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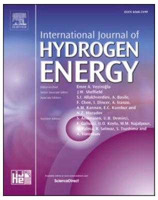

Key influencing factors on hydrogen storage and transportation costs: A systematic literature review

Xing Lu [a,*], Anne-Charlotte Krutoff [b], Mona Wappler [b], Anja Fischer [a]

[a] Department of Business and Economics, TU Dortmund University, Vogelpothsweg 87, Dortmund, North Rhine-Westphalia, Germany
[b] Faculty Communication and Environment, University Rhein-Waal, Friedrich-Heinrich-Allee 25, Kamp-Lintfort, North Rhine-Westphalia, Germany

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ABSTRACT

Cost-effective hydrogen supply chains are crucial for accelerating hydrogen deployment and decarbonizing economies, with the storage and transportation sectors representing major challenges. This study presents a systematic literature review of 81 papers to identify and analyze the main influencing factors on hydrogen storage and transportation costs, with the aim of improving transparency across the hydrogen supply chain. The review identifies and assesses 25 technical, nine economic, and two environmental factors, highlighting capital expenditure and capacity of storage and transport facilities as the primary drivers of storage and transportation costs. Furthermore, transport distance for trucks and ships, as well as the discount rate for pipelines, are identified as additional critical cost-determining factors for the transportation sector.

1. Introduction

The Earth's climate has changed rapidly for decades. In 2023, the global average temperature had increased by 1.36 °C compared to the preindustrial average between 1850 and 1900 [1]. Over time, warm temperatures will result in serious consequences such as ice sheet melting and sea-level rise, endangering human beings and all other forms of life on Earth [2]. To address this concern, many countries have agreed to substantially reduce greenhouse gas emissions to limit the temperature increase to 1.5 °C based on the Paris Agreement. More than 100 countries engage to achieve their net zero targets in the period between 2030 and 2070 to prevent further global warming [3]. Key factors in meeting their net zero targets might be a reduction of energy intensity and an improvement of the energy mix [3].

Green or blue hydrogen, produced by electrolysis or traditional fossil fuel combined with carbon capture utilization and storage (CCUS), has great potential to accelerate the achievement of net zero targets [4]. Hydrogen is considered a promising alternative that can substantially improve the energy mix due to its low CO_2 emissions and high energy value. Around 60% of the reduction of global carbon emissions can be achieved through the integration of renewables, green hydrogen, and electrification into the energy mix [5]. Global hydrogen demand is expected to increase from 95 million tons in 2022 to 212 million tons in 2030 [6,7]. More than 30 countries have released roadmaps to support and accelerate their countries' large-scale hydrogen development and the international hydrogen trade with other players. However, with an increasing risk of economic degression, individuals and companies may not be able to afford blue or green hydrogen unless there is a cost reduction by technological advancements or more efficient planning of the hydrogen supply [8]. Several challenges still remain during blue and green hydrogen deployment, including but not limited to high production costs, the need for efficient hydrogen regulations, and the absence of an appropriate supply chain infrastructure [9–11].

The development and scaling up of the hydrogen market necessitate cost-effective hydrogen supply chain configurations and efficient operations. Understanding the hydrogen supply chain cost, which is typically represented by measures such as the levelized cost of hydrogen (LCOH), the total (net present) cost of the hydrogen supply chain, and the total annual or daily cost, is crucial for investigating and achieving efficient and optimal configurations. The hydrogen supply chain consists of seven main sectors: feedstock supply, production, storage, transloading, transportation, conversion and reconversion, and consumption. Depending on the chosen technology, there are diverse options in the abovementioned sectors. For instance, electricity generated from both renewable energy sources and traditional grid electricity can serve as feedstocks for electrolysis, while fossil fuels are the primary raw material used in steam reforming. After production, the hydrogen can be converted into suitable hydrogen carriers such as compressed gaseous

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* Corresponding author.
E-mail address: xing.lu@tu-dortmund.de (X. Lu).

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hydrogen (CGH_2) or liquefied hydrogen (LH_2). These carriers are then stored in storage hubs or transported through various modes (road, seaway, and pipeline transportation) to transloading locations or directly to end-users. The primary customers for hydrogen include the transportation industry (fuel cell vehicles and aviation), the chemical industry, refineries, and the power sector. Currently, green hydrogen production costs range between 3.24 €/kg_{H2} and 11.11€/kg_{H2} depending on the production region [6,7]. Processes subsequent to the production of hydrogen can account for 40%–75% of the total cost of hydrogen [12–15]. The main bottlenecks of hydrogen supply chains are hydrogen storage, transloading, and transportation due to the risk of high capital investment for developing the hydrogen delivery network and the lack of storage and transportation capacity [9]. Therefore, it is of significance to understand and break down the costs of hydrogen storage and transportation since a successful hydrogen deployment depends on a holistic understanding and planning of the entire supply chain, including storage and transportation costs.

Hydrogen supply chains have been reviewed in previous research. However, the focus was primarily on technology development and applications, hydrogen production technologies and costs, and hydrogen supply chain design methods. Monteiro and Brito [16] review the entire hydrogen supply chain, focusing on technology development for each sector, while Liu and Ma [17], Sambo et al. [18], and Li et al. [18] recap hydrogen supply chain network design models and methods to study the state-of-the-art and identify the gaps in this field. Megía et al. [19] review different hydrogen production technologies using renewable and traditional energy resources. Similarly, Chau et al. [20] review, evaluate, and compare different hydrogen production technologies regarding efficiency, safety, and infrastructure. Lastly, Yukesh Kannah et al. [21] focus on comparing the cost-effectiveness of various production processes. The authors consider hydrogen storage and transportation in the hydrogen supply chain mainly from a technological point of view. In summary, to the best of our knowledge, there is a lack of transparency regarding the multiple factors specifically affecting costs in the hydrogen storage and transportation stages. To provide holistic insights into the economic viability of these stages, a systematic identification and evaluation of these factors from multiple angles is required, building on and adding to the technology perspective.

In this paper, we conduct a systematic literature review to summarize and analyze the state-of-the-art hydrogen storage and transportation sectors with regard to cost drivers for different hydrogen carriers. To do so, we formulate our main research questions (RQ) as follows:

1. What technologies and hydrogen carriers are considered in research on the hydrogen supply chain storage and transportation?
2. Which factors impact hydrogen storage and transportation costs in the literature, and what are the key drivers?
3. How do key factors impact the storage and transportation costs of different hydrogen carriers?

To answer these questions, our paper is organized in the following way. Section 2 describes the methodology utilized for the systematic literature review and the analysis of the identified sample. Section 3 presents our findings regarding storage and transportation technologies and hydrogen carriers in hydrogen supply chains. Section 4 exhibits factors that have been identified as hydrogen storage and transportation cost drivers. Section 5 provides a hydrogen carrier-based analysis of how key factors impact hydrogen storage and transportation costs. Lastly, we discuss the results and limitations of this paper in Section 6.

2. Methodology

We conduct a domain-based systematic literature review (SLR) based on the literature review guideline in Ref. [22] that is designed to ensure a rigorous and transparent literature review [23]. It involves a reliable and replicable procedure for systematically searching, selecting, appraising, and synthesizing relevant studies, enabling researchers to draw well-founded conclusions based on the available evidence [23]. An SLR typically involves four main steps: formulating research questions, identifying and evaluating the studies, exacting and synthesizing the data, and publishing the review findings [24]. In this study, we focus on the first three steps, without particularly emphasizing the selection of the journal for publishing the results.

To answer the three RQs as mentioned in Section 1, we follow [25] to select more than one database, using Web of Science (WoS) and Scopus for our research queries. In the initial identification of the relevant studies, the search strings ‘supply chain’ AND ‘hydrogen’ AND (‘storage’ OR ‘transport’) are employed in the topic field. As a result, a list of 353 (WoS) and 80 (Scopus) peer-reviewed journal articles written in English are identified. After the elimination of duplications and review articles, 371 papers are retained. Following [22], we select articles published in Q1 and Q2 journals based on the SCImago Journal Rank within the fields of ‘Energy,’ ‘Chemical Engineering,’ and ‘Business, Management, and Accounting,’ totaling 1583 journals, to ensure a high-quality dataset. Besides, articles published between 2017 and 2023 are chosen because the publications before 2017 mainly consider hydrogen production and storage technologies but not the hydrogen supply chain. Furthermore, we assume that technologies developed before 2017 that are still relevant for the hydrogen supply chain should still be included in the papers published between 2017 and 2023. These exclusion criteria limit the sample to 180 articles, which are then further filtered by using the following criteria:

1. If focusing on the hydrogen supply chain and using hydrogen as an end-product;
2. If focusing on hydrogen storage and transportation from the supply chain perspective (as opposed to material development) or on hydrogen logistics and distribution;
3. And if including information on the factors influencing storage and transportation costs.

The above step results in 78 papers that are considered relevant for our research. During this procedure, it becomes apparent that the search terms = ‘supply chain’ AND ‘hydrogen’ AND (‘logistic’ OR ‘distribution’) might also be relevant in addition to the initial search since storage and transportation belong to two significant sectors in the traditional logistics and distribution. Thus, 220 (WoS) and 72 (Scopus) papers are identified additionally. After eliminating the duplications and checking the relevance, three articles were added. In total, 81 papers were used for the next step of coding and synthesizing the data. Excluded articles mainly include but are not limited to hydrogen production technologies, CCUS or carbon supply chains, power-to-gas applications, renewable energy systems, and medical or agricultural research areas.

For the 81 papers, it is notable that most of these publication outlets are energy-related. The International Journal of Hydrogen Energy, a journal dedicated to research in the field of hydrogen energy, contains the highest number of publications. The dominance of this journal is in line with the findings of other reviews, such as supply-chain-oriented [26] as well as general green hydrogen-focused ones [27]. Fig. 1 shows the distribution of the 81 papers across 23 different journals. We can see that although the search term includes supply chain terminology, the samples do not include journals in supply chain management.

Fig. 2 shows the distribution of the 81 published articles over the publication years. The number of publications has increased in recent years, with approximately 79% of the articles published within the last four years. This aligns with the overall increase in the publication of hydrogen-related papers, driven by growing interest, technological advancements, and increased funding availability [26].

