barriers are presented in Table A.4, Table A.5, and Table A.6 in Appendix I. Table 2, Table 3, and Fig. 5 show the overall prominence and the net influence of the drivers and barriers as well as their classification into causes and effects.

As it can be observed, the successful development and implementation of the HSC are hindered by a complex interplay of barriers, including regulatory and political circumstances (B1), public acceptance (B2), economic and financial aspects (B4), and challenges in designing and modelling (B12). These barriers (identified as effect) collectively influence the pace and direction of hydrogen infrastructure development, necessitating a comprehensive approach that addresses regulatory frameworks, fosters public support, ensures economic viability, and overcomes technical design and modelling hurdles to achieve a sustainable hydrogen economy.

The development of the HSC faces significant challenges due to a variety of causes, including the nascent state of the hydrogen market (B3), limited electricity generation capacity (B5), fluctuating consumer demand (B6), high facility capital cost (B7), instability of hydrogen supply (B8), insufficient domestic technological capability (B9), lack of flexibility, and responsiveness in supply chain operations (B10), and the need for improved quality and training of personnel (B11). These barriers (identified as cause) collectively impede the growth and efficiency of the HSC, necessitating targeted strategies to address each barrier and foster a more robust and sustainable hydrogen economy.

The advancement and optimization of the HSC are significantly influenced by positive effects stemming from key drivers such as favourable geographical condition (D1), entrepreneurship and innovation (D5), and specialized expertise (D4). These drivers (identified as effect) not only enhance the operational and strategic capabilities of the HSC but also contribute to its resilience and adaptability, enabling it to overcome existing challenges and capitalize on emerging opportunities within the energy sector.

The development and efficiency of the HSC are directly facilitated by foundational causes such as the establishment of industrial clusters (D3) and the expansion of infrastructure (D2). These drivers (identified as cause) act as catalysts, creating a supportive ecosystem for hydrogen production, distribution, and utilization. Industrial clusters promote collaboration and innovation, while robust infrastructure ensures the seamless integration of hydrogen technologies into existing energy systems, driving forward the hydrogen economy's growth and sustainability.

4.3. Mapping interrelationships

The interrelationship diagram in Fig. 6 illustrates the complex web of factors affecting the HSC, with various drivers (D1 to D5) and barriers (B1 to B12) interacting in a network of cause-and-effect relationships. The drivers include geographical condition (D1), which can influence the accessibility and potential for hydrogen production; the expansion of infrastructure (D2), crucial for the distribution and storage of hydrogen; the establishment of industrial clusters (D3), which can foster synergies

Table 2
Ranking and classification of drivers into causes and effects.

Drivers	Ri	Ci	Prominence Score (Ri + Ci)	Prominence Ranking	Net Influence Score (Ri – Ci)	Net Influence Ranking	Identity
D1	3.696	6.012	9.708	4	−2.316	5	Effect
D2	5.794	4.248	10.039	3	1.549	1	Cause
D3	6.054	5.450	11.505	1	0.603	2	Cause
D4	4.194	5.113	9.308	5	−0.919	3	Effect
D5	5.063	6.055	11.118	2	−0.992	4	Effect

Table 3
Ranking and classification of barriers into causes and effects.

Barriers	Ri	Ci	Prominence Score (Ri + Ci)	Prominence Ranking	Net Influence Score (Ri – Ci)	Net Influence Ranking	Identity
B1	5.065	6.420	11.485	1	−1.355	11	Effect
B2	5.187	5.998	11.186	3	−0.812	9	Effect
B3	4.800	4.100	8.900	12	0.700	6	Cause
B4	3.797	5.803	9.601	10	−2.007	12	Effect
B5	5.672	4.448	10.120	8	1.224	3	Cause
B6	5.434	4.269	9.703	9	1.164	4	Cause
B7	5.849	5.406	11.256	2	0.442	8	Cause
B8	5.519	4.972	10.491	7	0.547	7	Cause
B9	5.748	4.489	10.238	6	1.258	1	Cause
B10	6.068	4.815	10.884	4	1.252	2	Cause
B11	5.572	4.858	10.431	5	0.714	5	Cause
B12	4.213	5.265	9.478	11	−1.052	10	Effect

