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Review

Next leap in the sustainable transport revolution: Identifying gaps and proposing solutions for hydrogen mobility

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ABSTRACT

Amid escalating global climate concerns, the reliance of the transportation sector on high-carbon fossil fuels urgently demands sustainable alternatives. Hydrogen has emerged as a potent solution because of its zero-emission usage, but its overall impact hinges on its full life cycle, which this review comprehensively examines. This article delves into the environmental, economic, and safety dimensions of hydrogen as an alternative fuel by systematically reviewing the life cycle assessment (LCA) literature across the production, storage, delivery, and usage phases, with a focus on electrolysis and natural gas reforming methods, among others. A key insight from this study is the critical importance of considering the entire delivery system holistically rather than isolating the delivery phase. Many studies have overlooked two important aspects: first, the distribution of hydrogen as a product itself is often underemphasized; second, the integration of storage and delivery (the "storage-delivery nexus") is crucial since separating them can lead to misleading conclusions about cost and emissions. For example, while certain delivery methods may appear cost-effective, their associated storage processes (such as hydrogenation and dehydrogenation in liquid organic hydrogen carrier systems) can have significant emission impacts. To address these gaps, this study introduces a novel "surface-level" LCA framework to enhance the assessment of the environmental impacts of hydrogen, promoting a more integrated understanding of the storage-delivery system. This framework aims to provide more accurate insights into hydrogen's life cycle, thereby facilitating better-informed policy-making and technological advancements. This study underscores the imperative for robust policy support, public engagement, and continuous innovation to overcome these barriers, advocating for strategic initiatives that bolster the sustainability and adoption of hydrogen mobility, particularly in hydrogen fuel cell vehicles (HFCVs).

1. Introduction

At the COP28 climate summit, nearly 200 countries made a collective commitment to triple the capacity of renewable energy, increase energy efficiency, phase out fossil fuels, and deploy new technologies, all aimed at maintaining global warming within 1.5 °C (International Energy Agency (IEA), 2024). This ambitious goal is supported and monitored by the International Energy Agency (IEA) to ensure its realization (IEA, 2024). Among various strategies, hydrogen has emerged as a crucial clean energy source, particularly in sectors that are challenging to electrify, such as shipping, aviation, and heavy industry (Hassan et al., 2024a). In 2023, the global transportation sector emitted 8.4 Gt CO_2 equivalent (CO_2eq) of greenhouse gases, accounting for 16% of global emissions, indicating both the urgency and potential for reduction in this area (Statista, 2024a). In response, the European Union (EU) has allocated 35 million USD to kickstart South Africa's green hydrogen industry (Bloomberg, 2024) and collaborated with the Chinese company Envision Energy to develop a 1 billion USD green hydrogen industrial park in Spain (Baker, 2024). This park will utilize locally produced solar, wind, and biomass energy to manufacture electrolyzers for splitting water into hydrogen. Construction is expected to begin in the first half of 2026. These initiatives not only propel the advancement of hydrogen technology but also significantly support the decarbonization of the global transportation system (Baker, 2024).

Research indicates that while full electrification significantly reduces CO_2 emissions in the transportation sector (by more than 80%), it is

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Nomenclature

Abbreviation			
AE	alkaline electrolyte	IMO	International Maritime Organization
AG2S	acid gas to syngas	kWe	kilowatt-electric
AO	aluminum oxidation	LCA	life cycle assessment
AP	acidification potential	LCC	life cycle costing
ATR	autothermal reforming	LCCA	Life cycle cost analysis
AWE	alkaline water electrolyzer	LCOE	levelized cost of energy
BAR	biogas autothermal reforming	LCOHT	levelized cost of hydrogen transportation
BEV	battery electric vehicle	LH_2	liquid hydrogen
BF	biomass fermentation	LHSEP	liquid hydrogen superconducting energy pipeline
BG	biomass gasification	LNG	liquefied natural gas
BSR	biogas steam reforming	LNH_3	liquid NH_3
CAP	chlor-alkali process	LOHC	liquid organic hydrogen carrier
CAPEX	capital expenditures	MDO	marine diesel oil
CCH	cryo-compressed hydrogen	MET	methanol
CCS	carbon capture and storage	MH	metal hydride
CCUS	carbon capture unit system	NH_3	ammonia
CCUS	carbon capture, utilization, and storage	OPEX	operational expense
CFRP	carbon fiber reinforced thermoplastic	PDH	propane dehydrogenation
CG	coal gasification	PEM	polymer electrolyte membrane
CGH_2	compressed gaseous hydrogen	PEMFC	polymeric electrolytic membrane fuel cell
CNs	carbon nanotubes	PPA	power purchase agreement
CnG	corn gasification	PRISMA	Preferred reporting items for systematic reviews and meta-analyses
COG	coke oven gas	PS	physical storage
CS	chemical storage	PT	photothermal
CSP	concentrated solar power	PV	photovoltaic
DAFCV	direct use of ammonia in fuel cell vehicles	RDF	refuse derived fuel
DBT	dibenzyltoluene	RE	renewable energy
DBT-HDBT	dibenzyltoluene-hydrodibenzyltoluene	RETA	renewable energy, energy storage medium, transportation options, automotive powertrain
DBT-PDBT	dibenzyl toluene-perhydro-dibenzyltoluene	SBE	salt brine electrolysis
DF	dark fermentation	SCBA	social cost–benefit assessment
EIs	environmental impacts	SCG	surface coal gasification
EP	enrichment potential	SMR	steam methane reforming
EU	Europe	SR-AW	steam reforming of alcoholic waste
FCEB	fuel cell electric bicycle	SR-G	steam reforming of glycerol
GHG	greenhouse gas	TCO	total cost of ownership
GTT	Gate-to-tank	TOL	toluene
GWP	global warming potential	TOL-MCH	toluene-methylcyclohexane
HC	hydrocarbon cracking	TTW	tank-to-wheel
HFCEA	hydrogen fuel cell electric aircraft	UCG	underground coal gasification
HFCV	hydrogen fuel cell vehicle	UHV	ultrahigh voltage
HRSs	hydrogen refueling stations	WE	water electrolysis
HTC	hydrocarbon thermal cracking	WG	wood gasification
HTE	high temperature electrolysis	WTG	Well-to-gate
H_0DBT-$H_{18}DBT$	dibenzyltoluene-perhydro-dibenzyltoluene	WTT	Well-to-tank
ICL	iron-based chemical looping	WTW	well to wheel
IEA	international energy agency		

projected to increase the overall energy system costs by 12% by 2050 (Rinaldi et al., 2023). Compared with hydrogen fuel cell vehicles (HFCVs), battery electric vehicles (BEVs) have superior energy demand and cost effectiveness, making them particularly suitable for passenger cars and short-haul freight. However, the limitations in range and charging times for BEVs restrict their application in heavy industry and long-haul transportation (Aryanpur and Rogan, 2024). Additionally, although hydrogen (primarily green hydrogen) is increasingly used in some key industrial processes, the use of hydrogen as a long-term electricity storage medium is not cost effective, with an overall round-trip efficiency of only 27% (Rinaldi et al., 2023). To address these challenges and achieve net-zero emission targets, future energy transition strategies must consider cost efficiency, technological advancements, and policy support, including potential applications of carbon capture and the optimization of battery and hydrogen technologies (IEA, 2021; Noor and Amin, 2024).

Hydrogen energy, as a clean energy source, has immense potential for supporting renewable resources and driving the decarbonization of the transportation sector (Locke, 2024). Candelaresi et al. (2023) conducted a comprehensive study in Italy, comparing eight passenger vehicle fleet strategies utilizing renewable hydrogen and traditional fuels (natural gas or gasoline) under the constraint of equivalent energy input. The findings demonstrate that strategies incorporating a mix of hydrogen energy significantly reduce the carbon footprint by 7%–35%. This emphasizes that using hydrogen mixtures as a transitional solution on the basis of existing technology and infrastructure not only facilitates the development of a hydrogen economy but also lays the groundwork for the long-term implementation of hydrogen in the transportation sector.

Hydrogen energy is used globally as a key technology to decarbonize transportation. For example, Republic of Korea has increased the number of hydrogen-powered buses from 500 in 2023 to 3000 in 2024, deploying 992 hydrogen buses nationwide and achieving a 46% year-over-year increase in hydrogen consumption for transportation (Collins, 2024; Parikh, 2024). China has expanded the capacity of its hydrogen electrolysis facilities to 2.5 GW, anticipating an annual production of 220, 000 t of green hydrogen (Xue, 2024), whereas Hong Kong, China is testing hydrogen-powered buses and trains and planning multiple hydrogen projects (Zhang, 2024). The USA is building seven clean hydrogen hubs funded by a 7 billion USD bipartisan infrastructure bill, aiming to produce 10 million t of clean hydrogen annually by 2030 (Robles, 2024). Japan is developing hydrogen fuel cell vessels, such as the Raicho N (Jiji, 2024), and establishing a commercial-scale liquid hydrogen (LH_2) supply chain with Australia while strengthening the support for hydrogen infrastructure through legislation (Iannucci, 2023; Bocobza et al., 2024a, 2024b). Germany is formulating a hydrogen import strategy and building a hydrogen network to facilitate decarbonization in industries such as steel and chemicals (Grostern and Kyllmann, 2024). Australia plans to use its abundant renewable resources to massively produce and export hydrogen fuel, anticipating a significant reduction in carbon emissions by 2050 (Spiegel, 2024). These examples demonstrate that hydrogen energy is a promising pathway for decarbonizing transportation, offering vast potential for international cooperation and technological innovation.

When discussing the future of hydrogen mobility, key elements include technological innovation, economic feasibility, and support and challenges from policy and market factors. Technological innovation is a central driver and is currently focused on enhancing the efficiency of hydrogen fuel storage and delivery, which is essential for reducing costs and increasing safety (Calandra et al., 2023). Economically, although the initial investment costs for hydrogen are high, scalability and technological advancements are expected to significantly decrease operational costs in the future, thereby improving economic viability (Sandaka and Kumar, 2023). Additionally, policy support is crucial for the promotion of hydrogen mobility, encompassing not only financial subsidies and tax incentives but also the development of necessary hydrogen infrastructure (Calandra et al., 2023). However, the widespread adoption of hydrogen mobility faces several challenges, such as the sustainability of resource acquisition, the financial and technical demands of infrastructure development, and market acceptance and adaptability. Therefore, a comprehensive analysis of these challenges and the formulation of corresponding strategies are key to achieving broad application of hydrogen in the transportation sector (Calandra et al., 2023; Sandaka and Kumar, 2023).

1.1. Background of hydrogen mobility

Hydrogen, the most abundant element in the universe, is increasingly acknowledged as a crucial energy carrier in the transition to a more sustainable energy landscape. Owing to its ability to generate power while emitting only water vapor and heat when consumed in fuel cells, hydrogen offers a zero-emission alternative to traditional fossil fuels. When used in internal combustion engines, hydrogen still significantly reduces emissions compared with those of conventional fuels, although minimal amounts of nitrogen oxides can be produced. These characteristics position hydrogen as a particularly attractive option for sectors striving to minimize environmental impact and enhance energy efficiency.

Bicer and Dincer (2018) conducted a comprehensive comparative life cycle assessment of vehicles powered by various fuels, including hydrogen. The findings demonstrate that hydrogen-fueled internal combustion engine vehicles have the lowest environmental impact across all the assessed categories, notably because of their high energy efficiency and lower fuel consumption during operation. This study highlights hydrogen as the most environmentally benign option, particularly when it is produced via electrolysis using renewable energy sources. This stance positions hydrogen vehicles as a superior choice for reducing emissions and advancing sustainable development in the transportation sector. Future research, as suggested by Bicer and Dincer (2018), should explore optimized production techniques and the life cycle costs associated with hydrogen fuel to further increase its feasibility and environmental benefits.

The production of hydrogen can be achieved through various methods, including steam methane reforming (SMR) and electrolysis of water. Among these, electrolysis—where electricity, ideally sourced from renewable energies such as wind, solar, or hydroelectric power, splits water into hydrogen and oxygen—stands out as the most sustainable approach. This method ensures that the production of hydrogen itself contributes to environmental preservation by avoiding the emission of greenhouse gases, provided that the electricity used is generated from renewable sources. The ability to use surplus renewable energy for hydrogen production not only bolsters the sustainability of this method but also enhances the overall integration of renewable energy into the energy grid, stabilizing supply and demand fluctuations (Li et al., 2019).

Balaji and You (2024) demonstrated that integrating offshore wind with green hydrogen production could cover 75% of the U.S. hydrogen demand by utilizing 0.96 TW of offshore wind capacity, achieving costs between 2.50 and 7.00 USD/(kg H_2) and maintaining life cycle emissions under 4 kg CO_2eq/(kg H_2). El Hassani et al. (2024) conducted a study on a hybrid concentrated solar power (CSP)/photovoltaics (PV) renewable energy system in Dakhla, Morocco, highlighting its effectiveness in green hydrogen production, with achievements such as up to 90% capacity factors and a levelized cost of energy (LCOE) of approximately 17 c/kWh (USD). This enhanced performance supports efficient hydrogen generation through water electrolysis, which is vital for clean energy transitions in the transportation sector, particularly in hydrogen-fueled vehicles and aviation. These findings emphasize the importance of further research into optimizing costs, system sizing, and storage solutions to ensure reliable and economical hydrogen production (El Hassani et al., 2024).

Compared with other alternative fuels such as electricity and biofuels, hydrogen offers superior energy density by weight, making it especially beneficial for applications demanding heavy-duty performance and long-range capabilities, such as trucks, ships, and aircraft (Martin et al., 2023). This high energy density ensures that vehicles powered by hydrogen can operate at a level of efficiency and autonomy comparable to those of conventional fossil fuel systems but without associated environmental degradation (Le et al., 2024). Furthermore, hydrogen fuel cells can be refueled in a matter of minutes, providing a significant logistical advantage over electric vehicles, which require extended periods for battery charging (Wang et al., 2023). This rapid refueling capability not only enhances the practicality of hydrogen-powered vehicles in commercial and industrial contexts but also aligns with consumer expectations for convenience, similar to traditional gasoline or diesel engines (Brown and Kisting, 2022).

The role of hydrogen as a clean energy source provides a significant advantage in reducing emissions within the aviation and maritime industries, where it can help mitigate the output of greenhouse gases and other pollutants (Bergero et al., 2023; Sürer and Arat, 2022). Nonetheless, to fully leverage the potential of hydrogen, ongoing research and technological development are essential. This work is crucial for overcoming challenges related to hydrogen storage, conversion efficiency, and the assessment of environmental impacts (Le et al., 2024). Addressing these issues is key to maximizing the role of hydrogen in global efforts to reduce emissions and transition toward a more sustainable energy landscape (Ajanovic and Haas, 2021). Additionally, hydrogen can serve as a versatile energy storage medium, enabling the effective harnessing of intermittent renewable energy sources (Fokkema et al., 2022; Gabrielli et al., 2020). By storing excess energy produced during peak generation periods and releasing it on demand, hydrogen can facilitate a more stable and reliable energy supply, further supporting the integration of renewables into the energy network (Mayyas et al., 2020).

In conclusion, the adoption of hydrogen as a viable fuel source is instrumental in reducing dependence on fossil fuels and transitioning toward a low-carbon economy. Its capacity to integrate seamlessly with renewable energy strategies enhances its potential as a cornerstone of sustainable mobility and energy systems. As technologies in hydrogen production, fuel cell efficiency, and internal combustion engine adaptation continue to advance and as economies of scale improve, hydrogen is poised to play an increasingly vital role in the global energy landscape, particularly in sectors where direct electrification poses significant challenges.

1.2. Importance of life cycle assessment

Life cycle assessment (LCA) is an essential methodology for evaluating the environmental and economic impacts of hydrogen as a transportation fuel from production to disposal (Liu et al., 2023). It provides a comprehensive view, helping identify the most sustainable and cost-effective strategies in hydrogen production, whether through SMR or electrolysis (Bai et al., 2024; Spath and Mann, 2000). While SMR is currently more cost-effective but less environmentally friendly, electrolysis, especially when powered by renewable sources, offers significant long-term environmental benefits despite its higher initial costs. Life cycle cost (LCC) integrated into LCA also examines economic implications, balancing upfront investments against long-term operational savings and environmental benefits.

Wang et al. (2024) analyzed the economic viability of HFCVs in the UK's heavy-duty vehicle sector and reported that the total cost of ownership (TCO) for HFCVs is currently 37%–78% higher than that of internal combustion engine vehicles (ICEVs). The study suggests that to achieve cost parity with ICEVs, the price of fuel cell systems must decrease by 60%, targeting a future cost of 110 GBP/kWe. It also highlights that the analysis does not include the costs of refueling infrastructure, which could impact economic assessments. Additionally, operational expenses, particularly fuel prices, are noted as significant factors affecting the TCO for heavy-duty HFCVs because of their longer operational ranges and heavier payloads (Wang et al., 2024).

The distribution and storage of hydrogen also require careful analysis because of its various economic and environmental impacts. LCA helps compare the feasibility and sustainability of different methods, such as pipelines, road delivery, or cryogenic liquefaction. In the transportation sector, hydrogen is employed in various forms, including in fuel cell vehicles (Tanç et al., 2019), hydrogen internal combustion engines (Boretti, 2020), hydrogen-powered marine vessels (Melideo and Desideri, 2024), and alternative fuels in aircraft (Adler and Martins, 2023), each offering distinct environmental advantages. Notably, fuel cell vehicles emit only water during operation, highlighting their clean energy benefits. However, to gain a comprehensive understanding of the environmental and economic impacts of hydrogen, LCA is essential. LCA evaluates the emissions and economic indicators throughout all stages of the hydrogen life cycle, including production and recycling, and provides a comparative analysis against other vehicle technologies (Bai et al., 2024).

Solomon et al. (2024) assessed the levelized cost of hydrogen transportation (LCOHT) within the European context, analyzing five modes of hydrogen delivery. The study reveals that LCOHT varies from 0.3 to 3.44 EUR/(kg H_2), influenced by delivery distances from 25 to 500 km and hydrogen demands of up to 100,000 kg/day. For demands up to 30,000 kg/day, gas trailers prove to be the most cost-effective option, with the 350-bar trailer optimal for distances up to 350 km and the 540-bar trailer more suitable for longer distances. For higher demands, pipeline delivery becomes more effective, particularly for the 100 mm diameter pipeline for shorter distances and the 200 mm diameter pipeline for the shortest routes at maximum demands. Bai et al. (2024) conducted a study on 17 different hydrogen supply pathways under the renewable energy, energy storage media, transportation options, automotive powertrain (RETA) framework, connecting renewable energy generation in western China to automotive use in eastern China. The analysis of the cost structure for HFCVs reveals that both the hydrogen production and refueling stages contribute approximately 40% of the total costs. Moreover, hydrogen production costs dominate the expenses across all hydrogen-based pathways, with some, such as the GH_2 pipeline, accounting for more than half of the well-to-wheel (WTW) costs. Storage costs remain minimal across these pathways, facilitated by the use of large-volume, low-cost hydrogen storage systems.

Hydrogen production facilities are required to adhere to strict emission intensity thresholds to align with environmental and sustainability goals (Climate Bonds, 2022). The initial target of 3.0 kg CO_2eq/(kg H_2), set for certification, is derived from the EU taxonomy. Future targets are shaped by guidance from the Hydrogen Council's decarbonization report, with the 2030 threshold set at 1.5 kg CO_2eq/(kg H_2) and the 2040 threshold further reduced to 0.7 kg CO_2eq/(kg H_2). By 2050, the emission intensity for hydrogen production is expected to approach zero. These progressively stringent benchmarks reflect a trajectory toward minimizing emissions incentivized by current and emerging technologies. Compliance with these thresholds requires validation through a LCA that encompasses cradle-to-gate and delivery emissions, with results audited by an independent third party.Ultimately, the insights from LCA can guide policymakers and industry leaders in shaping effective strategies and regulations for implementing hydrogen technologies. By highlighting the trade-offs and synergies between economic costs and environmental impacts, LCA supports the development of a transportation sector that is both economically viable and environmentally sustainable. This comprehensive analysis paves the way for informed decision-making and the promotion of hydrogen as a key component in the transition to a low-carbon future.

1.3. Challenges and opportunities in hydrogen mobility

Hydrogen mobility presents a promising avenue for sustainable transportation; however, it faces a range of significant challenges. The production of hydrogen, especially through methods such as electrolysis, requires substantial energy inputs and incurs high costs, which challenge both its economic and environmental sustainability (Acar and Dincer, 2019; Yu et al., 2021). Additionally, the adoption of hydrogen as a fuel necessitates the development of extensive infrastructure, including hydrogen refueling stations, which demand significant capital investment and involve complex logistical planning (Zhao and Liu, 2024). One of the critical, yet often overlooked, aspects of hydrogen mobility is the delivery and storage of hydrogen (Ahn et al., 2024). Some renewable hydrogen production sites, often located far from points of use in the transportation sector, necessitate robust and efficient distribution solutions that can handle the high flammability and high-pressure storage requirements of fuel (Hermesmann et al., 2023; Yu et al., 2024). The geographical and environmental conditions between these points can significantly impact the viability and safety of these delivery solutions (Moradi and Groth, 2019). Moreover, various hydrogen supply structures and storage solutions play pivotal roles in the overall environmental and economic impact of hydrogen mobility (Pu et al., 2024; Sgarbossa et al., 2023). Most LCA studies lack a comprehensive, accurate, and practical framework to evaluate these aspects thoroughly, often overlooking crucial details that are vital for the effective implementation and scalability of hydrogen mobility solutions (Akhtar et al., 2021; Apostolou, 2021; Radner et al., 2024). In the push to promote hydrogen as an alternative fuel to reduce emissions in the transportation sector, the demand side faces significant challenges, including insufficient market penetration of hydrogen fuel cell vehicles and hydrogen internal combustion engine vehicles, as well as technical and cost barriers in retrofitting existing traditional internal combustion engine vehicles to utilize hydrogen (Reigstad et al., 2022; Terlouw et al., 2024). Additionally, the adoption of hydrogen vehicles competes with other emerging clean technologies, such as electric vehicles, and is constrained by the maturity and specific application scenarios of various hydrogen technologies (Liu et al., 2023, 2024a, 2025; Parikh et al., 2023).

Despite these challenges, hydrogen mobility holds substantial potential for decarbonizing the transportation sector, which is a major contributor to global carbon emissions (Fang et al., 2023). The ability to produce hydrogen from a variety of renewable sources reduces reliance on fossil fuels and enhances energy security. Technological advancements could lead to reduced production costs, enhanced safety measures, and increased operational efficiency, all of which are essential for the broader adoption of hydrogen fuel (Bhandari and Adhikari, 2024).

The effectiveness of policy frameworks in supporting hydrogen mobility is evident from research findings. Stechemesser et al. (2024), who reviewed 1500 climate policies over 25 years, demonstrated that strategic policy frameworks can significantly reduce emissions. This study particularly highlights the success of policies such as the UK's phased elimination of coal-fired power plants, which was supported by a carbon pricing mechanism and achieved substantial reductions in greenhouse gas emissions. These results highlight the importance of implementing tailored policy mixes that are sensitive to the unique needs of different industrial and economic contexts, aligning with the emission reduction targets established by the Paris Agreement. This mix of challenges and opportunities underscores the need for a coordinated approach that integrates robust policy support, technological innovation, and public engagement to fully harness the potential of hydrogen to sustainably transform transportation.

1.4. Aims and research questions of the review

The imperative to decarbonize the transportation sector is urgent. Among potential solutions, hydrogen has unique, irreplaceable advantages. Specifically, it offers high energy efficiency and the capacity for rapid refueling, properties not as effectively matched by other alternative fuels. Furthermore, the existing challenges and difficulties associated with hydrogen implementation are surmountable, establishing hydrogen as a formidable candidate for alternative fuels. This underscores the reason for selecting hydrogen as the focus of this study. Despite its significant advantages, the current contribution of hydrogen to emission reduction in transportation remains minimal (Bencekri et al., 2023). There is a critical need to review and understand the full LCA from production to usage, as well as other pertinent studies, to identify the core developmental obstacles. The research questions guiding this review are as follows:

What is the scientific framework for LCA studies of hydrogen as an alternative fuel in transportation?