The reviewed 81 papers can be classified into five groups according to their research methods. Specifically, we distinguish them by the

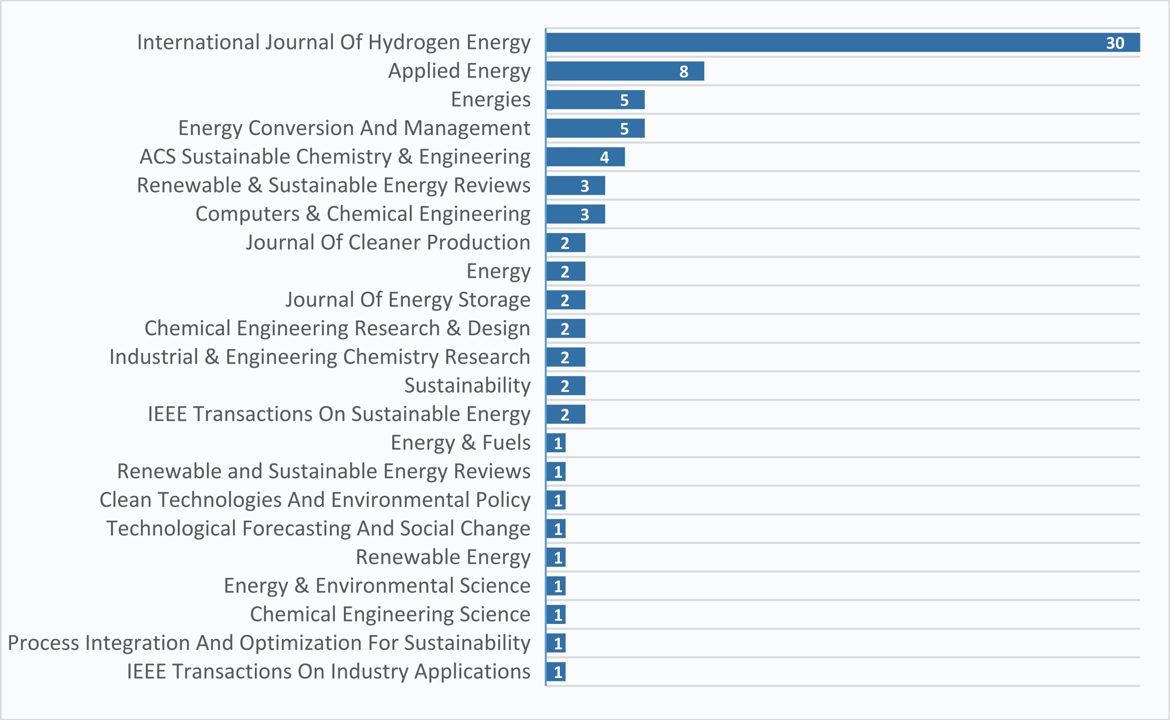

Fig. 1. Distribution of papers by publication journals (sample size = 81).

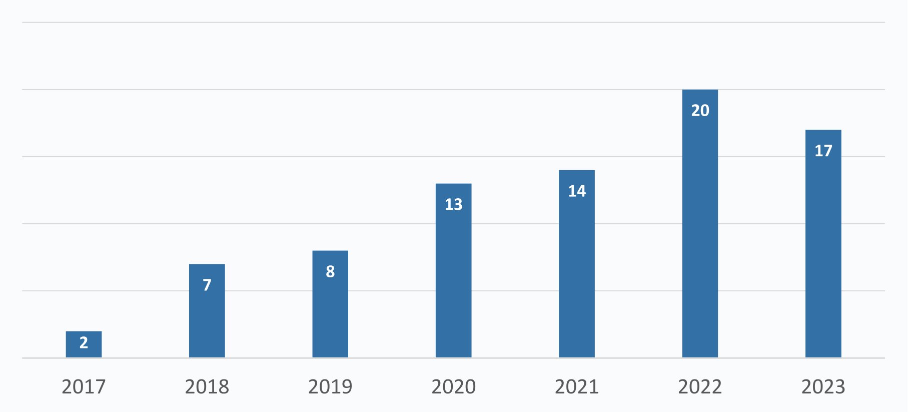

Fig. 2. Chronology of reviewed papers (sample size = 81).

operations research (OR) model, techno-economic-environmental assessments (TEEA) of the hydrogen supply chain or supply chain sectors, life cycle assessments (LCA), OR model and LCA (OR&LCA), and other methods as depicted. 51 of the papers are based on OR modeling, and 21 papers are related to TEEA (see Fig. 3). Five articles are related to LCA and three papers use other approaches, such as the analytic hierarchy process. Considering the publication database mentioned above, it is somewhat surprising that despite the high number of OR models, no OR

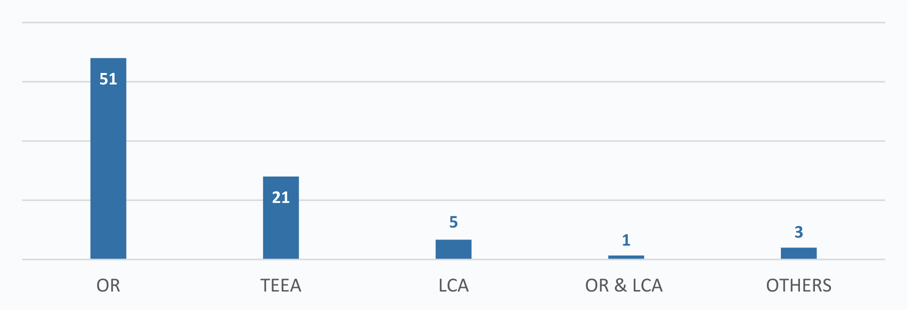

Fig. 3. Distribution of papers by research methods (sample size = 81).

journals are included. This finding, however, is similar to the previously noted absence of supply chain journals despite the papers' focus on supply chains.

The 81 papers are fully coded across several dimensions. The main focus is placed on the interplay between storage facilities and modes of transportation based on the hydrogen carriers. For each hydrogen carrier included in the paper, factors impacting the hydrogen storage and transportation costs associated with the state-of-the-art and the possible utilization scenarios are collected. Data extraction and synthesis are conducted based on the method of content analysis, which allows an analysis of a medium corpus of articles (e.g., from ten to less than hundreds) by organizing the reviewed content into themes [22]. Therefore, this method can assist in identifying, analyzing, and categorizing key information regarding hydrogen storage and transportation costs. Based on this method, the identified cost drivers are then analyzed and categorized into three groups, technical, economic, and environmental factors.

3. Overview of hydrogen storage and transportation

In this section, we answer the 1st RQ by summarizing the technologies considered for hydrogen storage and transportation in the supply chain context, highlighting research interests and the technology readiness level (TRL) based on the concept developed by Ref. [28]. TRL is a globally accepted benchmarking tool used to track the maturity of specific technologies through the early stages of the technology development chain, starting from basic research (TRL 1) to the actual system demonstration under real-world conditions (TRL 9).

3.1. Hydrogen storage

Given the unstable nature of renewable energy resources (RES), long-term and large-scale hydrogen storage can contribute significantly to developing a large-scale hydrogen economy (on a GW scale) in the future since it can satisfy the hydrogen demand during RES valleys by storing the excess energy during peak times [15,29–32]. Therefore, several works in the literature emphasize the importance of hydrogen storage capacity planning in the whole supply chain for a cost-effective network (e.g., Refs. [30,33]). Both [34,35] assume in their research that about 30% of the produced hydrogen needs to be stored before transportation to tackle the instability issue of RES. However, due to the dynamic development of hydrogen supply and demand, a continuous evaluation of storage requirements is needed to enable a tailored supply chain planning throughout the hydrogen scale-up.

Hydrogen can be stored via gaseous, liquid, or solid states to increase the energy density. Linked to these storage states, above- and underground storage facilities are required for both short- and long-term storage [36]. Fig. 4 displays the hydrogen carrier possibilities for the storage stage. Among different hydrogen storage forms, compressed gaseous hydrogen stored in above-ground steel pressure tanks is the most common storage technology due to the mature technology of pressure vessels and their commercial availability with a TRL of 9 (see Table 1) compared to other hydrogen carriers [12,14,15,37–45]. The main challenge of CGH_2 tanks is the low storage capacity, even when using the high-pressurized CGH_2 tank option. Therefore, with the expectation of a rapid growth of the hydrogen economy, underground facilities associated with a larger capacity for large-scale and long-term CGH_2 storage play a more vital role in the hydrogen supply chain. Plenty of underground facilities, such as salt caverns, aquifers, and depleted oil and gas reservoirs, display great potential to store hydrogen in the long term [46]. Of these, only salt caverns are considered in the reviewed papers due to their technological and commercial maturity, having been researched 15 times [30]. There are four sites across the globe that employ underground salt caverns, all of which are located in the USA (three facilities) and in the UK (one facility), with capacities from 760 t_{H2} to 8230 t_{H2} [18]. The underground storage facilities present a long-term and large-scale option to store CGH_2 in large-scale quantities, whereas the aboveground option offers flexibility both in space and time [30].

LH_2 stored in cryogenic tanks is the second standard storage system [12,15,35,45,54], which has been mentioned 34 times in the reference papers. Compared to CGH_2, LH_2 allows for storing hydrogen at a higher density by cooling the hydrogen below 12K, which enables the configuration of bulk storage while avoiding costly hydrogen storage in CGH_2 tanks [15,35,42,55]. Chemical liquefied molecules, including liquid organic hydrogen carriers (LOHC), liquid ammonia (LNH_3), and methanol (CH_3OH), are other potential hydrogen carriers that have been studied in recent years. They store hydrogen in a liquid state under ambient conditions, enabling storage and transportation using existing infrastructure [15,34,35,42,55,56]. The LOHC storage system consists of reusable liquid organic compounds for hydrogen storage, storage tanks, a reusable catalyst for hydrogenation, and a catalyst for dehydrogenation [15,35,42,56]. The storage capacity, referring to the hydrogen molecule content stored in the utilized chemical compounds, is vital for LOHC and is typically expressed as gravimetric storage capacity (also known as weight percent capacity, wt.%/kg_{H2}). Depending on the selected compounds, the storage capacities of LOHC range between 5.7 wt%/kg_{H2} and 7.3 wt%/kg_{H2} [57]. Dibenzyl toluene (DBT) and Toluene (TOL), which can last for 1000 cycles of hydrogenation and dehydrogenation, are the most considered compounds due to the high storage capacity of DBT and the high cost-effectiveness of TOL. Although LOHCs are the third most mentioned hydrogen carrier in our database, following CGH_2 and LH_2 (see Fig. 5), their technologies are still in the demonstration phase with a TRL between 4 and 7, indicating that they are not commercially mature yet (see Table 1). The chemical storage technologies LNH_3 and CH_3OH can benefit the hydrogen economy due to their mature supply chains and high energy density (17.8 wt%/kg_{H2} and 12.5 wt%/kg_{H2}, separately) [58]. LNH_3 is generated through the Haber-Bosch process, then cooled to a liquid state (about - 30 °C) and injected into a storage tank for storage and transportation [54,59]. CH_3OH is generated by the hydrogenation of carbon dioxide on the surface of Cu-based heterogeneous catalysts, such as Cu/ZrO2, Cu–ZnO/ZrO2, etc. [47]. Their supply chains - from ammonia and methanol synthesis to storage and transportation - are industrially mature due to regular demand from the chemical industry. Many practical projects (e.g., Ref. [60]) consider LNH_3 and CH_3OH as hydrogen carriers since they are foreseen as potential long-term hydrogen storage forms. However, far too little attention is paid to these two hydrogen carriers in the supply chain context (see Fig. 5).

Solid-state carrier metal hydrides (MH) are more recently investigated solid hydrogen carriers, which store hydrogen in metal or their alloys (e.g., magnesium, titanium) using adsorption technologies [61,62]. Solid-state carriers have various advantages, such as lower costs due to the avoidance of additional conversion equipment, lower storage pressure in a small space, and dehydrogenation at a low-temperature condition [61,63]. However, MHs are still emerging with a TRL from 4 to 7 and are hardly considered in the following discussion because our sample lacks evaluation of these hydrogen carriers from a supply chain perspective (see Table 1).

