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Hydrogen mobility: activating the transition towards the future

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Abstract
The global transition to hydrogen as a sustainable alternative fuel is ongoing, owing to its ability to decarbonize the hard-to-abate industries of mobility. However, barriers to adoption still exist, and enabling solutions are needed. This study explores barriers and enabling solutions, in terms of infrastructure development, operational requirements, and supply chain demands, to the large-scale adoption of hydrogen technologies in road, maritime, and aviation transport industries. By means of a systematic literature review, reinforced by industry perspectives gathered from a survey of Italian professionals, common barriers are identified together with those specific to each industry. These include barriers related to fuel (e.g., clean energy sourcing for production), infrastructure (e.g., location and geographical dispersion of refueling), vehicle (e.g., availability of low-cost components), and operations (e.g., availability of refueling). Potential enabling solutions to lower them are explored (e.g., innovations, economies of scale, development of pilot projects). One possible development of the industry is a gradual shift toward modes of transport that are considered better suited to hydrogen technologies. The study assists policymakers by outlining the next steps to take for decarbonizing transportation, with actions aligned with a prioritization that identifies infrastructure as the starting point.

Keywords Hydrogen · Mobility · Supply chain management · Road · Maritime · Aviation

JEL Classification O33 · Q55

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1 Introduction

The mobility sector has the opportunity to pursue decarbonization due to the emergence of sustainable alternative fuels, notably hydrogen (Koilo et al. 2020). The market is currently in the activation phase (2020–2030), which represents the early phases of hydrogen technologies adoption (Sgarbossa et al. 2023). Individual transport industries (i.e., road, maritime, and aviation) across the mobility sector are exploring the potential for hydrogen to replace traditional fossil fuels. Technological feasibility has been demonstrated (Nerheim et al. 2021), and the sector is committed to greener alternatives (Mallouppas et al. 2022). However, many barriers persist to the large-scale adoption of hydrogen technologies (Bolz et al. 2024).

These barriers are diverse, ranging from economic to social and regulatory, and affect various stages of the hydrogen supply chain (HSC) (Rawat et al. 2024). Since transport industries will share some of the future hydrogen infrastructure (e.g., production facilities, distribution networks, and refueling stations), solutions common to all transport industries are needed to overcome these barriers (Lahnaoui et al. 2021; Robles et al. 2020). At the same time, individual transport industries can be either vulnerable or not to specific barriers to hydrogen technologies adoption, necessitating ad hoc enabling solutions. For instance, the road transport industry faces challenges related to the capillarity of refueling infrastructure, which is necessary to support widespread vehicle use. In contrast, the aviation transport industry needs to focus on the centralization of refueling (Degirmenci et al. 2023) and the management of weight and size of on-board hydrogen storage systems (Gray et al. 2021). Essentially, identifying similarities can help define enabling solutions for a shared HSC, while identifying differences can help adapt interventions to the unique characteristics of each industry.

Although the literature on hydrogen adoption is expanding, there has been no comparative analysis of barriers and enabling solutions across transport industries. This study aims to fill this gap by identifying and analyzing the barriers and the enabling solutions to the large-scale adoption of hydrogen technologies in road, maritime, and aviation transport industries. To achieve this objective, the research is structured into two parts: a literature review to identify barriers and enabling solutions in each industry as discussed by research so far and a survey of Italian professionals, including supply chain actors, policymakers, and academics, to evaluate perspectives and priorities to reach the large-scale adoption of hydrogen technologies. The study is guided by the following research questions:

RQ1: What are the main barriers to the large-scale adoption of hydrogen technologies across road, maritime, and aviation transport industries?

RQ2: How can these barriers to the large-scale adoption of hydrogen technologies be overcome across road, maritime, and aviation transport industries?

Section 2 outlines the background of the research, Sect. 3 details the methodology, Sect. 4 presents the results, with Sect. 4.1 reporting the review of the literature and Sect. 4.2 reporting the industry perspectives of Italian professionals. Finally, Sect. 5 discusses the results, and Sect. 6 concludes the study.

2 Background

In recent years, the need to adopt sustainable energy systems to mitigate the negative consequences of climate change has generated great interest in the research on sustainable alternative fuels (Koilo et al. 2020). Hydrogen can be produced from a variety of sources, including biomass, natural gas, and water, providing plenty of opportunities for its diffusion as an energy carrier (Inal et al. 2022). When burned or combined with fuel cell technologies, hydrogen simply produces water vapor as a byproduct (Ming et al. 2023). Consequently, its potential as a clean fuel is rather great, and it provides a means to significantly lower greenhouse gas (GHG) emissions in a range of industries.

Hydrogen production strategies are commonly denoted by color coding (e.g., green hydrogen is sourced from renewables, pink hydrogen from nuclear power, and grey hydrogen from fossil fuels), and include steam methane reforming, electrolysis, and thermochemical processes, among others (Rozzi et al. 2020). Every pathway leads to different environmental and economic results. A life cycle perspective is needed to assess the many hydrogen production methods (Harahap et al. 2023). Recent studies have stressed the need to include renewable energy sources in hydrogen production to maximize its decarbonization potential (Rezk et al. 2023). This would result in the production of green hydrogen, which stands at the basis for its adoption as a sustainable alternative to fossil fuels. To reach climate neutrality, green hydrogen must be the focus of production, with electrolysis driven by renewable energy (Dall'Armi et al. 2023). However, particularly when compared to conventional fossil fuels, there are challenges in scaling fuel production and ensuring its economic viability, as well as that of hydrogen technologies.

The uses of hydrogen technologies in the mobility sector are promising. Emerging applications include fuel cell propulsion and internal combustion engines (Hassan et al. 2023). Hybrid propulsion systems that combine hydrogen fuel cells with traditional engines are being developed, providing a path to improve fuel efficiency while reducing emissions (Dall'Armi et al. 2023). The technological maturity of these solutions varies (Prussi et al. 2021). In the road transport industry, hydrogen-fueled vehicles are developing in both the light-duty and heavy-duty segments (Ren et al. 2022). In the maritime transport industry, hydrogen is seen as a great opportunity; however, its applications are still in the early stages, with some technologies in the conceptual phase (Yip et al. 2019). Similarly, the aviation transport industry faces major emissions regulations, and hydrogen is seen as an answer to meet the requirements for sustainable air travel (Degirmenci et al. 2023). However, technological feasibility is not sufficient, and each industry must overcome significant barriers to facilitate the large-scale adoption of hydrogen technologies.

3 Methodology

3.1 Systematic literature review

The systematic literature review aligns with well-defined methodical approaches to ensure rigor in the process (Whittemore and Knafl 2005). To address the research questions, relevant articles within the existing body of scientific literature were identified. To enhance reproducibility and reduce bias, detailed instructions on the search terms, filters, and databases used are provided. The following query outputted an initial sample of 78 articles: TITLE-ABS-KEY (“*supply chain*”) AND TITLE-ABS-KEY (*hydrogen*) AND TITLE-ABS-KEY (*road* OR *automotive* OR *aviation* OR *maritime* OR *mobility* OR *train* OR *truck* OR *car* OR *bus* OR *airplane* OR *aircraft* OR *helicopter* OR *ship* OR *vessel*) AND (LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-TO (SUBJAREA, “ENGI”)) AND (LIMIT-TO (DOCTYPE, “*ar*”) OR LIMIT-TO (DOCTYPE, “*re*”)) AND (LIMIT-TO (LANGUAGE, “*English*”)).

The search was conducted on Scopus due to its coverage of management and engineering studies. The terms “*hydrogen*” and “*supply chain*” were first, followed by synonyms defining the context. The search was further refined to include only peer-reviewed articles and reviews within business, management, and engineering published in English. The results were last updated on December 31st, 2024.

To ensure relevance, inclusion and exclusion criteria were applied (Tranfield et al. 2003). First of all, articles had to focus on hydrogen applications for road, maritime, or aviation transport industries. Moreover, HSC barriers or enabling solutions related to vehicles, infrastructure, fuel, or operations needed to be addressed. On the contrary, the exclusion criteria conveyed a lack of direct relevance to barriers and enabling solutions and/or a preference for other sustainable alternative fuels. The final sample of articles, following screening, totaled 53 entries (Table 1).