What are the primary obstacles to the development of hydrogen mobility, and what potential solutions exist?

How do policy frameworks, supply-demand dynamics, and economic considerations influence the adoption and scalability of hydrogen in transportation?

These questions aim to dissect the layers of complexity within the hydrogen life cycle and propose actionable solutions to enhance its role in decarbonizing transportation.

1.5. Originality and structure of the review

Prior research has thoroughly analyzed the hydrogen supply chain and its application in the transportation sector. Despite this, the current review offers a refreshed perspective by focusing on the “well-to-wheel” (WTW) perspective to explore the difficulties and barriers associated with advancing hydrogen as a sustainable transportation fuel. This approach encompasses the entire chain from hydrogen production to its ultimate use and examines the key technological and strategic issues that affect its widespread adoption. This review updates the understanding of obstacles to hydrogen mobility, providing an analysis on the basis of the latest data and research findings. The innovations in this review are listed below:

Holistic perspective: This review expands its scope to encompass the complete WTW life cycle, explicitly incorporating all stages and essential infrastructure required for hydrogen mobility. This approach is taken to effectively differentiate this article, which is a review focused on studying hydrogen mobility and its LCA, from reviews that solely examine hydrogen production. Beyond conventional metrics: It extends the analysis beyond traditional factors like emissions and economics to include the impacts of policy, supply and demand dynamics, and other interconnected elements that influence hydrogen's deployment in transportation.

Introduction of a surface-level LCA framework: A new “surface-level” LCA framework is introduced, designed to support and enhance the LCA model for hydrogen use in transportation, with a special focus on renewable hydrogen. This holistic LCA approach aims to assess the environmental impacts of hydrogen more accurately and support the development of related policies and technological advancements.

Unified flexibility approach: This review emphasizes the importance of considering geographic and environmental diversity, advocating for a unified and clear strategy that addresses flexibility on both the supply and demand sides of the hydrogen market. This strategic consideration is crucial for promoting the sustainable application of hydrogen globally, particularly in the transportation sector.

These innovative points collectively address existing gaps in hydrogen mobility research and propose a comprehensive framework for the future development of the hydrogen industry. By considering a wider range of factors and introducing new methodologies, this review sets the stage for more sustainable and effective hydrogen applications in transportation, fostering a robust foundation for industry growth.

The remainder of this review is organized as follows: Section 2 introduces the methodology used for the literature review. Section 3 presents the analysis and conclusions derived from the review of LCA. Section 4 discusses the barriers and difficulties associated with using hydrogen to reduce transportation emissions. Section 5 offers a comprehensive discussion and forward-looking recommendations. Finally, Section 6 concludes the review, summarizing the key findings.

2. Methodology for literature review

A literature review is crucial in research and decision-making processes, as it consolidates existing studies to establish a foundation of knowledge, identifies gaps in research, and guides future inquiries (Paul et al., 2021). The primary types of literature reviews include narrative reviews, which rely on the author's expertise; systematic reviews, which use a rigorous method to minimize bias; meta-analyses, which quantitatively synthesize multiple studies; and scoping reviews, which map out major concepts and evidence in a field.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines have evolved to ensure transparency and replicability in research reporting. Originating from the Quality of Reporting of Meta-analyses (QUOROM) statement in 1999 (Moher et al., 1999), PRISMA was introduced in 2009 to increase the reporting quality of systematic reviews and meta-analyses (Liberati et al., 2009). It was later supplemented by PRISMA-P in 2015 for protocols (Moher et al., 2015) and updated in 2020 to include more detailed guidelines on research processes (Page et al., 2021a). The development of the PRISMA underscores the scientific community's commitment to improving research quality and credibility through standardized reporting.

Although PRISMA was initially developed to guide the reporting of systematic reviews and meta-analyses, specifically in the fields of medicine and health sciences, its application has significantly broadened over time. Today, PRISMA is widely employed across various disciplines beyond its original scope. Researchers in fields such as social sciences (Ar et al., 2024), environmental studies (Aigwi et al., 2023), and engineering (Liu et al., 2024b) now utilize the PRISMA guidelines to increase the transparency and rigour of their systematic reviews. This expansion reflects the universal need for clear and replicable research methodologies, demonstrating how the principles of PRISMA have been effectively adapted to meet diverse research requirements across different scientific domains.

2.1. Primary procedure: PRISMA methodology

2.1.1. Eligibility and ineligibility criteria

To thoroughly explore the LCA, technological innovations, policy frameworks, and infrastructure development of hydrogen mobility, the original eligibility and ineligibility criteria for the literature review must be meticulously selected. These adjustments ensure that the selected studies comprehensively cover the entire process from production to usage and focus specifically on the applications and challenges of hydrogen in reducing carbon emissions in the transportation sector. The criteria are as follows:

Eligibility criteria.

1) Comprehensive LCA studies: Only studies that perform an exhaustive LCA of hydrogen mobility systems, particularly those that cover both the WTT and TTW phases.
2) Technological innovations and future pathways: Research exploring technological advancements and future pathways that could increase the efficiency and adoption of hydrogen mobility.
3) Environmental and economic impact studies: Studies that aim to analyze both the environmental impacts and economic implications throughout the entire life cycle of hydrogen mobility solutions comprehensively whenever possible.
4) Policy and infrastructure analysis: This research addresses policy frameworks, infrastructure development, and economic factors that influence the scalability and practical implementation of hydrogen as a transportation fuel.

Ineligibility criteria.

1) Studies limited to nonhydrogen energy sources: Research focusing exclusively on alternative forms of mobility or energy sources other than hydrogen, unless they provide a direct comparative analysis with hydrogen mobility.
2) Market-only analyses: Studies that focus solely on market trends and consumer behavior without integrating LCA or technological insights specific to hydrogen mobility.
3) General environmental or economic studies: Studies that do not specifically address the life cycle, policy impacts, or economic challenges related to hydrogen mobility.
4) Outdated studies: Research that is more than 10 years old is excluded unless it is considered seminal work within the field of hydrogen mobility to ensure that the review reflects the latest advancements and data.

2.1.2. Selection of the scientific database

For the systematic literature review (SLR) conducted in this study, aimed at addressing the research questions and achieving the objectives outlined, a carefully planned search strategy was executed. The choice of database was critical to ensuring comprehensive coverage and access to pertinent scientific articles. The Web of Science (WoS) was selected as the sole database for this SLR because of its extensive indexing of journals and the availability of quality metrics such as impact factors, which are calculated annually in the Journal Citation Report. The search was carried out up to August 15, 2024, ensuring that the most recent and relevant studies were included.

The decision to use the WoS as the primary source for literature retrieval was based on several considerations, including its extensive coverage across diverse academic disciplines, the availability of detailed metadata essential for reference analysis, and its compatibility with various bibliometric and reference management tools. The detailed metadata provided by the WoS, such as titles, abstracts, keywords, publication years, citation counts, lists of authors, and countries, enable a comprehensive and nuanced analysis of the scholarly landscape. Additionally, the WoS is renowned for its reliability in capturing high-quality scholarly literature, making it an ideal resource for conducting detailed and comprehensive reviews, particularly in alignment with the thematic focus of this study.

To enhance the depth and breadth of the literature review, citation analysis will also be conducted using the papers retrieved from the WoS. This method helps identify seminal works and the most influential studies within the field, providing insights into the development of research trends and the evolution of academic discourse. Furthermore, a secondary search will be performed to expand the review's literature base. This secondary search involves examining the references of key studies to uncover additional relevant articles that may not have been directly indexed in the WoS. This approach ensures more exhaustive coverage of the topic, capturing a wider array of perspectives and contributions that may be critical for a holistic understanding of the subject matter. The specific search results and screening process are presented in Fig. 1, with the involved data and corresponding explanations further elaborated in the subsequent methodology section.

2.1.3. Sampling procedure

The literature search results for this study were retrieved primarily

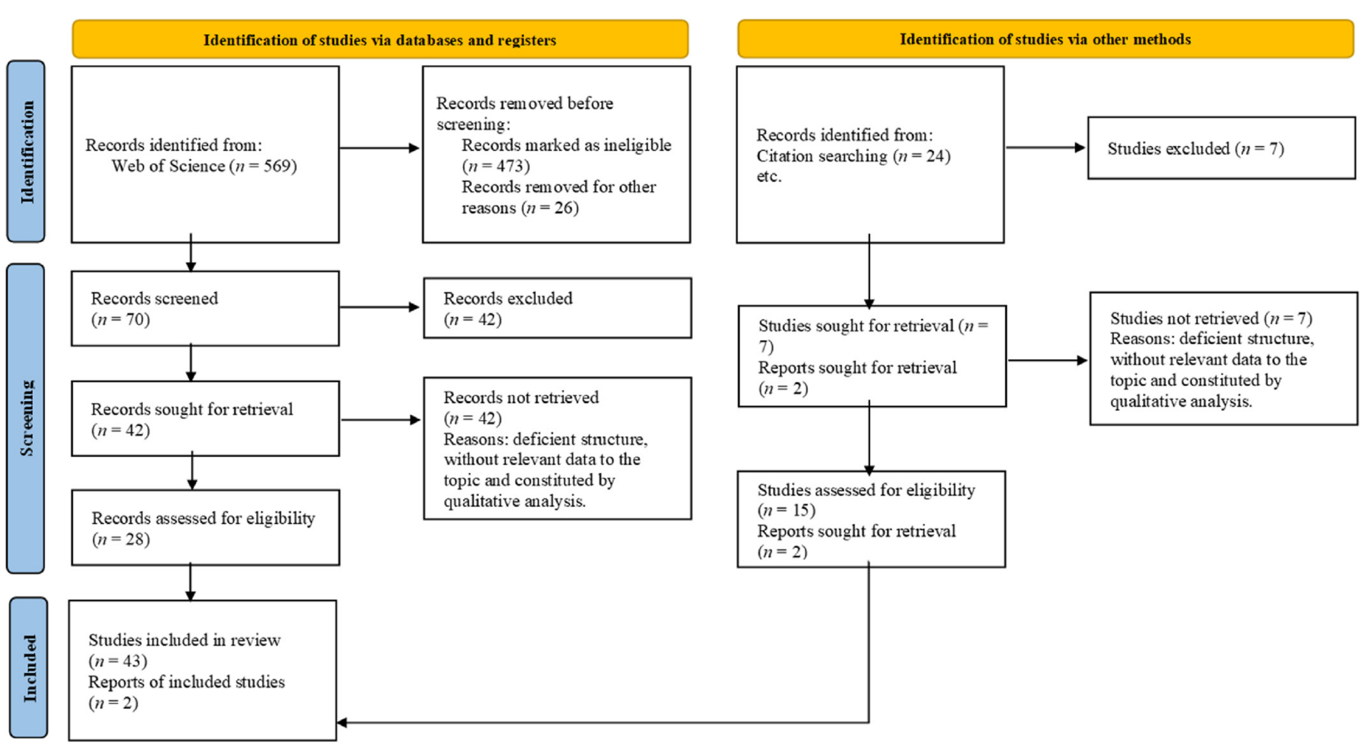

Fig. 1. PRISMA flow diagram.

from the WoS platform. Given that the goal of this study was to thoroughly investigate the life cycle impacts, technological breakthroughs, and policy strategies pertinent to hydrogen mobility, a meticulous search strategy was crafted to capture a broad spectrum of research topics and potential developments. The primary keywords were linked via "AND" to combine essential concepts, whereas different expressions and synonyms of the keywords were connected via "OR" to broaden the search scope. The advanced search string was as follows: TS = "hydrogen mobility" OR "hydrogen transport" OR "hydrogen vehicles" OR "hydrogen marine transport" OR "hydrogen in aviation") AND (TS = ("life cycle assessment" OR "LCA") OR TS = ("barriers" OR "challenges" OR "gaps") OR TS = ("future" OR "recommendations" OR "prospects")).

The use of "OR" to connect the themes TS=("life cycle assessment" OR "LCA"), TS=("barriers" OR "challenges" OR "gaps"), and TS=("future" OR "recommendations" OR "prospects") in the search strategy is essential for ensuring a comprehensive and inclusive approach. This method captures a broad spectrum of studies, encompassing not only life cycle assessments but also research specifically addressing future prospects, recommendations, and the identification of barriers and challenges that may not be covered in LCA studies. By employing "OR" rather than "AND", the search avoids excluding relevant studies that do not simultaneously discuss all these aspects, thereby enhancing the rigor and reliability of the research by ensuring that all pertinent insights and critical perspectives are considered. This approach is crucial for developing a thorough understanding of the diverse issues influencing hydrogen mobility.

The literature search conducted on the WoS returned a total of 569 articles related to hydrogen use in the transport sector with LCA, focusing on aspects such as the environment, economic influences, etc. Following these stringent eligibility and ineligibility criteria ensures that the studies selected for Table 1 are highly relevant and detailed, directly addressing the multifaceted aspects of hydrogen mobility from technological innovations to life cycle assessments. However, for the broader narrative and themes of the article, the scope of review has expanded. This means that while the core data for Table 1 are extracted from studies that meet all specified criteria, additional literature that may focus exclusively on either the economic or environmental aspects of hydrogen mobility is also considered to ensure a comprehensive understanding of the subject matter within the overall review.

The selection of the 43 studies from the initial pool of 569 articles ensures that the most relevant and high-quality research is included in Table 1 for detailed information collection. These studies were meticulously chosen on the basis of their direct relevance to hydrogen use in the transportation sector, ensuring that each article significantly contributes to the objectives of this review. The rigorous screening process adhered to the PRISMA (Page et al., 2021b) guidelines and guaranteed that only studies with substantial insights into the environmental and economic impacts of hydrogen in transportation were selected. This careful curation helps provide a focused and valuable analysis of the current state of hydrogen application in the sector.

Furthermore, the inclusion of over 200 articles in the review after secondary searches, including citations and other methods, indicates a comprehensive and extensive examination of the literature. This expanded scope allowed for a thorough synthesis of the broader context and nuances surrounding the role of hydrogen in transportation, enriching the overall findings and discussions presented in the review.

2.1.4. Reference analysis

The literature review leverages Zotero and Microsoft Excel 2019 for detailed management and systematic analysis of the studies, with a focus on differentiating research by geographical region, data year, scope within the hydrogen supply chain, and the inclusion of usage phases and other indirectly related factors. Each article is cataloged with a focus on these dimensions, in addition to standard methodological elements such as assessment tools and settings. This organization aids in identifying temporal and regional trends, as well as variations in research focus across different segments of the hydrogen supply chain.

By expanding the analysis to cover specific segments of the hydrogen supply chain or its entirety, the review addresses a comprehensive array of issues, from production and distribution to storage and end-use. This includes an evaluation of the technological, economic, and regulatory factors that influence the scalability and viability of hydrogen-based systems. The review also considers indirect factors such as environmental impacts during the usage phase and potential social implications, providing a holistic view of the challenges and solutions associated with hydrogen mobility. This broader perspective allows for a more detailed understanding of how different factors interact to affect the advancement of hydrogen technologies in the context of global decarbonization efforts.

2.1.5. Content analysis

In the systematic literature review, each article included in the final sample was meticulously cataloged via Zotero software, which effectively managed the metadata sourced from the selected scientific database. For the content analysis, the articles were strategically classified to distinguish between those that focused on LCA and those that extended into different types of research related to the field.

Within the LCA-focused studies, further categorization was applied on the basis of geographical location, time frame, and specific segments of the hydrogen supply chain. This methodical classification allows for a nuanced understanding of the variations and commonalities in LCA methodologies across different regions and periods. It also helps in identifying the scope of application, relevant industries, and distinct objectives of each study. Moreover, the advantages and limitations of the processes used to derive research results were critically evaluated to provide a comprehensive overview and insightful analysis of the literature. This structured approach using Zotero not only facilitated efficient data management but also enhanced the depth and breadth of the content analysis in this review.

2.2. Secondary procedure: critical (interpretive) analysis

Critical analysis is a pivotal research technique designed to dissect and interpret complex issues, facilitating a deeper understanding of specific conditions and challenges (Gil-Guirado et al., 2021). In this study, critical analysis was employed to intricately explore the hurdles associated with the use of hydrogen in the transportation sector, not merely focusing on its production. This method involves several iterative cycles of interpreting and understanding segments of the phenomenon, which collectively enhance comprehension of the broader context (Valor et al., 2018).

The goal of this analysis was not to develop a new theory but to refine the understanding of the specific barriers to hydrogen adoption in transportation. Each researcher involved in the study engaged in continuous cycles of reflection and discussion, aiming for a "cognitive fusion" that yields a more refined grasp of the phenomena under study. This iterative process facilitated the identification and detailed classification of the barriers, making it possible to pinpoint specific difficulties and challenges more precisely.

The initial cycle involved a rigorous review, synthesis, and interpretation of the articles selected through the structured PRISMA procedure. This was followed by a collaborative critical process in subsequent cycles, where the main methodological features were dissected on the basis of the identified categories of barriers. Each cycle contributed progressively to a more nuanced understanding of the issues, culminating in a final interpretive cycle where insights from earlier phases were integrated. This comprehensive approach allowed for a layered understanding of the barriers to hydrogen use in transportation, highlighting the complexities and offering clearer pathways for addressing these challenges.

2.3. Risk of bias

The methodological quality of the articles included in the study was

Table 1
Key parameters of hydrogen energy application in the transportation sector.

Ref.	Area or delivery line	Time horizon/ reference year	Energy resource	H_2 production method	H_2 storage method	H_2 delivery mode	Delivery distance	Powertrain
Ahn et al. (2024)	Australia–Republic of Korea	2018	RE	WE	[CS] TOL-MCH	Ship	4500 nautical miles	—
Balaji and You (2024)	30 coastal states in USA	2050	Offshore wind	WE	[PS] LH_2, CGH_2	Ship, pipeline	100 km	—
Radner et al. (2024)	Austria, Croatia, Chile, Egypt, Tunisia, and the United Arab Emirates	2022	Off-grid wind and PV	WE	[PS] LH_2, [CS] LOHC, NH_3	Ship, pipeline	350–1850 km	—
Bai et al. (2024)	Northwestern China–Shanghai	—	RE	AWE	[PS] LH_2, CGH_2	Tube trailer, LH2 truck, H2 pipeline, NG pipeline, UHV	2000 km	HFCV
Solomon et al. (2024)	Europe	—	—	—	[PS] CGH_2	Truck, pipeline	25–500 km	—
Genovese et al. (2024c)	Southern Italy	2023	Average grid mix	WE	[PS] LH_2, CGH_2	Railway	4.7–119.93 km	HFCV, HFCEA
Zhou et al. (2024)	China	2050	Fossil fuel, RE	SMR, SMR-CCS, CG, CG-CCS, WE	[PS] CGH_2	Tube trailer	100–3000 km	HFCV
Candelaresi et al. (2023)	Italy	2025	Wind power	WE	[PS] CGH_2	Pipeline	100 km	HFCV
Noh et al. (2023)	Australia–Republic of Korea	—	Offshore wind, average grid mix	WE	[PS] LH_2, CGH_2, [CS] LOHC, NH_3	Ship	100–10,000 km	Ship
Kanz et al. (2023b)	Africa–Germany	2030	PV	WE	[PS] CGH_2	Pipeline	3,000, 5,500, 6700 km	—
Hren et al. (2023)	Slovenian, Europe	2019, 2020, 2021, 2050	Average grid mix, biomass	SMR, BG, BSR, BAR, SR-AW, SR-G, AG2S, AO, WE, DF, ICL	[PS] CGH_2, LH_2, CCH, [CS] MH, LOHC, CNs, MOFs	Ship, pipeline, lorry, train	100 km	—
Kanz et al. (2023a)	Africa, Germany, Africa–Germany	—	PV	WE	[PS] LH_2	Ship	300 km	—
Dulău (2023)	Romania	2022	Coal and natural gas, wind, solar, and hydro	SMR, WE	—	—	—	HFCV
Anastasiadis et al. (2023)	Island of Sifnos	2020	Wind, PV	WE	—	—	—	HFCV
Lundblad et al. (2023)	Sweden	2019, 2050	Wind, PV, average grid mix	WE	[PS] CGH_2	Truck	50–500 km	HFCV
Akdağ (2023)	Turkey	2023, 2050	Offshore wind	WE	—	—	—	HFCV
Hermesmann et al. (2023)	Germany	2040	Wind, solar	WE	[PS] CGH_2	Pipeline	1000–4000 km	—
Godinho et al. (2023)	Sines–Rotterdam	2030–2050	RE	WE	[CS] LOHC	Ship	2060 km	—
Wang et al. (2023)	Dalian, China	—	Fossil fuel, biomass	SMR, CG, COG, PDH, WE, BG	[PS] LH_2	Pipeline, tube trailer, LH2 tanker	50–1000 km	Ship
Miller et al. (2023)	USA	2050	Fossil fuel, RE, biomass	WE, Thermalchemical processes	[PS] LH_2	—	—	Aviation
Li et al. (2024)	France	—	NG, average grid, biomass	SMR (CCS), WE, BG	[PS] LH_2, CGH_2	Tube trailer, tanker truck	—	Road transportation
Johnston et al. (2022)	Potential export nations (Australia, Saudi Arabia, Chile, USA, and Algeria)–potential import markets (Europe and Asia)	—	—	—	[PS] LH_2, [CS] NH_3, LNG, CH_3OH, LOHCs	Ship	1773–10,850 nautical miles	—
Lee et al. (2022)	Melbourne, Australia–Seoul, Republic of Korea	2018	Fossil fuel, average grid mix	SMR, WE, CG, SMR-CCUS, CG-CCUS	[PS] LH_2, [CS] NH_3, TOL-MCH, H_0DBT-H_{18}DBT, methanol	Ship, pipeline	5700 km (seaborne delivery distance) + 104 km (pipeline)	—
Burchart et al. (2023)	Poland	—	Coal	CG, CG-CCS	[PS] CGH_2	Truck	300 km	HFCV
Di Lullo et al. (2022)	—	—	—	—	[PS] LH_2, [CS] LOHC, NH_3, hythane	Pipeline, truck, railway	100, 1,000, 3000 km	—

(continued on next page)

Table 1 (*continued*)

Ref.	Area or delivery line	Time horizon/ reference year	Energy resource	H_2 production method	H_2 storage method	H_2 delivery mode	Delivery distance	Powertrain
Akhtar et al. (2021)	—	—	Wind	WE	[PS] CGH_2, [CS] LOHC, LNH_3	Pipeline, tube trailer	100, 400 km	HFCV
Candelaresi et al. (2021)	Europe	—	Wind	WE	[PS] CGH_2	Road delivery	100 km	HFCV
Machhammer et al. (2021)	Germany	2030	Wind, NG	SMR, WE	—	Pipeline, tube trailer	< 50 km	—
Apostolou (2021)	Huesca, Spain	—	—	WE	[PS] CGH_2, [CS] WH	Tube trailer	—	HFCV
Reuβ et al. (2021)	Germany	2050	54% of the energy from renewables curtailed	WE	[PS] LH_2, CGH_2, [CS] LOHC	Tube trailer	0–735 km	HFCV
Liu and Liu (2021)	China	2030	Coal	UCG, SCG	—	—	—	—
Delpierre et al. (2021)	the Netherlands	2050	Wind	WE	—	—	—	—
Amaya-Santos et al. (2021)	UK	2030, 2050	Coal, RE, biomass	SMR, ATR, WE, CG	—	—	—	—
Kim et al. (2021)	Indonesia–Republic of Korea	2030	NG, coal	SMR-CCS, CG-CCS	[PS] LH_2, [CS] LOHC, NH_3	Ship, pipeline, tube trailer,	5000 km (ship) + 100 (pipeline/ trailer) km	—
Siddiqui and Dincer (2021)	—	—	Fossil fuel, RE	HC, SBE	[PS] LH_2	—	—	Aviation
Navas-Anguita et al. (2020)	Spain	2020–2050	Fossil fuel, wind, solar, biomass	SMR-CCS, CG-CCS, WE, BG	—	—	—	Road transportation
Wulf and Zapp (2018)	Germany	2050	Wind	WE	[PS] LH_2, [CS] LOHC (DBT, TOL)	Truck	>400 km	HFCV
Wulf and Kaltschmitt (2018)	Germany	2032	Wind, solar, fossil fuel, biomass energy	SMR, WE, CG, WG, BF, HTE, CAP	[PS] CGH_2, [CS] LOHC	Truck, ship	20–250 km	HFCV
Bicer and Dincer (2018)	EU	—	Fossile fuel, solar PV, renewable mix and nuclear electricity	WE, HTC	[PS] CGH_2	—	—	HFCV
Wulf et al. (2018)	Germany	2050	Wind	WE	[PS] CGH_2 (cavern), [CS] LOHC	Pipeline, trailer	100, 400 km	HFCV
Bicer and Dincer (2017)	Europe	–	Fossil fuel, RE	HC, SBE, CG-CCS	[PS] LH_2, [CS] NH_3, methanol	—	—	Aviation
Burkhardt et al. (2016)	Berlin, Germany	2010–2015	Wind	WE	[PS] CGH_2	—	—	HFCV
Pereira et al. (2014)	Portugal	2011	NG	SMR	[PS] LH_2, [CS] LOHC, NH_3, hythane	Truck, ship	—	Aviation

evaluated via the Prediction Study Trend Risk Assessment Tool (PROBAST) (Aboud and Diab, 2019). This tool organizes the assessment into four domains—participants, predictors, outcomes, and analysis—with each domain's risk of bias classified as either low, high, or unclear. This structured approach facilitates a comprehensive evaluation of the articles' methodological rigor. Each article's risk of bias was independently assessed by two researchers employing the PROBAST tool to ensure objective analysis. Discrepancies in the assessments were resolved through discussion, and if unresolved, a third reviewer was consulted to achieve consensus.