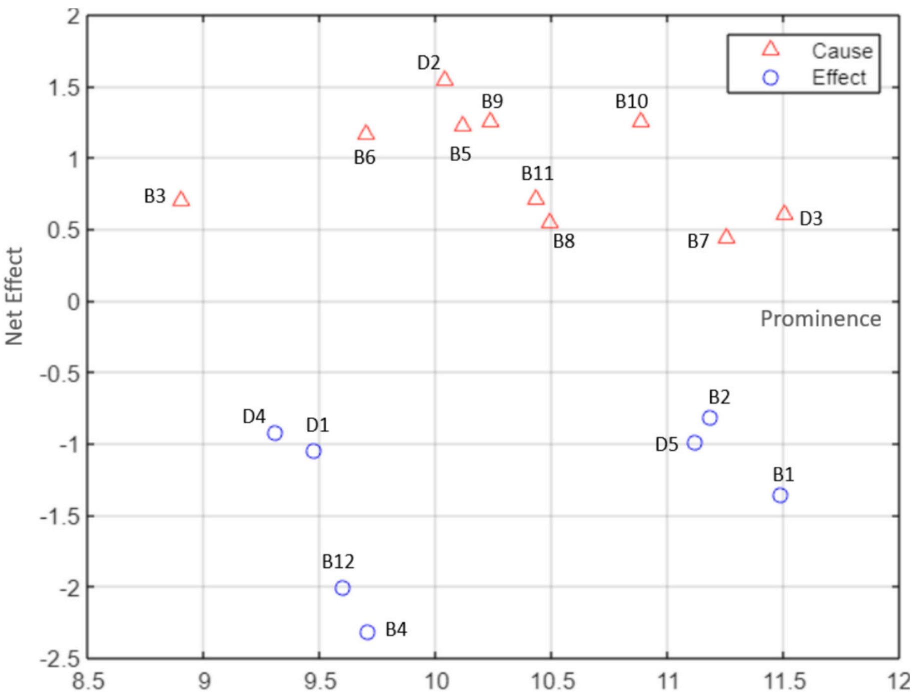

Fig. 5. Influence Prominence Map.

and economies of scale; specialized expertise (D4), necessary for technological advancements; and entrepreneurship and innovation (D5), which drive the sector's growth and adaptation.

These drivers interact with barriers such as regulatory and political circumstances (B1) that can stifle or encourage the market; public acceptance (B2), which is vital for market penetration; the nascent state of the hydrogen market (B3), affecting market stability; economic and financial aspects (B4), which determine the commercial viability; limited electricity generation capacity (B5), essential for green hydrogen production; fluctuating consumer demand (B6), which impacts supply chain planning; high facility capital cost (B7), a significant barrier to entry; instability of hydrogen supply (B8), affecting reliability; insufficient domestic technological capability (B9), which can slow innovation; lack of flexibility and responsiveness in supply chain operations (B10), affecting the ability to meet market demands; the need for improved quality and training of personnel (B11), which is critical for safety and efficiency; and challenges in designing and modelling (B12), which are necessary for optimizing the supply chain.

The Fig. 6 reveals how drivers may mitigate barriers or how barriers might limit the effectiveness of drivers. For instance, expansion of infrastructure (D2) may help overcome the instability of hydrogen supply (B8), while at the same time, the nascent hydrogen market (B3) could be holding back innovation (D5). However, interestingly, this study identifies one driver: expertise (D4) and one barrier: designing and