Table 1 Identification and screening of the literature

Step	Explanation	Number of articles
Identification		
Keyword search	TITLE-ABS-KEY (“*supply chain*”) AND TITLE-ABS-KEY (*hydrogen*) AND TITLE-ABS-KEY (*road* OR *automotive* OR *aviation* OR *maritime* OR *mobility* OR *train* OR *truck* OR *car* OR *bus* OR *airplane* OR *aircraft* OR *helicopter* OR *ship* OR *vessel*)	284
Filter 1 *Subject area*	AND (LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-TO (SUBJAREA, “ENGI”))	130
Filter 2 *Document type*	AND (LIMIT-TO (DOCTYPE, “*ar*”) OR LIMIT-TO (DOCTYPE, “*re*”))	83
Filter 3 *English publication*	AND (LIMIT-TO (LANGUAGE, “*English*”))	78
Screening		
Title and abstract screening	Out-of-scope entries: focus on other sustainable alternative fuels and/or other industries of application; perspective differing from that of barriers and enabling solutions to the large-scale adoption of hydrogen technologies for mobility	25
Total	Studies included in the review	53

Data extraction was systematic, involving a full-text assessment of each article. Key details, including research questions, methods, and results related to different transport industries, were collected. The outcome is presented through thematic analysis. The literature review served to identify the major barriers and enabling solutions to the large-scale adoption of hydrogen technologies. A deductive coding approach was used, which means that prior research served as the foundation for grouping codes into categories and subcategories (Seuring and Gold 2012). The primary sources for this purpose were Rawat et al. (2024) and Bolz et al. (2024), who presented lists of barriers and enabling solutions related to the broader hydrogen economy for the former and vehicle adoption for the latter. Then, barriers were grouped to identify different areas of intervention to match those of the four supply chains of mobility (i.e., vehicle, infrastructure, fuel, and operations supply chains, respectively) (Bianchi et al. 2024).

3.2 Survey

The findings of the systematic literature review are complemented by the perspective of professionals in the Italian mobility sector. In particular, the survey aimed to validate the existence and assess the intensity of barriers and enabling solutions to the large-scale adoption of hydrogen technologies in the Italian context.

To ensure validity and reliability, the survey was designed in accordance with the best practices. The structure follows established methodologies (Malhotra et al. 2014), particularly in operations and supply chain management, where surveys have proved helpful in acquiring the insights of professionals (Melnyk et al. 2012). The survey was divided into sections addressing various aspects of hydrogen mobility (the full text is available in Appendix C). The first section gathered demographic information from respondents, such as their industry, area of involvement (e.g., vehicle and parts manufacturing, mobility services and operation), and familiarity levels towards hydrogen technologies. This was critical for assessing industry-specific responses and ensuring a diverse and qualified pool of respondents.

The second section investigated various applications, specifically inquiring about projected market readiness and market share of hydrogen mobility applications (i.e., vehicle types). According to earlier studies, future scenario analysis is relevant for strategic decision-making (Ketchen and Shook 1996). Consequently, a time horizon of 10 years was set to contextualize some of the questions.

Respondents expressed their opinion on the areas to prioritize for reaching the large-scale adoption of hydrogen technologies, as well as their expectations with respect to the future role of hydrogen in their industry (e.g., primary propulsion source, one of many alternatives, no significant role expected). In the third section, respondents evaluated barriers to the large-scale adoption of hydrogen technologies, aligning with the systematic literature review findings. The barriers were rated on a Likert scale (1–5). Similarly, the final section assessed enabling solutions to these barriers, using the same Likert scale (1–5).

Although studies based on surveys have been facing declining participation rates (Klassen and Jacobs 2001), an attempt was made to gather a sizable sample of respondents. The survey was distributed using a mixed-mode approach, including email and distribution through professional networks and social media (Klassen and Jacobs 2001). There were no incomplete answers, and no cleaning of data was required, no incentives were offered to respondents, and the language of the survey was English. The survey received 145 responses (80 road, 29 aviation, 36 maritime) with a response rate of 41%. These numbers do not hold statistical significance, but they provide an indication of the trajectory of adoption, as well as revealing the perception of hydrogen technologies from industry professionals.

The survey was distributed to a sample of Italian professionals. The choice is supported by the value of the mobility market in Italy, which is reflected in the number of employees by each industry: 268.300 professionals work in road transport (Anfia 2022), 35.300 in maritime transport (Eurostat 2023), and 19.486 in aviation transport (ISTAT 2020). Moreover, hydrogen technologies are diffusing in Italy, but many barriers are delaying their large-scale adoption. In fact, Italy is one of Europe's top five countries in terms of hydrogen production capacity (Clean Hydrogen JU 2024). However, only one of the 187 operational hydrogen refueling stations is located in Italy, rendering its distribution capacity almost null. The refining sector gathers the vast majority of conventional hydrogen use. The demand for conventional hydrogen is high, with Italy ranked fifth. At the same time, green hydrogen demand is limited, as Italy drops to the fourteenth place. Current fuel cell electric vehicles figures are less than encouraging, both in terms of light-duty (58 passenger cars) and heavy-duty segments (13 buses) (Clean Hydrogen JU 2024).

The quantitative data collected through the survey was statistically analyzed to identify trends and differences across transport industries. Moreover, Pearson correlation test and t-test were conducted to explore potential relationships and differences among the proposed solutions. These analyses did not produce any notable findings, but full results are provided in Appendix A and Appendix B, respectively.

4 Results

4.1 Review of the literature

4.1.1 Barriers

Existing studies were examined to determine the most significant barriers to the large-scale adoption of hydrogen technologies across transport industries (Table 2). Four main groups emerged: *GB1—Fuel production*, *GB2—Infrastructure development*, *GB3—Vehicle manufacturing*, and *GB4—Customer adoption* barriers. The first three relate to the upstream portion of HSCs, where organizations are concerned with producing fuel, distributing it, and pairing it to a suitable vehicle type. The latter, instead, are a direct result of those existing barriers and they represent their reflection downstream, from the perspective of the end-user. These adoption barriers imply a need to activate the transition, either driven by individual willingness or as an imposition resulting from policy. The upstream and downstream barriers will be analyzed separately to allow for a clear understanding of how the interplay between fuel, infrastructure, and vehicles plays out. The categories are articulated into sub-categories,

Table 2 Barriers to the large-scale adoption of hydrogen technologies across mobility industries

ID	Barrier	References
Upstream barriers		
GB1—Fuel production barriers		
B01	*Energy sourcing:* the sourcing of clean energy through renewables to produce green hydrogen and attain the goal of reducing GHG emissions	Cox and Mutel (2018), Ehrenstein et al. (2020), Lahnaoui et al. (2021), Vijayakumar et al. (2021), Ren et al. (2022), Wang et al. (2022), Harahap et al. (2023), Olabi and Jouhara (2024)
B02	*Water sourcing*: the availability of water supply for hydrogen production through electrolysis and its following distribution	Tayarani and Ramji (2022)
B03	*Fuel production costs*: the high investment and maintenance costs of hydrogen production facilities hinders the ramp up of production	Wulf and Kaltschmitt (2018), Rozzi et al. (2020), Madovi et al. (2021), Nerheim et al. (2021), De-León Almaraz et al. (2022), Olabi and Jouhara (2024)
B04	*Storage capacity*: the capacity, efficiency, and costs associated with hydrogen storage following production are considerable	Reuß et al. (2017), Madovi et al. (2021), De-León Almaraz et al. (2022), Liu et al. (2022), Rüdisüli et al. (2022), Olabi and Jouhara (2024)
B05	*Distribution capacity*: the feasibility and capacity of hydrogen distribution following its production	Wulf and Kaltschmitt (2018), Reuß et al. (2019), Rozzi et al. (2020), Lahnaoui et al. (2021), Madovi et al. (2021), Vijayakumar et al. (2021), Ren et al. (2022), Wang et al. (2022), Pedicini et al. (2023)
GB2—Infrastructure development barriers		
B06	*Location and geographical dispersion*: the geographical distribution and needed capillarity of refueling facilities depends on final application and can be challenging	Lahnaoui et al. (2021), Nerheim et al. (2021), Reuß et al. (2021), Vijayakumar et al. (2021), De-León Almaraz et al. (2022), Wang et al. (2022), Harahap et al. (2023), Oh et al. (2023)
B07	*Infrastructure costs*: the high investment and operating costs of hydrogen refueling and distribution facilities	Cerniauskas et al. (2019), Chen et al. (2021), Reuß et al. (2021), Deng et al. (2023), Godinho et al. (2023)
B08	*Re-skilling of personnel*: employees' acceptance of retraining or up-skilling at refueling facilities	Nerheim et al. (2021), Harahap et al. (2023)
B09	*Absence of standards*: missing directions in designing and running distribution and refueling facilities in compliance to safety requirements	Rozzi et al. (2020), Vijayakumar et al. (2021), Dall'Armi et al. (2023), Li et al. (2024)
GB3—Vehicles manufacturing barriers		
B10	*Lengthy regulatory approval*: the difficulty in receiving regulatory approval for hydrogen-fueled vehicle prototypes	Pedicini et al. (2023)
B11	*Absence of standards*: the absence of standards in designing and operating hydrogen-fueled vehicles	Nerheim et al. (2021), Dall'Armi et al. (2023), Pedicini et al. (2023)
B12	*Market-ready components availability*: the limited presence of suppliers offering components compatible with hydrogen propulsion	Cerniauskas et al. (2019), Rozzi et al. (2020), Tayarani and Ramji (2022), Raj Singh et al. (2024)
B13	*Low-cost components availability*: the lack of suppliers offering low-cost components compatible with hydrogen propulsion	Fitz (2022), Singh (2024), Robles et al. (2020), Nerheim et al. (2021)
B14	*Limited R&D*: developing further hydrogen technologies, including fuel cell systems, could open up new scenarios	Wulf and Kaltschmitt (2018), Robles et al. (2020), Nerheim et al. (2021), Li et al. (2024), Singh et al. (2024)