3. Life cycle assessment of hydrogen mobility

3.1. Methodologies in life cycle assessment for hydrogen mobility

LCA is a comprehensive methodological framework used to evaluate the environmental impacts associated with all stages of a product's life cycle, from raw material extraction ("cradle") to disposal ("grave") (Bhatt et al., 2019). Typically, LCA includes four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. This methodology provides a systematic approach to quantifying ecological burdens, such as energy consumption, greenhouse gas emissions, and resource depletion, throughout a product's life cycle. LCA is especially critical in comparing different technologies or pathways, helping decision-makers understand the full environmental impact, beyond just operational emissions or efficiency (Rebitzer et al., 2004).

The strength of LCA lies in its holistic perspective (Zamagni et al., 2013). Instead of focusing solely on the product's usage phase, LCA considers upstream and downstream processes, including raw material production, delivery, and end-of-life disposal. This holistic approach is particularly vital when assessing technologies such as hydrogen mobility, where operational benefits, such as zero tailpipe emissions, must be weighed against the environmental impacts of hydrogen production, distribution, and infrastructure development. For example, while hydrogen-powered vehicles produce no direct emissions, LCA can reveal the environmental burdens associated with hydrogen production methods, such as CO_2 emissions from SMR or the energy-intensive nature of electrolysis, depending on the energy mix used.

Additionally, LCA can be extended to include economic considerations through Life Cycle Cost Analysis (LCCA), which maps the economic expenses of a system (e.g., material costs, operational costs, and infrastructure investments) alongside its environmental impacts (Yu et al., 2013). This integrated approach is particularly valuable for policy-making, as it allows stakeholders to balance environmental sustainability with economic viability (Huang et al., 2021). For example, the costs associated with producing hydrogen using renewable energy sources can be evaluated against the long-term benefits of reduced emissions, providing a more comprehensive decision-making framework.

When applying LCA to hydrogen mobility, several key factors must be carefully considered to ensure an accurate and comprehensive assessment. One of the most critical considerations is the hydrogen production pathway. Hydrogen can be produced through various methods, such as SMR, electrolysis, or biomass gasification, each with its own environmental implications. For example, SMR is currently the dominant method but is associated with significant CO_2 emissions unless combined with carbon capture and storage (CCS) technologies (Collodi et al., 2017a). In contrast, hydrogen produced via electrolysis, particularly when powered by renewable energy such as wind or solar energy, can substantially lower the carbon footprint, contributing to broader decarbonization goals. Therefore, it is essential for LCA studies to clearly define the hydrogen production method and its associated energy source, as these factors heavily influence the life cycle impact of hydrogen mobility (Rinawati et al., 2021).

Another essential aspect to consider in the LCA of hydrogen mobility is the hydrogen storage and delivery network. The design and operational efficiency of this network, which includes delivering hydrogen to refueling stations, are crucial for minimizing environmental impacts. Methods such as liquefaction and compression, which are often required for hydrogen delivery, are energy intensive and can increase the overall carbon footprint if not powered by renewable sources (Aziz, 2021). The strategic placement of production facilities close to energy sources and consumer hubs can significantly reduce delivery distances and emissions, enhancing the sustainability of hydrogen mobility (Hermesmann et al., 2023).

Additionally, the layout of the hydrogen distribution network, including the placement and efficiency of refueling stations, plays a vital role in the practical implementation of hydrogen as a transportation fuel (Li et al., 2019). Efficient integration into existing infrastructure can promote broader adoption by improving accessibility and convenience for end users. This integration requires careful planning to ensure that the refueling stations meet safety standards and are capable of handling the unique challenges of hydrogen storage and distribution (Greene et al., 2020).

In conclusion, hydrogen storage and distribution networks are pivotal components in determining the viability and environmental impact of hydrogen mobility. By addressing these logistical and infrastructural challenges within a comprehensive LCA framework, stakeholders can better understand the trade-offs involved and guide the development of a sustainable hydrogen infrastructure. This approach supports the decarbonization of the transportation sector by optimizing the use of hydrogen in alignment with regional needs and global sustainability objectives.

Fig. 2 presents a LCA framework for hydrogen use in the transportation sector, which is structured around a core system boundary delineated by a dashed line, and an external logic framework. The core boundary encapsulates the WTT and TTW phases, which are essential for assessing the entire life cycle from hydrogen production to its use in transportation. Within this framework, the stages labeled A, B, and C represent three sequentially occurring phases of the hydrogen life cycle, specifically Well-to-Gate (WTG), Gate-to-Tank (GTT), and TTW, where 'Gate' refers to the point of hydrogen delivery or transition. The external framework guides future research, providing a blueprint for

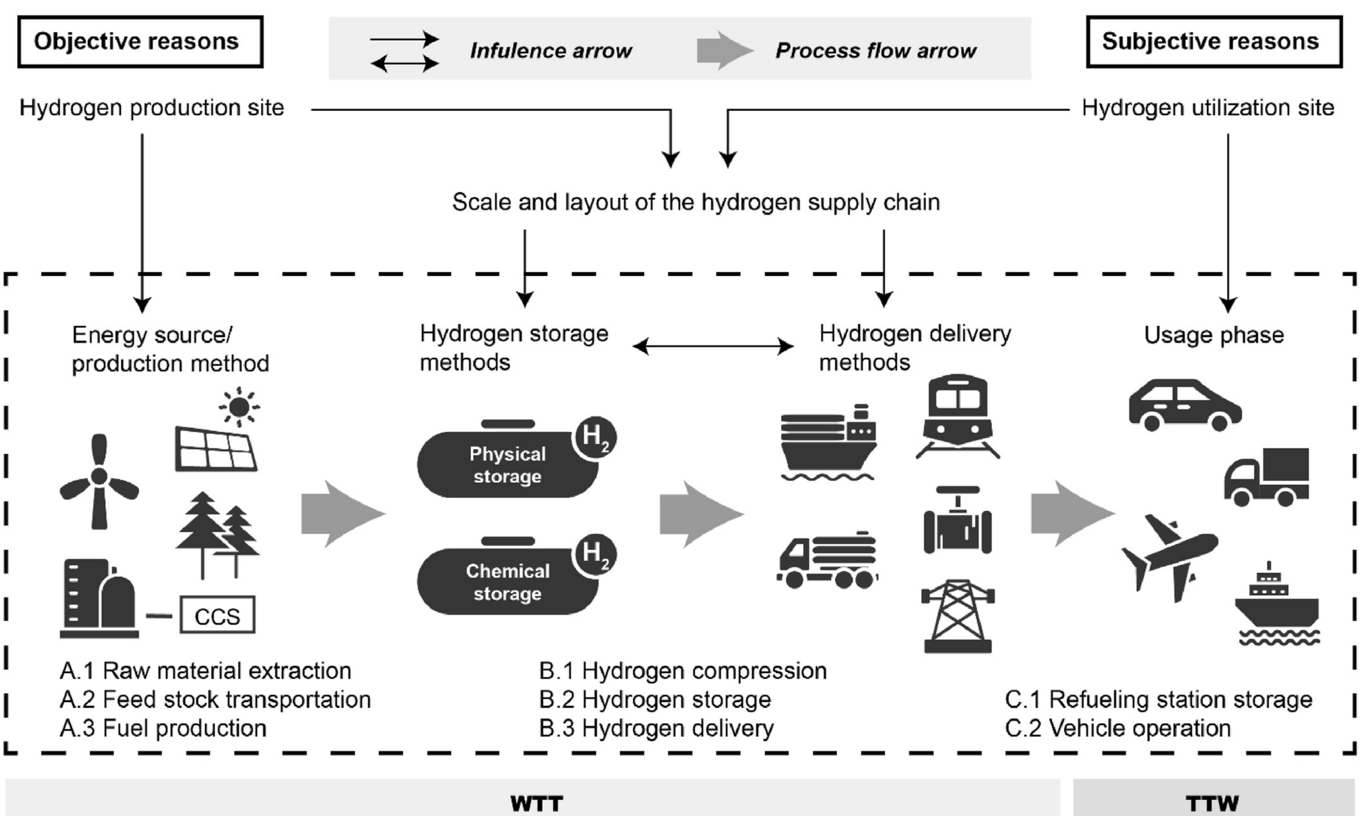

Fig. 2. Flowchart describing the phases of H_2 LCA for transport use.

incorporating both subjective factors—such as preferences for hydrogen use locations and transportation types aimed at emission reduction—and objective factors, which are influenced by geographical constraints that determine the viability of renewable energy sources such as wind, solar, and biomass.

The complex interplay between the locations of hydrogen production and consumption influences the scale and layout of the hydrogen supply chain. These logistical and geographical considerations dictate the methods of hydrogen storage and delivery, ensuring that all aspects of the supply chain are optimized for efficiency and sustainability. By integrating these elements, the framework aims to support the global shift toward sustainable energy solutions, facilitating the decarbonization of the transportation sector through strategic hydrogen use tailored to specific regional and logistical challenges.

Drawing from the LCA framework depicted in Fig. 2, Table 1 organizes critical data to reflect each phase of hydrogen mobility. By aligning the WTG, GTT, and TTW phases with specific global data on hydrogen production, storage, and distribution/delivery methods, Table 1 provides a structured and empirical basis that supports the comprehensive assessment of hydrogen use in transportation, facilitating a direct comparison and deeper understanding of regional variations and their impacts on the sustainability and efficiency of hydrogen mobility systems.

Table 1 compiles LCA research data from various global regions on hydrogen-powered transportation. The headers include area/delivery lines, time horizons/reference years, energy resources, H_2 production methods, H_2 storage methods, H_2 delivery modes, and delivery distances. Additionally, it summarizes the types of powertrains used, distinguishing between road transport, maritime shipping, and aviation, to categorize these different modes of transport. This information allows for an analysis and comparison of technological choices, energy use, and environmental effects across different regions. For example, the energy resources column reveals the primary energy types used for H_2 production, such as natural gas, wind, and solar, whereas the H_2 production methods column details various technologies, such as water electrolysis (WE) and SMR. These data points illustrate regional variations in technology preferences for hydrogen production and their potential environmental and economic impacts. Moreover, the H_2 storage methods column distinguishes between physical storage (PS) and chemical storage (CS), with abbreviations used throughout the table to maintain a compact format. The methods of hydrogen storage and delivery are crucial for assessing the feasibility of its extensive application in public and freight transport. Different storage and delivery methods play pivotal roles in the widespread adoption of hydrogen in these sectors.

Additionally, the table notes that "—" (not available) indicates instances where certain data could not be directly or indirectly obtained from the respective sources. Thus, Table 1 not only provides a snapshot of the current state of global research into hydrogen mobility systems but also helps identify technical and policy barriers in practical applications. This helps in offering data support and directional guidance for future research and implementation efforts.

The analysis of Table 1, which details hydrogen mobility configurations across different regions and timeframes, reveals several critical insights into the research landscape. Notably, studies focusing on non-road transport applications of hydrogen, such as maritime and aviation, are limited, indicating a significant gap in understanding the role of hydrogen across various transportation modes. Additionally, most research lacks a comprehensive life cycle perspective, often underestimating crucial phases such as production, storage, and delivery. These studies have focused primarily on hydrogen production, with less attention given to the complexities of real-world hydrogen logistics. There is also a geographical concentration of studies in Germany and other European countries, with few considering a global perspective that integrates potential hydrogen supply regions with consumer markets. This narrow focus might limit the broader applicability of the findings.

Furthermore, while some studies lack temporal specificity, others pinpoint significant future years such as 2050, aligning with major anticipated shifts in hydrogen infrastructure. Although hydrogen production methods are well documented, the details of storage and delivery are less explored, offering a simplified view of the supply chain and highlighting the need for more in-depth research into the complexities of hydrogen distribution networks. Overall, while existing research offers valuable insights into hydrogen production, it often falls short of the full life cycle approach necessary to optimize the role of hydrogen in sustainable mobility. Future studies need to be more diverse, comprehensive, and geographically expansive to explore the global potential of hydrogen fully.

3.2. Hydrogen production

Hydrogen is increasingly recognized as a pivotal element in the transition toward cleaner mobility solutions. It can be produced through various methods, each characterized by its primary energy source and process technology. Importantly, the environmental footprint of hydrogen production varies significantly, leading to the categorization of hydrogen into different "colors" on the basis of the carbon emissions associated with its production (Incer-Valverde et al., 2023). Green hydrogen, produced via electrolysis using renewable energy sources, emits no greenhouse gases when H_2 is used. Blue hydrogen, typically produced from natural gas where CO_2 emissions are captured and stored, and gray hydrogen, also derived from natural gas but without emission capture. Additionally, there are less common types, such as pink hydrogen, produced via nuclear-powered electrolysis, and yellow hydrogen, which uses solar energy specifically (Qureshi et al., 2022).

Broadly, hydrogen production techniques can be classified into three categories: thermochemical processes (Pandey et al., 2019), electrolytic processes (Chang and Rajuli, 2024), and biological methods (Aziz et al., 2021). Thermochemical methods include natural gas reforming, coal gasification, and biomass conversion, which are traditionally reliant on fossil fuels. On the other hand, electrolytic processes use electricity to split water into hydrogen and oxygen, and their environmental impact largely depends on the source of the electricity used. Finally, biological processes involve the use of microorganisms or enzymes to produce hydrogen from organic materials.

TÜV SÜD's CMS 70 standard (TÜV SÜD, 2021) sets rigorous criteria for certifying green hydrogen production to ensure sustainability. This standard outlines two certification types: green hydrogen and green hydrogen+. The key criteria include production being within a defined system boundary that covers the plant and ancillary units and requires a hydrogen purity of at least 99.9% by volume with an overpressure of at least 3 MPa. Compared with conventional steam methane reforming, hydrogen must reduce greenhouse gas (GHG) emissions by at least 70%, which is currently approximately 94 g CO_2eq/MJ. GreenHydrogen + adds further requirements by including hydrogen delivery to end-users and ensuring that no grid supply bottlenecks occur at commission. Both certifications adhere strictly to ISO 14040 and 14044 LCA principles and exclude hydrogen from fossil fuels, positioning this standard as a stringent and sustainable standard in hydrogen production.

The European Union's hydrogen taxonomy diagram, as part of Regulation (2020)/852, outlines criteria for classifying hydrogen production methods on the basis of their environmental impact. To qualify as sustainable, hydrogen must be produced from renewable nonfossil sources, resulting in power generation emissions of less than 100 g CO_2eq/kWh. Additionally, its life cycle must achieve a significant reduction in greenhouse gas emissions—73.4% less GHG for hydrogen or 70% less for hydrogen-based synthetic fuels compared with a fossil fuel comparator of 94 g CO_2eq/MJ. If these criteria are not met but hydrogen production still results in less than 36.4 g CO_2eq/MJ emissions, it can be classified as low carbon. This taxonomy helps guide and regulate the development of hydrogen projects to ensure that they contribute effectively to the EU's sustainability and low-carbon objectives (UNECE, 2022).

During the 31st meeting of the Sustainable Energy Committee on

September 22, 2022, it was resolved to extend the United Nations Framework Classification (UNFC) to hydrogen energy, emphasizing the role of hydrogen in achieving a low-carbon, resilient energy system and aiding the transition toward net-zero emissions. The meeting highlighted a taxonomy of hydrogen types—ranging from fossil-based black and gray hydrogen to low-carbon blue hydrogen and renewable green hydrogen—reflecting a shift toward cleaner energy production methods (UNECE, 2022). Organizations such as IRENA and the Hydrogen Council predict that by 2050, production will focus mainly on blue and green hydrogen, signifying a move toward sustainable energy solutions (UNECE, 2022).

On February 13, 2023, the European Commission (European Union, 2023) implemented stringent regulations under the Renewable Energy Directive for classifying hydrogen from renewable sources as "renewable fuel of nonbiological origin" (RFNBO), or green hydrogen. These rules impose specific requirements related to the additionality, temporal correlation, and geographic correlation of the energy sources used in hydrogen production. Notably, these regulations require that the electricity used must come from renewable installations initiated within the last three years and match both the time and location of hydrogen production to ensure genuine sustainability and efficiency. This set of criteria directly impacts the planning and operation of renewable energy and hydrogen facilities, mandating that developers closely align their project timelines, locations, and energy sourcing strategies with these regulations to optimize compliance and economic feasibility within the Europe green hydrogen framework (European Comission, 2023).

In this review article, the emphasis is on the role of hydrogen in decarbonizing transportation and related LCA studies rather than on hydrogen production methods per se. It is crucial to specify the modes of hydrogen production because not all methods are equally viable for supporting decarbonization goals. This distinction is necessary to focus the discussion on scenarios where hydrogen can effectively contribute to decarbonization, such as with green and blue hydrogen. These methods align with achieving national and regional carbon neutrality targets and the temperature goals of the Paris Agreement. Consequently, while the review covers hydrogen production, it selectively addresses those methods most likely to form the backbone of the future hydrogen supply for decarbonization, such as average grid electricity, green, and blue hydrogen, sidelining less significant methods. This approach ensures that the article differentiates itself from general reviews on hydrogen production or supply chains and aligns closely with the decarbonization context in the transportation sector.

Fig. 3 employs a modular display to categorize future mainstream and potential hydrogen production methods aimed at reducing emissions in the transportation sector. Fig. 3 illustrates the technological attributes of each method and the significant influence of geographical conditions on their implementation. For example, modules using offshore wind power have an ocean blue background, highlighting marine settings, whereas those utilizing Carbon Capture and Storage (CCS) technology emphasize geographical constraints related to CO_2 storage capabilities. The arrows within Fig. 3 indicate the directions of the material and energy flows, with the key processes of each hydrogen production method simplified into modules. The entire diagram represents the WTG process, depicting the journey from raw materials to the hydrogen gate.

By 2050, hydrogen production driven by renewable energy sources is expected to become pivotal for decarbonizing the transportation sector (Nnabuife et al., 2023). Specifically, green hydrogen production from wind and solar power is anticipated to constitute a significant portion of the total hydrogen production, collectively accounting for 41%, with exact percentages for each source to be determined by further data analysis, with exact percentages for each source to be determined by further data analysis (Statista, 2024b). Additionally, blue hydrogen, produced from natural gas, will constitute a substantial proportion of total hydrogen production, estimated at 50%, particularly in regions where renewable resources cannot fully support large-scale hydrogen demand (Statista, 2024b). These projections are based on the technological maturity and cost-effectiveness of renewable technologies, supportive policies, and climate targets committed by numerous countries, and the enhanced energy security provided by the utilization of local energy resources (IEA, 2021, 2022).

Environmental impact considerations place wind and solar-powered hydrogen production at the forefront, as these methods emit no direct carbon emissions and align with global decarbonization trends (Herdem et al., 2024). Economically, the costs associated with renewable energies have significantly decreased due to technological advancements and mass production, making these options increasingly attractive in the long term (Le et al., 2024). Additionally, improvements in electrolysis technologies have made the conversion of electricity generated from renewable sources to hydrogen more efficient and feasible (Shiva Kumar and Lim, 2022).

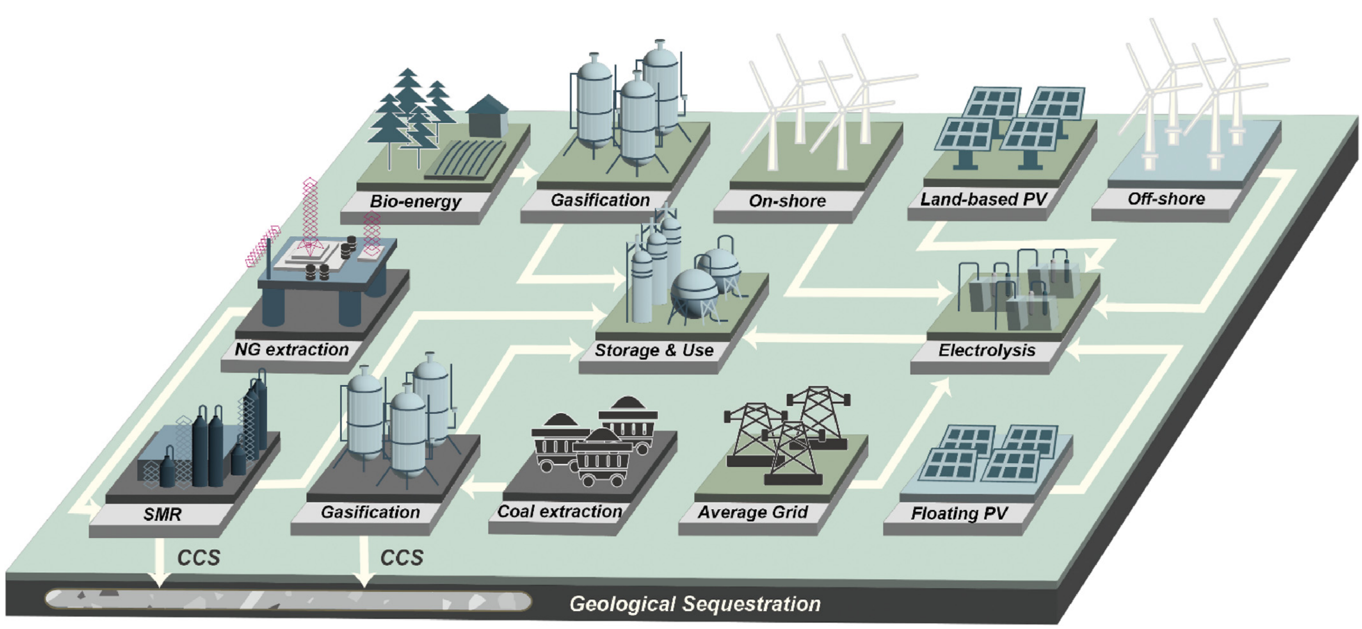

Fig. 3. Advanced hydrogen production methods for transportation decarbonization.