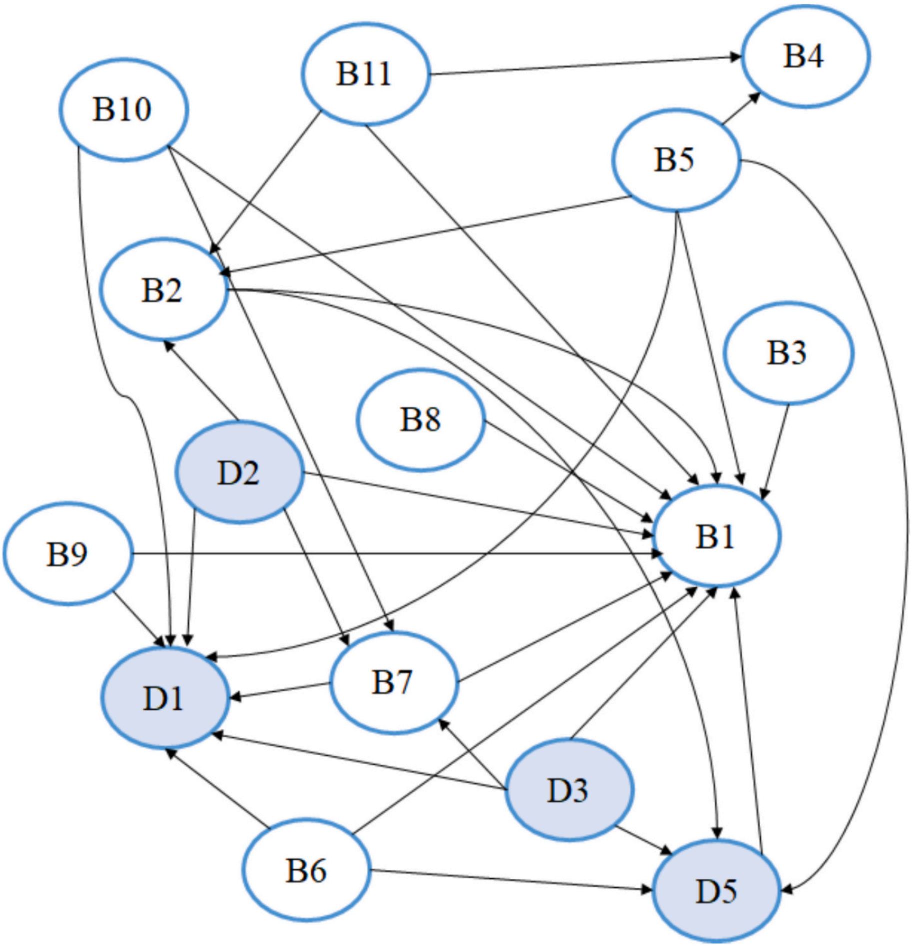

Fig. 6. Interrelationships of drivers and barriers.

modelling (B12) as distinctive as these are emerged as without interrelationships, representing the independent impact on HSC without influencing other drivers and barriers. Understanding these relationships is vital for strategically addressing the barriers and leveraging the drivers to enhance the HSC's efficiency and growth.

5. Discussion and implications

In this study, the findings provide valuable insights into the dynamics and key determinants of HSC which can shape this landscape. The DELPHI method was used for validation, ensuring the accuracy of the drivers and barriers of HSC by leveraging iterative rounds of expert feedback and consensus building. This rigorous process ensures a robust framework for refining and validating the identified factors, ensuring they were comprehensive and relevant to the HSC. Ultimately, five drivers and twelve barriers were validated, and their details are provided in Section 3.4. These validated factors are critical for understanding the drivers and barriers within the HSC and have qualified for the next phase of analysis, Grey-DEMATEL, to further explore their interrelationships. With the insights from Grey-DEMATEL, drivers as well as barriers to HSC are successfully identified and further categorized for in-depth understanding of the complexities around HSC infrastructure. The assigned prominence scores and net influence rankings for each driver and barrier provide a comprehensive understanding of their relative significance and impact within the HSC (Haleem et al., 2019), leading for strategic decision-making. Particularly, the identification of drivers such as geographical condition (D1), infrastructure (D2), and industrial clusters (D3) underscores the importance of physical and logistical factors in driving the adoption and deployment of hydrogen technologies. For instance, geographical condition (D1), such as access to renewable energy sources and ideal territory for hydrogen production and storage facilities, are significant factors in assessing hydrogen project feasibility and cost-effectiveness. Similarly, infrastructure (D2) expenditures, including hydrogen refuelling stations and pipelines, are critical to enable hydrogen's broad usage as a clean energy carrier. Furthermore, the clustering (D3) of hydrogen-related industries and skills promotes knowledge sharing, collaboration, and economies of scale, thus improving supply chain innovation and efficiency. On the other hand, barriers such as regulations, economic concerns, and societal acceptance all represent substantial obstacles to the broad deployment of hydrogen technologies. Uncertainty and unsupportive policies hinder hydrogen investment and innovation, delaying infrastructure development and market deployment. Moreover, high initial investment costs and unpredictable market demand are two further economic variables that pose significant challenges to stakeholders seeking to fund hydrogen initiatives. Lastly, there is also a requirement for coordinated attempts to inform and involve people about the advantages and potential of hydrogen as a clean and sustainable energy source, as there is still a low level of public awareness and acceptance of hydrogen technologies.