Table 2 (continued)

ID	Barrier	References
B15	*Vehicle manufacturing costs*: the high investment costs required in establishing hydrogen-fueled vehicles production lines	Ren et al. (2022), Singh et al. (2024)
Downstream barriers		
GB4—Customer adoption barriers		
B16	*Limited choice*: the limited choice of models of hydrogen-fueled vehicles on the market, from different producers	Hassan et al. (2023)
B17	*High purchasing costs*: the high ownership costs of hydrogen-fueled vehicles	Cox and Mutel (2018), Rabiega et al. (2021), Fitz et al. (2022), Dall'Armi et al. (2023), Hensher and Wei (2024)
B18	*High operating costs*: the high costs associated with running and maintaining hydrogen-fueled vehicles	Dall'Armi et al. (2023), Harahap et al. (2023), Hensher and Wei (2024), Montignac et al. (2024)
B19	*Limited operations*: the limited range or other variables of hydrogen-fueled vehicles affecting operations	Cox and Mutel (2018), Hensher and Wei (2024)
B20	*Refueling availability*: availability of hydrogen fuel along the network of infrastructure necessary to carry out operations	Vijayakumar et al. (2021), Hensher and Wei (2024), Cerniauskas et al. (2019), Reuß et al. (2021), Pedicini et al. (2023), Nerheim et al. (2021), Harahap et al. (2023)

those are based on previous studies in the field of hydrogen economy (Bolz et al. 2024; Rawat et al. 2024).

GB1—Fuel production barriers. The ultimate goal of fuel production is fulfilling GHG emissions reduction targets by sourcing clean energy (*B01—Energy sourcing*). In particular, the production of green hydrogen depends on the availability of energy from renewables (Ren et al. 2022). However, integrating renewable energy into hydrogen production systems has proved challenging. When it comes to green hydrogen production through electrolysis, the availability and the proper management of large volumes of water are a determinant to the sustainability of the process (*B02—Water sourcing*) (Tayarani and Ramji 2022). The elevated costs associated in running hydrogen production plants, coupled with existing constraints in technologies for electrolysis, complicate attempts to scale operations *(B03—Fuel production costs*) (Olabi and Jouhara 2024). Beyond production, distribution and storage present their barriers too (Madovi et al. 2021). Storage systems have yet to find a balance between capacity and costs while maintaining operational requirements, namely temperature and pressure (*B04—Storage capacity*) (Olabi and Jouhara 2024). Additionally, significant planning of logistics goes in hydrogen transportation and distribution from productive plants to end-customers (*B05—Distribution capacity*). The limited presence of production facilities across territories implies greater costs of distribution, either by pipeline or truck (Wulf et al. 2018; Lahnaoui et al. 2021).

GB2—Infrastructure development barriers. The development of proper infrastructure, capable of providing the backbone to HSCs, faces major technical, financial, and logistical constraints. One of the most challenging aspects is the definition of the geographical distribution of refueling stations (*B06—Location and geographical* *dispersion*). The need is to ensure a sufficiently capillary network that can support a range of applications (Reuß et al. 2019, Wang et al. 2022). The high costs of constructing and maintaining distribution and refueling facilities, in absence of existing infrastructure, present a threat to practical applications (*B07—Infrastructure costs*) (Li et al. 2024). Moreover, the demand for qualified personnel running and supervising these facilities comes naturally. The requirement is retraining and up-skilling staff to handle hydrogen operations safely (*B08—Re-skilling of personnel*) (Nerheim et al. 2021). Additionally, at international level, standards and regulations for running hydrogen refueling facilities are yet to be defined, and the lack of consistent practices for designing them is detrimental to the transition (*B09—Absence of standards*) (Harahap et al. 2023).

GB3—Vehicles manufacturing barriers. Currently, the manufacturing of hydrogen-fueled vehicles can hardly compete with traditional propulsion sources. Among others, the lengthy regulatory approval for new vehicle designs slows down the process (*B10—Lengthy regulatory approval*). The absence of clear regulations and standards for hydrogen vehicles adds another layer of complexity (*B11—Absence of standards*). Furthermore, there is limited supply of components meant specifically for hydrogen propulsion systems (*B12—Market-ready components*) (Tayarani and Ramji 2022; Singh et al. 2024). Even with such components available, their costs render hydrogen vehicles less financially competitive than their counterparts (*B13—Low-cost components availability*) (Fitz et al. 2022; Singh et al. 2024). The lack of significant research and development (R&D) in this field also hinders advancements in fuel cell technology and related innovations (*B14—Limited R&D*). Moreover, the very high costs of establishing dedicated production lines without an existing demand are both risky and costly for manufacturers (*B15—Vehicle manufacturing costs*). These issues are connected and, together, form a complex web of problems that delay the move from established technological feasibility to adoption.

GB4—Customer adoption barriers. The general acceptance and consequent adoption of hydrogen-fueled vehicles is still very much restrained. The limited choice of models on the market reduces customer interest (*B16—Limited choice*). Hydrogen vehicles are less appealing than conventional ones because of their high upfront costs and costly running expenses (*B17—High purchasing costs, B18—High operating costs*) (Hensher and Wei 2024). Another problem is represented by the suitability of hydrogen towards the operational needs of different end-uses (*B19—Limited operations*). In particular, one of the criticalities lies in the balance between a potentially voluminous tank and the range of operations (Hensher and Wei 2024). For instance, many hydrogen cars fall short of the desired range that users wish for, undermining adoption. Moreover, a big deterrent is the lack of a comprehensive refueling system. Customers hesitate to commit to hydrogen-fueled vehicles when convenient refueling options are unknown (*B20—Refueling availability*) (Reuß et al. 2017; Vijayakumar et al. 2021).

4.1.2 Solutions

In contrast to the identified barriers, the literature also outlines various enabling solutions designed to overcome them and activate the large-scale adoption of hydrogen technologies across mobility. These solutions include industry-driven measures, such as economies of scale, as well as a range of policy interventions led by governments (Table 3).

SO1—Innovation, economies of scale. The literature evidences opportunities for cost reduction within the industrial setting, namely innovation and economies of scale. In particular, advances could be made in the research of materials used in fuel cells and storage systems. The advancements in polymer electrolyte membranes (PEM) can significantly enhance fuel cell efficiency, thereby lowering overall costs (Pedicini et al. 2023). Similarly, the same result can be achieved through the optimization of production methods, such as electrolysis powered by renewable energy (Lahnaoui et al. 2021). When it comes to storage, the use of liquid organic hydrogen carriers (LOHC) can facilitate storage density requirements and safety, making hydrogen more manageable for transportation (Li et al. 2024). On the other hand,

Table 3 Solutions to the large-scale adoption of hydrogen technologies across mobility industries