Notably, Radner et al. (2024) reported that the cost of hydrogen production can vary significantly by region and method. For example, in Austria, the costs range from 7.4 to 8.6 EUR/kg due to the current technological and economic conditions. Conversely, in Chile, the production costs are considerably lower, reaching as low as 5.1 EUR/kg with photovoltaic energy and 6.75 EUR/kg with wind energy, reflecting the advantageous exploitation of their vast solar and wind resources. From an international perspective, Australia (Kar et al., 2023) and the Middle East (Gado, 2024), also known for their extensive solar and wind capabilities, are poised to become significant green hydrogen exporters. In North Africa, countries such as Morocco and Egypt, with their untapped solar and wind resources, are well positioned to establish themselves as production and export bases for green hydrogen. These regions are chosen on the basis of their resource richness, supportive policy environments, and openness to emerging technologies, potentially making them key suppliers of green hydrogen in the global effort to reduce carbon emissions in transportation.

Following this overview, subsequent sections delve into the specific hydrogen production methods outlined in Fig. 3 and review the results from LCA studies related to these methods. While some additional potential hydrogen production techniques will be introduced, they will receive less emphasis, as they are not the primary focus of this section. This detailed analysis further elucidates the role of various hydrogen production technologies in facilitating the decarbonization of the transportation sector.

3.2.1. Fossil fuel-based hydrogen production

Given environmental concerns and technological advancements, traditional fossil fuel-based hydrogen production, known as gray hydrogen production, is being phased out due to its high carbon emissions (Saha et al., 2024). However, by integrating CCS technology with these fossil fuel methods, it is possible to produce blue hydrogen, which significantly reduces carbon emissions. Currently, blue hydrogen is more cost effective than green hydrogen because of the mature infrastructure and technologies associated with fossil fuels (Saha et al., 2024). Nonetheless, as renewable energy technologies improve and become more widespread, the costs associated with green hydrogen—produced through electrolysis using renewable energy—are expected to decrease further (Le et al., 2024). While blue hydrogen has lower carbon emissions than gray hydrogen does, it still emits more than green hydrogen does, which virtually produces no GHG. Future advancements and cost reductions in CCS could increase the feasibility and reduce the environmental impact of blue hydrogen, but green hydrogen may remain the preferable option because of its minimal environmental footprint. This section discusses mainstream fossil fuel-based hydrogen production methods, such as natural gas reforming and coal gasification, followed by an examination of the role of CCS technology in fostering cleaner hydrogen production, which is essential for meeting carbon reduction goals in transportation.

SMR is the most common and cost-effective method for producing hydrogen in large quantities. The process involves reacting methane, the primary component of natural gas, with steam at high temperatures (700–1000 °C) and pressures in the presence of a catalyst (Heino, 2023). This reaction produces hydrogen and carbon monoxide. A subsequent reaction called the water-gas shift reaction converts carbon monoxide and more steam to produce additional hydrogen and carbon dioxide. The final step involves the removal of carbon dioxide and other impurities to produce high-purity hydrogen. The chemical reactions can be summarized as follows.

The primary reforming reaction is shown in Eq. (1):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

The water-gas shift reaction is shown in Eq. (2):

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

SMR is responsible for producing the majority of the world's hydrogen supply. As of the latest estimates, SMR accounts for approximately 95% of the hydrogen produced in USA and approximately 76% globally (Ryan, 2024). This widespread use is attributed to the process's economic efficiency and the abundant availability of natural gas. Large-scale hydrogen production facilities using SMR are typically located near petrochemical plants, refineries, and areas with extensive natural gas resources. While SMR is highly efficient and cost-effective, it is also a significant source of carbon dioxide emissions, contributing to GHG emissions unless coupled with CCS technologies. The potential for SMR in the future hydrogen economy depends significantly on advancements in CCS to mitigate environmental impacts.

Patel et al. (2024) reported that gray hydrogen, produced through the SMR process without CCS, results in the highest emissions among hydrogen production methods. Specifically, the LCA indicated that gray hydrogen's CO_2eq emissions are 13.9 kg CO_2eq/(kg H_2) when the liquefied natural gas (LNG) route from USA is used and 12.3 kg CO_2eq/(kg H_2) when it is sourced via pipelines from Russia. The study highlighted a significant increase in climate change impact, with a 12%–25% rise in the global warming potential (GWP) for a 20-year time horizon compared with a 100-year horizon for gray hydrogen. These findings underscore the substantial environmental impact of gray hydrogen, particularly compared with lower-emission alternatives such as blue and green hydrogen, emphasizing the need to consider upstream emissions from natural gas and LNG processes in any comprehensive environmental assessment. Navas-Anguita et al. (2020) highlighted that while SMR is the main hydrogen production technology in Spain's short term due to its cost-effectiveness, it leads to high emissions, exceeding 25 Mt CO_2eq by 2050 under moderate demand. However, with carbon footprint restrictions, emissions could be significantly reduced to less than 11 Mt CO_2eq. This transition from SMR to cleaner technologies such as electrolysis and biomass gasification in the long term supports substantial GHG savings, potentially over 50 Mt CO_2eq by 2050.

Coal gasification (CG) for hydrogen production is a process that converts coal into hydrogen gas by reacting with oxygen and steam under high temperatures and pressures, producing a gas mixture rich in carbon monoxide and hydrogen, known as syngas (Midilli et al., 2021). The process begins with the crushing of coal to suit the requirements of the gasifier, where it is subsequently exposed to high temperatures, often exceeding 1000 °C, to ensure complete transformation. During this reaction, coal interacts with oxygen and steam to form syngas, which then undergoes purification to remove impurities such as hydrogen sulfide and ammonia. A shift reaction further converts carbon monoxide and steam into additional hydrogen and carbon dioxide, with the final step involving the separation and purification of hydrogen from the syngas through methods such as compression and cooling (Midilli et al., 2021). Coal gasification accounts for approximately 22% of hydrogen production worldwide, which is significantly less than the 76% share held by natural gas reforming methods (Ryan, 2024). This smaller share is due in part to the environmental impacts and higher operational costs associated with coal gasification than those associated with other technologies.

In the future, coal gasification faces significant challenges and opportunities (Midilli et al., 2021). The major hurdles associated with this technology include its substantial environmental footprint, as it produces large amounts of carbon dioxide and other harmful gases, and its economic competitiveness against more efficient technologies such as natural gas reforming and electrolysis, which are becoming more cost-effective with advancements in renewable energy. However, technical improvements in gas cleaning and carbon capture and storage could enhance the environmental and economic viability of coal gasification. Additionally, the future of this technology will rely heavily on policy and regulatory frameworks, which are increasingly focused on reducing carbon emissions (Jaradat et al., 2024). In summary, while coal gasification can leverage abundant coal reserves and meet large-scale industrial hydrogen needs, its role in the global hydrogen market may diminish as more sustainable and economically viable technologies gain prominence. The trajectory of coal gasification will largely depend on technological advancements and policy support aimed at mitigating its environmental impact and improving its cost-effectiveness.

Burchart et al. (2023) conducted an LCA on hydrogen production via hard coal gasification via shell technology, considering scenarios both with and without carbon dioxide sequestration. The findings highlight that implementing CO_2 sequestration significantly reduces GHG emissions by approximately 44%, lowering emissions from 34.8 to 19.5 kg CO_2eq/functional unit. However, this reduction in GHG emissions is accompanied by an increase in other environmental impacts: The acidification potential index increased by 4%, the eutrophication potential by 7.5%, and abiotic depletion by approximately 2%. These increases are attributed to the additional energy required for CO_2 compression and injection, which is primarily sourced from fossil fuels in Poland. Despite the increase in other environmental impacts, the substantial reduction in GHG emissions supports the use of CO_2 sequestration in coal gasification for hydrogen production as a meaningful step toward reducing the carbon footprint of this energy carrier. Burchart et al. (2023) emphasized that strategic decisions should not only focus on the color categorization of hydrogen but also consider comprehensive environmental impacts, as shown by their LCA, especially in regions such as Poland, where the energy sector heavily relies on coal.

The integration of carbon capture, utilization, and storage (CCUS) technologies with traditional fossil fuel-based hydrogen production methods, such as CG and SMR, represents a significant advancement in reducing the carbon footprint associated with these processes (Qureshi et al., 2022). Both methods can be adapted to include CCUS to capture the CO_2 emitted during hydrogen production, thus minimizing their environmental impact. The captured CO_2 can then be either stored underground in geological formations or used in other industrial processes. The deployment of hydrogen production with CCUS, whether through CG or SMR, is still in its early stages compared with its conventional counterparts. However, several projects across the globe are either operational or under development (Collodi et al., 2017b; Kawai et al., 2022; Moosazadeh et al., 2024). This adoption is particularly notable in regions with strict carbon emission regulations and access to suitable geological storage sites, such as the USA, Canada, Norway, and some Middle Eastern countries that are rich in NG reserves (Fattouh et al., 2024; Kobakhidze and Balasubramanian, 2023; Larkin et al., 2019; Ning and Tura, 2023).

The potential of integrating CCUS with traditional hydrogen production methods lies in significantly lowering the carbon emissions of these processes, making them more sustainable. As the global focus on decarbonization intensifies: 1) Energy Transition: Both CG and SMR with CCUS could play essential roles in the energy transition by providing a more environmentally friendly hydrogen production method (Qureshi et al., 2022); 2) Industrial applications: Hydrogen produced via these methods can be used in refining, ammonia production, and other heavy industries, offering a lower-carbon pathway for these sectors (Altaf et al., 2024).

The successful implementation of CCUS in hydrogen production via CG or SMR depends on several conditions:

1) Technological Feasibility: Adequate technology must be available for the effective capture, transport, utilization, or storage of CO_2. This includes advancements in capture technologies to ensure high capture rates and cost-effectiveness (Zhao et al., 2023).
2) Geological conditions: Appropriate geological formations, including depleted oil and gas fields or deep saline aquifers, are crucial for CO_2 storage. The selection of these sites requires detailed geological surveys and long-term monitoring to ensure safe and permanent storage of CO_2 (Bachu, 2008).
3) Regulatory Frameworks: Strong regulatory support is necessary to govern the safety, environmental impact, and long-term monitoring of CO_2 storage sites (Damen et al., 2006).
4) Economic viability: The economics of integrating CCUS with fossil fuel-based hydrogen production rely heavily on carbon pricing, subsidies, or incentives to counterbalance the additional costs associated with carbon capture and storage (Soto, 2021)
5) Market Demand: There must be sustained demand for low-carbon hydrogen to justify investments in CCUS technology (Reigstad et al., 2022).

Integrating CCUS with CG or SMR represents a promising but challenging pathway toward sustainable hydrogen production. Its success hinges on aligning technological, regulatory, and economic factors with global carbon reduction goals. As the technology matures and more projects come online, this approach could become standard in hydrogen production, especially in regions aiming for carbon neutrality. The availability of geologically suitable sites is critical, directly impacting the scalability and acceptance of CCUS technologies.

Liu and Liu (2021) conducted a comprehensive LCA to compare the energy consumption and GHG emissions between underground coal gasification-based hydrogen production (UCG-H_2) and surface coal gasification-based hydrogen production (SCG-H_2). The findings reveal that UCG-H_2 consumes only 61.2% of the energy required by SCG-H_2, representing a significant energy-saving advantage. With an 80% CO_2 capture rate, the GHG emissions from both methods are nearly equivalent, providing a balanced approach between energy consumption and emission reduction. The study also highlights that substituting SCG-H_2 with UCG-H_2 could reduce energy consumption in the hydrogen industry by 38.8% while slightly increasing average GHG emissions by 5.1%. Overall, Liu and Liu (2021) underscores the potential of UCG-H_2 with CCS to meet future hydrogen demands more sustainably, particularly emphasizing its benefits in reducing energy consumption and managing GHG emissions effectively. Zhou et al. (2024) integrated life cycle GHG assessment with regional supply-demand optimization to analyze hydrogen production and distribution for HFCVs in China. The findings reveal significant disparities in GHG emissions across the six hydrogen production methods, with SMR as the highest emitter and WE using RE as the lowest. The research also highlights a prominent north–south hydrogen supply chain. Sensitivity analysis revealed that the CG-CCS and RE-WE pathways have limited responsiveness to efficiency improvements. Scenario analysis advocates for a phased transition from gray to green hydrogen, with an interim focus on blue hydrogen pathways to achieve China's 2060 net-zero emissions target. Recommendations include enhancing the efficiencies of NG-SMR and corn gasification (CnG) production, monitoring life cycle emission hotspots, and implementing sustainability certifications for HFCV stakeholders. This study provides guidance for policymakers to prioritize green hydrogen initiatives while ensuring energy security and addressing logistical challenges in hydrogen distribution. Future research should incorporate more advanced modeling tools for a more comprehensive analysis of the hydrogen supply chain.

3.2.2. Hydrogen production from renewable energy

This section focuses on the potential of hydrogen production from renewable sources to decarbonize the transportation sector, specifically through wind and solar power, as depicted in Fig. 3. These two methods are highlighted for their significant potential driven by rapid technological advancements, substantial cost reductions, and strong policy support. The choice of wind and solar power for green hydrogen production aligns with global trends toward sustainable energy solutions and is backed by increasing economic feasibility and governmental incentives. The discussion begins with hydrogen production via wind power, followed by solar photovoltaics, exploring their roles in supporting the decarbonization of the transportation industry.

Wind-powered hydrogen production is a process that uses electricity generated from wind power technologies to electrolyze water, thereby producing hydrogen (Dutton et al., 2000). This method can be classified into two primary types on the basis of the location of the wind power facility: onshore wind-powered hydrogen and offshore wind-powered hydrogen. Onshore wind-powered hydrogen benefits from easier maintenance and lower construction costs, but it may be limited by geographical constraints and wind speed, resulting in lower efficiency than offshore setups (Kim et al., 2023). Offshore wind-powered hydrogen harnesses strong and stable winds at sea, and although it involves higher initial investments and complex maintenance, it can produce hydrogen on a larger scale (Ibrahim et al., 2022). Each type of wind-powered hydrogen production has advantages and challenges, and the choice between them depends on cost-effectiveness, technological maturity, and specific application needs, making it a crucial component of the global energy transition.

The efficiency, production, and safety of wind-powered hydrogen production are influenced by several key factors. First and foremost, wind speed and stability directly affect the electricity generation of wind turbines and their operational continuity, thus determining the electricity supply available for hydrogen production. Second, the capacity factor of the wind farm is another crucial element; a higher capacity factor signifies greater electricity output, thereby enhancing the efficiency and yield of hydrogen production. The efficiency of electrolysis equipment is also vital, as it directly determines the efficiency of converting electrical energy into hydrogen energy. Additionally, the integration and optimization of the system play significant roles in reducing energy loss and improving overall efficiency. Environmental factors such as temperature and humidity, along with essential safety control measures, significantly impact the performance of electrolysis equipment and the safe operation of the entire system. Finally, economic viability and policy support are factors that cannot be overlooked, as they directly influence the cost-effectiveness and sustainable development of a project. By synthesizing these factors, design and operational strategies can be optimized, enhancing the overall performance of wind-powered hydrogen projects (Benghanem et al., 2023; Dutton et al., 2000).

Delpierre et al. (2021) conducted a focused analysis on the environmental impacts of hydrogen production via wind-powered alkaline electrolyte (AE) and polymer electrolyte membrane (PEM) electrolysers in the Netherlands. The study revealed that both technologies have similar environmental impacts, with only minor differences noted in the ozone depletion category. Crucially, the research underscores that the primary environmental burden in hydrogen production originates from the electricity source, which, even when derived from wind energy, constitutes over 90% of the environmental impacts across all assessed categories. The electrolysers themselves contribute minimally, less than 10%, to the total environmental impact. This work by Delpierre et al. (2021) highlights the importance of the electricity source in determining the environmental sustainability of hydrogen production and emphasizes the necessity of further improving the efficiency and sustainability of wind energy technologies to optimize hydrogen production in the Netherlands. The integration of ex ante LCA with scenario analysis provided a comprehensive view of potential future impacts and developments, advocating for enhanced renewable energy solutions to bolster the environmental benefits of hydrogen production. Noh et al. (2023) examined the environmental and energy effects of delivering hydrogen from Australia to Republic of Korea via a LCA and compared four methods: compressed gaseous hydrogen (CGH_2), liquefied hydrogen (LH_2), liquid organic hydrogen carriers (LOHC), and ammonia (NH_3). The study highlighted that the power source is pivotal, with a GWP ranging from 1.15 to 10.11 kg CO_2eq when a mix of grid and offshore wind power is used, and it is significantly lower at 1.15–2.05 kg CO_2eq when only offshore wind is used. The delivery distance also critically affects the outcome, with a GWP of 25.32–35.42 kg CO_2eq for mixed power sources within 10,000 km. Among the storage methods, CGH_2 was the most efficient, with NH_3 also emerging as a viable option because of its developed infrastructure. This underscores the importance of optimizing electrical sources and delivery strategies for efficient and sustainable hydrogen supply chains.

Zhang et al. (2023a) conducted a comprehensive LCA to compare the environmental impacts of onshore and offshore wind-powered hydrogen production via alkaline, PEM, and solid oxide (SOEC) electrolysis technologies. These findings reveal that PEM electrolysis combined with onshore wind energy has the lowest GWP, making it the most environmentally favorable method. The study also highlights the benefits of coupling offshore wind power with seawater desalination for direct hydrogen production, which results in lower environmental impacts than traditional offshore hydrogen production methods do. Additionally, the research identified significant environmental burdens during the construction phase, especially for offshore wind turbines, and suggested that increasing the system lifespan, reducing submarine cable use, and improving electrolysis efficiency can effectively reduce overall environmental impacts.

Solar-powered hydrogen production utilizes electricity generated from PV systems to electrolyze water, producing hydrogen. This method can be broadly classified into two types on the basis of the configuration of the PV installations: ground-mounted solar-powered hydrogen and rooftop or floating solar-powered hydrogen (Huang et al., 2023; Muthia et al., 2024). Ground-mounted solar photovoltaic systems allow for the efficient use of land but require significant space, which can be a limitation in densely populated or sensitive areas. Floating solar photovoltaic systems, on the other hand, generate more energy because of lower temperatures and efficient use of space but face challenges such as corrosion, particularly in aluminum frames and other metallic components (Dzamesi et al., 2024; Temiz and Javani, 2020).

The efficiency, production, and safety of solar-powered hydrogen production are influenced by several key factors (Burton et al., 2021). Solar irradiance, which varies with geography and time of day, directly impacts the power output of PV panels and their operational continuity, thereby affecting the electricity supply for hydrogen production. The capacity factor of the PV installation is also critical; higher capacity factors mean more consistent power output, which enhances the efficiency and yield of hydrogen production. The efficiency of the electrolysis equipment is crucial, as it determines how effectively electrical energy is converted into hydrogen energy. Moreover, the integration and optimization of the system are vital for minimizing energy losses and improving overall efficiency. Environmental conditions such as temperature and shading impact PV performance, and safety measures are essential for ensuring the stable operation of the system. Economic viability and policy support strongly influence the cost-effectiveness and sustainability of solar-powered hydrogen projects (Burton et al., 2021; Singh and Tiwari, 2024; Song et al., 2022).

Anastasiadis et al. (2023) implemented a hybrid system on the island of Sifnos, Greece, that integrates renewable energy sources with hydrogen production, storage, and utilization to minimize environmental impacts while meeting energy needs. The system generates 714,620.5 kWh of electricity annually through wind and photovoltaic facilities at an average cost of 0.1253 EUR/kWh, with hydrogen production costs of 4.17 EUR/(kg H_2). Hourly hydrogen production varied from 0 to 2.6385 kg, with peak power consumption reaching 238.799 kW and a maximum power supply of 147.337 kW. Zhang et al. (2022) conducted a detailed LCA to evaluate the environmental impacts of three hydrogen production methods using solar energy: PEM water electrolysis coupled with PV and photothermal (PT) power generation and thermochemical water splitting via the sulfur–iodine (S-I) cycle coupled with solar photothermal technology. The assessment focused on GWP, acidification potential (AP), ozone depletion potential (ODP), and nutrient enrichment potential (EP). These findings indicate that thermochemical water splitting by the S-I cycle with solar photothermal coupling has the lowest GWP, AP, EP, and ODP, making it the most environmentally advantageous method. The study also highlights that solar photothermal power generation coupled with PEM water electrolysis has a smaller environmental impact than does the PV coupled method. Key environmental burdens stem largely from the construction phases of solar power plants and electrolysis facilities. Additionally, the study suggests that increasing the system's operational lifetime significantly mitigates the environmental impacts across all methods, with pronounced benefits in systems initially presenting greater environmental impacts. Ajeeb et al. (2024) conducted a thorough review of LCAs on green hydrogen production through electrolysis, focusing on the environmental sustainability of various electrolysis techniques and the integration of renewable energy sources. The study highlights that wind energy is particularly effective for hydrogen production, with a notably lower GWP than that of solar energy. Among electrolysis technologies, PEM technology has been reported to have lower environmental impacts (EIs) and higher efficiency than alkaline and solid oxide electrolysis, which results in higher GWP values. This study emphasized the importance of advancing electrolyser technologies, such as enhancing system efficiency, reducing energy and material consumption, and extending operational lifetimes. This study also suggests integrating strategies such as waste heat recovery and improving material recycling to further optimize the efficiency and reduce the environmental impacts of hydrogen production systems. This comprehensive evaluation sheds light on potential technological improvements and underscores the necessity for future LCA studies to include advancements at each stage of the hydrogen value chain to ultimately support decarbonization and sustainability goals in the hydrogen production industry.

3.2.3. Hydrogen from alternative energy sources

Biomass-powered hydrogen production involves the conversion of biomass materials, such as agricultural residues, forest waste, and organic municipal waste, into hydrogen (Pal et al., 2022). This method is generally classified into two primary types on the basis of the technology used: thermochemical and biochemical hydrogen production. Thermochemical processes involve the high-temperature conversion of biomass into hydrogen through gasification or pyrolysis, offering high efficiency but requiring complex and expensive infrastructure. Biochemical processes, which include fermentation and anaerobic digestion, operate at relatively low temperatures and can utilize a wide variety of biomass sources but typically yield relatively low hydrogen production rates.

The efficiency, production, and safety of biomass-powered hydrogen production are influenced by several critical factors (Kalinci et al., 2009). The type and quality of biomass feedstock directly affect the yield and energy requirements of the hydrogen production process, with more homogeneous and energy-dense materials leading to better efficiencies. The technology used also plays a crucial role; for instance, advancements in gasification and fermentation technologies can significantly increase the hydrogen yield and process efficiency. Integration and optimization of the entire biomass-to-hydrogen pathway are vital to minimize energy losses and maximize output. Environmental factors such as the local availability of biomass and logistical considerations impact the overall sustainability and feasibility of these projects, whereas safety measures are essential for handling biomass materials and operating high-temperature equipment. Economic viability, which is heavily influenced by the cost of biomass feedstock and the scale of production facilities, along with policy support, is indispensable for the commercial success of biomass hydrogen systems (Pal et al., 2022).

Wulf and Kaltschmitt (2013) introduced a LCA on biohydrogen production in Germany identified woody biomass gasification, especially from forest residues and short rotation coppice (SRC), as the optimal method because of its low GHG emissions and minimal fossil energy demand. This contributes significantly toward Germany's goal of a 40% reduction in GHG by 2020. The recommendations emphasize expanding SRC over other crops and optimizing byproduct use, such as glycerol, to increase efficiency. However, this assessment does not consider the economic and political factors necessary for widespread hydrogen mobility adoption. Amaya-Santos et al. (2021) conducted a comprehensive LCA of hydrogen production from municipal solid waste (MSW) via advanced gasification coupled with CCS, which demonstrated significant environmental benefits. This study revealed that biohydrogen (bio-H_2) production not only offers a viable alternative to landfill and incineration due to its negative carbon footprint but also outcompetes both blue hydrogen (produced via steam methane reforming/autothermal reforming with CCS) and green hydrogen (produced from solar and offshore wind energy) in terms of the impact of climate change. Specifically, bio-H_2 results in a reduction of 183 kg CO_2eq/MW_{HHV} (higher heating value basis) H_2, enhancing its viability as the electricity grid continues to decarbonize. The analysis identified the gas cleaning process as the dominant contributor to acidification, eutrophication, and ecotoxicity, whereas material recovery and net electricity generation during refuse-derived fuel (RDF) preparation significantly offset these burdens, further bolstering the benefits of climate change. Amaya-Santos et al. (2021) suggested that the future of hydrogen production could consider Bio-H_2 as a competitive, sustainable solution in both the near and long term, particularly as it aligns with the Net-Zero 2050 objectives, making it a promising carbon-negative technology.