3.2. Hydrogen transportation

Large-scale hydrogen production, storage, and consumption are expected to occur at different times and locations. Therefore, hydrogen transportation is another significant sector in the hydrogen supply chain, seeking to satisfy the hydrogen demand on time in the right locations under an optimized supply chain. In the literature, hydrogen transportation often distinguishes between transmission and distribution to organize the large-scale transportation demand over long transport distances [14,38,64,65]. Hydrogen transmission refers to the transportation of produced hydrogen to storage locations or hubs, while hydrogen distribution denotes the delivery from storage locations to the

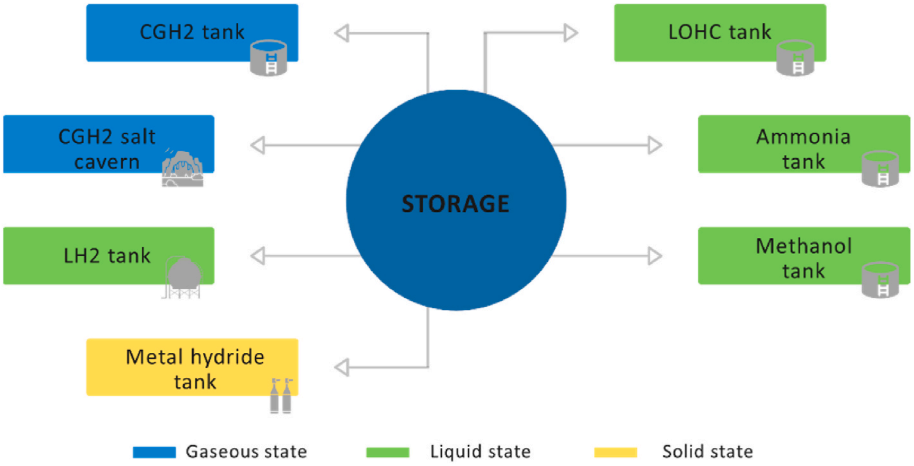

Fig. 4. Hydrogen carriers for the storage stage.

Table 1
The technology readiness level of the hydrogen carriers.

	CGH_2 (tank)	CGH_2 (salt cavern)	CGH_2 (pipeline)	Hythane	LH_2	LOHC	LNH_3	CH_3OH	MH	Main sources
TRL	8–9	6–9	7–9	7–9	6–9	4–7	7–9	6–9	4–9[a]	[47–53]

[a] The TRL depends on the considered hydrogen carriers.

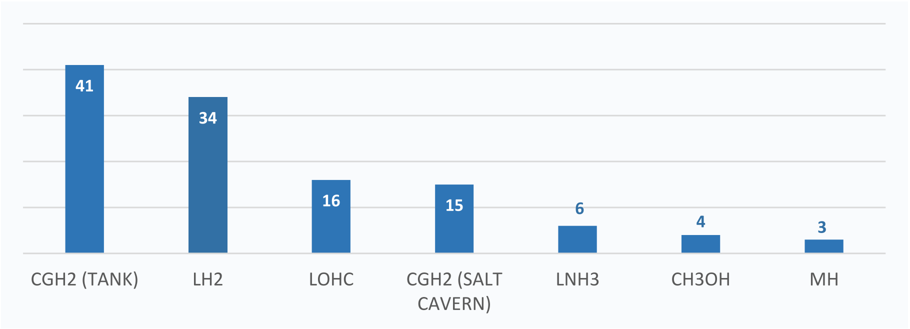

Fig. 5. Distribution of hydrogen carriers in the sample – storage stage.

end users. Since the hydrogen carriers for the transportation stage are equivalent to those in hydrogen storage, hydrogen can be transported via four systems: pipeline, train, truck, and ships (see Fig. 6). Trucks and pipelines are the most common transportation means in the study (see Fig. 7). Since the demand for hydrogen increases due to international trade development, vessels and trains are expected to become more

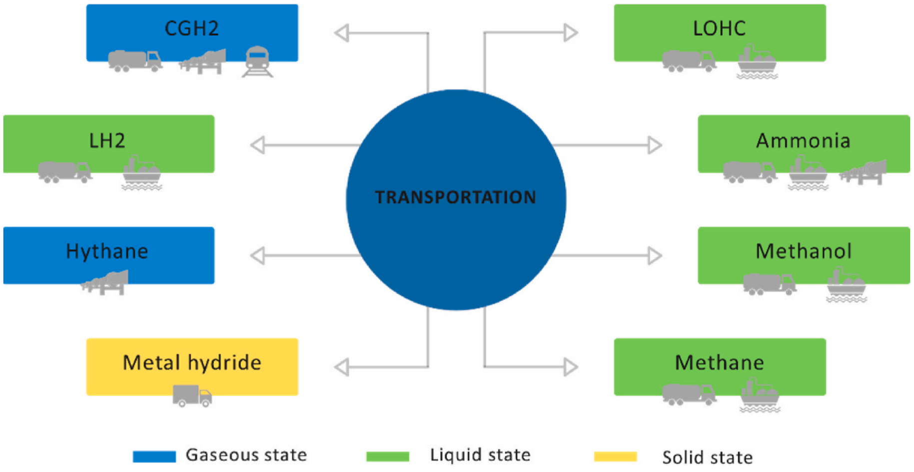

Fig. 6. Hydrogen transportation modes and carriers for the transportation stage.

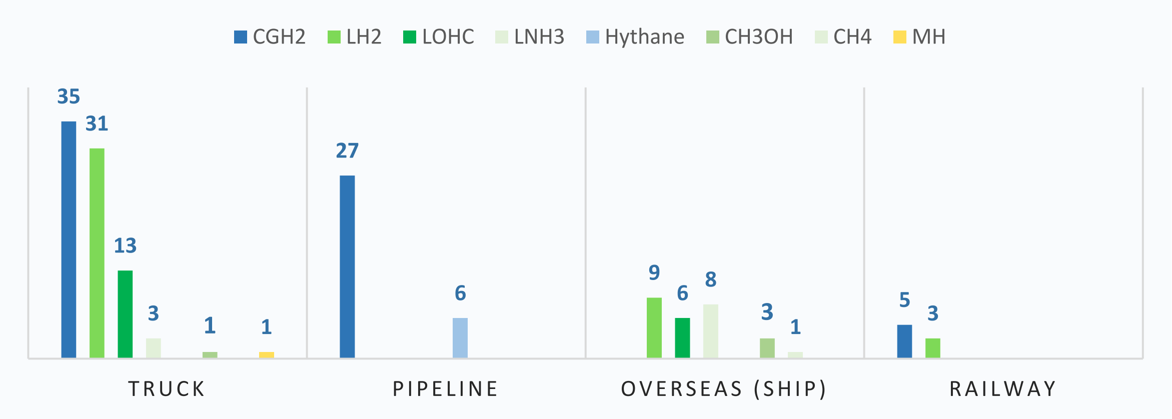

Fig. 7. Distribution of hydrogen carriers - transportation means.

crucial [42].

Truck transportation allows the transportation of CGH_2, LH_2, LOHC, LNH_3, CH_3OH, and methane (CH_4). For these hydrogen carriers, the truck transportation systems are similar, consisting of a carrier-independent towing vehicle (or truck tractor) and specific trailers suitable for defined carrier(s) and in accordance with country-specific regulations. The most common means of transportation is the CGH_2 truck due to its commercial availability (35 times studied in the reviewed papers, see Fig. 7). The CGH_2 truck delivers hydrogen using a tube trailer bedding with 12–20 cylinders [38]. Depending on the material of the cylinders, namely steel or composite material, the pressures, capacities, and costs of the tube trailers are heterogeneous [35,37,38]. Like CGH_2 tube trailers, LH_2 trucks are another well-established means of transportation. LH_2 is transported via a single cryogenic tank trailer with a temperature lower than 33K. LOHC transportation benefits the hydrogen supply chain by using existing steel tanks for diesel and gasoline under ambient temperatures [35]. Therefore, the costs and capacities of these steel tanks can be used for LOHC transportation analysis. LNH_3 is considered a relevant hydrogen carrier for transportation because of its relatively high energy density (17.8 wt %/kg) and high capacity of the tanks (from 2600 to 7200 kg), as well as the industry's mature production technology and transportation network [34,54]. However, despite its mature supply chain, LNH_3 has received less focus in research, being only mentioned three times in the database. Similar to LNH_3, CH_3OH and MH are only evaluated once each in the sample. Fig. 7 describes the study frequency of the combination of transportation means and hydrogen carriers in the reference literature.

Pipeline systems encompass hydrogen pipelines and natural gas pipelines reassignment for hydrogen. Hydrogen pipeline systems are the most studied pipeline in the sample (see Fig. 7), consisting of newly constructed pipelines and compressors to boost the pressure of produced hydrogen. Hydrogen pipelines feature high transportation capacity, high investment cost, and longer construction time than truck transportation. Currently, the TRL of pipelines ranges from 7 to 9 (see Table 1). While small-scale hydrogen pipelines are commercially mature, there is still a lack of experience in the construction and operation of large-scale hydrogen pipelines. Natural gas pipeline reassignment denotes utilizing the existing natural gas grid for transporting hydrogen by blending the hydrogen into the natural gas (hythane) or repurposing the natural gas pipelines for 100% hydrogen transportation. As many studies have indicated, the available capacity of the current natural gas delivery networks provides opportunities to reassign them for hydrogen transportation. For instance, Ref. [66] reveals that 80% of the German pipeline network has the potential for a technically viable reassignment to hydrogen transportation. They also indicate that reassigning the natural gas delivery network for hydrogen transportation offers a cost reduction of hydrogen transmission by more than 60% compared to new hydrogen pipelines. Since the technology of using natural gas pipelines for hydrogen transportation is still emerging, there are ongoing projects to assess the technical and economic parameters of delivering hydrogen via natural gas pipelines in the real environment, for example, the project HyNTs in the US [67].

Besides truck and pipeline transportation, overseas transportation has attracted particular attention in recent years due to the development of international hydrogen trade. The produced hydrogen is usually converted into liquid conditions such as LNH_3, LH_2, LOHC, CH_4, and CH_3OH for ship transportation. Similar to road transportation, overseas transportation has different pathways and is evaluated according to the characteristics of the above-mentioned hydrogen carrier technologies. Since LNH_3 and LH_2 ships are expected to undergo a large technological development until 2025, these carriers are currently the most studied hydrogen carriers for seaway (see Fig. 7) [68]. Following LNH_3 and LH_2, LOHC has also received more attention thanks to the possibility of transporting hydrogen by using existing crude oil tankers [38].

4. Influencing factors on hydrogen storage and transportation costs

In this section, we answer the 2nd RQ via an in-depth analysis, focusing on identifying and describing the main influencing factors that impact hydrogen storage and transportation costs. The main parameters utilized in our database to evaluate hydrogen storage and transportation costs, such as the levelized cost of hydrogen and the annual supply chain cost, are defined as target factors.