ID	Solution	References
SO1	*Innovations, economies of scale*: innovation, efficiency, and economies of scale can help in lower manufacturing, production, and distribution costs	Reuß et al. (2017), Wulf and Kaltschmitt (2018), Fitz et al. (2022), Tayarani and Ramji (2022), Dall'Armi et al. (2023), Pedicini et al. (2023), Li et al. (2024), Olabi and Jouhara (2024), Whittle et al. (2024)
SO2	*Lower purchase price of vehicles*: financial incentives with the ultimate goal of lowering the purchase price of vehicles	Haider et al. (2024), Hensher and Wei (2024)
SO3	*Infrastructure development*: government developing or repurposing distribution and refueling network through public–private partnerships or direct investment	Wulf and Kaltschmitt (2018), Madovi et al. (2021), Reuß et al. (2021), Vijayakumar et al. (2021), Ren et al. (2022), Wang et al. (2022), Dall'Armi et al. (2023), Harahap et al. (2023), Montignac et al. (2024), Olabi and Jouhara (2024)
SO4	*Regulations and standards*: institutional interventions capable of promoting the hydrogen economy and establishing pathways, directions, and rules for its development	Cerniauskas et al. (2019), Rabiega et al. (2021), Vijayakumar et al. (2021), Tayarani and Ramji (2022), Dall'Armi et al. (2023), Harahap et al. (2023), Hensher and Wei (2024)
SO5	*Funding R&D:* promoting research through grants, partnerships, or direct investment in research projects	Cerniauskas et al. (2019), Nerheim et al. (2021), Ren et al. (2022), Harahap et al. (2023), Li et al. (2024), Montignac et al. (2024)
SO6	*Pilot projects*: governments stimulating interest in hydrogen technologies through public procurement (e.g., integrating hydrogen-fueled vehicles into public transportation fleets)	Harahap et al. (2023), Hassan et al. (2023), Li et al. (2024)
SO7	*Promotion of education and awareness*: education and public awareness campaigns promoting an understanding of hydrogen technologies and their benefits to the society	Nerheim et al. (2021), Harahap et al. (2023), Hassan et al. (2023), Hensher and Wei (2024)
SO8	*Cross-domain collaboration*: collaboration amongst stakeholders from the fuel, vehicle, and infrastructure supply chains, or even across different industries, coming together strategically	Reuß et al. (2019), Ehrenstein et al. (2020), Harahap et al. (2023), Hassan et al. (2023), Singh et al. (2024)

streamlined processes are essential for achieving economies of scale across organizations (Reuß et al. 2017). As a result, the establishment and scaling of HSCs can significantly enhance competitiveness with respect to fossil fuels.

SO2—Lower purchase price of vehicles. Governments can play a determining role in facilitating the large-scale adoption of hydrogen technologies by providing financial incentives, such as tax credits, grants, and subsidies, to lower the purchase price of hydrogen-fueled vehicles (Hassan et al. 2023). Implementing carbon taxes creates a more favorable economic environment for hydrogen technologies by increasing the cost of fossil fuels (Cerniauskas et al. 2019). Such financial mechanisms can stimulate demand for hydrogen and, as a result, improve competitiveness (De-León Almaraz et al. 2022).

SO3—Infrastructure development. The establishment of an extensive hydrogen refueling infrastructure is crucial for the large-scale adoption of hydrogen technologies (Montignac et al. 2024). Governments can fund the development of infrastructure through public–private partnerships, grants, or direct investments. Existing studies argue that a properly planned refueling network is essential for supporting the growth of hydrogen mobility (Reuß et al. 2021). By collaborating with stakeholders in the private sector, governments can leverage additional resources and expertise to accelerate infrastructural deployment. This collaborative approach can also help to ensure that hydrogen refueling stations are strategically located to meet customer demand (Olabi and Jouhara 2024).

SO4—Regulations and standards. At this stage, governments implementing regulations and standards are needed. They can establish safety standards for hydrogen production, storage, and transport. As a possibility, regulations could allow the blending of hydrogen into the current network of gas pipelines and incentivize the repurposing of natural gas pipelines to transport hydrogen (Vijayakumar et al. 2021). Moreover, their role as institutions is to outline pathways, directions, and rules to the development of the hydrogen economy. By creating a favorable regulatory environment, governments can further push investment into hydrogen technologies. Even the most adverse companies may be motivated to comply if more stringent regulations were to come (Harahap et al. 2023).

SO5—Funding R&D. The funding of research and development is crucial for advancing the adoption of hydrogen technologies. Through collaboration with academic institutions and research centers, governments can fund initiatives investigating fuel cell technologies, alternatives to storage, and hydrogen production methods (Hassan et al. 2023). The establishment of research grants and collaborative projects can also encourage knowledge sharing. To promote the production of hydrogen from renewable sources, new financial instruments are being explored, such as the European Hydrogen Bank (Montignac et al. 2024). Currently, the trend is for governments and organizations not to invest in the entire hydrogen supply chain, but only a part of it, to test the feasibility and cost-effectiveness of one section; however, integrated efforts will soon be required (Li et al. 2024). In the literature, comprehensive assessments of hydrogen supply chains can inform R&D efforts and guide policymakers in making informed decisions (Wulf and Kaltschmitt 2018).

SO6—Pilot projects. By starting with pilot projects, governments can build public trust and acceptance while providing visibility to the technology. Institutions would lead by example, integrating hydrogen-fueled vehicles into public transportation fleets (Hassan et al. 2023). It can be helpful in demonstrating the viability of the solutions but also in creating an early market for hydrogen-fueled vehicles. Furthermore, the deployment of hydrogen fuel cell buses and other public transport options can stimulate demand for hydrogen refueling infrastructure (Vijayakumar et al. 2021). This approach can create a positive feedback loop that encourages further investment in hydrogen mobility.

SO7—Promotion of education and awareness. The public acceptance of hydrogen technologies is central to their large-scale adoption. Comprehensive education and public awareness campaigns can inform stakeholders about the benefits of hydrogen mobility and its role in achieving sustainability goals. In particular, by addressing safety concerns, these efforts can be supportive of operations (Harahap et al. 2023). Engaging with communities and stakeholders throughout the development process can further promote acceptance and support for hydrogen initiatives. The social cost–benefit assessments can provide valuable insights into the socio-economic impacts of hydrogen projects, which can be communicated to the public to enhance understanding (Robles et al. 2020).

SO8—Cross-domain collaboration. Another strategy emerging in the literature is collaboration across areas of expertise, which involves stakeholders from the fuel, vehicle, and infrastructure supply chains coming together to align their efforts. Such collaboration is critical for addressing systemic barriers and creating synergies (Singh et al. 2024). By working together, stakeholders can optimize resource allocation, define standards, and develop integrated solutions that benefit the entire HSC (Hassan et al. 2023). This approach not only helps overcome fragmented efforts but also promotes a shared vision and mutual investment in hydrogen technologies.

4.2 Industry perspectives

Before diving into the results of the survey, we examine the characteristics of the sample to understand the respondents' background and their behavior when evaluating barriers and enabling solutions. Figure 1 summarizes the respondents' composition by industry of origin (road, maritime, and aviation), by area of expertise (e.g., fuel production, vehicle and parts manufacturing), and by level of familiarity with hydrogen technologies (not familiar, somewhat familiar, very familiar).

The final sample consisted of 145 respondents, with 55% of professionals coming from road transport, 36% from maritime transport, and 29% from aviation transport. The sample gathered insights from professionals across various areas of expertise, with 12% representing academic and research institutions, 10% working in fuel and energy production, and 12% involved in infrastructure management and development. A significant share, 27%, were from mobility services and operations, while 9% were engaged in policy, regulation, and environmental sustainability. The largest portion of respondents, 30%, came from vehicle and parts manufacturing. When it comes to familiarity with hydrogen technologies, the majority of respondents had some prior knowledge of hydrogen, with 63% categorized as somewhat familiar with the technology. A smaller portion, 25%, reported being not familiar, while 28% were very familiar with hydrogen technologies. This distribution suggests that most

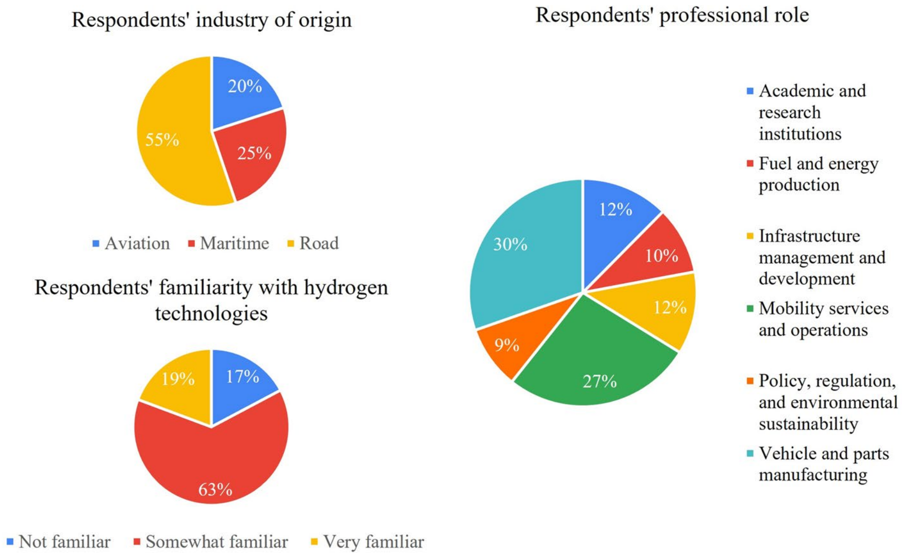


Fig. 1 Survey sample composition by industry of origin, professional involvement, and familiarity. with hydrogen technologies

Table 4 Mean value of the rating of solutions (SO1-SO8) by the participants of each cluster

	SO1	SO2	SO3	SO4	SO5	SO6	SO7	SO8
C1—Moderates	3.99	3.31	3.84	3.47	3.63	3.56	3.13	3.51
C2—Enthusiasts	4.13	4.24	4.71	4.35	4.24	4.40	4.19	4.32
C3—Skeptics	2.50	2.67	3.17	2.67	2.5	2.17	2.08	2.42

participants had at least a basic understanding of hydrogen applications, providing informed insights into the survey.