In addition to the mainstream and potential hydrogen production methods discussed, several niche methods that, while not the focus of this study, deserve brief mention. These methods include photoelectrochemical water splitting (Landman et al., 2017), plasma arc gasification (Favas et al., 2017), thermal decomposition of methane (Keipi et al., 2018), high-temperature electrolysis (Posdziech et al., 2019), and chemical looping (Luo et al., 2018).

Hren et al. (2023) evaluated the environmental impacts of various hydrogen production methods. The study revealed that water electrolysis has the highest GHG emission footprint when the conventional European power mix is used, particularly when a significant proportion of the electricity is derived from fossil fuels. Other methods, such as iron-based chemical looping and aluminum processes, also lead to high emissions due to their considerable electricity demands. Additionally, natural gas steam reforming and the acid gas to syngas (AG2S) process, despite their lower electricity requirements, predominantly emit greenhouse gases during steam production. Moreover, methods that utilize biomass gasification and biogas reforming, particularly those involving agricultural crops such as corn, are notable for their high emissions during production and transportation.

These methods, while less common, contribute to the diverse portfolio of technologies aimed at producing hydrogen in environmentally friendly or more efficient ways.

3.3. Infrastructure development

Following the detailed discussions on LCA methodologies for hydrogen applications in the transportation sector and the production processes of hydrogen, this section focuses on the infrastructure and network configuration of hydrogen. Understanding the layout of hydrogen infrastructure is key to comprehending how different components of the hydrogen supply chain work together to support decarbonization in transportation. From the perspective of LCA, the use of hydrogen encompasses not only production but also storage and distribution/delivery—both of which are crucial since they directly affect the efficiency of hydrogen as a medium for reducing carbon emissions in transportation. Specifically, both storage and delivery depend heavily on the effective connectivity between points of hydrogen production and utilization, i.e., the supply layout and network. Therefore, the arrangement of this section aims to lay the groundwork for a detailed discussion in the following sections about hydrogen storage and distribution/delivery, ensuring that readers understand how the design and functionality of the entire hydrogen supply chain facilitate its application in transportation.

The layout of hydrogen infrastructure can be divided into three categories: onsite (Lee et al., 2024), centralized (Santos et al., 2024), and semicentralized (Kaheel et al., 2023). Centralized and semicentralized hydrogen supply configurations can be classified under the offsite category. Onsite layouts are suitable for locations requiring a rapid supply of large quantities of hydrogen, such as bus depots or large industrial facilities. This setup enhances energy efficiency by reducing the need for hydrogen distribution and minimizing energy losses. In contrast, centralized layouts involve producing hydrogen at a large-scale facility and distributing it to various filling stations via pipelines or vehicles. This method is suitable for regions with an extensive network of hydrogen stations. Moreover, semicentralized layouts support regional hydrogen production for areas with concentrated but smaller-scale needs, striking a balance between efficiency and logistical feasibility (Kaheel et al., 2023).

Considering a centralized offshore hydrogen production model in the USA, while costs may be reduced, for some states, the distribution of hydrogen from hubs due to longer distances could double GHG emissions (Balaji and You, 2024).

Wu et al. (2024) presented a comprehensive economic analysis of hydrogen refueling stations (HRSs) across four operational modes, utilizing an annualized cost model for hydrogen delivery and a levelized cost model for HRSs. Key findings indicate that pipeline delivery is the most cost-effective method for distances up to 1000 km, especially at 100% capacity utilization, with costs increasing significantly at 20% utilization. Tube trailers are economically viable for distances less than 300 km, whereas liquid hydrogen tankers are preferable for distances between 300 and 1000 km. On-site hydrogen production is not economically feasible, with a levelized cost of hydrogen (LCOH) of 35.24 CNY/kg. The study also highlights that hydrogen supply costs account for more than 50% of the LCOH for off-site production, increasing with the source distance. Additionally, the economic viability of HRSs is strongly influenced by the network size and the social discount rate, highlighting the need for future studies to explore different hydrogen supply scales and discount rates to determine optimal operational modes. Machhammer et al. (2021) discussed the pressing challenges and potential solutions in Germany's energy transition toward hydrogen use by 2030, highlighting the grid fluctuations caused by increased shares of renewable energy sources such as photovoltaics and wind turbines. The research examined the possibility of using existing natural gas pipelines for hydrogen delivery, noting that this approach reduces the value of hydrogen to merely that of the caloric content of natural gas, making it economically unviable without ecological motivations. The findings suggest that while onsite electrolysis is costly and lacks ecological appeal due to high electricity demands, delivering hydrogen to decentralized stations such as H_2 refueling stations via natural gas pipelines is the most ecologically favorable option. However, the results identify a significant challenge in scaling up wind-powered hydrogen production due to the limited capacity of existing wind parks, indicating that natural gas-based technologies such as pyrolysis or SMR with CCS are more practical for future hydrogen supplies. The key challenge remains in balancing economic viability with ecological benefits while scaling up hydrogen infrastructure to meet future demands.

Refueling methods for hydrogen vary slightly across different transportation sectors. For land vehicles, such as cars and buses, refueling primarily occurs at hydrogen stations where high-pressure storage tanks pump hydrogen at pressures typically between 350 and 700 bars or through mobile hydrogen equipment in regions lacking permanent infrastructure. Marine vessels may receive hydrogen at large-scale port facilities or via ship-to-ship methods to satisfy their greater demands (Melideo and Desideri, 2024). In aviation, hydrogen refueling stations at airports are specifically designed to meet stringent safety and operational speed requirements, or aircraft may employ prefilled high-pressure cylinder exchange systems for rapid refueling (Yusaf et al., 2024). These methods, which are still under development and experimentation, highlight the diverse approaches to hydrogen fueling in various transportation modalities.

As the hydrogen infrastructure expands to the surface layer, the scale and functionality of the filling stations become crucial. The size of a filling station directly depends on the number and type of vehicles it serves, ranging from small passenger cars to large trucks and public transport vehicles. Accordingly, the daily hydrogen dispensing capacity of these stations can vary from a few hundred kilograms to several tons to meet different demands.

The key components of a filling station include hydrogen reception, storage, compression (if necessary), precooling equipment, and the distribution system. Hydrogen is delivered to stations via pipelines or high-pressure tube trailers, after which it is stored in high-pressure gas cylinders or cryogenic liquid tanks. Despite their higher energy efficiency and simpler operations, liquid hydrogen refueling stations currently have higher overall energy consumption than do gaseous hydrogen stations because of the substantial energy required for the liquefaction process (Bauer et al., 2019). If the hydrogen delivered does not meet the pressure requirements for refueling, onsite compressors are used to pressurize the hydrogen to the required level. High-pressure refueling often necessitates precooling hydrogen to prevent excessive heat generation during compression. The design of the refueling machines at the station is similar to that of traditional fuel pumps, but they must handle high pressures safely and ensure leak-proof connections during refueling. Given the flammability of hydrogen, safe and monitoring systems are indispensable components of a filling station. These stations are equipped with leak detectors, fire suppression systems, and emergency shut-off mechanisms to ensure operational safety. Additionally, continuous monitoring systems track the flow and pressure of hydrogen throughout the facility to ensure that all operations remain within safe parameters. Through such comprehensive planning and design, the hydrogen infrastructure efficiently supports the decarbonization of the transportation sector while ensuring safety, efficiency, and scalability. This foundation is critical for fostering the widespread adoption of hydrogen-powered vehicles.

The adoption of HFCVs is significantly hampered by the uncertainties and high costs associated with the transition from fossil fuel dependency to a hydrogen-based system. A notable challenge is the lack of commercial hydrogen refueling infrastructure. According to Genovese and Fragiacomo (2023), building a comprehensive hydrogen infrastructure, which includes production facilities, distribution networks, and refueling stations, presents complex technological and economic challenges. These projects are capital intensive and fraught with market uncertainties, highlighting the importance of minimizing financial risk in long-term infrastructure strategies. In the analysis of the HRS, it is noted that there is no universally ideal configuration; designs must consider local conditions, geopolitical factors, market demands, and regulatory environments. The issue of hydrogen distribution via pipelines, despite its potential, faces challenges, including hydrogen embrittlement and significant capital investment requirements. This research points to a shift toward onsite hydrogen production to reduce the energy consumed in transportation and emissions related to delivery, with water electrolysis emerging as a cleaner, more adaptable method. Research efforts are directed toward enhancing the efficiency and safety of hydrogen storage and dispensing systems and developing new, sustainable hydrogen production technologies. The insights from Genovese and Fragiacomo (2023) on potential HRS layouts provide valuable perspectives on the evolving dynamics of hydrogen-fueling infrastructure and its implications for transportation, energy systems, and environmental sustainability.

When airplanes are refueled with LH_2, ensuring a reliable and cost-effective source of green hydrogen is critical, as this accounts for 60%–70% of the total refueling costs. Additionally, establishing LH_2 infrastructure, such as liquefaction facilities and delivery systems, demands significant upfront investment but can yield economic benefits through optimized design and technological innovation. Safety and ease of operation are also crucial in designing LH_2 refueling systems, especially in space-constrained environments such as large airports. The choice between using LH_2 pipeline systems or refueling trucks depends not only on cost-effectiveness but also on considerations related to safety and operational convenience (Hoelzen et al., 2022).

3.4. Storage and delivery

The selection of storage, delivery, and refueling station storage modes for hydrogen is a complex decision-making process involving considerations of cost, efficiency, safety, and specific application scenarios. For hydrogen storage, it is crucial to evaluate the cost and efficiency differences among various methods, such as high-pressure gaseous, liquid, or solid-state storage. In terms of hydrogen delivery, the choice of the most suitable method (pipeline, tank truck, or marine ship) depends on distance, cost, and safety standards. The storage mode at refueling stations must balance construction costs, the hydrogen supply speed, and geographic location demands. Therefore, a comprehensive understanding and evaluation of different storage and delivery technologies are essential for enhancing the overall feasibility of hydrogen projects, facilitating the selection of optimal solutions to ensure safe, economical, and efficient energy supplies (Wulf and Kaltschmitt, 2018).

Hren et al. (2023) categorized hydrogen storage methods into physical storage (PS) and chemical storage (CS). This study, through a literature review, also adopts the same categorization scheme. However, unlike Hren et al. (2023), who focused primarily on introducing classification methods and only considered environmental impacts with calculated values for different delivery methods, this study emphasizes the more complex interplay in practical applications among the hydrogen supply chain, supply chain layout, hydrogen storage methods, and delivery modes. Instead of merely providing an introductory exposition, this text organizes and integrates various types of information in a structured and systematic manner.

Hydrogen storage technologies include compression, liquefaction, the use of metal hydrides, and chemical methods, each with its own advantages but also face challenges in terms of cost, safety, and energy efficiency (Mulky et al., 2024). Compressed hydrogen allows for rapid charging and discharging but requires high-pressure containers, liquefied hydrogen offers high density but is energy intensive, metal hydrides provide safe low-pressure storage but are slow and costly, and chemical storage has high energy density but involves complex processing. Future research will focus on developing economical, efficient, environmentally friendly, and safe new storage technologies to optimize the use of hydrogen as a clean energy source and promote its widespread adoption in the global energy market (Hassan et al., 2023; Mulky et al., 2024).

The delivery method for hydrogen, which depends heavily on its storage form—be it as compressed gas, liquefied gas, solid compounds, or organic liquid carriers—significantly influences its cost, efficiency, environmental impact, and safety (Abdalla et al., 2018; Faye et al., 2022). For example, although pipelines involve higher initial infrastructure costs, they are more efficient for long-distance delivery. Compared with truck or ship distributions of compressed or liquid hydrogen, pipelines can significantly reduce energy consumption and environmental emissions, thereby minimizing their environmental impact. However, it is important to note that regardless of the delivery method chosen, an increase in delivery distance will lead to higher overall costs and increased energy consumption, further affecting the sustainability of hydrogen as an energy source. Additionally, the safety requirements and technical handling differ with each delivery method, and ensuring safety is a prerequisite for any chosen approach. Therefore, selecting the most appropriate hydrogen delivery method for specific applications and distance requirements is crucial (Li et al., 2022).

Table 2
Hydrogen storage and delivery solutions.

Storage method	Delivery method	Supply chain scenario
[PS] Compressed Hydrogen	High-pressure trucks (Road delivery)	Semicentralized
[PS] Compressed Hydrogen	Pipeline (Pipeline delivery)	Centralized
[PS] Liquid Hydrogen	Cryogenic tankers (Marine delivery)	Centralized
[PS] Liquid Hydrogen	Cryogenic rail cars (Rail delivery)	Semicentralized
[CS] Metal Hydrides	Specialized containers (Road delivery)	On-site, Semicentralized
[CS] LOHC	Tanker trucks, ships (Road delivery, Marine delivery)	Centralized, Intercontinental
—	UHV electrical transmission (Electrical power transmission)	Distributed generation

Table 2 provides a comprehensive overview of the various hydrogen storage and delivery methods, illustrating their integration within diverse supply chain scenarios. Each storage method, whether it is physical storage, such as compressed or liquid hydrogen, or chemical storage, such as metal hydrides and LOHCs, is paired with a suitable delivery method to optimize efficiency and feasibility. Delivery methods range from high-pressure road trucks and pipelines to cryogenic tankers and rail cars, each of which are chosen on the basis of the specific needs and constraints of the supply chain scenario. These scenarios—centralized, semicentralized, intercontinental, or distributed generation—are crucial, as they dictate the logistical requirements and infrastructural investments necessary for deploying each combination of storage and delivery. The selection of both storage and delivery methods is therefore interdependent and strategically aligned to meet the energy distribution, storage stability, and regional accessibility requirements dictated by the overarching supply chain strategy. The inclusion of UHV electrical transmission highlights a unique scenario where electricity, rather than hydrogen itself, is delivered over long distances to facilitate onsite hydrogen production through water electrolysis, further exemplifying the adaptability and complexity of modern hydrogen supply networks.

Wulf et al. (2018) conducted a detailed LCA on hydrogen delivery options to evaluate both environmental and economic impacts. This assessment compared pipeline delivery, LOHC, and high-pressure truck delivery across various distances. The findings revealed that pipelines consistently offer the greatest environmental and economic advantages, especially for high-demand scenarios and across all distances. Conversely, for shorter distances of approximately 100 km, high-pressure trucks were found to be more efficient in certain environmental aspects. However, despite the economic benefits of the LOHC for longerdistance, they demonstrated greater environmental impacts than pressurized gas trucks did. This study underscores that while hydrogen production primarily drives environmental impact, the selection of delivery method also plays a crucial role in the overall sustainability of hydrogen distribution, with pipelines emerging as the most beneficial option when operations are scaled up (Wulf et al., 2018).

To understand distribution impacts, Reuβ et al. (2021) explored the logistics of hydrogen delivery via trucks from 15 electrolysis sites to 9683 fuel stations across Germany. Using Dijkstra's shortest path algorithm to optimize routes, this study compared the costs associated with three hydrogen storage modes: CGH_2, LH_2, and LOHC. The findings indicated delivery costs of 2.69 EUR/kg for CGH_2, 0.73 EUR/kg for LH_2, and 0.99 EUR/kg for LOHC. CGH_2 emerged as the most cost-effective option for distances below 130 km, whereas LH_2 was favored for distances exceeding 130 km. Considering an average delivery distance of 427 km and an average speed of 55.8 km/h, the study highlighted a detour factor of 1.32, suggesting that actual travel routes are 32% longer than direct distances. Furthermore, a potential 20% increase in load capacity could reduce delivery costs significantly—by 26.77% for CGH_2, 18.21% for LH_2, and 17.33% for the LOHC. With truck traffic expected to nearly double by 2050 and current highway infrastructures likely insufficient for future demands, this study advocates for alternative delivery methods such as pipelines. This research illustrates the intricate relationships and economic considerations essential to optimizing the hydrogen delivery supply chain in Germany, offering insights that might be applicable to other regions globally.

These studies collectively highlight how the elements of hydrogen supply chain management, including storage and delivery methods, interact in complex scenarios that influence both the environmental footprint and economic viability of hydrogen as a sustainable energy carrier.

3.4.1. Physical storage

The physical storage of hydrogen involves storing the gas in its elemental form without altering its chemical structure. The most common methods include compressing hydrogen in high-pressure tanks, liquefying it at extremely low temperatures, and storing it in metal hydrides where hydrogen is absorbed into a metal matrix. These techniques prioritize the safety, energy density, and economic efficiency of storing hydrogen, making them suitable for a range of applications from industrial uses to fuel for transportation.

Ye and Lu (2023) conducted a detailed examination of typical hydrogen storage technologies, including metallic liners fully wrapped with high-pressure carbon fiber-reinforced thermoplastic (CFRP) and polymer liners fully wrapped with high-pressure CFRPs, as well as cryogenic vessels, through an LCA approach. The analysis reveals that polymer liners fully wrapped with CFRP high-pressure vessels are the most environmentally friendly option, generating the least amount of GHG at 5539 kg CO_2eq, whereas metallic liners fully wrapped with CFRP high-pressure vessels and 135,000 kg CO_2eq for cryogenic vessels generate 7219 kg CO_2eq. Economically, a polymer liner fully wrapped with CFRP high-pressure vessels is also more cost-effective, costing 10.4 USD/kg of hydrogen with the lowest energy consumption at 5.2 kWh/kg. This makes a polymer liner fully wrapped with CFRP high-pressure vessels a viable and superior option for hydrogen distribution, providing comprehensive insight into sedan hydrogen storage systems and laying a pathway for future hydrogen utilization. Berstad et al. (2022) reviewed studies on long-distance hydrogen delivery, specifically focusing on LH_2, and highlighted significant discrepancies due to varying assumptions in energy efficiency and cost estimates. This review discusses critical factors such as the boiloff ratio in LH_2 storage tanks, which significantly influences energy losses, and explores the impact of technoeconomic assumptions and system boundaries on study outcomes. The study advocates for a detailed, bottom-up approach and consistent methodologies in hydrogen value chain analyses to increase the accuracy and relevance of predictions regarding the scaling up of emerging technologies. Akhtar et al. (2021) conducted a comprehensive cradle-to-gate LCA of seven hydrogen delivery methods, focusing first on physical storage methods. Compressed gaseous hydrogen delivered via pipelines (CGH_2-PL) has emerged as the most environmentally friendly option, with the lowest GWP of 1.57 kg CO_2eq/(kg H_2). The use of high-pressure tube trailers (CGH_2-TT) for delivery resulted in a GWP of 1.81 kg CO_2eq/(kg H_2) for short distances, which escalated to 2.78 kg CO_2eq/(kg H_2) for long distances of 400 km. LH_2, another form of physical storage, has a short-distance GWP of 1.86 kg CO_2eq/(kg H_2).

The reviewed studies collectively emphasize the critical need for selecting hydrogen storage and delivery technologies on the basis of their environmental impact and cost-effectiveness. High-pressure vessels using advanced materials notably reduce GHG emissions and increase cost efficiency, aligning with broader sustainability goals. Discrepancies in studies, especially in long-distance delivery, such as liquid hydrogen, highlight the need for uniform methodologies to improve the accuracy and relevance of predictions. Comprehensive LCAs revealed that pipeline delivery of compressed gaseous hydrogen effectively minimizes the global warming potential. These findings advocate for consistent and thorough evaluations in research and policy-making to support the scalable and sustainable advancement of hydrogen technologies, emphasizing the necessity of advanced technologies and materials for achieving commercial viability and environmental objectives in the hydrogen sector.

3.4.2. Chemical storage

Chemical storage of hydrogen encapsulates methods where hydrogen is bonded within chemical compounds, allowing for increased storage densities and enhanced safety features. This includes technologies such as storing hydrogen in liquid organic carriers, converting it into ammonia for easier delivery and storage, and using metal hydrides, where the focus is on the chemical interaction between hydrogen and the storage material. These methods offer controlled release and are considered particularly viable for large-scale energy storage solutions and long-distance delivery.

Lee et al. (2022) conducted a comprehensive study on the hydrogen delivery supply chain by shipping and evaluated five storage technologies: liquid hydrogen, ammonia, toluene-methylcyclohexane (TOL-MCH), dibenzyltoluene-hydrodibenzyltoluene (DBT-HDBT), and methanol. The research revealed that the TOL-MCH supply chain was the most cost-effective and environmentally friendly option, with a levelized cost of 5.8 USD/(kg H_2) and a carbon intensity of 18.5 kg CO_2eq/(kg H_2). The ammonia supply chain was the next best performer due to favorable operational conditions. Assuming a future dominated by renewable energy and green hydrogen, the ammonia supply chain demonstrated the lowest carbon emissions at 2.23 kg CO_2eq/(kg H_2) and a cost of 4.92 USD/(kg H_2), whereas the TOL-MCH supply chain was the most economical at 4.57 USD/(kg H_2). The integration of LNG to aid hydrogen liquefaction in the supply chain allowed for an 18% cost reduction but led to a 16% increase in carbon emissions due to direct emissions. With the application of commercial renewable electricity and green hydrogen, all supply chains saw significant reductions in cost and carbon emissions, except for LNG-integrated liquid hydrogen and methanol, which generated direct emissions. Ammonia technology showed the best environmental performance, while TOL-MCH was the most cost-effective. Lee et al. (2022) highlighted that operational conditions and the use of renewable energy are key factors in reducing costs and carbon emissions in hydrogen supply chains.

Akhtar et al. (2021) also evaluated chemical storage methods within the same study. The LOHC heated by natural gas was found to have the highest GWP of 3.58 kg CO_2eq/(kg H_2) at 100 km because of significant energy consumption during the dehydrogenation process. Liquid NH_3 (LNH_3), another chemical method, results in a GWP of 3.14 kg CO_2eq/(kg H_2), which is driven primarily by energy-intensive ammonia cracking processes. However, the direct use of ammonia in fuel cell vehicles (LNH_3-DAFCVs) significantly lowered the environmental impact to a GWP of 1.62 kg CO_2eq/(kg H_2), making it the second most sustainable option after pipelines. By using hydrogen as a heat source in the LOHC-Own method, the GWP was further reduced to 2.34 kg CO_2eq/(kg H_2). These findings underscore the vital importance of developing both economically viable and ecologically sustainable hydrogen delivery and storage infrastructures. Apostolou (2021) focused on Spain and compared the cost-effectiveness across two hydrogen storage strategies: compressed hydrogen storage and metal hydride storage. Research reveals that for hydrogen refueling stations serving fuel cell electric bicycles (FCEB), MH storage offers lower initial costs and hydrogen prices, as well as shorter payback periods, than compressed hydrogen storage does. Moreover, as demand for hydrogen fuel increases, future hydrogen refueling stations can reduce capital expenditures through economies of scale, further driving down the price of hydrogen. Godinho et al. (2023) conducted a comprehensive study assessing the economic and environmental benefits of using LOHCs for international hydrogen delivery via maritime routes. Research has focused on the viability of dibenzyl toluene-perhydro-dibenzyltoluene (DBT-PDBT) and TOL-MCH systems between Portugal and the Netherlands from 2030 to 2050. These systems can utilize existing infrastructure, significantly reducing logistical costs, which range from 0.28 to 0.37 EUR/(kg H_2). The study emphasized the strategic role of the port of Rotterdam in meeting future hydrogen demands and identified tank storage, port costs, and shipping rates as major cost components. Economically, DBT-PDBT was found to be more cost-effective than TOL-MCH because of lower conversion costs. Compared with conventional methods, the use of LOHCs could reduce CO_2 emissions by approximately 96%, which aligns with the goals of the RED II directive. These findings position LOHCs as promising solutions for the decarbonization of the energy sector through efficient and sustainable hydrogen logistics.