As a result, 36 influencing factors are identified and categorized into three groups from the technical, economic, and environmental points of view.[1] Technical factors refer to technical parameters linked to different storage and transportation options that have an impact on costs. Economic factors display monetary or financial parameters that influence storage and transportation costs, and environmental factors represent the hydrogen carriers' ecological effects. Technical and environmental factors play a crucial role in shaping the economic outcomes of hydrogen supply chains. For instance, technological advancements can reduce capital and operational expenditures, making hydrogen storage and transportation more economically viable. The technical, economic, and environmental factors depend mainly on the hydrogen carriers and the storage and transportation decisions made. Therefore, understanding the influencing factors on a hydrogen carrier basis is essential for effective decision-making and strategic planning in the hydrogen supply chain.

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[1] The factors that are identified both for the storage and transportation stage have only been counted once.

4.1. *Technical influencing factors on hydrogen storage and transportation*

4.1.1. *Technical influencing factors on hydrogen storage costs*

In our paper, hydrogen storage refers to the stage in which hydrogen is stored in hubs or dedicated facilities. According to Ref. [35], the storage sector accounts for the facilities (e.g., steel tanks) and the raw materials used to store hydrogen (e.g., hydrogenating LOHC). 11 main technical factors are identified for hydrogen storage, combining common factors valid for all hydrogen carriers and carrier-specific factors.

The primary common technical factor is the storage system capacity, which is the required storage volume of the whole storage system. The storage system capacity can be given as a fixed capacity. For instance Ref. [35], assumes that 30% of the hydrogen production capacity needs storage. Their assumption is then deployed by many other researchers, such as [14,15,64,69]. Another common main factor is the storage capacity of facilities. While above-ground storage tanks have a limited scaling factor, the underground storage option features a high scaling factor. Therefore, the storage capacity of the above-ground storage facilities is less discussed in the reviewed papers. Only two papers consider this factor and calculate the capacity assignment for different above-ground facilities [37,70]. In contrast, the capacities of salt caverns are more significant since they determine the facilities' capital expenditures (CapEx). It is of significance to consider and assess the capacity of underground storage facilities when designing and operating them. Table 2 summarizes the identified technical factors and their descriptions for the storage stage.

With regard to CGH_2 storage, for both above- and underground facilities, the pressure is an additional required factor that significantly impacts the capacity and costs of the storage tanks. Considering the liquid-state hydrogen carriers of LH_2 and LNH_3, the self-discharge rate due to the boil-off effect should be considered. Depending on the storage tank capacities, the boil-off rate may vary due to the difference in the contact of LH_2 with the container surface [89]. The larger-capacity tanks can better prevent the boil-off effect [89]. Compared to the boil-off rate of LH_2, the LNH_3 storage option features a negligible self-discharge rate of less than 0.025% per day [90]. The higher the boil-off rate, the more hydrogen is needed to satisfy the hydrogen demand, revealing the importance of this factor for storage and transportation costs. For chemical liquid-state storage options such as LOHC, LNH_3, and CH_3OH, raw materials (e.g., MCH for LOHC) are required to convert hydrogen into chemical compounds, which impacts the storage and transportation costs. Particularly for LOHC, as its raw materials are reusable, it is necessary to transport these materials between hydrogenation and dehydrogenation locations after the dehydrogenation process. This increases the complexity of the supply chain and may lead to higher storage and transportation costs. However, raw material handling has not been considered in the sample yet. This indicates the importance of evaluating raw materials (including process handling) when computing the LOHC supply chain costs in future research.

4.1.2. *Technical influencing factors on hydrogen transportation costs*

In this paper, the transportation stage refers to delivering the produced hydrogen from production sites to storage locations or from storage locations to end users. For the hydrogen transportation section, 16 technical factors that affect transportation decisions are identified. The identified technical indicators encompass common and specific factors for different transportation means and hydrogen carrier technologies.

Common technical factors for hydrogen transportation are the net capacity and transport distance. The capacity of the transportation equipment mainly depends on the means of transportation and the hydrogen carrier technologies. In the sample, trucks have the smallest net capacity, ranging from 181 to 1200 kg_{H2} for CGH_2 and 4000 kg_{H2} to 4554 kg_{H2} for LH_2, while the transportation capacity of the pipeline ranges from 84 to 120 t_{H2}/day [14,34,35,37,69,75,88,91]. The capacity of the transportation means will be discussed further in the next section.

Table 2
Technical influencing factors for the hydrogen storage sector (sample size = 81).

Influence scope	Factors	Descriptions	Main unit	Main Sources
All	Energy consumption	The required energy for the storage system, including electricity and thermal	Unit of energy	[37,56]
All	Energy efficiency	The ratio of hydrogen energy output to the hydrogen energy input plus the energy demand during the storage cycle length	Percentage	[32,39,43,56,71]
All	Hydrogen flow	The hydrogen volume on a hydrogen carrier basis that enters the storage system during the unit of time	Unit of weight	[72]
All	Storage cycle length	The average number of days or months required to turn over the storage capacity	Unit of time	[14,37,56,73]
All	Storage system capacity	How much hydrogen should or can be planned to be stored in the whole storage system	Unit of time or weight	[13–15,32,35,36,38,43,54,56,58,64,74–83]
All, mainly salt cavern	Storage capacity of facilities	How much hydrogen the storage tanks or the underground facilities can store	Unit of weight or volume	[14,15,35,56,64,69,70,81–84]
All	Time step	The time the storage system is exclusively blocked for charging or discharging hydrogen into/out of the system and unavailable for other activities.	Unit of time	[71]
CGH_2 tank, salt cavern	Pressure	The pressure in the storage tanks or the underground facilities	Bar	[12,13,32,33,35,38,44,64,65,75,85–87]
Chemical liquefied molecules storage tank, salt cavern	Raw material	The raw material consumed by the storage system, including catalysts for LOHC, surrounding material for salt caverns, etc.	Unit of weight or currency	[14,35,39,56,64,70]
LH_2, LNH_3 tank	Self-discharge loss	The hydrogen loss over time, even when it is not being used, e.g., caused by boil-off	Percentage per unit of time	[12,35,38,39,44,64,70,75,81,88]
LOHC tank	Degradation rate	The property changes of the raw material during the hydrogenation and dehydrogenation process	Percentage per cycle or unit of time	[44,70]

Besides the common factors, means-of-transportation- and hydrogen-carrier-specific indicators are also identified from the sample. Technical indicators such as fuel consumption, utilization of the equipment, and loading and unloading time are vital factors for truck and vessel transport. In contrast to this, factors such as diameter, flow rate, and energy consumption of the compressors are needed to adequately describe pipeline transportation systems due to their specific characteristics. The diameters of hydrogen pipelines vary from 100 mm to 650 mm, while those of existing natural gas pipelines with hydrogen blending vary between 10 mm and 1400 mm. Additionally, hydrogen carrier-specific factors need to be considered, such as the pressure of CGH_2 trailers or pipelines and the boil-off rate of LH_2 trailers or ships. Table 3 lists the relevant technical factors and the descriptions for the transportation sector.

4.2. Economic influencing factors identified on hydrogen storage and transportation

The economic influencing factors for the storage and transportation stages are identical and we combine the factors for these two stages in the same section. From the papers, nine economic factors are identified. The primary factors are capital expenditure (CapEx, also called investment cost), operational expenditure (OpEx), depreciation time, and capital recovery factor. Table 4 presents the main economic indicators and their descriptions.

CapEx is a vital factor in hydrogen storage and transportation costs, influencing the economic feasibility, scalability, and deployment of hydrogen. Since large-scale deployment of hydrogen infrastructures requires large capital investment, affordable capital costs can accelerate the development of the hydrogen market and make hydrogen economically competitive compared to traditional fuels. Because of the technological and commercial maturity of the technologies, the CapEx of the storage and transportation facilities is expected to decrease significantly in the future [109].

OpEx encompasses fixed and variable operational costs. Fixed operational costs refer to the type of expenditure that remains unchanged despite varied volumes of stored and transported hydrogen and include e.g., supervision cost, overhead cost for direct salary, maintenance cost, property taxes, insurance cost, decommissioning costs, and rent of the land (and/or buildings). Variable operational costs refer to the costs that depend on the hydrogen storage volume or transport flow rate, including but not limited to energy (utility) costs, emission costs (carbon tax), costs of self-discharge loss, cost of loading and unloading time, and fuel costs. The variable operational costs play a more vital role in the transportation stage since loading and unloading time and fuel costs need to be taken into account for truck and ship transportation, and energy costs need to be considered for pipeline transportation. However, many reference papers only address operational and maintenance costs (O&M) as a collective cost item without specifying details. Additionally, when considering the emission costs (carbon price), emission taxes may impact the operational costs significantly and can be one of the decisive factors for the economic efficiency of the green hydrogen supply chain, especially for truck and ship transportation [65]. Since hydrogen supply chains are often expected to operate over decades, storage facilities and transportation equipment should be replaced during the supply chains' operations. Therefore, paper [87] introduces replacement costs for this substitution, which may significantly impact the total supply chain costs.

The capital recovery factor (CRF) should be considered in the hydrogen storage and transportation stages to calculate the net present value of a series of equal annual cash flows for a given period of time, because hydrogen projects are expected to last over a long period of time, typically over ten years. CRF is generally calculated with a discount rate, also called WACC or interest rate in the sample. The discount rate is mainly assumed to be between 3% and 10%. When studying the sensitivity of the discount rate, this value can increase to 20%. Additionally, the inflation rate, typically set at 2% in the reviewed articles, should be considered when accounting for the real discount rate [12,56,91,104]. Since CRF affects all storage and transportation technologies that require investment and operations, it has a significant impact on the logistic costs, especially for the technologies that require high capital costs, such as newly constructed pipelines, salt caverns, and the purchasing of new ships. Therefore, the wide range of discount rates in the sample may result in a significant deviation in storage and transportation costs. When comparing results from different studies, this issue has to be taken into consideration. The expectation of hydrogen technology progress and the construction of large-scale hydrogen supply chain infrastructure attracts attention to the learning rate and the scaling factor. In the sample, the learning rate is mainly considered for the hydrogen production and conversion/reconversion processes. Depending on the technologies, its value is assumed to be 8% and 15%. Since hydrogen storage and transportation technologies are also expected to develop rapidly in the future, considering the learning rate when evaluating hydrogen storage and transportation costs is of significance. Another discounted cost factor, the scaling factor, influences the hydrogen storage and transportation cost when scaling up or down the installed capacity [35]. The scaling factor can also be critical in large-scale hydrogen storage and transportation since it denotes the potential for economies of scale of the technologies. Although the scaling effect on aboveground storage facilities is not noted in the sample, salt caverns are expected to have a strong scaling effect when increasing the capacity of the caverns [35]. Also, pipeline transportation systems feature a high scaling effect, while truck and ship transportation have a limited scaling factor [35].