As seen in Table 4, respondents' behavior when rating solutions demonstrates three distinct attitudinal clusters: C1—"moderates", C2—"enthusiasts", C3—"skeptics". These groups were identified using K-means clustering techniques. The skeptics, on average, rated all proposed solutions neutral or lower (<3); the enthusiasts, on average, rated most solutions highly (>4), moderates fell between these extremes.

Familiarity with hydrogen technologies significantly influenced the distribution of participants in the three clusters (Fig. 2). Among those not familiar with these technologies, 28% were skeptics, the largest share among all groups. In contrast, somewhat familiar respondents were more evenly spread, with moderates forming the largest portion, 58%, and a stable share of enthusiasts, 38%. Those who are highly familiar with hydrogen technologies were predominantly enthusiasts, over 60%, while skeptics became a small minority, 4%.

The maritime industry had the highest share of enthusiasts, 61%, while the road transport industry was mostly represented by moderates, 61%, and enthusiasts, 33%, with a small skeptic presence, 6% (Fig. 3). Across specific areas of involvement such as fuel production, infrastructure development, and policymaking, enthusiasts and moderates dominated, with no skeptic representation. However, skeptics were more

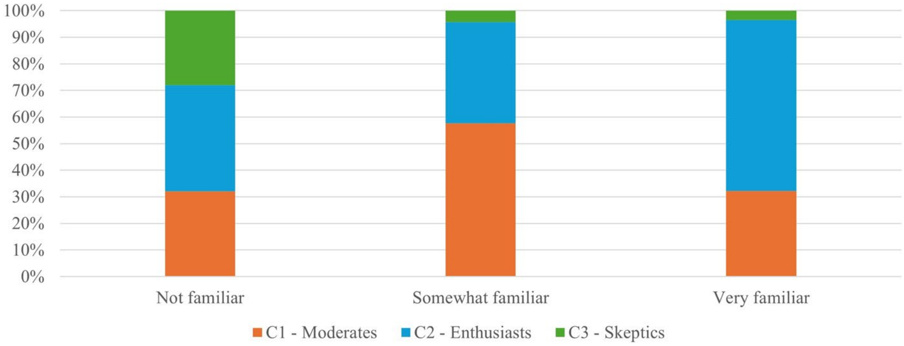


Fig. 2 Respondents' behavior towards solutions by familiarity level with hydrogen technologies

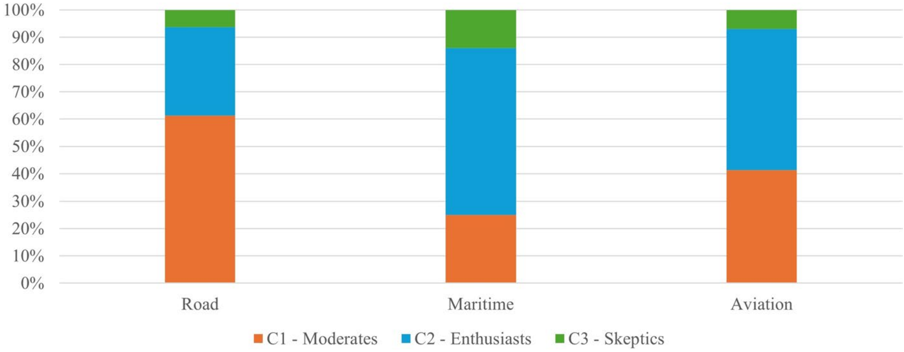


Fig. 3 Respondents' behavior towards solutions by industry of origin

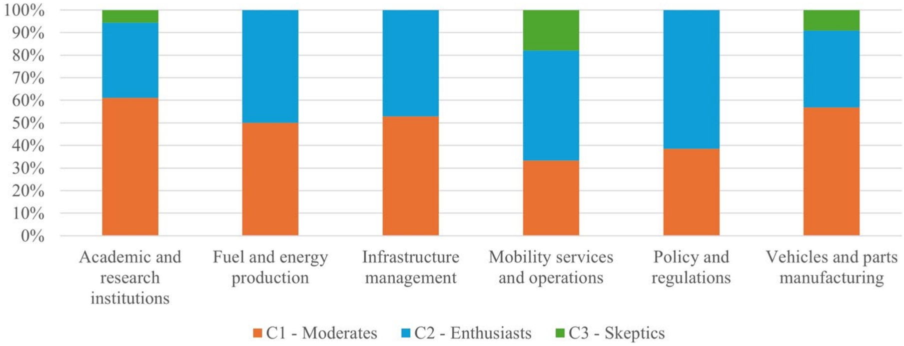


Fig. 4 Respondents' behavior towards solutions by professional role

numerous across mobility services and operations, 18%, and vehicles and parts manufacturing, 9% (Fig. 4).

Table 5 presents professionals' assessment of the expected role of hydrogen across road, maritime, and aviation transport industries, evaluating the projected market

Table 5 Vehicle types: projected market readiness and market share by 2035

Sector	Expected role of hydrogen	Vehicle type	MV	Market ready by 2035?	MV	Market share by 2035?
Road transport	One of several alternatives	Heavy-duty (truck)	3.45	Promising	2.25	Low (6–15%)
		Heavy-duty (bus)	3.66	Promising	2.48	Low (6–15%)
		Heavy-duty (train)	3.50	Promising	2.17	Low (6–15%)
		Light-duty (car, van)	2.65	Emerging potential	1.69	Low (6–15%)
Maritime transport	One of several alternatives	Cruise ship	3.19	Promising	2.25	Low (6–15%)
		Passenger ferry	3.39	Promising	2.31	Low (6–15%)
		Cargo ship	2.78	Emerging potential	2.08	Low (6–15%)
		Container ship	2.94	Moderately promising	2.19	Low (6–15%)
Aviation transport	One of several alternatives	Autogyro, Gyrodyne	2.72	Emerging potential	2.00	Low (6–15%)
		Continental airplane	2.93	Moderately promising	2.21	Low (6–15%)
		Intercontinental airplane	2.07	Unlikely	1.90	Low (6–15%)
		Helicopter	2.34	Unlikely	1.76	Low (6–15%)

"Promising": 3.00 or above, "Moderately promising": 2.75–2.99, "Emerging potential": 2.50–2.74, "Unlikely": 2.50 or below

1—Very Low (0–5%), 2—Low (6–15%), 3—Moderate (16–30%), 4—High (31–50%), Very High (51–100%)

Expected role of hydrogen: primary propulsion source, secondary propulsion source, one of several alternatives, no significant role expected

readiness and market share by 2035. The tables show the mean value (MV) of the scores given by the respondents.

Across all industries, hydrogen is expected to play a role as one of several alternatives, rather than becoming the dominant energy source. The highest-rated vehicle types in terms of market readiness are found in road transport, specifically heavy-duty trucks (MV: 3.45), buses (MV: 3.66), and trains (MV: 3.50), all classified as "promising". This shows that hydrogen can be an option where battery-electric solutions face limitations in range, refueling time, and weight. However, despite the premise, the market share projections remain low (6–15%), suggesting that barriers to the large-scale adoption of hydrogen technologies remain prominent. Similarly, in maritime transport, hydrogen adoption in passenger ferries (MV: 3.39) and cruise ships (MV: 3.19) is "promising", while container ships (MV: 2.94) and cargo ships (MV: 2.78) exhibit "moderately promising" and "emerging potential", respectively. Consequently, hydrogen may emerge as a feasible choice for certain vessel types, particularly in shorter regional routes rather than transoceanic journeys. In contrast, aviation transport presents the lowest market readiness scores. While continental airplanes (MV: 2.93) exhibit "moderately promising" potential, intercontinental ones (MV: 2.07) and helicopters (MV: 2.34) are deemed "unlikely" to emerge on a large scale by 2035. Overall, hydrogen adoption in the mobility sector appears most promising in the heavy-duty road transport segment and selected maritime applications. However, no industry is expected to see hydrogen surpass a 15% market share by 2035, emphasizing the need for enabling solutions in the short term.