These studies highlight the need to integrate economically viable and environmentally sustainable solutions in hydrogen storage and distribution, emphasizing advanced chemical storage methods because of their high density and safety in large-scale energy applications and long-distance delivery. Research reveals significant variations in economic and environmental impacts among different methods, which are heavily influenced by operational conditions and energy sources. Some methods excel in cost-effectiveness, whereas others minimize carbon emissions, especially under renewable energy scenarios, underscoring the importance of strategic energy choices in hydrogen supply chains. Additionally, integrating renewable energy and green hydrogen can substantially reduce carbon emissions and costs, except where direct emissions are inherent. Comparisons within specific applications suggest that advanced storage solutions can offer lower costs and shorter payback periods than traditional methods can, with the potential for further economic benefits through economies of scale as the market expands. Overall, these insights advocate for a balanced development approach in hydrogen infrastructure, focusing on the harmonious integration of economic viability, environmental sustainability, and technological innovation to foster advanced materials and renewable energy integration, paving the way for a resilient, cost-effective, and low-carbon energy future.

3.4.3. Land-based delivery

Land-based hydrogen delivery leverages road, rail, and pipeline methods to distribute hydrogen across various distances and terrains, each method being suited to specific operational needs. Road delivery of hydrogen is categorized into compressed (gaseous) and liquid forms, each requiring different vehicles and infrastructure that significantly influence delivery efficiency and scope. Compressed hydrogen is delivered in tube trailers equipped with high-pressure cylinders, which are ideal for short to medium distances and capable of carrying several hundred kilograms of hydrogen, making them a good fit for urban or regional distributions (Reddi et al., 2018). However, owing to the lower energy density of gaseous hydrogen, these trailers require a larger volume to store the same amount of energy as liquid hydrogen does, potentially increasing delivery costs and frequency (Faye et al., 2022).

Conversely, liquid hydrogen is delivered in tank trailers with highly insulated tanks designed to maintain temperatures of approximately −253 °C, minimizing evaporation losses (Xie et al., 2024). This form of hydrogen has a relatively high volumetric density, enhances delivery efficiency, makes it suitable for long-distance and large-scale delivery, and is capable of transporting several tons of hydrogen. While this method supports larger operations more efficiently, it demands complex and costly technology to manage extreme circumstances and associated risks safely (Lowesmith et al., 2014; Tang et al., 2020).

Safety measures are crucial for both forms of hydrogen delivery, including regular maintenance and pressure testing of vehicles, leak detection, and robust emergency response plans (Li et al., 2022). The infrastructure supporting these delivery routes, including refueling stations and storage facilities, must also be specifically designed to handle the unique properties of hydrogen safely and efficiently (Genovese et al., 2024a).

Road delivery remains essential to the hydrogen distribution network because of its flexibility and lower initial investment compared with pipelines or rail. By optimizing these delivery methods, stakeholders can increase efficiency, reduce costs, and meet high safety standards throughout the hydrogen supply chain (Khaligh et al., 2024). Hydrogen rail delivery, characterized by its stability and efficiency, bridges the gap between production sites and consumption endpoints. It employs compressed hydrogen gas, which is delivered in high-pressure containers, and liquid hydrogen, which is delivered in specialized cryogenic tank cars. Although compressed hydrogen is less volume efficient, the capacity and frequency of rail delivery make it viable for significant volumes. The high energy density of liquid hydrogen enables the delivery of larger quantities over longer distances, which is ideal for large-scale operations.

Rail delivery is particularly advantageous for domestic distribution, providing flexibility and frequent connections between multiple production and consumption sites (Genovese et al., 2024c). It is well suited for areas with complex geography or those requiring frequent, large-volume transfers, ensuring reliability and timeliness in routine and emergency hydrogen supply scenarios (Xu et al., 2024).

Hydrogen pipeline delivery, in which hydrogen is distributed in gaseous form directly from production sites to points of use, enhances operational efficiency by eliminating the need for return trips of empty vehicles or vessels (Moreno-Blanco et al., 2020; Reddi et al., 2016). This method involves unique challenges, including the risk of metal embrittlement and significant initial infrastructure investment. Pipelines can handle considerable volumes and provide a continuous supply over long distances, making them particularly suitable for regions with consistent, large-scale hydrogen needs.

As the network of hydrogen pipelines has expanded in response to increasing global demand, their role in the hydrogen distribution landscape has increased. The future prevalence of hydrogen pipelines will depend on advances in technology for safe and economical delivery, the scaling of hydrogen infrastructure, and supportive regulatory frameworks. Although pipelines offer a cost-effective solution for delivering large volumes over long distances, their fixed nature and high initial costs mean that they are likely to complement rather than replace other hydrogen delivery methods, adapting to specific regional needs and market conditions.

Di Lullo et al. (2022) conducted a detailed comparative study of large-scale, long-distance land-based hydrogen delivery systems, analyzing 32 different scenarios, including hydrogen pipelines, hydrogen (hydrogen-natural gas blends), ammonia, and LOHCs. The findings reveal that pure hydrogen pipelines and low-pressure hythane are the most cost-effective and environmentally friendly options for delivering hydrogen over distances of 1000 and 3000 km. The results indicate that other methods, such as truck delivery, high-pressure hythane, and LOHC, are significantly more expensive and have higher GHG emissions. Ammonia and LOHCs might be more advantageous in marine settings or warmer climates where the reductions in GHG emissions and delivery costs are more pronounced. Comprehensive assessment in this study underscores the importance of considering both economic and environmental factors in developing policies for clean hydrogen delivery, highlighting the potential for future innovations to optimize these systems further. Tayarani and Ramji (2022) comprehensively analyzed the environmental impacts of various hydrogen delivery methods, particularly focusing on comparisons between pipeline and truck delivery of gaseous hydrogen. These findings indicate that hydrogen delivery via pipelines is significantly less GHG intensive than truck delivery is. This conclusion was reinforced through a sensitivity analysis that examined the implications of different assumptions regarding the role of the pipeline in the life cycle assessment. The study consistently identified solar electrolysis as the most environmentally beneficial method of hydrogen production when coupled with pipeline delivery, emphasizing its lower carbon footprint of only 50.298 g of CO_2eq/MJ of hydrogen consumed. This analysis underscores the potential for pipelines to reduce the environmental impact of hydrogen delivery compared with that of road-based methods.

Hren et al. (2023) also explored the environmental impacts of different hydrogen delivery methods, identifying pipelines as more environmentally benign options. Delivering gaseous hydrogen via pipelines significantly reduces energy losses and GHG emissions, supporting hydrogen as a more sustainable energy alternative. The study recommends adopting production and delivery technologies with lower environmental burdens and suggests that future research should incorporate a comprehensive assessment of societal and risk factors associated with hydrogen technologies to promote the development of a sustainable hydrogen supply chain. Genovese et al. (2024b) reported that the cost contributions in hydrogen delivery systems vary significantly with delivery volume and system configuration: for a distribution of 1000 t, compressors account for approximately 73%–77% of costs, whereas pipelines contribute 23%–26%; for 100 t, the costs are more balanced, with compressors contributing 33%–45% and pipelines contributing 55%–67%. The impact of the pipeline diameter and outlet pressure on the LCOH is also significant, with the lowest LCOH recorded at 0.038

EUR/kg for the 15-inch diameter and 50 bar pressure setups and the highest at 0.058 EUR/kg for the 20-inch diameter and 350 bar pressure configurations.These studies collectively reveal that the choice of hydrogen delivery method significantly influences cost efficiency and environmental impact. The key conclusions include the economic viability of pure hydrogen pipelines and hythane for long-distance delivery, emphasizing cost optimization through precise system configurations. Furthermore, pipelines notably reduce GHG emissions compared with truck deliveries, highlighting their environmental advantages. The integration of renewable energy technologies, such as solar-powered electrolysis, also plays a crucial role in reducing the carbon footprint of hydrogen systems. Policy makers and industry leaders should consider these insights to optimize hydrogen delivery networks and foster technological innovation, thereby ensuring the sustainable development of the hydrogen energy sector. Future research should adopt a comprehensive approach that considers societal and risk factors to fully support the maturity of the hydrogen industry.

3.4.4. Maritime-based delivery

Hydrogen marine delivery is a critical link for connecting large-scale hydrogen production sites with remote consumption markets, providing a solution capable of handling high volumes of hydrogen for each voyage (Johnston et al., 2022). Marine delivery of hydrogen predominantly occurs in two forms: as liquid hydrogen in specialized cryogenic tankers and through chemical hydrogen carriers such as ammonia or toluene (Ahn et al., 2024; Godinho et al., 2023). These methods are favored because of their high energy density and compatibility with existing maritime transport infrastructure, which are essential for efficient and safe long-distance delivery of hydrogen (Ahn et al., 2024).

In terms of capacity, marine delivery systems are designed to carry thousands of tons of hydrogen, which plays a vital role in the international hydrogen trade (d'Amore-Domenech et al., 2023). This mode of delivery is especially significant for linking regions rich in renewable energy resources—ideal for hydrogen production—with high-demand areas that have limited local energy resources. As technology and infrastructure continue to develop, this sector must address unique challenges such as the construction of specialized handling facilities and the implementation of rigorous safety protocols to ensure the sustainable expansion and environmental safety of global hydrogen supply chains (Xie et al., 2024). Kanz et al. (2023a) analyzed various scenarios for the export of liquid hydrogen from Africa to Germany, utilizing an LCA to quantify the GWP. This study focuses particularly on the sustainable and economic production of hydrogen through PV-powered electrolysis processes in Africa, leveraging the continent's geographical advantage near the equator with high solar irradiance. Owing to the current lack of pipeline infrastructure, the most effective short-term method to deliver hydrogen from Africa to Germany is by sea. According to the scenarios, emissions from the delivery of hydrogen account for 35%–43% of the total GWP, with variations in delivery GWP primarily due to the distance traveled by the shipping vessels and the evaporation rates. Johnston et al. (2022) analyzed potential hydrogen-exporting countries such as Australia, Saudi Arabia, Chile, USA, and Algeria as well as major import markets in Europe and Asia to establish trade routes, with the Rotterdam–Australia route serving as the benchmark scenario. The study revealed that ammonia (0.56 USD/(kg H_2)) and methanol (0.68 USD/(kg H_2)) are the most cost-effective hydrogen derivatives for distribution via this route, followed by LNG (1.07 USD/(kg H_2)), LOHCs (1.37 USD/(kg H_2)), and LH_2 (2.09 USD/(kg H_2)). Additionally, the impact of using hydrogen or hydrogen carriers as ship fuel was explored, revealing a potential reduction in delivery costs for LNG (0.88 USD/(kg H_2)) when used as fuel, whereas costs for other carriers increased or were similar. This research provides crucial insights into cost dynamics and environmental benefits, shaping the future of the green hydrogen market (Johnston et al., 2022). Kim et al. (2021) conducted an in-depth analysis of hydrogen delivery via ships, highlighting crucial economic and environmental considerations for different hydrogen carriers. The study revealed that the cost-effectiveness of shipping hydrogen, whether LH_2 or LOHC, significantly depends on both the quantity of hydrogen delivered and the distance covered. Specifically, the crossover points where the LOHC becomes more cost efficient than LH_2 occur at a delivery capacity of approximately 1 million t/year and a distance of approximately 4000 km. This finding is essential for optimizing the logistics of hydrogen supply chains, particularly in scenarios involving long-distance delivery from production sites overseas to consumption areas. Kim et al. (2021) underscored the importance of selecting the appropriate hydrogen carrier and delivery mode to minimize costs while considering environmental impacts, providing a foundational guideline for future strategies in global hydrogen distribution.

These studies collectively emphasize that in the global hydrogen economy, geographical advantages, delivery modes, carrier selection, and strategic planning of international trade routes are crucial for the sustainability and economic viability of hydrogen mobility. This research underscores the necessity of integrating technological innovation, environmental protection, and economic considerations to effectively incorporate hydrogen as a key component of the future global clean energy framework. These conclusions provide valuable strategic and technical guidance for the development of global hydrogen infrastructure, helping shape a more sustainable and economically efficient international hydrogen market.

3.4.5. Electric-based delivery (ultrahigh voltage)

Ultrahigh voltage (UHV) transmission is a method for transmitting electrical energy generated from various clean energy sources, such as hydroelectric, wind, solar, and nuclear power, via UHV power lines. This approach contrasts with traditional methods of delivering hydrogen, which involve physically moving hydrogen in compressed or liquid forms via roads, seas, or pipelines. A significant advantage of UHV delivery is its efficiency in transmitting large amounts of electrical energy over long distances without the need for return trips with empty delivery vessels, an inefficiency common in road and maritime hydrogen delivery.

While UHV delivery is highly efficient for electricity, it has several challenges. This requires significant investments in infrastructure for UHV lines and associated grid integration technologies. Additionally, there are energy losses associated with long-distance transmission that must be managed. Currently, UHV technology is utilized primarily for electrical energy transmission, and its role in the hydrogen sector involves scenarios where excess clean electricity could be used to produce hydrogen at or near the renewable generation site (Jin et al., 2022). The hydrogen could then be stored or used locally or converted back to electricity as needed.

Zhang et al. (2023b) explored various modes of power-hydrogen coupling and presented a systematic analysis and a power–hydrogen coordinated planning optimization model. This research focused on southern Xinjiang, a region with abundant renewable energy resources and low local demand. The findings indicate that the most economically advantageous mode involves coupling power and hydrogen systems at the source, particularly for immediate local use or for hydrogen delivery via pipelines. This mode outperforms others, especially in scenarios with high volatility in renewable energy production, offering better economic competitiveness and operational stability for the power system. This study highlights the potential for integrating hydrogen systems with power systems to increase renewable energy utilization and suggests a future direction for national-scale coordinated planning research, aiming to optimize the interplay between these two critical energy systems. Bai et al. (2024) reported that combining UHVs with batteries in BEVs demonstrated optimal performance in the base scenario, which included an electricity price of 0.041 USD/kWh, a 4 h energy storage duration, and a delivery distance of 2000 km. Specifically, this combination resulted in a cost of 2.4 USD/(100 km) and 0.88 kg CO_2/(100 km). This finding indicates that using UHV in conjunction with battery technology offers a cost-effective and environmentally friendly solution for long-distance energy transmission. Qin et al. (2024) conducted a comprehensive review and proposed a novel long-distance renewable energy transmission scheme for China, focusing on the implementation of liquid hydrogen superconducting energy pipelines (LHSEP). This technology was identified as particularly suitable because of its potential to drastically reduce energy transmission losses over large distances and optimize energy allocation across regions. This study highlights the dual benefits of this approach, both in terms of energy efficiency and environmental impact. By integrating the LHSEP with existing renewable energy sources, the scheme promises to significantly increase renewable energy utilization, reduce system operating costs, and address the geographic imbalance between energy supply and demand in China. The proposed transmission method not only minimizes the loss of transmitted energy—potentially saving approximately 103.34 billion kWh annually—but also offers substantial economic benefits through peak shaving, with estimated savings reaching approximately 101.08 billion USD. Additionally, the scheme could lead to a reduction in CO_2 emissions of approximately 111.21 million t, aligning with China's carbon reduction goals. The financial analysis of the project suggests a return on investment within 14 years, underpinned by the conversion of surplus electricity into liquid hydrogen and subsequent benefits from its use in downstream industries.

Research indicates that the integration of UHV power transmission technology with hydrogen energy conversion offers a dynamic and efficient solution for optimizing the long-distance transmission and utilization of renewable energy. By leveraging the high-efficiency power transmission capabilities of UHV systems and producing hydrogen either at the endpoints or en route, this approach significantly minimizes energy conversion losses while enhancing the flexibility and stability of energy management. Furthermore, although this technology requires substantial infrastructure investments, it holds tremendous potential for environmental and economic benefits, especially with respect to policy support and market incentives. This could lead to broader adoption and more profound socioeconomic impacts. Overall, combining UHV with hydrogen energy not only increases the overall efficiency of energy systems but also supports sustainable development goals. Despite facing technical and economic challenges, the long-term benefits and positive environmental impacts position this innovative solution as a strong contender in future energy transmission and management strategies. To overcome these challenges, interdisciplinary research collaboration, continuous technological innovation, and proactive policy support are essential. Such efforts could gradually lead to the commercialization and large-scale application of this technology, achieving efficient and sustainable energy production and consumption.

3.5. Application and usage

Considering only the usage phase, the use of hydrogen as a clean energy source results in exceptional environmental performance. Particularly in the field of transportation, when hydrogen fuel cell technology is applied, zero emissions of carbon dioxide and harmful exhaust gases are achieved, with water vapor being the only emission. Thus, the operation of hydrogen fuel cell vehicles in urban transport does not contribute to local air pollution (Dulău, 2023). In contrast, while the direct combustion of hydrogen in ships or aircraft does not produce carbon dioxide, it can emit nitrogen oxides (NOx), which need to be controlled through measures such as low-NOx burners (Martin et al., 2023; Miller et al., 2023; Penke et al., 2021; Pereira et al., 2014).

Hydrogen fuel cells can achieve energy efficiencies exceeding 60%, significantly surpassing the performance of traditional internal combustion engines (U.S. Department of Energy, 2025). This high efficiency enables hydrogen fuel cells in electric and plug-in hybrid vehicles to achieve longer driving ranges and better energy utilization. However, the efficiency of using hydrogen in internal combustion engines is relatively low, especially in certain specially designed ships and small aircraft, where despite achieving zero carbon emissions, the energy conversion efficiency is comparable to that of traditional fuel engines, limiting their efficiency advantages (Boretti, 2020, 2024; Manigandan et al., 2023; Seddiek et al., 2015; Shadidi et al., 2021).

The economic viability of hydrogen is influenced primarily by production costs, delivery, and storage technologies. Although the initial costs of hydrogen fuel cells are high, advancements in technology and scaling up production are gradually reducing operational and maintenance costs (Ajeeb et al., 2024; Rolo et al., 2024). In public transport networks, such as city bus systems, hydrogen fuel cell buses have demonstrated lower operational costs and reduced maintenance needs (Ahmadi et al., 2022). For hydrogen-powered ships and aircraft, although significant initial investments are required for retrofitting or new system designs, these investments can be gradually recouped through savings on fuel costs and compliance with new environmental standards (Martin et al., 2023; Wang et al., 2023).

Safety is a crucial consideration in the application of hydrogen (Li et al., 2022). Despite their flammability, modern hydrogen-powered vehicles are equipped with various safety measures, such as leak detection, automatic shutoff systems, and collision protection designs (Foorginezhad et al., 2021). In hydrogen-powered aircraft and ships, strong emphasis is placed on leak-proof and explosion-proof designs of fuel systems to ensure safe operation under extreme conditions (Degirmenci et al., 2023; Li et al., 2018). Additionally, the rapid diffusion of hydrogen can reduce the risks of fire and explosion, but it also necessitates ensuring adequate ventilation to prevent the accumulation of hydrogen in enclosed spaces and mitigate potential hazards (Gojić et al., 2023).

The integration of hydrogen as a clean alternative fuel in the transportation sector holds great promise for decarbonization but faces significant challenges, primarily due to inadequate demand and the prevailing dominance of traditional fuels (Terlouw et al., 2024). To unlock the emission reduction potential of hydrogen, it is crucial to drive its adoption across various transport modalities through strategic initiatives (Rawat et al., 2024). Enhancing the market share of HFCVs is one such strategy (Precedence research, 2024). HFCVs, which convert hydrogen into electricity to power motors, have achieved success in public and commercial transport but struggle in the private sector due to limited refueling infrastructures, high production costs and the penetration of BEVs (Parikh, 2024; Shin et al., 2019). In parallel, promoting hydrogen internal combustion engine (HICE) vehicles offers a transitional solution where electric drivetrains may not yet be viable, despite their lower efficiency than fuel cells do (Wanitschke and Hoffmann, 2020). Boretti (2020) highlighted the competitive potential of hydrogen mobility with electric mobility, emphasizing that dual-fuel LH_2-diesel compression ignition (CI) ICEs and LH_2-only positive ignition (PI) ICEs can achieve over 50% peak fuel conversion efficiency with higher power density, suggesting the replacement of LNG with LH_2 in long-haul heavy-duty truck (HDT) dual-fuel engines as a strategic move to significantly introduce hydrogen use this decade. Turner (2025) presented strategies for advancing hydrogen combustion engine technology in both heavy-duty and light-duty vehicles, highlighting the importance of regulatory frameworks, innovative engine designs, and hybrid fuel systems to accelerate the transition toward a decarbonized transport sector.

Furthermore, retrofitting existing internal combustion engines to utilize hydrogen can expedite technology adoption by leveraging the existing vehicle fleet and infrastructure (Correa et al., 2024). This approach requires modifications to accommodate hydrogen's properties but can be cost-effective, albeit necessitating advancements in engine design and fuel system adaptations for safety and efficiency (Kolahchian Tabrizi et al., 2024). Correa et al. (2024) concluded that retrofitting locomotives with hydrogen technology significantly impacts life cycle costs, especially for shorter distances where operation and refurbishing phases contribute 62% and 24%, respectively, and emphasized that achieving cost competitiveness with diesel locomotives requires reducing the cost of clean hydrogen by approximately 5 USD/kg, which could decrease the overall life cycle costs by nearly 70% by 2050 (Correa et al., 2024). The utilization of hydrogen extends beyond road vehicles to the maritime and aviation sectors, where ships can effectively use both fuel cells and combustion engines because of their large size and energy requirements, whereas aviation relies on hydrogen combustion engines because of the inadequate power output of current fuel cell technologies (Boretti, 2024; Wang et al., 2023a).

Fernández-Ríos et al. (2022) conducted a comprehensive study using LCA to evaluate the environmental sustainability of alternative hydrogen-powered marine propulsion technologies, specifically comparing a hydrogen internal combustion engine (H_2ICE) and a polymeric electrolytic membrane fuel cell (PEMFC) with traditional diesel engines. The analysis revealed that H_2ICEs exhibited the most promising environmental benefits, with better performance in reducing GHG and other pollutants across most indicators. Both technologies demonstrated significant potential in facilitating the maritime sector's energy transition toward decarbonization. However, the technologies' early stage of development and low readiness level suggest that their ultimate environmental performance could improve as they mature and become widely implemented. This study stressed the need for active policy involvement and stakeholder collaboration to support the development and deployment of these technologies. This study also noted the importance of advancing cleaner production processes, such as brine electrolysis and hydrogen recovery from waste streams, to further increase the sustainability of these propulsion systems. The study underscores the critical role of government support in research and development, infrastructure, and public acceptance to successfully transition to a hydrogen-based economy in the shipping industry. Wang et al. (2023) conducted a detailed LCA of hydrogen-powered marine vessels to assess their environmental and economic performance compared with that of conventional diesel-powered ships. This study, aligned with ambitious emission reduction targets set by the International Maritime Organization (IMO), the European Union, and UK, demonstrated that hydrogen fuel can significantly reduce maritime emissions—by more than 80%—and reduce life cycle costs by approximately 60%. The in-house software SHIPLCA was used to analyze emissions and costs across the construction, operation, maintenance, and recycling phases of the vessels. Key findings highlighted the operational phase as the most impactful in terms of both environmental and economic factors due to high fuel consumption and the longevity of service years. Sensitivity analysis further revealed that the economic feasibility of hydrogen as a marine fuel is highly influenced by the cost of hydrogen and the price of carbon credits. Despite the higher costs associated with increased carbon credit prices, the overall costs remain substantially lower than those of traditional marine diesel oil (MDO)-powered ships. This study underscored the potential of hydrogen to revolutionize the marine industry by offering a cleaner and more economically viable alternative to fossil fuels, provided that there is favorable market conditioning regarding fuel prices and carbon valuation.