4.3. Environmental influencing factors identified on hydrogen storage and transportation

The identified environmental factors impact both hydrogen storage and transportation costs and are therefore combined in this section. CO_2 emission is the only environmental factor directly linked to the supply chain cost in the sample. According to Ref. [34], the hydrogen distribution stage can result in higher emissions than the hydrogen production stage. Due to this notable impact, the global warming potential of supply chains caused by CO_2 emissions has received more attention than other environmental factors, as their reduction shows the potential to decrease global warming directly. In our database, mainly two options are taken into account: carbon emissions during the planning time horizon or life cycle emissions. The detection of CO_2 emissions in the hydrogen storage and transportation stages enables the quantification and evaluation of the global warming potential by considering carbon pricing (carbon tax), which is important for salt caverns and transportation such as ships and trucks. The consideration of carbon emission and carbon tax may significantly impact the total transportation costs and the supply chain pathway selected, as traditional fuels are still mainly used in road and water transportation. Particularly for green hydrogen supply chains, the carbon tax somewhat determines their economic attractiveness compared to traditional energies or blue and grey hydrogen. Therefore, considering the CO_2 emission and the carbon emission penalty when designing a hydrogen supply chain is of significance to ensure an appropriate calculation of the costs and to achieve the emission targets. Other environmental factors, such as abiotic depletion potential, ozone layer depletion potential, marine aquatic ecotoxicity potential, and human toxicity potential, are primarily investigated for their environmental effects when considering the life cycle assessment. These factors may impact the development of hydrogen supply chains significantly since the utilization of hydrogen is expected to benefit the environmental challenges. However, the economic influence of these factors is not evaluated in the sample. Therefore, we summarize the parameters not considered by the economic assessment into one factor (see Table 5).

Table 3
Technical influencing factors for the hydrogen transportation stage (sample size = 81).

Influence scope	Factors	Descriptions	Main unit	Main sources
Truck, pipeline, ship	Net capacity	The capacity of the transportation system that the equipment can carry on and end users can utilize	Unit of volume	[12,32,33,35–38,42,44,72,73,75,79,81–83,91–97]
Truck, pipeline, ship	Transport distance	The transmission distance between production sites and storage hubs or/and the distribution distance between storage locations and customers	Unit of length	[13,37,42,64,72,73,75,80–84,93,95–97]
Truck, ship	Average speed	The average driving speed of the trucks or ships	Km/h	[12,33,35,37,58,70,73,74,79,82,83,88,92,93,95,96,98,99]
Truck, ship	Loading and unloading time	The loading and unloading or drop-off/pickup time during the transition	Unit of time	[33,35,64,72–74,79,82,92,93]
Truck, ship	Fuel consumption	The fuel (e.g., diesel) demand of trucks or ships	L/km	[12,33,35,36,42,58,64,73–75,79,83,84,92,93,95,96,98]
Truck, ship	Self-discharge loss	The hydrogen loss over time during transportation, e.g., caused by boil-off	Percentage per unit of time	[12,43,72,81,88,93,95,98]
Truck, ship	Utilization	The operational hours or availability of the equipment	Unit of time	[12,35,44,64,72,74,79,81,93]
Truck, pipeline	Flow rate	The hydrogen quantities that are transported through the modes of transportation in a given time period	Unit of weight/ Unit of time	[15,33,44,45,64,67,72,73,77,82,83,94,96,100–102]
Truck, pipeline	Pressure	The pressure in the pipeline or transportation tanks	Bar	[12,13,32,33,35,37,38,44,64,74–76,83,84,87,88,94,97,100]
Truck	Driving time	The average driving time from the production sites to the target place via trucks	Unit of time	[84,93,97,99]
Truck	Number of drivers	The number of drivers required for trucks	Number	[42,81,97]
Truck	Working hours	The daily average working hours of the drivers	Unit of time	[33,58,93]
Truck	Payload	The total capacity of the truck trailers for CGH_2, LH_2, LOHC, etc.	Unit of weight	[35,42,64,74,88,98]
Pipeline	Energy consumption	The energy, such as thermal or electricity, needed for the transportation system	Unit of energy (KWh)	[12,32,88]
Pipeline	Pipeline diameter	The diameter of the pipeline	Millimeter (mm)	[33,35,43,75,76,87,91,101]
Pipeline - H_2NG	Hydrogen blending ratio	The energy intensity or H_2 admixture rate, meaning the volume of H_2 injected into NG	Percentage	[63,67,84,91]

5. Roles of these influencing factors on hydrogen storage and transportation costs

In this section, we answer the 3rd RQ by highlighting the impact of the identified technical, economic, and environmental factors on hydrogen storage and transportation costs on a hydrogen carrier basis. The total hydrogen transportation and storage costs are mainly calculated by multiplying the number of facilities or equipment required to meet the hydrogen demand and their unit cost, i.e., the CapEx and OpEx associated with the technology-specific costs and the CRF. We address how the key factors affect the construction and deployment of the hydrogen supply chain when considering the economic aspect and commercial readiness index (CRI) from Ref. [110]. The CRI has been developed by ARENA to benchmark the commercial readiness of renewable energy technologies across the various aspects of a typical investment due diligence process following a successful initial demonstration, from the hypothetical commercial proposition (CRI 1) to the bankable asset class (CRI 6) [102].

5.1. *Key influencing factors on hydrogen storage costs*

In our analysis of the storage section, we focus exclusively on aboveground storage tanks for the hydrogen carriers, including CGH_2, LH_2, and LOHC, as well as the underground storage facility salt cavern due to the limited data availability for other hydrogen carriers and storage facilities.

5.1.1. *Aboveground storage*

For aboveground storage options, CapEx is the key factor influencing the overall cost, in each case associated with hydrogen carrier-specific factors. For CGH_2 storage tanks, the specific requirements for vessel materials to construct pressurized gas tanks result in significant investment costs [13,15,35,37]. Moreover, pressure is identified as a crucial factor that directly influences the capacity of storage tanks, thereby determining the number of tanks required. In the sample, the pressures range from 150 to 700 bars, with the corresponding storage capacities varying from 1.6 to 1000 tons of hydrogen (t_{H2}) [37,38,42,44,70]. It is worth noting that even high-pressure storage tanks have relatively low capacities, resulting in a higher unit investment cost for CGH_2 storage tanks than for other hydrogen carriers [56,105]. Furthermore, large-scale storage tanks for hydrogen are still not commercially mature, leading to high storage costs when this option is employed [49]. Consequently, CGH_2 storage tanks may not be viable for large-scale storage [70]. Nevertheless, CGH_2 remains critical in meeting the short-term demand (e.g., daily or weekly timescales) thanks to its mature TRL and CRI for small-scale storage tanks, as well as its high efficiency and flexibility. Table 6 presents the capacity, CapEx, and CRI of the storage technologies for the storage section.

For the LH_2 storage option, the high energy density of LH_2 enables larger storage tank capacities, resulting in lower unit CapEx and more affordable operational costs than other aboveground storage options, making LH_2 an attractive choice for large-scale storage [38,70,98,107]. However, the self-discharge rate, commonly known as the boil-off effect, must be considered, as completely preventing heat ingress into the cryogenic tank remains unfeasible [89]. Numerous studies estimate the boil-off rate of the storage volume between 0.03% and 0.25% per day, depending on the storage tanks' capacity [38,70]. In the entire LH_2 storage system, 0.3%–3% of the liquefied hydrogen could be lost due to self-charge [34]. Therefore, specific cryogenic vessels with advanced insulation are required to minimize the self-discharge rate, which may increase the investment cost of the LH_2 option [42]. Due to the boil-off effect, LH_2 is primarily considered an uncertain option for long-term hydrogen storage. Based on current technology, the reviewed literature cannot reach a consensus on this issue. Some researchers argue that the boil-off rate renders LH_2 less suitable for long-term or seasonal storage since more hydrogen would be needed to meet the demands after extended storage periods [32]. However, other studies suggest that LH_2 remains an attractive option for seasonal or long-term storage [57,70,98]. For instance Ref. [70], conducts a sensitivity analysis to evaluate the impact of the boil-off effect on LH_2 supply chain costs. Their findings suggest that even with a boil-off rate of 2.5%/day, LH_2 can still offer advantages for seasonal storage compared to CGH_2 steel storage tanks

Table 4
Economic influencing factors for the hydrogen storage and transportation stages (sample size = 81).

Factors	Descriptions	Main unit	Main Sources
Capital expenditure	Startup investment in hydrogen storage facilities and transportation network	Currency	[12,32,33,35–38, 43,44,56,58,64, 67,70,71–75, 77–83,85,87,93, 95–97,99–101, 103]
Fixed operational expenditure	Operational expenditures that remain unchanged with an increase or decrease in stored and transported hydrogen volume.	Currency	[12,33,36–39,42, 44,56,64,67, 71–75,79–83, 86–88,93,95, 97–99,101,103]
Variable operational expenditure	Operational expenditures that depend on the hydrogen storage or transport volume	Currency	[12,32,33,35–37, 42,44,56,67,70, 72–75,77,79, 81–85,88,93,91, 95,97,98,100]
Replacement expenditure	The expenditures for the complete substitution of the storage facilities or transportation equipment during the planning time	Currency	[87]
Depreciation time	The time period that the company uses to spread storage and transportation facilities' investments	Years	[12,32,33,35–38, 43,44,56,58,64, 67,70,71–75, 77–80,83,85,87, 93,91,97,98,100, 101,103]
Capital recovery factor	The financial factor to calculate the annual net present value to recover the investment of the future for a given period of time based on the discount rate	Percentage	[12,13,32,35,37, 39,41,42,56,64, 65,67,69,70, 71–75,77,79–81, 83,88,91,95,97, 98,101,102, 104–106]
Inflation rate	The rate of an overall increase in the price of goods or services in a country	Percentage	[12,56,91,104]
Learning rate	Description of technological progress as a function of accumulating experience with the technology	Percentage	[56,73,77,107, 108]
Scaling factor	Cost reduction or increase rate caused by scaling up or down the facilities' capacity	Decimal representation	[14,35,56,93]

Table 5
Environmental influencing factors for the hydrogen storage and transportation stages (sample size = 81).

Factors	Descriptions	Main unit	Main Sources
CO_2 emission	CO_2 emission factor for the storage and transportation systems, e.g., salt caverns, trucks, and ships	Unit of weight	[13,35,37,67, 70,73,75,76,79, 80,82,84,92,95, 96,102]
Other environmental impact	The factors that can be used to assess the environmental effect, e.g., abiotic depletion potential, abiotic depletion potential fossil fuels, ozone depletion, etc.	Diverse	[75,76]

and LOHC. Although LH_2 is theoretically well-suited for large-scale hydrogen storage, its deployment is challenging due to legal regulations on tank capacity and container capacity restrictions [56,111]. To achieve large-scale storage of LH_2, the commercialization of large-scale cryogenic tanks, which currently have a CRI between 1 and 2, is urgently needed [111].