Table 6 reports the barriers to the large-scale adoption of hydrogen technologies, in accordance with respondents' assessment. A dedicated question anticipated the evaluation of barriers by asking which of the groups of upstream barriers (GB1, GB2, GB3) to prioritize. The category weight of each group reflects the percentage of respondents that prioritize that category. Formula (1) was used to compute the local weights (LW).

$$\text{Local Weight}_{i,g} = \frac{\mu_{i,g}}{\sum_{j=1}^{n_g} \mu_{j,g}} \tag{1}$$

where: $\text{Local Weight}_{i,g}$: Local weight of barrier i within group g
$\mu_{i,g}$: Mean value of the impact of barrier i on adoption in group g
n_g: Number of barriers in group g
$\sum_{j=1}^{n_g} \mu_{j,g}$: Sum of mean impact values of all barriers in group g

GB2—Infrastructure development barriers are the most significant, with a category weight of 0.60, highlighting the critical role of physical assets such as refueling facilities and distribution networks. Within this category, *B07—Infrastructure costs* (MV: 4.31, LW: 0.30) emerges first, followed by *B06—Location and geographical dispersion* (MV: 3.89, LW: 0.27) and *B09—Absence of standards* (MV: 3.32, LW:

Table 6 Barriers: category weights, mean values, mean values by industry of origin

Category	Category Weight	ID—Barrier	MV	LW	MV Road	MV Maritime	MV Aviation
Upstream barriers							
GB2—Infrastructure Development barriers	0.60	B07—Infrastructure costs	4.31	0.30	4.31	4.23	4.41
		B06—Location and geographical dispersion	3.89	0.27	3.96	3.77	3.82
		B09—Absence of standards	3.32	0.23	3.31	3.73	3.35
		B08—Re-skilling of personnel	2.87	0.20	2.96	2.82	2.56
GB1—Fuel Production barriers	0.21	B03—Fuel production costs	4.03	0.23	4.39	3.57	3.40
		B01—Energy sourcing	3.87	0.22	4.11	4.00	3.00
		B04—Storage capacity	3.40	0.20	3.39	3.43	3.40
		B05—Distribution capacity	3.20	0.19	3.17	3.43	3.00
		B02—Water sourcing	2.73	0.16	2.72	3.29	2.00
GB3—Vehicle Manufacturing barriers	0.19	B15—Vehicle manufacturing costs	4.21	0.19	4.36	3.71	3.86
		B12—Market-ready components	3.89	0.18	3.79	3.71	4.29
		B13—Low-cost components	3.68	0.17	3.71	3.57	3.29
		B14—Limited R&D	3.54	0.16	3.43	3.86	3.43
		B11—Absence of standards	3.50	0.16	3.29	3.29	4.14
		B10—Lengthy regulatory approval	3.39	0.15	3.43	3.14	3.43
Downstream barriers							
GB4—Customer adoption barriers		B17—High purchasing costs	3.72	0.23	3.81	3.44	3,79
		B18—High operating costs	3.63	0.22	3.56	3.22	4.34
		B16—Limited choice of models	3.34	0.20	3.43	3.17	3.31
		B20—Refueling availability	2.92	0.18	2.40	3.53	3.59
		B19—Limited operations	2.88	0.17	2.66	3.19	3.10

0.23). These findings suggest that the high capital costs of developing hydrogen infrastructure, particularly in dispersed transport networks, pose a significant barrier to adoption. *GB1—Fuel production barriers* hold a category weight of 0.21, with *B03—Fuel production costs* (MV: 4.03, LW: 0.23) and *B01—Energy sourcing* (MV: 3.87, LW: 0.22) emerging as potential concerns. The production of hydrogen, especially green hydrogen, remains costly due to high energy input requirements. *B04—Storage capacity* (MV: 3.40, LW: 0.20) and *B05—Distribution capacity* (MV: 3.20, LW: 0.19) are also present. *GB3—Vehicle manufacturing barriers* had a slightly lower category weight, 0.19. *B15—Vehicle manufacturing costs* (MV: 4.21, LW: 0.19) is a concern. Additionally, *B12—Market-ready components availability* (MV: 3.89, LW: 0.18) and *B13—Low-cost components availability* (MV: 3.68, LW: 0.17) suggest that supply chain limitations may hinder the commercialization of hydrogen-fueled vehicles.

Table 6 completes the overview by presenting the relevant downstream barriers, based on respondents' assessments. The first barrier is *B17—High purchasing costs* (MV: 3.72) of hydrogen-fueled vehicles, closely followed by *B18—High operating costs* (MV: 3.63) of them. These concerns are reflected across all modes of transport. The score of *B16—Limited choice of models* (MV: 3.34) suggests that while the range of the offering of hydrogen-fueled vehicles may be a limiting factor, it is not the most pressing. *B20—Refueling availability* (MV: 2.92) and *B19—Limited operations* (MV: 2.88) show some variation between industries.

Table 7 shows respondents' assessment of solutions to overcome the aforementioned barriers. *SO3—Infrastructure development* is seen as very effective (MV: 4.17), emphasizing the importance of investments in hydrogen refueling stations, transportation networks, and storage facilities. This is consistent with the finding that GB2—Infrastructure development barriers (category weight: 0.60) are a priority to address. The next solution comprises *SO1—Innovation, economies of scale* (MV: 3.92), underlining the importance of cost reduction in fuel cells and supply chain efficiency. Similarly, governments *SO5—Funding R&D* (MV: 3.80) and defining *SO4—Regulations and standards* (MV: 3.79) are highly valued, meaning policy intervention can be effective in promoting adoption. The creation of *SO6—Pilot projects* (MV: 3.81) and *SO8—Cross-domain collaboration* (MV: 3.77) are seen as effective, implying that practical demonstrations and partnerships across areas of expertise could support adoption. Finally, *SO2—Lower purchase price of vehicles* (MV: 3.66) and *SO7—Promotion of education and awareness* (MV: 3.50) scored slightly lower but were still seen as potentially contributing to adoption.

Table 7 Solutions: mean values, mean values by industry of origin

ID—Solution	MV	MV Road	MV Maritime	MV Aviation
SO3—Infrastructure development	4.17	4.15	4.17	4.20
SO1—Innovation, economies of scale	3.92	3.98	3.75	4.00
SO6—Pilot projects	3.81	3.79	3.83	3.83
SO5—Funding R&D	3.80	3.63	3.97	4.07
SO4—Regulations and standards	3.79	3.74	3.83	3.86
SO8—Cross-domain collaboration	3.77	3.64	3.89	4.00
SO2—Lower purchase price of vehicles	3.66	3.65	3.83	3.48
SO7—Promotion of education and awareness	3.50	3.38	3.72	3.57

5 Discussion

The discussion begins by explicitly addressing the two research questions, providing an overview of the barriers and enabling solutions to the large-scale adoption of hydrogen technologies in the mobility sector (Fig. 5). Then, a reference framework is shown which summarizes similarities and differences across transport industries, matching enabling solutions and barriers, prioritizing areas for intervention (Fig. 6).

5.1 Response to RQ1—barriers

GB2—Infrastructure Development. Barriers related to infrastructure development are considered the most significant across transport industries. More than 60% of survey respondents prioritized infrastructure over other groups of barriers. A major concern is *B07—Infrastructure costs* (MV > 4.2 for all), reflecting the high investments needed for deploying refueling hubs and distribution facilities (Li et al. 2024). The maritime industry emphasizes *B09—Absence of standards*, underlining the regulatory uncertainty in designing hydrogen-ready ports.

GB3—Vehicle Manufacturing. Vehicle-related barriers differ across transport industries. Road transport expressed major concerns about *B15—Vehicle manufacturing costs* (MV: 4.36), stressing economic feasibility. Aviation transport identified *B12—Availability of market-ready components* (MV: 4.29) and *B11—Absence of standards* as critical, reflecting its stringent safety requirements. Maritime transport highlighted *B14—Limited R&D* as one of the industry's limits.