Wang et al. (2023) conducted a life cycle assessment of hydrogen-fueled ships at Dalian Port and evaluated six hydrogen production methods in terms of energy consumption, carbon emissions, and economic costs. The findings revealed that biomass gasification is the most energy-efficient and environmentally friendly method, although its viability decreases with increasing shipping distance. The study also highlights significant variations in environmental and economic impacts depending on the production method, with coke oven gas producing the highest emissions and water electrolysis being the most costly. Additionally, the optimal operating speed for hydrogen fuel cell ships was identified to be between 14 and 14.5 knots at 500 kW, indicating critical considerations for the maritime industry's shift toward hydrogen energy. Pereira et al. (2014) conducted a comprehensive life cycle assessment of alternative fuels in aviation, focusing on LH_2 derived from SMR and LNG. The findings indicate that while LH_2 from SMR reduces environmental and social impacts by 13%–21% compared with traditional jet fuel A, it generates 21% more greenhouse gas emissions than LNG-powered aircraft do. However, when LH_2 is produced using hydro energy, it significantly lowers environmental costs by 51%–60% and reduces energy consumption by 19% compared with jet fuel A. This study highlights the potential of renewable hydrogen, particularly from hydro and wind sources, in decreasing aviation's environmental footprint, although it also highlights the need to address the economic viability of hydrogen production to increase market penetration. The comprehensive life cycle assessment of alternative aviation fuels in Bicer and Dincer's (2017), which uses a well-to-wake approach, demonstrated that hydrogen, ammonia, methanol, and LNG are more environmentally friendly than conventional kerosene jet fuel. The study revealed that hydrogen produced via geothermal energy has the lowest greenhouse gas emissions, whereas renewable energy-based production of hydrogen and ammonia drastically reduces the environmental impact. However, the dependency of ammonia on natural gas can lead to higher emissions unless renewable energy sources are used. The study also highlights the significant environmental and operational costs associated with each fuel type, with nitrogen oxides and carbon dioxides being the major contributors. Although alternative fuels currently have higher operational costs than kerosene does, advancements in technology could make them competitive, suggesting a sustainable and economically viable future for the aviation industry. Kossarev et al. (2023) reported that employing hydrogen as an alternative fuel for long-range transport aircraft presents both environmental and economic challenges and opportunities. Hydrogen-fueled aircraft significantly reduce fuel mass but increase energy consumption, necessitating the use of renewable energy sources to mitigate environmental impact effectively. Although currently associated with higher operating costs and a lack of mission range flexibility, which could hinder full fleet integration, the potential environmental benefits of hydrogen are considerable. These include reduced radiative forcing and the possibility of using lightweight hydrogen storage tanks. This study underscores the importance of further research into hydrogen aircraft design improvements, including enhanced hydrogen safety standards and adaptations to increase operational flexibility, to make hydrogen a viable sustainable aviation fuel.

Siddiqui and Dincer (2021) conducted a comprehensive life cycle assessment of alternative aviation fuels, focusing on hydrogen, among others. The study revealed that hydrogen produced via conventional steam methane reforming has a significantly greater global warming potential of 0.098 kg CO_2eq/(t-km) than hydrogen produced via routes based on renewable energy. Additionally, the solar-based production route for hydrogen is associated with a higher ionizing radiation potential, mainly due to emissions of cobalt and iodine isotopes. Research has emphasized the environmental advantages of renewable energy-based production methods for hydrogen, highlighting their potential to reduce the life cycle environmental impacts in aviation fuel applications. Miller et al. (2023) conducted a comprehensive LCA on the climate impact of LH_2 as an alternative aviation fuel and compared it with that of conventional jet fuel and biofuels. These findings reveal that while LH_2 does not emit CO_2 during combustion, its production, especially via common commercial pathways, often results in greater greenhouse gas emissions than does conventional fuel production. Notably, some novel LH_2 pathways, particularly those involving the use of biomass with CCS, green hydrogen from renewable energy, and pink hydrogen from nuclear sources, demonstrate the potential for significant reductions in life cycle climate impacts. However, the higher water vapor emissions from LH_2 combustion could increase cumulative cirrus formation, exacerbating its climate impact unless mitigative actions such as optimal flight routing are implemented. This study underscores the importance of advancing hydrogen production technologies and contrail cirrus research to ensure that LH_2 can provide a genuine climate benefit for aviation. Penke et al. (2021) explored the potential of renewable hydrogen as a future aviation fuel, emphasizing the varied technical maturity of production pathways. The study confirms that while hydrogen from renewable energy sources such as solar and wind through water electrolysis currently has the lowest GHG emissions, the high costs and undeveloped infrastructure limit its immediate adoption compared with HEFA biofuels. Looking ahead, it is anticipated that decreasing costs for renewable electricity could expand LH_2 infrastructure and enhance its cost-effectiveness. However, current electricity mixes used for hydrogen production may result in higher GHG emissions than conventional fuels do. The study also highlights the need for advanced models to assess non-CO_2 aviation effects and suggests that the robustness of these findings should be tested through future sensitivity analyses considering the limited availability of raw materials and the potential impact of land use change. The study concluded that while significant challenges remain, the progressive deployment of renewable hydrogen could play a crucial role in the long-term decarbonization of the aviation sector.

4. Barriers and research gaps

In exploring the use of hydrogen for emission reduction in transportation systems, LCA serves not only as a comprehensive tool for assessing the environmental impacts of hydrogen systems but also as the gold standard for environmental evaluation because of its systematic framework and high reproducibility. The LCA begins by identifying key environmental and economic indicators such as “emissions”, “economic costs”, “energy consumption”, and “energy efficiency”, all of which are of significant concern to stakeholders. These indicators are then applied to every link and step in the hydrogen life cycle, including production, storage, delivery, and usage, thus providing specific values or ranges for each phase or step.

By conducting a thorough analysis of these values, the LCA can reveal which stages do not meet the expected targets. For example, if the energy efficiency during the production phase is below expectations, the LCA helps determine whether this is due to current technological limitations, indicating that there is room for technological advancement. Conversely, if the economic costs at certain stages are significantly higher than expected and there is limited scope for technological improvement, this could highlight underlying policy or economic issues, such as a lack of effective policy support or high initial investment costs. However, while LCA is highly effective in identifying technological and environmental barriers, it has limitations in addressing nontechnological barriers. Factors such as policy and regulatory issues, market demand, supply chain complexities, and societal acceptance are crucial in the adoption of hydrogen energy but are not directly analyzed by LCA. Moreover, economic factors such as cost, return on investment, and funding avenues are key to driving the commercialization of hydrogen technologies, and these factors typically require supplementation through LCC or other economic assessments.

Therefore, although LCA provides a solid foundation for understanding and evaluating the challenges at the technological and environmental levels within hydrogen systems, a comprehensive understanding of the actual barriers to the potential for emissions reduction in the transportation sector also necessitates integration with other analytical tools and methods to reveal and address complex factors beyond the traditional scope of LCA. This multidimensional assessment strategy helps clarify directions for future research, fills existing gaps in studies, and more effectively promotes the application and development of hydrogen technology in the transportation sector. Ultimately, the discussion in this chapter will include two parts: one part identified by LCA as technological barriers and the other covering nontechnical barriers that LCA cannot directly identify, such as policy, economic, and societal acceptance issues.

Fig. 4 presents a comprehensive visualization of the barriers and challenges identified through a review of both LCA and non-LCA studies regarding the deployment of hydrogen in decarbonizing the transportation sector. The graphic categorizes these obstacles across the life cycle stages of hydrogen: production, storage and delivery, and utilization. It highlights issues such as high water and energy intensity, dependence on rare elements, and high capital and operational expenditures in the production phase; resource-intensive infrastructure, supply chain complexities, and the need for network optimization in the storage and distribution phase; and lack of policy support, limited refueling infrastructure, consumer hesitancy, and concerns over durability and environmental performance in the utilization phase. Additionally, the diagram addresses crosscutting issues such as policy and regulation, supply and demand barriers, and social and cultural factors, which include challenges such as lowering hydrogen production costs, direct competition with established technologies, and public acceptance variability. This synthesis of barriers and challenges serves as a crucial foundation for formulating strategic policies and interventions in the hydrogen fuel landscape within the transportation sector.

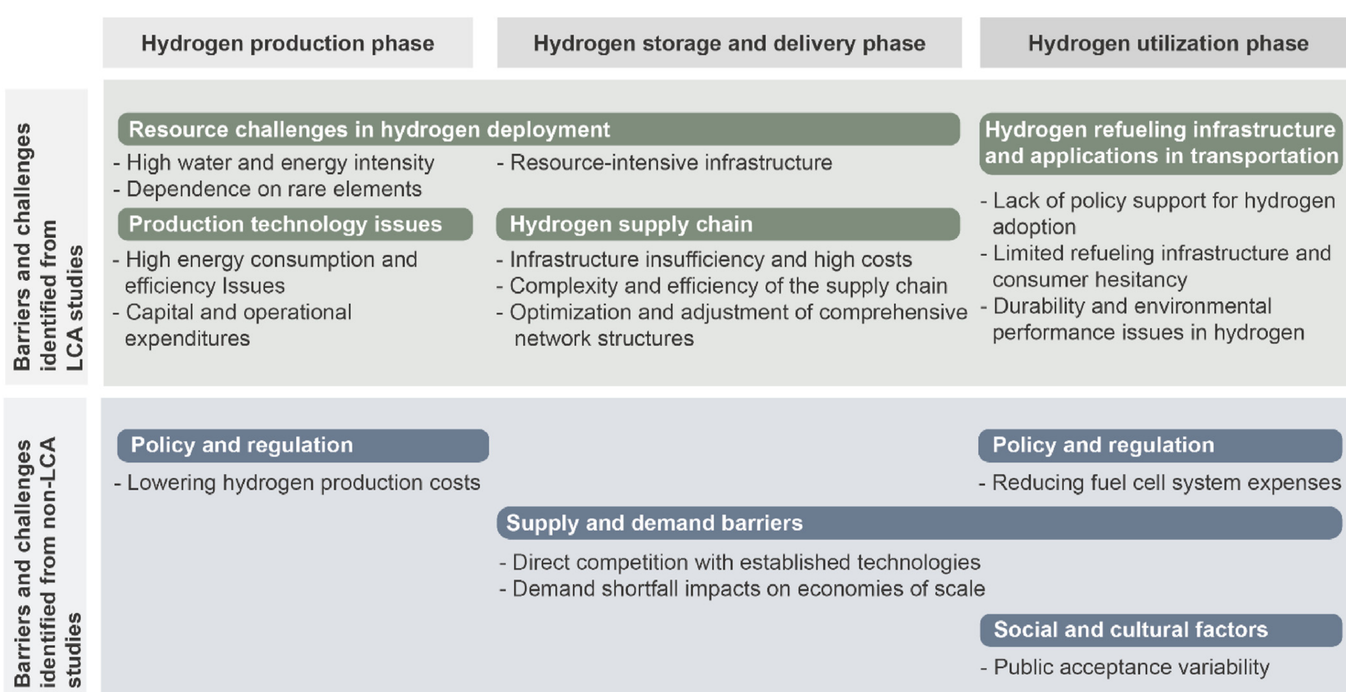

Fig. 4. Barriers to hydrogen mobility.

4.1. Barriers identified by life cycle assessment

This section explores the obstacles to the role of hydrogen in decarbonizing transportation, as identified through reviews of LCA studies. While the discussion references the stages typically included in LCA—such as extraction, production, and disposal—it also extends beyond these to include deeper and more nuanced findings. This approach ensures a comprehensive overview of both the immediate and complex barriers that impact the scalability and effectiveness of hydrogen technologies in the transportation sector.

4.1.1. Resource issues

This subsection examines the resource-related barriers that are evident in the deployment of hydrogen fuel within the transportation sector. The production and utilization of hydrogen involve significant water use, especially for electrolysis in regions where water is scarce. Additionally, the process demands substantial energy inputs, which must predominantly come from renewable sources, to maintain the benefits of decarbonization. The dependency of catalysts on rare elements such as palladium and iridium introduces challenges because of their high costs and uneven global distribution. Extensive infrastructure development for hydrogen distribution and refueling is also resource intensive, requiring large amounts of materials such as steel, which can contribute to carbon emissions if not sourced sustainably. Furthermore, the life cycle management of hydrogen technologies necessitates effective recycling and disposal strategies for spent catalysts and fuel cell components to minimize environmental impacts. Addressing these resource issues is critical for the successful integration of hydrogen fuel systems in the transportation sector.

Robles et al. (2020) developed a comprehensive framework to optimize the hydrogen supply chain for HFCVs and combined it with a societal cost-benefit analysis (SCBA) to assess the socioeconomic impacts in the Occitanie region of France, targeting a transition period 2020–2050. The key findings indicate that while carbon dioxide emission reductions represent the principal external benefit, the depletion of platinum emerges as the second most significant external cost, slightly diminishing the benefits from reduced emissions. The study also explored subsidy policy scenarios, revealing that these policies have limited effectiveness in accelerating the market penetration of HFCVs. Societal payback in scenarios incorporating externalities is projected for 2043, slightly earlier in 2042 with subsidies, and delayed until 2046 under baseline economic conditions. Employing multiobjective optimization and decision support tools such as Technique for Order Preference by Similarity to Ideal Solution(TOPSIS), this study identified optimal configurations for hydrogen supply networks, demonstrating potential societal benefits in terms of greenhouse gas reduction, local air pollution, and noise compared with ICEVs. However, the widespread adoption of hydrogen fuel cell technology still faces significant challenges, requiring enhanced policy support and technological advancements to improve its market competitiveness.

4.1.2. Production technology issues

This subsection explores the technological challenges associated with hydrogen production within the transportation sector, focusing on the environmental and economic impacts that hinder its broader adoption and implementation.

The main challenges in hydrogen production include environmental impacts, high energy demands and efficiency issues, significant economic costs, technological and material challenges, and complex policy and regulatory frameworks. Although hydrogen is considered a clean energy source, achieving sustainable and economical production requires overcoming these obstacles through technological innovation, cost optimization, and supportive policies. Burkhardt et al. (2016) conducted a comprehensive environmental assessment of an HRS with an onsite alkaline electrolyser in Berlin, revealing significant environmental impacts from construction phases that challenge previous assumptions of negligible impacts. The findings indicate that the construction of the HRS and electrolyser demands substantial energy and material, contributing substantially to the total GHG emissions, measured at 1.92 kg CO_2eq/(kg H_2), equivalent to the emissions from burning 0.8 L of gasoline. The study underscores the importance of operating the electrolyser at a high load factor, suggesting a 30% reduction in GHG emissions when increasing from 3000 to 6000 full-load hours annually. However, relying solely on excess electricity for operations may compromise economic and environmental efficiency. This study highlighted that while the electrolyser and HRS contribute 9%–15% of the overall GHG emissions when vehicle production is included, their impact remains significant. Future research should explore renewable energy integration and update material inventories to align with technological advancements. Anastasiadis et al. (2023) conducted a sensitivity analysis on a hybrid renewable energy system involving wind and photovoltaic power installations in Sifnos, Greece, emphasizing the critical impact of initial capital costs on hydrogen production economics. The results demonstrated that a yearly 2% reduction in initial capital costs could lower hydrogen production costs from 4.17 to 2.49 EUR/kg. This substantial decrease highlights the importance of optimizing capital expenditures to increase the competitiveness of hydrogen prices. Although factors such as the capacity of photovoltaic and wind installations and the cost of electrolyzers also influence production costs, their impact is significantly less than that of initial capital investments.

Cardella et al. (2017) developed a comprehensive study on the optimization of hydrogen liquefaction processes, aiming to significantly reduce specific liquefaction costs and energy consumption in large-scale operations ranging from 25 to 100 t/day. The research highlights the use of a high-pressure hydrogen cycle with mixed-refrigerant precooling as the optimal method, achieving specific cost reductions of approximately 50% at 25 t/day (tpd) and 67% at 100 tpd, while targeting an energy consumption of $\leq$ 6 kWh/kg of liquid hydrogen. Despite these advancements, the study underscores substantial challenges, particularly high capital expenditures (CAPEX) and operational expenses (OPEX), which are exacerbated by the costs of electricity. These economic hurdles are critical, as they impact the feasibility and scalability of hydrogen liquefaction technologies in meeting global clean energy goals. The findings of Kanz et al. (2023a) indicate that the GWPs of hydrogen delivered from Morocco, Senegal, and Nigeria are 3.32–3.41, 3.88–3.99, and 4.27–4.38 kg CO_2eq/(kg H_2), respectively. These emission levels are influenced by factors such as the GWP of the PV electricity, the efficiency of the electrolyzers, and the delivery distance. The study also revealed that, in most cases, the production of hydrogen in Germany driven by PV electricity (including 300 km of distribution) has a lower GWP ranging from 3.48 to 3.61 kg CO_2eq than importing hydrogen from the aforementioned African locations. If grid electricity (with a GWP of 0.420 kg CO_2eq/kWh) instead of PV electricity is used for hydrogen production in Germany, the GWP significantly increases to between 24.35 and 25.42 kg CO_2eq. Evers et al. (2023) conducted a comprehensive analysis and integration of existing LCA studies on hydrogen-fuel cell drivetrains for shipping. Research reveals that the number of LCA studies specifically focused on hydrogen applications in shipping is relatively limited, and there is a lack of uniform standards in the selection of system boundaries and functional units, making it difficult to directly compare these results. Despite these challenges, the findings indicate that the production process of hydrogen is the major source of environmental impact, particularly when the hydrogen is produced via electrolysis powered by renewable energy sources such as wind, which has the smallest environmental footprint. This study also emphasized the importance of producing hydrogen from renewable sources, optimizing the efficiency and material usage of fuel cells, and highlighted the need for strategic investments and policy support to promote the broader adoption of hydrogen fuel in maritime applications.

4.1.3. Hydrogen supply chain

This section explores the intricacies of the hydrogen supply chain, focusing on the systemic challenges that span from production through to distribution and storage and emphasizing the integration and efficiency of the entire supply chain network.

The hydrogen supply chain faces multifaceted challenges that encompass production, delivery, storage, and distribution complexities. These obstacles include the high costs and energy requirements of producing hydrogen, particularly through electrolysis, which is energy intensive. The distribution/delivery of hydrogen also presents significant issues due to its low density, requiring either high-pressure compression or liquefaction, both of which are costly and energy-consuming. Additionally, the storage of hydrogen necessitates specialized infrastructure to handle its volatile nature and maintain its purity, further increasing costs and operational complexities. Distribution networks are still in their infancy stages and require substantial investment to become robust and widespread. Furthermore, the integration of these components into a cohesive and efficient system is hindered by current technological limitations, regulatory barriers, and a lack of standardized practices across different regions. These combined factors contribute to the overall inefficiency and high operational costs of the hydrogen supply chain, challenging its scalability and viability as a widespread energy solution in the transportation sector.

A study by Wulf and Kaltschmitt (2018) noted that while solar power has low environmental impact during production, it has significant impacts during distribution to Germany. This finding indicates that in the design and optimization of hydrogen supply chains, the distance and logistical conditions between production and consumption sites significantly affect the overall environmental footprint and cost efficiency. Therefore, selecting optimal production locations and delivery methods is crucial for reducing the environmental and economic costs of the entire supply chain. Wulf and Zapp (2018) conducted a comprehensive study on hydrogen delivery methods and evaluated the economic and environmental impacts of using LOHCs such as toluene and dibenzyltoluene compared with liquefied hydrogen. These findings reveal that while LOHCs are more cost-effective due to lower liquefaction investment, liquefied hydrogen is significantly more environmentally friendly, emitting less than half the greenhouse gases of LOHCs. Toluene-based LOHC has the lowest hydrogen cost (77% from electrolyzer), while liquid hydrogen transport, though cheaper per trip, incurs higher overall costs due to energy-heavy liquefaction. The study also examines the effects of different heat sources for dehydrogenation and the electricity mix used for liquefaction, emphasizing the importance of renewable energy for reducing the environmental impact. This study suggested further research into broader supply chain evaluations and technological advancements to better balance economic and environmental considerations in hydrogen transport. Reuβ et al. (2019) examined the impact of simplifying hydrogen pipeline network topologies and fluid flow models on investment and system costs in energy models. While the widespread adoption of hydrogen fuel cell technology still faces significant challenges, necessitating enhanced policy support and technological advancements to improve market competitiveness, this significant reduction in pipeline costs translates to a modest 1.4% decrease in total electricity reconversion costs. Given the complexities and computational demands of nonlinear models, this study recommended the application of postprocessing to validate and enhance the reliability of the results without compromising computational efficiency. This approach improves the strategic planning and development of future energy systems that rely on hydrogen transport. Lundblad et al. (2023) developed a technoeconomic optimization model to compare three electrolysis-based hydrogen supply systems: the decentralized standalone system (Dec-Sa, costing 2.5–6.7 EUR/(kg H_2)), the decentralized grid-connected system (Dec-Gc, costing 2.2–3.3 EUR/(kg H_2)), and the centralized grid-connected system (Cen-Gc, costing 3.5–4.8 EUR/(kg H_2)). This study, covering regions such as electricity pricing zone SE3 in Sweden, Ireland, Croatia–Slovenia–Hungary, and western Spain, investigated how different electric power system compositions and renewable energy potentials impact costs. The results reveal that the decentralized grid-connected system offers the lowest hydrogen supply costs in most areas, with future projections indicating a potential reduction in hydrogen production costs of 23%–42%, assuming decreased investment costs and lower electricity prices. Al-Sharafi et al. (2024) conducted a study in Saudi Arabia that focused on the LCOH for hybrid PV/wind systems at hydrogen refueling stations. In the off-grid scenarios, the LCOH ranged from 9.49 to 9.90 USD/kg, with the minimum observed in the industrial area and the maximum in the tourist area. The on-grid scenarios presented a lower LCOH, ranging from 7.80 to 8.61 USD/kg,

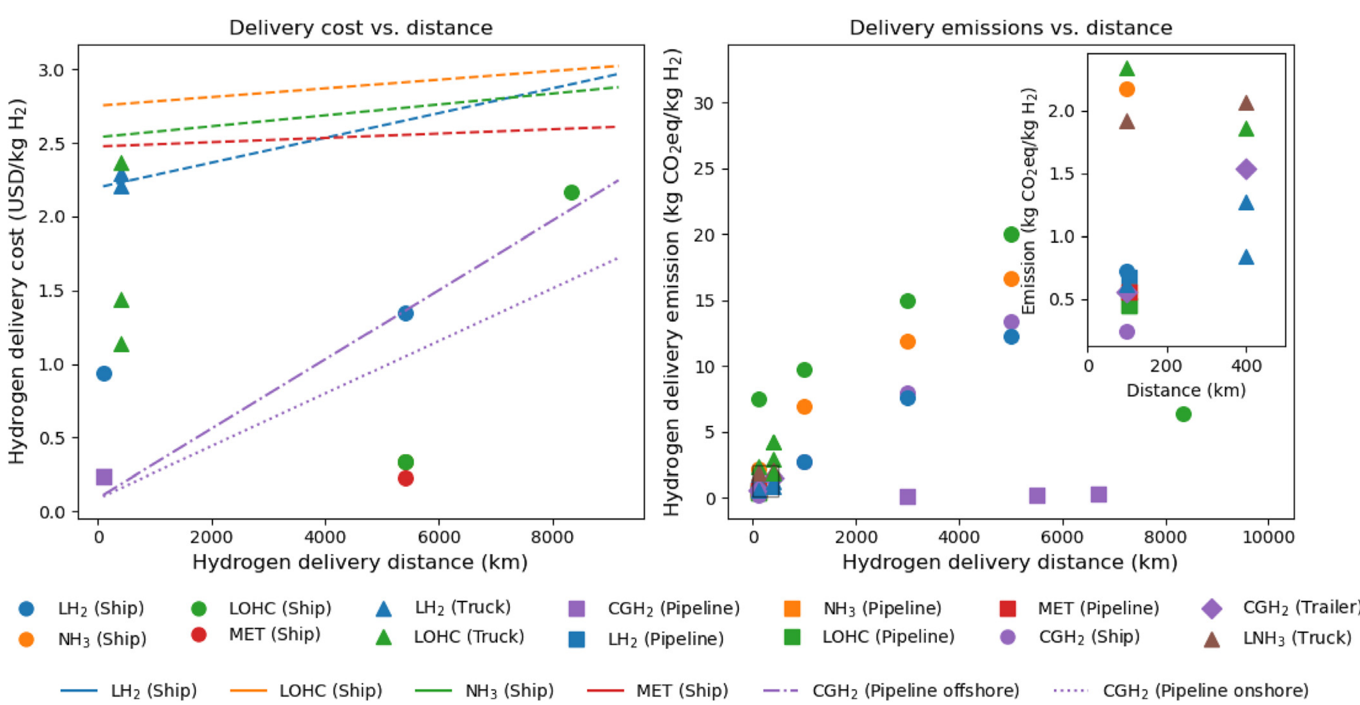

Fig. 5. Compilation of hydrogen delivery cost and emission data by delivery distance for various storage and delivery methods (Ahn et al., 2024; Akhtar et al., 2021; Balaji and You, 2024; Kanz et al., 2023b; Lee et al., 2022; Noh et al., 2023; Radner et al., 2024; Reuβ et al., 2021; Wulf and Zapp, 2018).

with the lowest and highest costs reported in the industrial and tourist areas, respectively.