In the reviewed papers, LOHC is frequently compared to CGH_2 and LH_2, with its CapEx including the costs of storage tanks and raw materials. The raw material refers to the liquid organic compound required during the hydrogenation process. Several raw materials, such as TOL (MCH) and DBT, show great potential for hydrogen storage. Their investment cost differs, ranging from 0.4 €/kg_{LOHC} to 4 €/kg_{LOHC}, and significantly impacting the CapEx of LOHCs [35,55,64,70]. It is worth noting that the properties of LOHC raw materials may change during the hydrogenation and dehydrogenation cycles, which is known as degradation. The materials' reduction during each usage cycle can result in higher CapEx. The authors in Ref. [69] indicate that degradation is one of the most significant uncertainties in storage costs, second to the CapEx of the compounds. This highlights the importance of considering degradation in the LOHC chains. However, only two of the reviewed papers address the issue of raw material degradation, considering an annual markup rate of 2.4% or a degradation rate of 0.1%/cycle [70, 74]. The CapEx of LOHC is generally lower than that of CGH_2, and its competitiveness compared to LH_2 depends on the specific LOHC compounds (see Table 6). Using the most affordable compound, i.e., TOL (MCH), the CapEx of LOHC can be the second lowest, following the salt cavern [56]. However, papers [33,35] denote that LOHC provides the most promising storage and transportation alternative primarily for small hydrogen demand scenarios, owing to the energy-intensive nature of the dehydrogenation process. Moreover, many challenges are associated with LOHC, such as uncertainties in CapEx and scalability due to newly emerging chemical compounds and the lack of consideration for the return process of these compounds to the hydrogenation plants [56, 68,74].

5.1.2. *Underground storage*

For long-term and large-volume storage, underground salt cavern facilities are considered a viable option for storing CGH_2 [14,37,44,56, 65]. The storage cost of salt caverns is primarily determined by the CapEx, which includes construction costs and expenses for aboveground infrastructure, largely influenced by the storage capacity and scaling factor. The volume (ranging from 7000 m^3 to 500,000 m^3 in our database) and pressure of the caverns are critical elements in determining their storage capacity [43]. Similar to pressurized steel tanks, higher pressure in caverns leads to increased storage capacity but also results in higher CapEx [43]. Therefore, assessing the impact of different pressures on CapEx is essential to optimize the construction strategy of salt caverns. However, only two studies have evaluated caverns under medium and high pressures [30,43]. Moreover, salt caverns exhibit a strong scaling effect, meaning that increasing storage capacity can significantly reduce unit investment costs [35]. In the reviewed papers, the scaling factor is commonly ed at 0.28 [35]. This scaling effect, along with the lowest CapEx, long storage cycles, and negligible self-discharge during the storage period compared to other hydrogen carriers, positions salt caverns as an economically competitive option (0.13–0.19 €/kg_{H2}) for large-scale and seasonal storage [35,56,64,65].

The current CRI of salt caverns ranges from 4 to 5 [49]. Challenges still exist when considering salt caverns as a large-scale storage option. These challenges include but are not limited to geological constraints, design complexities, limited operational experience with large-scale caverns, and legal and social obstacles [30,113]. In the existing studies, salt cavern construction sites are often assumed to be located either adjacent to hydrogen production facilities to minimize delivery costs or at any locations easy to reach [12,15,43]. This assumption introduces variability in the calculated hydrogen costs and may lead to deviations in the designed hydrogen supply chains, as salt cavern

Table 6
Capacity, CapEx, and CRI of hydrogen storage technologies.

	CGH_2 tank	LH_2 tank	LOHC tank	NH_3 tank	CH_3OH tank	MH tank	Salt cavern	Main Sources
Capacity[a]	1.68 -1000 t_{H2}	n.a.	n.a.	n.a.	n.a.	n.a.	6.29–44,580 t_{H2}[b]	[14,15,30,34,35,37,43,56,58,64,65,69]
CapEx[c]	250 - 624 €/kg_{H2}[d]	25 - 33 €/kg_{H2}	50 €/kg_{H2}	4.65 - 13 €/kg_{H2}	4 €/kg_{H2}	n.a.	29.6 M – 363 M €/cavern	[12,14,35,37,38,43,56,64,69,70,78,85,88,97,103]
CRI	2–6	1–6	5–6	5–6	1	1 - 5*	–4	[48,49,53,112]

[a] Data from the sample.
[b] Hydrogen density = 0.08988 kg/m^3 [15].
[c] Data from the sample.
[d] Exchange rate: 1 EUR = 1.08 USD.

construction or hydrogen production sites are not permitted everywhere [15]. Therefore, future research should consider technological factors such as pressure and geographical constraints to mitigate the uncertainties associated with cavern storage costs.

In conclusion, the storage costs of hydrogen carriers are predominantly influenced by CapEx, which depends greatly on the capacity of the storage tanks or facilities. The differences in capacity and CapEx between hydrogen carriers make them suitable for various storage scenarios. Notably, although LNH_3 and CH_3OH are crucial in real-world applications for hydrogen storage and transportation due to their mature supply chains, there is a lack of comprehensive data on these hydrogen carriers within the reviewed sample. Thus, future research should incorporate these carriers and also compare them with other hydrogen carriers within the broader context of the hydrogen supply chain. Such comparison may help in developing more advanced and efficient hydrogen storage strategies, potentially reducing storage and supply chain costs and accelerating the growth of a large-scale hydrogen economy.

5.2. Key influencing factors on hydrogen transportation costs

In this section, we describe the key indicators determining the transportation cost for different modes of transportation on a hydrogen carrier base. The modes of transportation for hydrogen consist of roads, railways, pipelines, and seaway. Due to the lack of studies on railways in the sample, we only consider truck, pipeline, and ship transportation systems.

5.2.1. Hydrogen transportation via trucks

Truck transportation exhibits a limited scaling effect, meaning that as the flow rate increases and the transport distance extends, more trucks are required to meet the hydrogen demand without benefiting from economies of scale. Similar to the storage stage, there are common factors applicable to all hydrogen carriers and also specific factors unique to the individual carrier.

The flow rate, transport distance, fuel demand, and CO_2 emission are the main common factors influencing the costs of tractors and trailers. Firstly, associated with the tanks' capacity, the flow rate determines the required number of shipments to deliver the demand to the customer or the storage hubs. Secondly, the distance determines the required time for one hydrogen shipment. Particularly for the CGH_2 trailer, the distance plays a significant role in its transportation costs due to the low capacity of the tanks [95]. Lastly, CO_2 emission and the carbon price are important for transportation costs, primarily impacting the OpEx. A higher carbon tax may make truck transportation less economically competitive than other modes of transportation (e.g., hydrogen pipelines), since most of the trucks still consume traditional fuels and are associated with carbon emissions [74].

For truck trailers, the cost-determining indicators are similar for different hydrogen carriers, such as CapEx, net capacity, and loading and unloading time (see Table 7). However, the value of these indicators differs depending on the hydrogen carrier technologies, leading to a difference in transportation costs when constructing the hydrogen supply chain. The trailer's net capacity determines the number of trucks and the delivery networks and, hence, is one of the primary factors that plays a decisive role in the transportation cost [64,100]. Similar to the CGH_2 storage tanks, the pressure determines the capacity of the tube trailer and thus impacts the hydrogen transportation costs significantly. In the database, the pressure for the tube trailer ranges from 162 to 500 bar, corresponding to capacities from 181 kg_{H2} to 1200 kg_{H2} [14,36–38,64]. The most common option to date is using a trailer with pressure up to 250 bar, which corresponds to a capacity of 560 kg_{H2}, whereas the 500-bar tube trailer, with a capacity of 1200 $kg_{H2,}$ is expected to be employed for the increased demand from 2025 onwards [14,64]. It is noteworthy that higher capacities also lead to higher expenses for CapEx and OpEx. For example, the CapEx of tanks with a capacity of 1100 kg_{H2} reaches up to € 660,000, while the cost of tube trailers with a capacity of 300 kg_{H2} is lower than € 300,000 [37,64]. Due to its higher energy density, the LH_2 trailer can transport up to 4554 kg of LH_2, which is three times more than the maximum capacity of the CGH_2 tube. This implies that the number of tanks required to transport the same volume of hydrogen by LH_2 could be significantly lower than by CGH_2. This cost benefit of the larger capacities surpasses the increase in required CapEx, leading to a cheaper unit cost and total transportation cost and representing LH_2 as a promising option for long-distance transportation [32,64,92,105]. However, like the storage stage, the boil-off effect reduces the benefit of LH_2 because evaporative hydrogen results in increased transportation costs. Depending on the capacity of the transport tank, the daily boil-off rates in the sample are considered to be between 0.03% and 0.3% [12,35,38,98]. Paper [93] assesses LH_2 delivery from Sines in

Table 7
Capacity, CapEx, and CRI of truck transportation technologies.

	CGH_2 tube	LH_2 tank	LOHC tank	NH_3 tank	CH_3OH tank	MH tank	Main sources
Capacity (kg_{H2})[a]	181–1200	4000–4554	1680–1800	2600	2930	n.a.	[12,14,34,37,64,69,75,88,92,97]
CapEx (k€)[b]	230–1292	860–1732	10–150	200	200	n.a.	[12,37,38,64,65,74,75,93,97]
CRI	2–6[c]	1–6[d]	5–6	5–6	1	1–5[e]	[48,49,53,112,116]

[a] Data from the sample.
[b] Data from the sample.
[c] The CRI depends on the capacity.
[d] The CRI depends on the capacity.
[e] The CRI depends on the technology.

Africa to Stuttgart in Germany. The total observed boil-off loss in the transport route is 1.9%. Accordingly, this loss will be higher with longer transport distance and storage time, causing increased transportation costs and raising the importance of boil-off gas management [93]. The capacities of other liquid hydrogen carriers, including LOHC, LNH_3, and CH_3OH, are determined by the storage capacity of the compounds. Depending on the chemical compounds used for hydrogenating, the storage capacity of LOHC ranges from 1.7 wt%/kg_{H2} to 7.2 wt%/kg_{H2}, and is 6.2 wt%/kg_{H2} for the most commonly used compound TOL (MCH) [114]. LNH_3 and CH_3OH have significantly higher storage capacities, with 12.5 wt%/kg_{H2} and 17.7 wt%/kg_{H2}, respectively [115]. Table 7 lists the capacity, CapEx, and CRI of the storage tanks for hydrogen transportation. The lower storage capacity of CGH_2 and LOHC results in a higher transportation OpEx and CapEx than LH_2, LNH_3, and CH_3OH, especially for long-distance transportation [12].

All in all, the transportation cost highly depends on the trailer capacity and transport distance, which determines the number of trucks required and the fuel consumption. In our database, many studies focus on designing hydrogen supply chains for the transportation industry in Germany or France. In these studies, the unit transportation cost of LH_2 ranges from 0.15 €/kg_{H2} to 0.73 €/kg_{H2}, while the cost of LOHC varies from 0.67 €/kg_{H2} to 1.1 €/kg_{H2}, and the CGH_2 road transportation cost is between 0.72 €/kg_{H2} and 2.69 €/kg_{H2} [12,14,15,35,42,64,78,87,97]. Only one identified paper breaks down the transportation cost of ammonia and methanol with transportation costs of 0.67 €/kg_{H2} and 0.29 €/kg_{H2}, respectively [12]. Despite the high transportation cost of CGH_2 trucks, they show great potential for small-demand scenarios thanks to the high TRL (9) and CRI (2–6) and avoidance of a conversion process. The LH_2 option is slightly cheaper than LOHC transportation because of the higher transportation capacity of liquid hydrogen [57]. The attractive transportation cost of LH_2 trailers makes them an alternative for long-distance and large-scale transportation. For the LOHC option, one challenge is that its large-scale transportation is still not commercially mature with a CRI between 1 and 2, resulting in uncertainty regarding rapid commercialization and large-scale transportation [53,74]. Besides, the return process of the raw material between the hydrogenation and dehydrogenation process is not considered in the sample yet, which may lead to non-negligible costs for the LOHC option. A similar challenge is identified for LH_2, which still has a low CRI for large-scale transportation. It is worth noticing that although ammonia and methanol are cheaper than other options, they have attracted limited attention regarding truck transportation, which should be investigated in future research.