Overall, the findings of this study deepen our understanding of the HSC's dynamics and complexities, emphasizing the importance of removing barriers while enabling critical drivers to fully harness hydrogen's potential. By addressing these challenges and leveraging the identified drivers, the HSC can progress towards more sustainable and resilient infrastructure development.

5.1. Implications

This research work is beneficial for practitioners, policymakers, and researchers. The upcoming section discusses significant implications.

5.1.1. Managerial implications

The findings emphasize the importance of HSC managers strategically allocating resources for proper use and overcoming HSC barriers successfully. To enhance operational resilience and competitiveness, investments in factors such as financial and economic conditions, electricity generation capacity, and supply stability are crucial. Furthermore, understanding the interrelationships identified in this study, such as consumer demand (B3) and industrial cluster (D3) both influences entrepreneurship and innovation (D5) can assist managers in making more informed decisions to manage the HSC operations efficiently. Additionally, recognizing critical barriers such as domestic technological capability (B9) and the lack of flexibility and responsiveness (B10) will enable managers to focus on advancing technological development and improving operational flexibility. Similarly, the prominent barriers highlighted in this study, including regulation and political circumstances (B1) and economic and financial aspects (B4) will facilitate decision-makers in aligning their strategies with regulatory requirements and ensuring effective financial allocation. Moreover, given the substantial influence of political and regulatory environments on supply chain dynamics, proactive engagement with regulatory authorities is imperative. As market requirements continue to evolve, managers should prioritize understanding customer demand trends and fostering operational flexibility. Furthermore, cultivating an environment that encourages innovation, and intellectual exchange can contribute to the development of sustainable solutions and enhance the long-term viability of the HSC.

5.1.2. Theoretical implications

This study contributes a robust empirical foundation for advancing theoretical research in supply chain management, particularly within the HSC domain. By delineating causal relationships among key barriers and their respective impacts on HSC functionality, it establishes a structured framework for future research aimed at exploring these dynamics in greater depth. This framework aids scholars in analyzing the interplay among diverse factors influencing supply chain sustainability and resilience, fostering a nuanced understanding of how these elements collectively shape HSC effectiveness.

The study also underscores the value of interdisciplinary collaboration across fields such as policy studies, engineering, and economics, encouraging dialogue that can support comprehensive approaches to complex HSC challenges. Future research directions, including in-depth case studies, simulation modelling, and comparative analyses, offer promising avenues to enrich academic insights and inform practical responses. By leveraging these methods, researchers can contribute both theoretical insights and actionable strategies, ultimately enhancing the adaptability and robustness of HSCs in evolving market and regulatory environments.

5.1.3. Policy implications

The findings of this research offer valuable insights for policymakers, underscoring the need for proactive measures to foster a resilient hydrogen economy. Regulatory frameworks should be flexible and responsive, facilitating an environment that encourages investment and innovation across the HSC. Targeted incentives and funding mechanisms must be designed to address key challenges, particularly those related to infrastructure development, technological advancements, and regulatory compliance. Furthermore, government efforts should prioritize public engagement and awareness initiatives to build widespread support for hydrogen projects, addressing any concerns related to safety and environmental impact.

Capacity-building initiatives are also essential, with a focus on equipping the workforce with the skills and knowledge necessary to sustain a robust talent pool that can drive innovation and growth within the hydrogen sector. By addressing these areas, policymakers can help ensure that the HSC develops in a sustainable and resilient manner, laying a solid foundation for hydrogen's role in a low-carbon energy future.