GB1—Fuel Production. Fuel production remains a critical upstream barrier as it closely follows vehicle manufacturing. Among all, road transport professionals are especially concerned with *B03—Fuel production costs*, as they stress, once again, that the economic feasibility of hydrogen remains unresolved (Melnyk et al. 2012). Scaling up green hydrogen production is technically possible, but cost-effectiveness

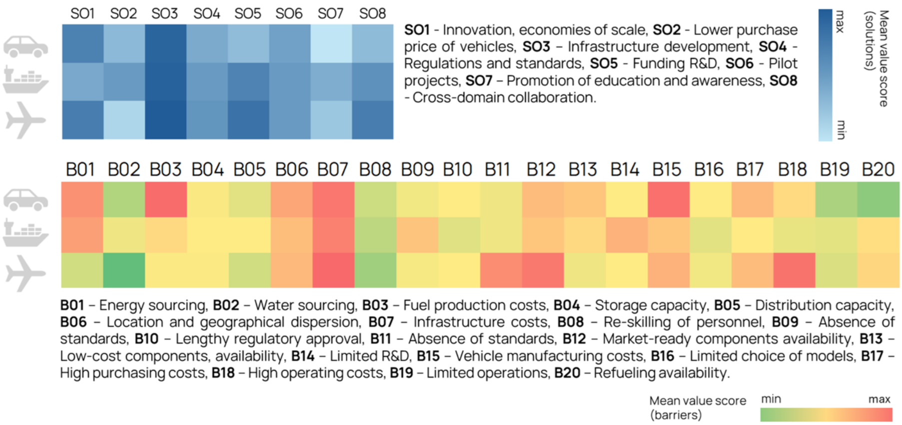
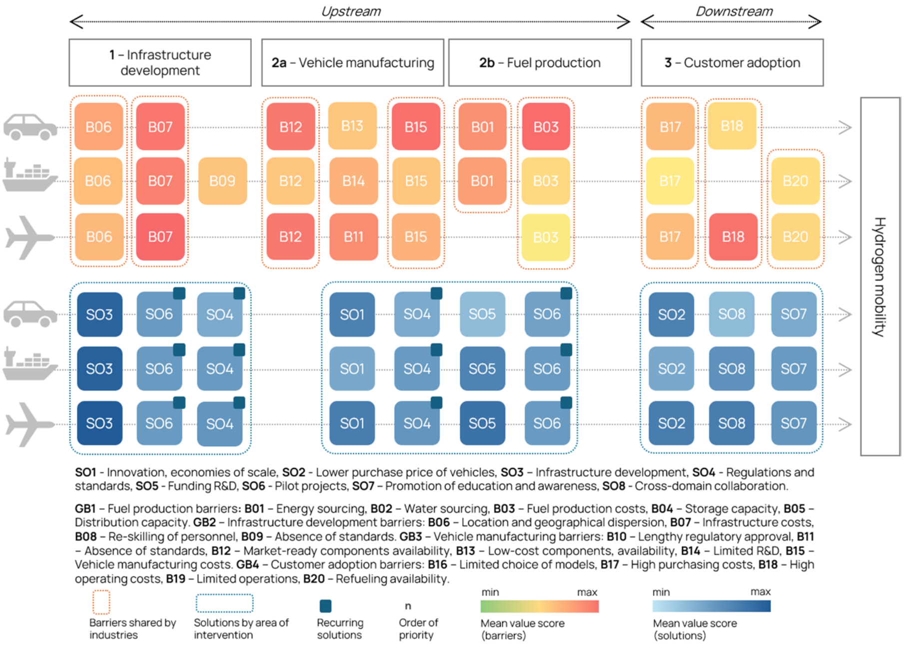


Fig. 5 Heatmap of barriers and enabling solutions for the large-scale adoption of hydrogen technologies in the mobility sector



SO1 - Innovation, economies of scale, **SO2** - Lower purchase price of vehicles, **SO3** – Infrastructure development, **SO4** - Regulations and standards, **SO5** - Funding R&D, **SO6** - Pilot projects, **SO7** - Promotion of education and awareness, **SO8** - Cross-domain collaboration.

GB1 – Fuel production barriers: **B01** – Energy sourcing, **B02** – Water sourcing, **B03** – Fuel production costs, **B04** – Storage capacity, **B05** – Distribution capacity. **GB2** – Infrastructure development barriers: **B06** – Location and geographical dispersion, **B07** – Infrastructure costs, **B08** – Re-skilling of personnel, **B09** – Absence of standards. **GB3** – Vehicle manufacturing barriers: **B10** – Lengthy regulatory approval, **B11** – Absence of standards, **B12** – Market-ready components availability, **B13** – Low-cost components, availability, **B14** – Limited R&D, **B15** – Vehicle manufacturing costs. **GB4** – Customer adoption barriers: **B16** – Limited choice of models, **B17** – High purchasing costs, **B18** – High operating costs, **B19** – Limited operations, **B20** – Refueling availability.

Fig. 6 Reference framework for the large-scale adoption of hydrogen technologies in the mobility sector

is still limited by high investment and operational costs across all industries (Olabi and Jouhara 2024).

GB4—Customer Adoption. Customer adoption barriers reflect market immaturity. Aviation showed the greatest concern for *B18—High operating costs* (MV: 4.34). Across all sectors, *B17—High purchasing costs* and *B20—Refueling availability* are major barriers. Notably, *B19—Limited operations* was not considered as pressing across all industries.

5.2 Response to RQ2—solutions

Regarding *GB1—Fuel production barriers*, the economic feasibility is once again questioned. To address these concerns, *SO1—Innovation and economies of scale* is considered essential for reducing fuel production costs through the optimization of production methods (e.g., electrolysis) (Lahnaoui et al. 2021). Additionally, *SO5—Funding R&D* from governments can also advance knowledge in hydrogen production methods and related sourcing strategies (Hassan et al. 2023).

GB2—Infrastructure development barriers are among the most significant, with the only exception being *B08—Re-skilling of personnel*. Solutions to lessen these barriers include *SO3—Infrastructure development* with governments developing or repurposing distribution and refueling networks through public–private partnerships or direct investment (Olabi and Jouhara 2024). *SO4—Regulations and standards* are crucial for ensuring safety and training accordingly the operators at refueling hubs (Harahap et al. 2023).

When it comes to *GB3—Vehicle manufacturing barriers*, solutions vary depending on priorities. For road transport, *SO1—Innovation, economies of scale* to reduce manufacturing costs can help. For aviation transport, *SO5—Funding R&D* is crucial to promote innovation and component availability, coupled with *SO4—Regulations and standards* to ensure safety in operations (Cerniauskas et al. 2019; Li et al. 2024).

The importance given to *GB4—Customer adoption barriers* shows the limited opportunities for hydrogen-fueled vehicles to emerge on the current market. To address these, solutions such as *SO2—Lower purchase price of vehicles* through financial incentives can render hydrogen-fueled vehicles more appealing (Haider et al. 2024; Hassan et al. 2023). Although present in the literature (Nerheim et al. 2021; Hensher and Wei 2024), *SO7—Promotion of education and awareness* was rated lower than other solutions across all industries.

5.3 Reference framework—hydrogen mobility

The study outlines four main groups of barriers to the large-scale adoption of hydrogen technologies in the mobility sector. Figure 6 is structured according to the same four groups, with the upstream barriers ordered by priority according to survey results. *1—Infrastructure development* comes first, then *2a—Vehicle manufacturing*, closely followed by *2b—Fuel production*, with *3—Customer adoption* as the final target. For each group, the most relevant barriers for each industry are listed, with the color indicating their significance based on survey scores. Then, according to each group, enabling solutions are offered based on the systematic literature review results.

The survey results suggest that hydrogen will not be the primary transportation fuel but rather one of many alternatives, based on specific applications. In some market segments, hydrogen will remain niche, whereas in others, it may emerge as a valid alternative (e.g., heavy-duty market segment). The issue is not whether hydrogen can rival established energy sources but rather whether the necessary conditions can be created. The analysis conducted thus far, and visualized in Fig. 6, offers some insights into the prioritization of actions for the large-scale adoption of hydrogen technologies:

> *1—Infrastructure development* comes first, with the large majority of respondents prioritizing it over *2a—Vehicle manufacturing* and *2b—Fuel production*. From the literature, it emerges the need for the strategic placement of refueling stations along logistics corridors, ports, and regional airports where demand is most predictable (Wulf et al. 2018; Lahnaoui et al. 2021). Yet, survey findings show that *B07—Infrastructure costs* is a prominent barrier across all three transport industries. Consistently, *SO3—Infrastructure development* is strongly supported as an enabling solution, ranking as first too.
>
> *2a—Vehicle manufacturing* and *2b—Fuel production* follow closely in succession. Common enabling solutions across intervention areas exist and can facilitate the coordination of various upstream HSC activities. *SO6—Pilot projects* are necessary, particularly for those applications identified as promising (e.g., trucks, buses, ferries). These projects validate both the technology and the market,

demonstrate the feasibility of solutions, and can be used to gain wider acceptance while combined with *SO4—Regulations and standards* at all levels. They are central to the alignment and testing of the upstream supply chains: the ones of fuel, vehicles, and infrastructure. In practical terms, governments can integrate hydrogen-fueled vehicles into public transport fleets (e.g., buses and ferries). This measure is designed to ensure a consistent early demand for hydrogen, thus contributing to the formation of an initial market for hydrogen-fueled vehicles and boosting demand for supporting *1—Infrastructure development*.