5.2.2. *Hydrogen transportation via pipelines*

Due to the data availability in the reference papers, the hydrogen pipeline and the existing natural gas pipeline delivering a hydrogen and natural gas mixture (hythane) are considered in this section.

The hydrogen pipeline (generally operating in the range of 70–100 bar) is another way for CGH_2 transportation, requiring high investments in advance and a long construction time, but having low operational cost [30,64,70,100,105]. The cost of the hydrogen pipeline is determined by CapEx, which depends primarily on technical factors such as diameter, gas velocity, average pipeline pressure, and terrain and is about 20% higher than that of a natural gas pipeline [15,30,78]. In the sample, CapEx is mainly calculated by considering the diameter and length. Among these technical factors, the diameter, ranging from 10 mm to 1905 mm, is the key decisive factor of the pipeline CapEx since it determines the maximum flow rate, linking to the capacities of the pipelines [44]. Furthermore, the diameter relates directly to the costs of materials, construction labor, right-of-way, and miscellaneous other costs [13]. Moreover, the diameter is also the key factor to distinguish transmission and distribution pipelines. For example [12], considers a 400 mm diameter pipeline for national transportation and a 100 mm diameter pipeline for local distribution, with corresponding transportation capacities of 8278 kt_{H2}/p.a. And 278 kt_{H2}/p.a. Considering the positive relation between the diameters and the CapEx of newly constructed pipelines, evaluating the trade-off between higher flow rates and lower CapEx is of particular importance [101]. Table 8 lists the capacity, CapEx, and CRI for hydrogen pipelines in the sample.

Due to the high CapEx and the long construction time of new hydrogen pipelines, the discount rate may significantly affect the investment cost and construction of new pipelines. In the sample, the discount rate ranges from 3.5% to 10%. This range is investigated by the study [100] in a sensitivity analysis to detect its influence on the pipeline investment decision. The authors find that a high discount rate of 10% might cause a delay in the capital investment and the construction of new pipelines due to the high CapEx requirements compared to a scenario with a discount rate of 3.5%. Therefore, the wide-ranged discount rate in the reference papers may lead to differences in transportation costs and the overall structure of the supply chain. Besides, since the comparison of different transportation means (e.g., pipeline and truck) is addressed in many articles, this wide range of discount rates might cause a deviation in their comparison results.

Hythane pipelines, in which hydrogen is blended into natural gas and transported as a natural gas-hydrogen mixture, are the most studied options using natural gas pipelines in the hydrogen transportation in the sample. They show great potential for reducing transportation costs and construction time thanks to the avoidance of constructing new hydrogen pipelines, enabling large-scale hydrogen transportation and acceleration of the hydrogen economy development. The transportation cost of hydrogen is determined by the OpEx, which is mainly influenced by the hydrogen blending ratio. The hydrogen blending ratio, also called hydrogen admixture rate in some papers, presents the percentage of hydrogen that can be mixed in natural gas, determining the energy content of the mixture and the delivery capacity. According to the literature, this ratio can range from 10% to 30% [63,67,84,91]. Hydrogen has a detrimental influence on the natural gas pipeline metal, which can also significantly impact the O&M costs. A low hydrogen blending ratio of 10%–15% hydrogen would not increase the annual O&M cost of the existing pipeline due to the negligible corrosion impact [91]. However, when considering a low blending ratio, more hythane is required in order to deliver the same amount of hydrogen compared to hydrogen pipelines that transport 100% hydrogen, resulting in a high OpEx. In fact, the hydrogen blending ratio also impacts the cost of the supply chain downstream processes separation and purification. Therefore, this ratio needs to be investigated and evaluated to determine whether the low transportation cost and the avoidance of investment costs can cover the cost of separation and purification.

In the sample, hydrogen pipelines are mainly compared to trucks or hythane pipelines in the supply chain. Decisions regarding economically competitive modes of transportation highly depend on the hydrogen demand.[2] For high-demand scenarios, the pipeline system, including transmission and distribution pipelines, could be more cost-effective [14]. When considering the carbon price in the supply chain network, hydrogen pipelines show even greater potential for transportation

Table 8

Capacity, CapEx, and CRI of the pipeline transportation systems.

	CHG_2-Pipe	Hythane-Pipe	Main Sources
Capacity (t_{H2}/day)[a]	84–607	n.a.	[37,91]
CapEx[b]	270 - 2790 €/km	n.a.	[37,67,88]
CRI	1–4	2–4	[48,49,51,52]

[a] Data from the sample.

[b] Data from the sample.

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[2] Hydrogen demand is defined below: very small demand: 10–20 kt_{H2} p.a.; small demand: 21–99 kt_{H2} p.a.; medium demand: 100–500 kt_{H2} p.a.; high demand: from 500 kt_{H2} p.a.

thanks to lower CO_2 emissions than truck transportation with hydrogen carriers CGH_2, LH_2, LOHC, and LNH_3 [34,76]. In medium-demand scenarios, the cheapest transportation option might be using transmission pipelines to deliver the hydrogen from the production side to the storage hubs and using truck trailers to distribute the last mile to the end user. For the low-demand scenario [91], compares hythane that is assumed to be transported via the existing long-distance natural gas pipeline network between Eastern Canada and California, considering 15% hydrogen and 85% natural gas for the demand scenarios from 1.32 kt_{H2} p. a. To 1.95 kt_{H2} p. a. They highlight the highest and cheapest hythane transportation cost in the range of 0.37 €/kg_{H2} to 1.07 €/kg_{H2},[3] which is more than three times cheaper than using a new hydrogen transportation pipeline (between 2.43 €/kg_{H2} to 3.24 €/kg_{H2}). When adding the cost of separation and purification with 1.09 €/kg_{H2}, the hythane transportation cost is still cheaper than hydrogen pipeline transportation.

As the demand for hydrogen grows, pipeline solutions are treated as an attractive option to realize large-scale hydrogen transportation at affordable costs. However, to achieve this goal, several challenges need to be addressed. Firstly, although the operation of small-scale distribution hydrogen and hythane pipelines is technically and commercially mature, experience in the construction and operation of large-scale transmission pipelines is still missing (with the CRI between 1 and 4) [51]. Moreover, there is a limited number of papers that consider the hythane supply chain and compare it with other transportation modes in high-demand scenarios. There is a need to evaluate and compare with other transportation modes based on a holistic consideration of the hydrogen supply chain, to determine the optimal transportation pathways with regard to cost-efficiency or sustainability. Lastly, despite the existing piping norm in the industry, the reassigned pipelines' operations have not yet been regulated. This would be urgently needed to realize transportation on an industrial scale [66].

5.2.3. Hydrogen transportation via ships

Seaway transportation is widely discussed for hydrogen transportation in international trade, which can facilitate a large-scale hydrogen economy and enable the construction and operation of cost-efficient hydrogen supply chains. As mentioned in Section 3, ship transportation is investigated for various hydrogen carriers, including LH2, LNH_3, LOHC, and CH_3. The latter is not considered for the detailed analysis in this section due to the limited information availability in the reviewed papers.

Similar factors are required to calculate the ship transportation cost for different hydrogen carriers, while the value of these factors depends on the characteristics of the hydrogen carrier technologies. Ship transportation costs consist of travel costs and port management and passage fees [86]. Travel costs indicate the expenditure caused by the transport vessel itself, encompassing the CapEx and the fixed and variable OpEx. It depends mainly on the CapEx, ship capacity, fuel consumption, and transport distance [98]. The ship's capacity impacts the total amount of shipments and the number of ships required, which determines the total CapEx and total fuel consumption. Since the availability of information on LH_2, LOHC, and LNH_3 ships is limited, existing NG ships or prototype ships are often adopted for small-scale transportation requirements [86], while the capacities and the corresponding Capex and OpEx for large-scale ships are often assumed based on the report of [68]. In the long term, LH_2 ships can transport more H_2 than LNH_3 and LOHC, while its CapEx is also far more expensive than the latter technologies. For instance, the capacity of LNH_3 ships is expected to increase from 0.3 kt_{H2} to 6.3 kt_{H2} by 2025, while the capacity of LH_2 ships may increase to 11 kt_{H2} according to Ref. [68]. Table 9 shows the assumed capacities and the CapEx of the different technologies. The transport distance determines the travel days and shipping requirements in terms of the number of ships and total shipments, which in turn determines CapEx and fuel consumption [91]. compares the travel cost for hydrogen transportation via LH_2 and LNH_3 ships from western Canada to Asia and Europe, respectively. They highlight that shipping to Europe is 11% more expensive than to Asia due to the longer transport distance. Longer transport distance requires higher fuel consumption and the potential of a larger number of ships to transport the same amount of hydrogen. The last cost-significant factor identified in the sample is the unit fuel consumption, which is affected by the propulsion systems. These systems are foreseen to make significant technological progress by 2025, meaning a reduction in fuel consumption. Especially for LH_2 ships, boil-off gas may be used as fuel by optimizing the propulsion system, leading to a reduction of fuel consumption by up to 70% [68].

The port, passage and management fees are another crucial part of ship transportation costs. The passage cost incurred during the hydrogen transition via the export and import port is charged by the canal authority when ships voyage through a passage. It is usually calculated based on the size of the ships at a daily rate. Port management fees indicate the charges for using the ports and their facilities, such as berthage and wharfage fees. These charges are also determined by the size of the ships (net or gross registered tonnage) and the loading/unloading time [91]. Depending on the services needed in the ports, charges such as costs for storage and demurrage could be charged on the ships, which can also strongly affect the total transportation cost. For ships with high capacity, the port management fees could be even more expensive than the travel cost [93]. For instance Ref. [93], evaluates the hydrogen export from Portugal to Germany via LH_2 with a capacity of 11 kt_{H2}. The results show that the total fees at the departure and arrival ports (0.25 €/$kg_{H2.}$) are five times higher than the travel cost (0.05 €/kg_{H2}) [86]. assesses the LH_2 and LNH_3 export pathways for both low- and high-capacity scenarios of ships, considering travel costs and port management fees. In the low-capacity scenario, more ships and shipments are required to meet the hydrogen demand, making transportation cost dominant in the supply chain cost, accounting for approximately 55% and 40% of the total costs for the LH_2 and LNH_3 cases, respectively. In this case, high CapEx and fuel consumption costs are the main components of the transportation cost, while the port management fee is neglectable since nearly half of the ships can be loaded and unloaded in one day. In the high-capacity scenario, the transportation cost is strongly reduced (about 20%–35% of the total costs) thanks to the increased capacities of the ships. During this period, port management fees, particularly for LH_2 ships, increase significantly due to prolonged loading and unloading times, which exceed the travel costs. Fig. 8 illustrates the key influencing factors on hydrogen storage and transportation costs.