6. Conclusion, limitations, and future scope

This paper explored the nexus between drivers and barriers of HSC. It examines the impacts of different drivers and barriers that influence the development and scalability of the HSC. To access these factors, we employed the Grey-DEMATEL method to uncover the links between the drivers and barriers of HSC. This involved developing a fuzzy direct relationship matrix, using five-point linguistic scale, which was subsequently refined with expert opinions using pair-wise comparison and the integration of the grey numbers to replace linguistic terms. The study finds that the deployment of HSC is hindered by a complex interplay of barriers, including regulatory and political circumstances, public acceptance, economic and financial aspects as well as challenges related to designing and modelling. These barriers (identified as “effects”) collectively influence the pace and direction of hydrogen infrastructure development. Other militating factors against HSC include the immaturity of hydrogen market, limited electricity generation capacity, fluctuating consumer demand, high take off capital, instability of hydrogen supply, insufficient domestic technological capability, lack of flexibility in supply chain operations and need to be upskilling the workforce. These barriers (identified as “causes”) collectively impede the scaling and efficiency of the HSC.

Conversely, certain drivers positively influence HSC development. Favourable geographical conditions, entrepreneurship and innovation, and specialized expertise (identified as “effects”) enhance HSC's operational resilience and adaptability, positioning it to capture emerging opportunities in the energy and transport sectors. Similarly, the establishment of industrial clusters and infrastructure expansion (identified as “causes”) act as catalysts by fostering collaboration and supporting the seamless integration of hydrogen into energy systems. Industrial clusters drive promote collaboration and innovation, while robust infrastructure expansion supports hydrogen production, distribution, and utilization, advancing the hydrogen economy's growth and sustainability.

This paper acknowledges several limitations. First, it does not include an in-depth analysis of citizen perceptions regarding hydrogen fuel and HSC, an area where expanded expert samples from social and behavioural sciences would broaden understanding. Second, only the main production techniques of hydrogen have been considered in this study. Fringe and upcoming approaches such as hydrogen storage using metal hydrides and production from thermochemical processes have not been considered. When these techniques gain traction and reach maturity in terms of efficiency, safety, modularity, and scalability, they may become new drivers of HSC development.

Hydrogen as a low-carbon fuel is still in its early stages of development. However, as additional research is conducted and more cost-effective production and storage technologies are refined, the HSC is expected to benefit substantially. Future studies should focus on the phased evolution of the HSC, with particular emphasis on the adoption timelines for each enabling technology, which will be critical for developing a comprehensive development roadmap. Lastly, further investigation is required to understand the impact of large-scale carbon pricing mechanisms on HSC growth. Specifically, examining how carbon pricing influences investment incentives and cost-competitiveness could yield valuable insights into the scalability of hydrogen infrastructure. Collectively, these research initiatives will contribute to a deeper understanding of how emerging technologies and policy frameworks can drive HSC acceleration, ultimately supporting the broader transition to a sustainable hydrogen economy.

CRediT authorship contribution statement

Yasanur Kayikci: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Md. Ramjan Ali:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Sharfuddin Ahmed Khan:** Writing – original draft, Software, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Augustine Ikpehai:** Writing – review & editing, Visualization, Validation, Formal analysis.

Appendix I

Table A.1
Experts Demographics for DELPHI Validation Process

Attributes	n	Total	Attributes	n	Total
Years of Experience			Designation		
20+ years	3		CEO	2	
15-19 years	2		Manager	2	
		5	Professor	1	5
Education			Age		
PhD	3		51 + Years	4	
Masters	2	5	41-50 Years	1	5
Gender			Regions		
Male	4		Asia	3	
Female	1		Europe	2	
Not mentioned		5			5
Industry Background					
Hydrogen production, storage, and logistics				3	
Supply chain management and green technologies				1	
Renewable energy systems and low-carbon infrastructure				1	5

Note: This panel of experts was meticulously selected to ensure comprehensive validation of the identified drivers and barriers within the hydrogen supply chain, thereby enhancing the robustness and credibility of the DELPHI validation process.