Fig. 5 presents the cost and emission data for hydrogen delivery systems collected from a literature review on various hydrogen storage and delivery methods. Among the articles selected for this review, only 9 studies provided suitable and relevant data for Fig. 5, highlighting the importance of the integrated concept of storage and delivery proposed in this review. In other words, it is crucial to consider the entire delivery system holistically rather than focusing solely on the delivery phase itself. Many studies have not adequately addressed the cost and emissions of the overall delivery system, which is evident in two key aspects: First, the delivery of hydrogen as a product is often overlooked; second, the storage and delivery processes are not considered integrated systems. For example, while the delivery costs for LOHCs may be low, the hydrogenation and dehydrogenation processes associated with LOHCs can result in significantly higher emissions. Fig. 5 aims to calculate and represent the total system-level data from the reviewed studies as comprehensively as possible, showing the relationship between hydrogen delivery costs (USD/(kg H_2)) and delivery distance (km), as well as the relationship between hydrogen delivery emissions (kg CO_2eq/(kg H_2)) and delivery distance. The legend distinguishes between different storage and delivery methods, aiding in the visualization of how various technological pathways impact both delivery costs and emissions. However, it is inevitable that some studies did not directly or indirectly account for the predelivery and postdelivery phases in their calculations. Therefore, Fig. 5 not only presents the collected data on hydrogen delivery costs and emissions but also underscored the critical importance of considering the integrated storage and delivery system when assessing the hydrogen supply chain.

In Fig. 5, studies on hydrogen storage and delivery methods span a variety of scenarios across different countries and delivery routes, including significant transcontinental routes such as Australia to Republic of Korea and Africa to Germany, as well as regional analyses within USA and between several European and Middle Eastern countries such as Austria, Croatia, Chile, Egypt, Tunisia, and the United Arab Emirates (UAE) (Akhtar et al., 2021; Lee et al., 2022; Radner et al., 2024; Reuβ et al., 2021; Wulf and Zapp, 2018). These studies collectively explore the environmental and economic impacts of hydrogen delivery and include multiple modes of delivery, such as ships, pipelines, trucks, and tube trailers. For example, a study on off-grid hydrogen production in countries such as Austria and the UAE discussed the costs and logistics of supplying hydrogen to Europe, with delivery distances ranging from 350 to 1850 km (Radner et al., 2024). Another notable study focused on the use of LOHCs for long-distance transport from Australia to Republic of Korea, spanning 4500 nautical miles (Ahn et al., 2024), highlighting the utilization of renewable energy sources. In USA, another research effort centers around offshore wind for hydrogen production with delivery distances of approximately 100 km (Balaji and You, 2024). More extensive studies include the analysis of transcontinental pipeline transport from Africa to Germany with pipeline lengths of 3,000, 5,500, and 6700 km and the examination of offshore hydrogen supply chains between Australia and Republic of Korea, which consider a wide array of delivery distances from 100 to 10,000 km (Kanz et al., 2023b; Noh et al., 2023). The methodologies predominantly rely on WEs for hydrogen production and incorporate storage techniques such as LH_2, CGH_2, and various organic carriers. This wealth of data underscores the complexity and variability in hydrogen delivery costs and emissions, which are crucial for developing efficient and sustainable hydrogen infrastructures.

Fig. 5 reveals significant differences in both cost and emissions across various hydrogen storage and delivery methods. For CGH_2 delivered via pipelines, the cost increases substantially with distance, particularly for offshore pipelines, which are notably more expensive than onshore pipelines. This suggests that while pipelines can be economically viable over short distances, their costs rise sharply with increasing distance. In contrast, LH_2 delivered by ships shows a more gradual cost increase over distance, indicating its economic advantage for long-distance delivery. Both NH_3 and LOHCs present higher delivery costs that increase with distance, with costs exceeding those of LH_2, whereas the MET remains relatively stable and unaffected by delivery distance.

On the emission side, the LOHC and NH_3 stand out with significantly higher emissions, particularly for longer delivery distances. LOHC, in particular, reaches emission levels above 15 kg CO_2eq/(kg H_2) between 2000 and 6000 km, highlighting its environmental drawbacks. In contrast, CGH_2 pipeline delivery, especially via onshore pipelines, results in minimal emissions at shorter distances, highlighting its clear environmental advantage for short-range delivery. The inset zooms in on the 0–500 km range, further confirming CGH_2's low emissions over short distances, whereas LOHC and NH_3 still exhibit higher emissions even at these shorter ranges. When both costs and emissions are compared, it becomes evident that while the LOHC offers some cost advantages, its high emissions make it less environmentally sustainable. Conversely, CGH_2 pipelines demonstrate a clear low-emission benefit for short distances but become more costly over longer distances. LH_2, however, strikes a balance between cost and emissions, offering a competitive option for long-distance delivery. These findings emphasize that considering either delivery cost or emissions in isolation is insufficient—both must be evaluated in the context of the entire storage and delivery system to identify the most cost-effective and environmentally sound pathway.

However, it is important to note that these results come from different studies, each with its own set of assumptions and contextual variations. In addition to the differences in storage and delivery methods, these studies also vary in terms of the technologies considered, the years of assessment, geographic locations, and other factors. As such, the comparisons presented in Fig. 5 should be treated as a reference rather than definitive conclusions. For practical applications, a comprehensive evaluation that accounts for the specific technological, geographical, and temporal context is necessary to assess the feasibility of hydrogen delivery options.

4.1.4. Hydrogen refueling infrastructure and applications in transportation

In the transition toward decarbonized transport solutions, the deployment of hydrogen fuel faces significant challenges, particularly in establishing a comprehensive refueling infrastructure. The construction of hydrogen refueling stations involves substantial costs due to the need for advanced, high-pressure storage and cryogenic technology. Additionally, the delivery and storage of hydrogen entail considerable energy losses, highlighting overall efficiency concerns from production to end use. Despite technological advancements, the lack of sufficient policy incentives further impedes the widespread adoption of hydrogen infrastructure. These factors collectively slow the pace of hydrogen application in transportation, necessitating a concerted effort from governments, industry, and research institutions to overcome these barriers through technological innovation and supportive policies, as identified in LCA studies.

While the establishment of a hydrogen refueling infrastructure is critical, the application of hydrogen within various modes of transportation presents complex challenges. The integration of hydrogen technology in vehicles, such as buses, trucks, and personal cars, necessitates adaptations in vehicle design and manufacturing processes to accommodate hydrogen fuel cells and internal combustion engines capable of using hydrogen. These adaptations require substantial investments in new technologies and materials to ensure safety and efficiency. According to Candelaresi et al. (2021), LCAs of hydrogen-powered vehicle technologies highlight that while all hydrogen vehicles offer significant decarbonization potential, hybrid electric vehicles using hydrogen and pure hydrogen internal combustion engine vehicles show particularly promising life cycle environmental performance across metrics such as the carbon footprint, energy footprint, and acidification potential. However, HFCVs, despite their benefits, face durability challenges that diminish their life cycle performance, underscoring the need for advancements in fuel cell technology.

Moreover, the overall energy efficiency of hydrogen fuel, from production through to utilization in vehicles, often faces scrutiny in LCAs, highlighting significant energy losses at multiple stages. The limited range and density of refueling stations also restrict the practical usability of hydrogen-powered vehicles, thereby affecting consumer adoption rates. Addressing these challenges requires not only technological advancements and infrastructure development but also robust policy frameworks that encourage the adoption of hydrogen technologies in transportation. These aspects, evaluated through LCAs, underscore the need for a multifaceted approach to effectively harness hydrogen's potential in decarbonizing transportation, including transitioning through mixed-use vehicles that utilize both hydrogen and traditional fossil fuels as intermediate solutions.

4.1.5. Funding and investment

Funding and investment in hydrogen technologies are pivotal yet challenging, primarily because of the significant upfront capital required for infrastructure development and the high costs associated with advanced production techniques. Technologies such as electrolysis, particularly when powered by renewable sources such as wind energy, are environmentally friendly, are more expensive than traditional hydrogen production methods are. For example, Wulf and Kaltschmitt (2018) reported that while wind-powered electrolysis has the least environmental impact in most categories, it is associated with higher production costs. Additionally, the study highlights that while alternatives such as hydrogen sourced from the chemical industry present lower supply costs, they bear greater environmental burdens, particularly in terms of climate change impacts. Moreover, even more sustainable options, such as steam reforming of biomethane, which substantially reduces climate impacts, face their own set of challenges, including high impacts on acidification and particulate matter. These complexities underline the critical need for increased investments in cost-effective and environmentally sustainable hydrogen production technologies. Such financial commitments must be bolstered by policy support to create a conducive environment for both the private and public sectors to invest in hydrogen infrastructure, thus bridging the gap between cost and environmental performance, as suggested by ongoing research.

4.1.6. Market factors (supply and demand relationship)

The market for hydrogen fuel in transportation is complex and influenced by a variety of factors that can either facilitate or impede its broader adoption. The key among these factors is the balance between supply capabilities and demand needs, which directly impacts the economic viability of hydrogen solutions. The economic performance of hydrogen systems, such as those illustrated by the Hydrogen Valley project in southern Italy, is heavily dependent on factors such as power purchase agreement (PPA) pricing. As Genovese et al. (2024c) noted, the LCOH can vary significantly on the basis of PPA prices and the capacity utilization of production facilities. For example, under scenarios where the PPA price is high and production operates at diminished capacity, LCOH can become prohibitively expensive, potentially stalling market competitiveness. Conversely, when production is maximized and PPA prices are controlled, the TCO remains competitive, suggesting that careful management of these economic inputs is crucial for maintaining a viable hydrogen market. The economic viability of hydrogen systems is significantly influenced by operational scenarios, reflecting varying levels of hydrogen demand and system loads. Different types of HRSs exhibit varying cost dynamics; for example, forklift refueling stations range from 6.15 to 17 EUR/kg; city bus stations vary from 5.2 to 13 EUR/kg; and bicycle refueling infrastructure generally maintains a cost between 4 and 6 EUR/kg, rising above 8 EUR/kg during lower demand periods (Genovese et al., 2024c). These figures highlight the importance of high demand and appropriate system loads in maintaining competitive hydrogen costs.

Furthermore, market competition between HFCVs and EVs adds another layer of complexity. Studies such as that of Kim et al. (2020) highlight the need for strategies that address market segmentation and targeted investments to balance the growth of these technologies and achieve significant greenhouse gas reductions. This dynamic interplay between economic factors and technology adoption underscores the need for strategic planning and regulatory support to enhance the hydrogen market's structure and drive the transition toward decarbonized transportation systems.

4.2. Barriers beyond life cycle assessments cope

This section synthesizes findings from the literature on the challenges in deploying hydrogen for transportation decarbonization that extend beyond the scope of LCAs. It specifically examines policy and regulatory hurdles, social and cultural factors, issues related to technology transfer and innovation, and barriers affecting supply and demand. These topics highlight critical factors that influence the broader context of hydrogen implementation, offering insight into the multifaceted challenges that must be navigated to advance hydrogen as a key component of sustainable transportation strategies.

4.2.1. Policy and regulation

The successful integration of hydrogen technologies into the mainstream transportation sector has faced numerous policy and regulatory hurdles. These issues often revolve around the need for substantial reductions in hydrogen production costs and fuel cell system expenses to make HFCVs economically viable. For example, according to Wang et al. (2024), achieving a competitive market for HFCVs requires lowering the price of hydrogen from 5.8 to 2.5 GBP/kg and reducing the cost of fuel cell systems from 267 to 110 GBP/kWh. These cost reductions are essential not only for the affordability of HFCVs but also for their role in decarbonizing transportation. Similarly, studies such as that of Sadik--Zada et al. (2023) highlight the economic benefits of fuel cell electric buses in Germany post-2035, provided that there are supportive policies such as enhanced carbon pricing and subsidies for hydrogen fuel cell technology. Moreover, Jones et al. (2020) suggested that with tax reliefs and grants, HFCVs can achieve cost competitiveness against diesel and battery electric vehicles in the UK's urban logistics. As critical policy measures, increasing capital subsidies and promoting hydrogen production from renewable sources are recommended. Finally, Espin et al. (2021) underscore the potential for Ecuador to leverage its abundant renewable energy sources to significantly lower hydrogen costs, thereby increasing the economic and environmental viability of hydrogen vehicles. However, barriers such as limited research, insufficient academic training, and the absence of adequate regulatory frameworks need to be addressed. Collectively, these studies illustrate that while technological advancements are crucial, the establishment of a favorable policy and regulatory environment is equally vital to facilitate the transition toward a hydrogen-fueled transportation system.

4.2.2. Social and cultural factors

Social and cultural acceptance of HFCVs plays a crucial role in their adoption and overall success in transportation decarbonization efforts. Al-Amin et al. (2019) highlight the importance of public acceptance in Malaysia, where the survey indicates varying levels of enthusiasm for HFCVs across different demographic groups, suggesting that age, education level, and income significantly influence acceptance levels. The study underscores the necessity for policies that incentivize both consumers and manufacturers, promote research and development, and introduce disincentives for conventional vehicles to foster a more hydrogen-friendly culture. Moreover, the study by Al-Sharafi et al. (2024) highlights the technical and economic challenges arising from the need to synchronize the hydrogen supply with demand fluctuations, which are influenced by variable solar energy availability. This synchronization affects the size of the necessary infrastructure, such as photovoltaic arrays and hydrogen storage systems, directly impacting the cost-effectiveness and public perception of hydrogen-based systems.

These elements demonstrate that beyond the mere technological readiness of hydrogen solutions, successful implementation also heavily depends on aligning them with social patterns and cultural expectations, which can vary widely across different regions and communities. Understanding and addressing these social and cultural dimensions are essential for creating enabling environments that support the transition to hydrogen-fueled transportation systems.

4.2.3. Technology transfer and innovation

Technology transfer and innovation are pivotal in advancing the deployment of hydrogen fuel cell vehicles and realizing their potential to enhance sustainable mobility. Chakraborty et al. (2022) provided a comprehensive analysis of the environmental and energy efficiency advantages of fuel cell vehicles, which use significantly less energy and produce markedly less CO_2 emissions than gasoline vehicles do. These benefits are crucial for aligning with sustainable development goals and mitigating climate change impacts. However, the transition to a hydrogen-based transportation system is encumbered by several formidable barriers. High production and infrastructure costs, coupled with the logistical complexities of hydrogen distribution, present significant challenges. Additionally, hydrogen technologies must compete with established energy sources and emerging alternatives such as electric vehicles. For hydrogen technologies to be viable and competitive by critical future milestones such as 2035 and 2050, substantial reductions in costs are imperative. Moreover, breakthroughs in hydrogen generation and storage technologies are needed to meet the sustainability criteria and ensure the safe, reliable, and effective implementation of hydrogen solutions across various transportation modalities, including the marine, railway, and aerospace sectors. Addressing these challenges through enhanced technology transfer and fostering innovation is crucial for overcoming the technical and economic barriers that currently limit the widespread adoption of hydrogen fuel cell vehicles.

4.2.4. Supply and demand barriers

The supply and demand dynamics of HFCVs present significant obstacles to their mainstream market penetration and scalability. Albatayneh et al. (2023) reported that despite potential technological improvements, HFCVs struggle to compete directly with BEVs, which currently dominate the market because of their cost efficiency, advanced technological development, and established charging infrastructure. The commercialization of hydrogen vehicles is further complicated by a demand shortfall, which hinders the achievement of economies of scale essential for reducing costs and enhancing competitiveness (Terlouw et al., 2024). Although HFCVs have advantages in specific applications, such as heavy transportation in remote areas where their longer range and fast refueling capabilities could be beneficial, these niche applications do not generate sufficient market demand to support widespread adoption. This limited demand exacerbates the challenges in establishing a robust and economically viable supply chain for hydrogen, further restricting the proliferation of hydrogen technologies in the broader transportation market. Addressing these supply and demand barriers is crucial for enabling the growth of hydrogen as a key component of decarbonizing the transport sector.

5. Discussion and future recommendations

5.1. Discussion

The challenges and strategic recommendations discussed in this review highlight the complexity of implementing hydrogen mobility. The economic viability and broader acceptance of HFCVs depend not only on technological advancements but also on policy frameworks, social acceptance, and supply-demand dynamics. LCA studies have emphasized that while hydrogen can substantially reduce the environmental impact of transportation, numerous barriers must be addressed.

Policies and regulations are crucial, as current LCAs suggest that without substantial policy support, including subsidies and tax relief, the costs of hydrogen production and fuel cell technologies remain high. Social and cultural factors also significantly influence public perceptions and acceptance, which are essential for HFCV market penetration. Additionally, technological innovation is required to address the efficiency and cost issues highlighted by many LCAs.

Market dynamics present another challenge, with HFCVs competing against established technologies such as battery electric vehicles. The lack of sufficient demand hinders the achievement of economies of scale, which are crucial for reducing costs and environmental impacts.

A further difficulty noted in related LCA studies is the oversight of the storage and delivery phases of hydrogen as a fuel, which are critical to understanding the economic and environmental impacts unique to hydrogen mobility. Even when these phases are considered, a unified and accurate framework to evaluate their complete economic and environmental impacts is lacking. Many studies focus on emissions or costs during delivery but fail to comprehensively account for stages such as hydrogenation and dehydrogenation in chemical hydrogen storage methods such as LOHCs. An equitable assessment should consider the entire storage and delivery process—including the predelivery, delivery, and postdelivery stages—to compare the impacts of various hydrogen storage and supply chain processes fully.

5.2. Future recommendations

On the basis of the insights gathered from the literature reviews, including both LCA and non-LCA sources, and the observed gaps, the following future recommendations have been refined to further increase the sustainability and adoption of hydrogen mobility.

Recommendations for policy makers.

1) Strengthening policy support: Long-term government subsidies for green hydrogen production should be encouraged to increase cost competitiveness, and regulatory frameworks should be amended to facilitate the integration of hydrogen technologies into existing infrastructures. This will help in building a supportive environment for hydrogen adoption at various levels of society and industry (Jaradat et al., 2024; Jones et al., 2020).
2) Expand market opportunities: Target niche markets in heavy-duty transport, remote, maritime, and aviation areas, where HFCVs and technologies can provide significant advantages. Strategic early adopter incentives should be utilized to increase market demand and facilitate the initial buildup of a user base, ensuring that hydrogen mobility can reach a critical threshold of market presence (Jaradat et al., 2024; Kim et al., 2023).
3) Build scalable production and distribution networks: Invest in expanding hydrogen infrastructure, including production facilities and refueling stations, to reduce costs and increase the availability of hydrogen fuel. This strategic development is crucial for creating a robust framework that supports the widespread adoption and accessibility of hydrogen-based solutions (Khaligh et al., 2024; Robles et al., 2020; Wulf and Kaltschmitt, 2018).

Recommendations for the scientific community.

4) Enhance public engagement and education: Scale up educational and public engagement initiatives to improve awareness and acceptance of hydrogen technologies. It is essential that these efforts align with local cultural and social expectations to foster a supportive environment for technological adoption (Hassan et al., 2024b; Hienuki et al., 2021).
5) Foster technological innovations across all sectors: Increase investment in research and development to improve hydrogen production, fuel cell efficiency, and storage solutions. This includes advancing hydrogen use in the maritime and aviation sectors by tackling specific challenges, such as increasing the energy density of storage systems

and ensuring operational safety in high-vibration environments. Strengthening partnerships among academia, industry, and the government should be prioritized to accelerate technological advancements and commercialization (Boretti, 2024; Degirmenci et al., 2023; Fernández-Ríos et al., 2022; Rolo et al., 2024).

6) Integrate storage and transportation delivery with a rigorous framework: Develop and implement a scientifically rigorous framework to assess the environmental and economic impacts of hydrogen storage and transportation delivery across the entire supply chain. This approach should incorporate a complete LCA framework considering the full system boundaries due to the diversity in renewable hydrogen production locations and usage sites. Emphasis should be placed on evaluating storage and delivery, as these are critical components that significantly affect the cost and emission of hydrogen. Adopting LCA best practices suited for diverse technologies and geographies is crucial for ensuring that all aspects of hydrogen mobility are comprehensively evaluated (Ahn et al., 2024).
7) Monitor and adapt strategies: Continuously update LCAs to monitor the environmental and economic performance of hydrogen mobility, adapting strategies as needed to meet evolving sustainability goals. This ongoing assessment is vital for maintaining alignment with long-term decarbonization targets in the transportation sector (Akhtar et al., 2021; Osman et al., 2022).
8) Research on demand-side adoption: Academic research should also explore advancements in hydrogen conversion technologies such as hydrogen fuel cells, hydrogen internal combustion engines, and retrofitting existing engines to adapt to hydrogen fuel. Enhancing the demand side of hydrogen mobility is crucial not only for competing with traditional fuel systems but also for ensuring that hydrogen can be effectively integrated into the energy system of the transportation sector (Reigstad et al., 2022; Terlouw et al., 2024).

By addressing these refined recommendations, stakeholders can better align the development of hydrogen mobility with sustainability objectives, leading to a more robust and environmentally friendly transportation sector. The pathway to hydrogen mobility requires concerted efforts across multiple domains, and by addressing the identified gaps through strategic initiatives, significant progress can be achieved in decarbonizing transportation.

6. Conclusions

This comprehensive review meticulously examines the life cycle of hydrogen as an alternative fuel in the transportation sector, encompassing production, storage, delivery, and usage, with a focus on electrolysis and natural gas reforming methods. Insights from an array of LCAs illustrate the environmental, economic, and safety impacts of hydrogen, highlighting its potential to significantly reduce greenhouse gas emissions compared with those of conventional fossil fuels, primarily when green hydrogen is produced via electrolysis using renewable energy. However, the realization of these environmental benefits depends heavily on the production methods employed. Economically, hydrogen encounters challenges with cost competitiveness and scalability, which could be alleviated through robust policy measures such as subsidies and tax incentives, alongside technological advancements that increase efficiency and lower costs. The development of a comprehensive infrastructure to support hydrogen production and distribution is crucial for its economic viability. Additionally, safety concerns, especially regarding high-pressure storage and delivery, necessitate continuous innovation and strict regulatory compliance to ensure safe deployment on a large scale.

This review underscores the necessity of an integrated approach to assessing the life cycle of hydrogen, proposing a “surface-level” LCA framework that incorporates the “storage–delivery nexus” to provide a more holistic view of its environmental impact. This refined assessment not only increases the accuracy of environmental evaluations but also aids in shaping effective policies and technologies that address existing gaps. As hydrogen mobility progresses, coordinated efforts across various domains, including policy, technology, market dynamics, and public perception, are needed. The strategic recommendations put forth in this review advocate for a comprehensive, multifaceted approach to foster the adoption and sustainability of hydrogen, which is essential for the decarbonization of transportation.

In conclusion, while the path to hydrogen mobility presents numerous challenges, the combined efforts of governments, industries, and communities are vital for unlocking the transformative potential of hydrogen. The effective integration of hydrogen into the transportation sector depends on addressing these challenges through innovative solutions and a strong commitment to sustainability goals. Such efforts not only pave the way for a more sustainable transportation sector but also position hydrogen as a cornerstone in the global fight against climate change.

CRediT authorship contribution statement

Fangjie Liu: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Shafique:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization, Funding acquisition, Resources, Validation. **Xiaowei Luo:** Writing – review & editing, Supervision, Project administration, Formal analysis, Conceptualization, Data curation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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