Finally, *3—Customer adoption* is expected to grow as a result of the aligned efforts of the upstream HSC (*SO8—Cross-domain collaboration*). At the same time, dedicated enabling solutions are backed, including *SO7—Promotion of education and awareness*.

Other notable findings include professionals' perspectives on the expected market readiness and market share of specific vehicle types. The literature results support the idea that any vehicle may run on hydrogen (Gray et al. 2021). However, survey results indicate that this is not the best fit for every vehicle type. As a result, pilot projects should be focused on developing specific applications (e.g., trucks, buses, ferries).

Furthermore, the results show some promising scores in terms of market readiness for specific applications but discouraging numbers in terms of projected market share (i.e. adoption). In the Italian context, we may see a situation similar to that of electric cars, where the technology has been available for a long time (market readiness) but the numbers remain very low in comparison to other European countries (market share), with financial incentives thought to have a greater impact on adoption than technological breakthroughs (Danielis et al. 2020).

6 Conclusions

This study examines the role of hydrogen technologies for mobility across the road, maritime, and aviation transport industries, focusing on the barriers that prevent a large-scale adoption and the enabling solutions to overcome them. Through a systematic literature review and a survey of professionals, key barriers related to hydrogen fuel production, infrastructure development, and vehicle manufacturing were identified. While hydrogen technologies present a promising pathway towards the decarbonization of the mobility sector, a series of actions are needed to create the necessary conditions for the development of HSCs.

The research has some limitations. The survey of professionals, while insightful, reflects the perspective of a limited sample within a specific context, the Italian one. However, with the exception of big players such as Germany, France, and the Netherlands, the current Italian hydrogen landscape is similar to that of other European countries (Clean Hydrogen JU 2024). Since adoption is still in its early stages, many countries are moving in different directions, though they are all facing the same barriers and exploring similar solutions.

As the mobility sector intensifies its efforts toward sustainability, hydrogen is expected to play a varying role, ranging from niche to potential market contender, depending on applications. Addressing existing barriers through enabling solutions capable of lessening them will be decisive in the activation process, eventually progressing hydrogen mobility into the next stages of adoption.

Appendix

Appendix A: Pearson correlation test

r	SO1	SO2	SO3	SO4	SO5	SO6	SO7	SO8
SO1	x							
SO2	0.239	x						
SO3	0.217	0.324	x					
SO4	0.054	0.387	0.36	x				
SO5	0.101	0.181	0.268	0.323	x			
SO6	0.197	0.254	0.381	0.301	0.274	x		
SO7	0.29	0.355	0.299	0.315	0.236	0.415	x	
SO8	0.317	0.291	0.269	0.317	0.423	0.419	0.413	x

Appendix B: T-test results

p value	SO1	SO2	SO3	SO4	SO5	SO6	SO7	SO8
SO1	x	**0.029**	**0.028**	0.238	0.279	0.315	**0.001**	0.176
SO2	**0.029**	x	**0.000**	0.311	0.252	0.236	0.225	0.350
SO3	**0.028**	**0.000**	x	**0.001**	**0.001**	**0.002**	**0.000**	**0.000**
SO4	0.238	0.311	**0.001**	x	0.907	0.863	**0.028**	0.905
SO5	0.279	0.252	**0.001**	0.907	x	0.953	**0.019**	0.807
SO6	0.315	0.236	**0.002**	0.863	0.953	x	**0.018**	0.764
SO7	**0.001**	0.225	**0.000**	**0.028**	**0.019**	**0.018**	x	**0.031**
SO8	0.176	0.350	**0.000**	0.905	0.807	0.764	**0.031**	x

Appendix C: Survey questions

General questions

1. In which industry are you involved?

- Road transport
- Maritime transport
- Aviation transport

2. In which area are you involved?

- Vehicle and parts manufacturing
- Infrastructure management and development
- Fuel and energy production
- Mobility services and operations
- Academic and research institutions
- Policy, regulation, and environmental sustainability
- Other (please specify)

3. How familiar are you with hydrogen technologies for mobility?

- Not familiar
- Somewhat familiar
- Very familiar

Section A: road transport

4. Is this hydrogen-fueled vehicle type going to be market-ready by 2035? *(Rated from Very Unlikely to Very Likely)*

- Trucks
- Buses
- Cars and vans
- Trains

5. What is the projected market share for this type of hydrogen-fueled vehicle by 2035? *(Very Low: 0–5%, Low: 6–15%, Moderate: 16–30%, High: 31–50%, Very High: 51–100%)*

- Trucks

- Buses
- Cars and vans
- Trains

6. What role will hydrogen play in your industry by 2035?

- Primary propulsion source
- Secondary propulsion source
- One of several alternatives
- No significant role expected

7. From a customer perspective, when it comes to hydrogen-fueled vehicles adoption, there is a problem of… *(Rated from Strongly Disagree to Strongly Agree)*

- Limited choice of models
- High ownership costs
- High operating costs
- Limited operating range
- Refueling availability

8. Right now, which aspect should be prioritized for a successful transition?

- The production of hydrogen fuel
- The development of hydrogen infrastructure
- The manufacturing of hydrogen-fueled vehicles

Section B: maritime transport

9. Is this hydrogen-fueled vehicle type going to be market-ready by 2035? *(Rated from Very Unlikely to Very Likely)*

- Cruise ships
- Ferries
- Bulk carriers
- Container ships

10. What is the projected market share for this type of hydrogen-fueled vehicle by 2035? *(Very Low: 0–5%, Low: 6–15%, Moderate: 16–30%, High: 31–50%, Very High: 51–100%)*

- Cruise ships
- Ferries
- Bulk carriers
- Container ships

11. What role will hydrogen play in your industry by 2035? *(Same options as Question 6)*
12. From a customer perspective, there is a problem of…*(Rated from Strongly Disagree to Strongly Agree) (Same statements as Question 7)*
13. Right now, which aspect should be prioritized for a successful transition? *(Same options as Question 8)*

Section C: aviation transport

14. Is this hydrogen-fueled vehicle type going to be market-ready by 2035? *(Rated from Very Unlikely to Very Likely)*

- Autogyro, Gyrodyne
- Continental airplane (<4000 km)
- Intercontinental airplane (>4000 km)
- Helicopter

15. What is the projected market share for this type of hydrogen-fueled vehicle by 2035? *(Very Low: 0–5%, Low: 6–15%, Moderate: 16–30%, High: 31–50%, Very High: 51–100%)*

- Autogyro, Gyrodyne
- Continental airplane (<4000 km)
- Intercontinental airplane (>4000 km)
- Helicopter

16. What role will hydrogen play in your industry by 2035? *(Same options as Question 6)*
17. From a customer perspective, there is a problem of…*(Rated from Strongly Disagree to Strongly Agree) (Same statements as Question 7)*
18. Right now, which aspect should be prioritized for a successful transition? *(Same options as Question 8)*

Section D: barriers

19. When it comes to hydrogen fuel production, there is a problem of…*(Rated from Strongly Disagree to Strongly Agree)*

- Energy sourcing through renewables
- Supply of water for electrolysis
- High investment and maintenance costs
- Storage capacity

- Distribution capacity

20. When it comes to hydrogen infrastructure development, there is a problem of… *(Rated from Strongly Disagree to Strongly Agree)*

- Geographical distribution
- High investment and operating costs
- Employees' acceptance of retraining
- Absence of standards

21. When it comes to hydrogen-fueled vehicles manufacturing, there is a problem of…

- Complex regulatory framework
- Absence of standards
- Availability of market-ready components
- Availability of low-cost components
- Limited R&D in Fuel Cell systems
- High investment costs

Section E: solutions

22. Please rate each solution on a scale from 1 (Not Effective) to 5 (Very Effective):

- Lower manufacturing costs through innovation, efficiency, and economies of scale
- Financial incentives to lower the purchase price of vehicles
- Government development of infrastructure via PPPs or direct investment
- Government regulations and standards encouraging hydrogen vehicles
- Government funding for R&D through grants, partnerships, or direct investment
- Integration of hydrogen vehicles into public transport fleets
- Education and public awareness campaigns
- Cross-sector collaboration to share knowledge and create standards

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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