Table A.2
Experts Demographics for Grey-DEMATEL Analysis

Attributes	n	Total	Attributes	n	Total
Years of Experience			Designation		
20+ years	6		CEO	7	
15-19 years	7		Manager	8	
6-9 years	4		Professor	2	
2-5 years	2		Researcher	1	
		19	Others	1	19
Education			Age		
PhD	4		51 + Years	9	
Masters	9		41-50 Years	4	
Bachelors	4		31-40 Years	6	
Post graduate diploma	2		26-30 Years		
		19	Others		19
Gender			Regions		
Male	12		Asia	10	
Female	7		Europe	9	
Not mentioned					
		19			19
Industry Background					
Hydrogen production, storage, and logistics				8	
Energy policy and sustainable development				5	
Supply chain management and green technologies				2	
Renewable energy systems and low-carbon infrastructure				4	19

Note: This diverse panel of experts was meticulously selected to ensure comprehensive insights into the hydrogen supply chain, thereby enhancing the robustness and credibility of the Grey-DEMATEL analysis.

Table A.3
Final DELPHI Output for Validated Drivers and Barriers of the HSC

		Mean	Median	Agreement (%)	Result
Drivers	Geographical Condition	4	4.23	84.60	Accepted
	Infrastructure	4	4.11	82.20	Accepted
	Industrial Cluster	3	3.57	71.40	Accepted
	Expertise	4	4.21	84.20	Accepted

(*continued on next page*)

Table A.3 (*continued*)

		Mean	Median	Agreement (%)	Result
	Entrepreneurship & Innovation	4	4.29	85.80	Accepted
Barriers	Regulation & Political Circumstances	4	4.56	91.20	Accepted
	Public Acceptance	4	4.74	94.80	Accepted
	Hydrogen Market	4	4.68	93.60	Accepted
	Economic & Financial Aspects	4	4.55	91.00	Accepted
	Electricity Generation Capacity	3	3.91	78.20	Accepted
	Consumer Demand	4	4.56	91.20	Accepted
	Designing & Modelling	4	4.88	97.60	Accepted
	*Facility Capital Cost	3	3.85	77.00	Accepted
	*Instability of Hydrogen Supply	4	4.37	87.40	Accepted
	*Domestic Technological Capability	4	4.25	85.00	Accepted
	*Lack of Flexibility & Responsiveness	4	4.26	85.20	Accepted
	*Quality & Training of Personnel	4	4.78	95.60	Accepted

Note: Factors marked with an asterisk (*) indicate those identified through expert input as part of the DELPHI process.

Table A.4
Direct Relationship Matrix

	D1	D2	D3	D4	D5	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
D1	0	1	2	2	3	3	2	2	4	2	1	3	2	2	3	2	4
D2	3	0	4	3	3	4	4	3	3	3	4	4	3	3	3	3	2
D3	4	4	0	4	3	4	4	2	3	3	3	3	4	3	4	3	4
D4	3	1	3	0	4	3	3	2	3	2	2	3	2	2	3	2	3
D5	3	2	3	3	0	4	3	2	3	3	3	3	3	3	3	3	3
B1	3	2	3	3	3	0	4	2	3	3	3	3	3	3	3	3	3
B2	3	2	3	3	4	4	0	2	3	3	3	3	3	3	3	3	3
B3	3	2	3	3	3	4	3	0	3	2	3	3	3	2	3	3	2
B4	3	1	2	2	3	3	3	2	0	2	2	3	2	2	3	2	3
B5	4	3	3	4	3	4	4	2	3	0	3	3	4	2	4	3	3
B6	4	4	3	3	4	3	3	3	3	3	0	3	2	3	3	3	3
B7	4	4	3	3	4	4	3	4	4	3	3	0	3	4	3	2	2
B8	3	3	4	3	4	3	4	3	3	3	2	4	0	3	3	3	2
B9	4	4	4	3	3	3	4	3	4	3	3	3	4	0	3	2	2
B10	4	4	4	3	4	4	4	4	4	4	2	3	3	3	0	2	3
B11	4	4	4	3	3	4	4	3	4	3	3	3	3	3	3	0	3
B12	3	2	3	3	4	4	3	2	3	1	2	3	3	2	3	3	0

Table A.5
Normalized Matrix

	D1	D2	D3	D4	D5	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
D1	0.000	0.050	0.388	0.388	0.700	0.700	0.388	0.388	0.988	0.388	0.050	0.700	0.388	0.388	0.700	0.500	1.000
D2	0.700	0.000	0.988	0.700	0.700	0.988	0.988	0.700	0.700	0.700	0.988	0.988	0.700	0.700	0.700	0.750	0.500
D3	0.988	0.988	0.000	0.988	0.700	0.988	0.988	0.388	0.700	0.700	0.700	0.700	0.988	0.700	0.988	0.750	1.000
D4	0.700	0.050	0.700	0.000	0.988	0.700	0.700	0.388	0.700	0.388	0.388	0.700	0.388	0.388	0.700	0.500	0.750
D5	0.700	0.388	0.700	0.700	0.000	0.988	0.700	0.388	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.750	0.750
B1	0.700	0.388	0.700	0.700	0.700	0.000	0.988	0.388	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.750	0.750
B2	0.700	0.388	0.700	0.700	0.988	0.988	0.000	0.388	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.750	0.750
B3	0.700	0.388	0.700	0.700	0.700	0.988	0.700	0.000	0.700	0.388	0.700	0.700	0.700	0.388	0.700	0.750	0.500
B4	0.700	0.050	0.388	0.388	0.700	0.700	0.700	0.388	0.000	0.388	0.388	0.700	0.388	0.388	0.700	0.500	0.750
B5	0.988	0.700	0.700	0.988	0.700	0.988	0.988	0.388	0.700	0.000	0.700	0.700	0.988	0.388	0.988	0.750	0.750
B6	0.988	0.988	0.700	0.700	0.988	0.700	0.700	0.700	0.700	0.700	0.000	0.700	0.388	0.700	0.700	0.750	0.750
B7	0.988	0.988	0.700	0.700	0.988	0.988	0.700	0.988	0.988	0.700	0.700	0.000	0.700	0.988	0.700	0.500	0.500
B8	0.700	0.700	0.988	0.700	0.988	0.700	0.988	0.700	0.700	0.700	0.388	0.988	0.000	0.700	0.700	0.750	0.500
B9	0.988	0.988	0.988	0.700	0.700	0.700	0.988	0.700	0.988	0.700	0.700	0.700	0.988	0.000	0.700	0.500	0.500
B10	0.988	0.988	0.988	0.700	0.988	0.988	0.988	0.988	0.988	0.988	0.388	0.700	0.700	0.700	0.000	0.500	0.750
B11	0.988	0.988	0.988	0.700	0.700	0.988	0.988	0.700	0.988	0.700	0.700	0.700	0.700	0.700	0.000	0.000	0.750
B12	0.700	0.388	0.700	0.700	0.988	0.988	0.700	0.388	0.700	0.050	0.388	0.700	0.700	0.388	0.000	0.750	0.000

Table A.6
Total Relationship Matrix

	D1	D2	D3	D4	D5	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
D1	0.214	0.154	0.221	0.209	0.266	0.279	0.241	0.174	0.277	0.185	0.155	0.242	0.205	0.188	0.219	0.209	0.259
D2	0.386	0.239	0.374	0.336	0.388	0.428	0.405	0.279	0.374	0.300	0.309	0.371	0.328	0.302	0.320	0.325	0.331
D3	0.420	0.316	0.318	0.367	0.404	0.444	0.420	0.268	0.389	0.310	0.298	0.366	0.359	0.312	0.350	0.337	0.378
D4	0.293	0.175	0.269	0.206	0.315	0.310	0.291	0.193	0.285	0.208	0.200	0.268	0.229	0.210	0.244	0.232	0.268

(*continued on next page*)

Table A.6 (*continued*)

	D1	D2	D3	D4	D5	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
D5	0.344	0.236	0.316	0.299	0.296	0.382	0.343	0.228	0.333	0.267	0.258	0.313	0.293	0.269	0.285	0.290	0.311
B1	0.344	0.236	0.316	0.300	0.346	0.313	0.362	0.228	0.334	0.267	0.258	0.314	0.293	0.269	0.285	0.290	0.311
B2	0.351	0.241	0.322	0.306	0.372	0.390	0.300	0.233	0.340	0.273	0.263	0.320	0.299	0.275	0.290	0.296	0.317
B3	0.328	0.224	0.302	0.286	0.330	0.366	0.327	0.190	0.318	0.235	0.247	0.300	0.279	0.237	0.273	0.278	0.281
B4	0.270	0.159	0.227	0.215	0.272	0.285	0.268	0.178	0.213	0.191	0.183	0.247	0.210	0.193	0.225	0.214	0.247
B5	0.397	0.280	0.348	0.349	0.382	0.420	0.397	0.252	0.367	0.244	0.282	0.346	0.340	0.274	0.333	0.319	0.342
B6	0.384	0.291	0.335	0.317	0.386	0.387	0.363	0.264	0.354	0.283	0.224	0.333	0.289	0.285	0.302	0.308	0.330
B7	0.408	0.307	0.357	0.337	0.410	0.431	0.388	0.300	0.397	0.301	0.291	0.305	0.330	0.322	0.323	0.310	0.333
B8	0.370	0.276	0.359	0.322	0.391	0.392	0.389	0.268	0.359	0.288	0.257	0.357	0.266	0.290	0.307	0.312	0.317
B9	0.402	0.304	0.371	0.333	0.385	0.405	0.402	0.277	0.391	0.297	0.286	0.350	0.345	0.249	0.319	0.306	0.328
B10	0.420	0.315	0.387	0.349	0.422	0.445	0.420	0.308	0.408	0.329	0.279	0.366	0.341	0.312	0.283	0.321	0.362
B11	0.391	0.295	0.361	0.324	0.374	0.414	0.391	0.268	0.380	0.287	0.280	0.341	0.317	0.291	0.262	0.262	0.337
B12	0.293	0.198	0.270	0.257	0.315	0.330	0.292	0.193	0.285	0.185	0.202	0.269	0.251	0.212	0.196	0.251	0.215

Appendix II

Survey - Round 1

Participant Information

Please provide the following details:

Age:
Gender:
Experience (Years):
Education:
Industry Background:
Position/Job Title:
Working Region:

Instructions

Please rank the factors based on the Likert scale below:

1. Strongly Disagree (Very Unimportant)
2. Disagree (Unimportant)
3. Neutral (Neither Disagree nor Agree)
4. Agree (Important)
5. Strongly Agree (Very Important)

Section 1: Drivers

Please rate the significance of each driver in the development of the hydrogen supply chain.

Drivers	Brief Description	Likert Scale (1-5)				
		1	2	3	4	5
Geographical Condition	Includes both natural and artificial factors that affect hydrogen availability, accessibility, and transportation within different regions.					
Infrastructure	Encompasses physical facilities and structures required for hydrogen production, storage, and transportation.					
Industrial Cluster	Represents a geographical concentration of interconnected companies, institutions, and facilities engaged in hydrogen production, distribution, storage, and utilisation of hydrogen feedstock.					
Expertise	Refers to professional experience and technical knowledge in managing the hydrogen supply chain effectively.					
Entrepreneurship & Innovation	Involves identifying emerging hydrogen markets, developing new production technologies, and designing advanced hydrogen fuel cell systems for various applications.					

Section 2: Barriers

Please rate the impact of each barrier on the development and adoption of the hydrogen supply chain.

Barriers	Brief Description	Likert Scale (1-5)				
		1	2	3	4	5
Regulation & Political Circumstances	Government policies and regulations can either facilitate or hinder hydrogen infrastructure development.					
Public Acceptance	Public perception and trust in hydrogen technology are essential for widespread adoption.					
Hydrogen Market	The hydrogen industry is still developing, with limited infrastructure and uncertain demand.					
Economic & Financial Aspects	High production and distribution costs may discourage investment and large-scale commercialization.					
Electricity Generation Capacity	Adequate renewable energy generation is required for sustainable green hydrogen production.					
Consumer Demand	Low demand for hydrogen in various sectors poses challenges to market growth.					
Designing & Modelling	The development of efficient hydrogen systems requires advanced design and modeling techniques.					

Additional Input

If you believe there are any **missing drivers or barriers**, please list them below along with a brief description:

- **Driver/Barrier:** ____________________
- **Brief Description:** ____________________

Thank you for your participation!

Data availability

Data will be made available on request.

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