Ship transportation will play an increasingly important role in the hydrogen economy since the expected domestic hydrogen supply of many countries, such as Japan, South Korea, and Germany, cannot their satisfy hydrogen demands. In the sample, large-scale hydrogen transportation cost over long-distances (between 5000 km and 17,500 km) of LH_2 ships ranges from 0.05 €/kg_{H2} to 1.55 €/kg_{H2}, while the costs of LOHC and LNH_3 vary from 0.04 €/kg_{H2} to 0.57 €/kg_{H2} and from 0.03 €/kgH2 to 0.4€/kg_{H2}, respectively [12,55,86,91,95]. The ship transportation cost via LNH_3 is the cheapest option due to its higher capacity, making it slightly cheaper than LOHC. LH_2 ship transportation is less attractive owing to high CapEx and OpEx caused by the requirement of low-temperature preservation during transportation over long-distances [54,55]. However, the overseas supply chain evaluation is still lacking in the sample. Although LOHC can be a suitable alternative for long-distance transportation with the existing infrastructure (CRI between 5 and 6), its applications are still limited [112]. For LH_2 shipment, only one commercial LH_2-Ship is prevailing, lacking operational experience regarding ships with different scales [93,118]. This obstacle leads to uncertainty regarding the costs and commercial availability of the techniques (both LOHC and LH_2). Large-scale transport ships and corresponding ports have to be developed and constructed to realize a

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[3] Exchange rate: 1 EUR = 1.08 USD.

Table 9
Capacity, CapEx, and CRI of ship transportation systems.

	LH_2 ship	LOHC ship	LNH_3 ship	Methanol ship	Main Sources
Capacity (t_{H2})[a]	10,840 - 11,000	6500 – 9381	6710	n.a.	[54,86,98]
CapEx (k€)[b]	162,000–428,000	23,000–88,000	79,000–109,000	65,300	[12,54,65,86,98]
CRI	1–2	5–6	5–6	2–3	[112,117]

[a] Data from the sample.
[b] Data from the sample.

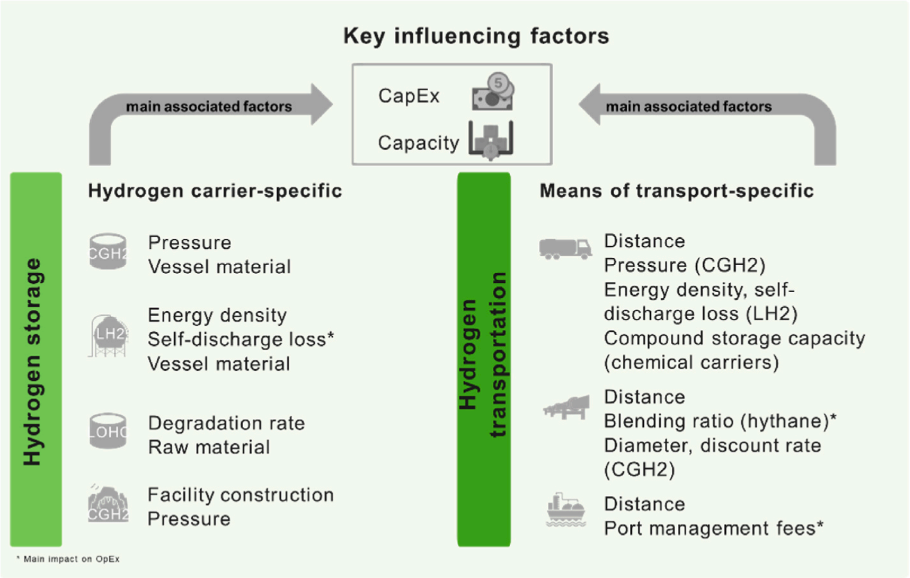

Fig. 8. Overview of the key factors that impact hydrogen storage and transportation costs.

large-scale international trade of hydrogen, with consideration of handling facilities and processes to ensure the hydrogen transition.

6. Conclusions and research directions

This section recaps the primary points and contributions covered in this paper, followed by limitations and recommendations for future research directions.

6.1. Conclusions

The main goal of this research is to improve the transparency of hydrogen storage and transportation costs by conducting a systematic literature review. This review identifies and analyses different hydrogen carriers for the hydrogen storage and transportation stages and the key factors that affect the costs of designing, constructing, and operating the storage and transportation infrastructure and equipment.

Given that hydrogen has yet to achieve economic competitiveness with other energy carriers, a thorough understanding of the costs associated with its storage and transportation is essential for optimizing the hydrogen supply chain. To address this, 25 technical, nine economical, and two environmental factors with an impact on hydrogen storage and transportation costs are identified and discussed in our review. The key factors determining the costs are based on the hydrogen carriers and means of transportation. CapEx and the capacity of the storage infrastructure and transportation equipment are detected as two primary parameters that are decisive for hydrogen storage and transportation costs. CapEx is influenced by various aspects such as required raw materials for hydrogen storage and transportation, the specific materials to construct storage and transport tanks, and technological developments. The high CapEx associated with technological development uncertainty for many hydrogen carriers remains a significant challenge in reducing hydrogen storage and transportation costs, which is essential for realizing a large-scale hydrogen economy. Capacity is the second decisive factor for storage and transportation costs because it determines the number of storage and transportation facilities needed to meet hydrogen demands. Factors such as pressure, energy density, and flow rate for pipelines impact the capacity noticeably. However, large-capacity storage and transportation options are still not commercially available, challenging the large-scale hydrogen deployment.

The hydrogen carrier CGH_2 demonstrates low hydrogen transportation and storage costs when salt cavern storage and pipeline transportation are deployed in the supply chain. This enables long-term storage and long-distance transportation, which is essential for a large-scale hydrogen economy. However, this option also poses challenges. For hydrogen pipelines, the primary concerns are long construction times and high investment costs. For hythane pipelines, optimization of the blending ratio and the absence of an operating model necessitate further research. When utilizing steel storage and transport tanks, costs increase significantly, even for high-pressure options. Nevertheless, CGH_2 steel tanks offer flexibility for the entire supply chain, particularly in scenarios with low demand and short distances, as conditioning and reconditioning processes can be avoided.

LH_2 options are characterized by high energy density and lower unit CapEx compared to CGH_2 high-pressure tanks, making LH_2 favorable for large-scale storage and transportation. Although self-discharge (boil-off) is a primary concern for LH_2 storage and transportation, research suggests that LH_2 remains an attractive option for long-term storage and long-distance transportation. It is noteworthy that for truck transportation, LH_2 is economically competitive compared to LOHC. However, for overseas transportation, based on the results from the sample, LOHC is slightly cheaper than LH_2 owing to the need for specialized and expensive ships to maintain low temperatures and prevent the boil-off effect. Therefore, the reduction of negative effects from boil-off is crucial for reducing transportation costs via LH_2 ships, e.g., by improving the propulsion system to being able to reuse the boil-off gas as a fuel for the shipments [68].

LOHC is suitable for low-demand and long-distance transportation. Using existing crude oil storage and transportation equipment leads to the cost-efficiency of LOHC. However, the uncertainty of the raw material CapEx remains a significant concern for this option. In contrast, the transportation equipment for both LNH_3 and CH_3OH is commercially viable. Hence, these two options can address the commercialization challenges of large-scale LH_2 and LOHCs. However, despite of this potential, these two options are still less frequently considered as hydrogen carriers for storage and road transportation in the sample, making it challenging to identify the key factors that influence related costs.

Our results create a better transparency of hydrogen storage and transportation costs, making it possible to increase the accuracy and efficiency of hydrogen supply chain design and optimization, as well as supply chain infrastructure planning and operations. Since cost optimization is a key driver for establishing hydrogen as an economically competitive energy carrier, the technological, economic, and environmental factors that impact the storage and transportation costs of different hydrogen carriers should be considered in supply chain-related decision processes. Based on the holistic insight into cost drivers and their interrelations in this paper, stakeholders can determine the relevant factors for their practices and adopt the crucial parameters into their planning processes. It is worth noticing that the identified factors are, in general, viable for most decision cases, while the adopted values for the factors are influenced by various aspects such as countries and industries.

6.2. Limitations and research directions

While our review provides a holistic viewpoint of hydrogen storage and transportation costs, this paper has two main limitations. First, we focus on the hydrogen supply chain, i.e., hydrogen as an end product consumed by customers, such as fuel cell vehicles, the steel industry, and refineries. Therefore, ammonia and methanol are only considered in this study if the reviewed papers have a research focus on hydrogen carriers, for instance, for the ship transportation option. Ammonia and methanol supply chains themselves are out of scope in the sample since their supply chain processes differ from those of hydrogen supply chains. For instance, when utilizing ammonia as a hydrogen carrier, the process of ammonia cracking is required to obtain hydrogen in the final stage, whereas this process is not necessary in the ammonia supply chain. However, since ammonia and methanol are crucial hydrogen users, evaluating their supply chains is important to support a better planning of hydrogen supply chains. Second, while the identified factors apply to hydrogen supply chains in general, their adoption with corresponding values depends on the decision practice, which is shaped by the spatial and temporal conditions. For instance, driver salaries in Europe may vary from salaries in Asian regions. This regional and temporal cost variation is one of the main reasons for the wide range of storage and transportation costs identified (another reason potentially being different assumptions by the researchers). However, this difference is not analyzed in-depth in this review and should be addressed in future research. In line with the evidenced gaps throughout the review, several main research directions are deduced as follows.

Firstly, the hydrogen storage section with regard to a detailed breakdown of storage costs is currently overlooked. In the sample, hydrogen storage is primarily considered with a fixed storage system capacity and the unit CapEx to simplify the cost calculation and hydrogen supply chain design. Therefore, it is suggested that a granular calculation of total storage costs, along with the optimization of the capacity of total storage systems and the location of storage hubs, is a relevant subject for hydrogen supply chain research.

Secondly, hydrogen carriers such as ammonia, methanol, and hythane require more attention in the context of hydrogen supply chain design and planning, as they may benefit the hydrogen economy development through mature supply chains or by avoiding high CapEx and long construction times, thus accelerating large-scale storage and transportation. A more comprehensive comparison of these storage forms with other carriers like CGH_2, LH_2, and LOHC in supply chain pathway contexts, particularly regarding costs and carbon emissions, should be pursued to identify the key factors that impact storage and transportation costs and to optimize decisions about cost-effective supply chains. Furthermore, research on the emerging storage materials MHs is worth conducting from a supply chain perspective to evaluate the economic viability by considering technological aspects, since commercial tanks for materials such as Magnesium hydride have been released [61].

Thirdly, concerning the data utilized to calculate the costs, there is a notable lack of data transparency and accuracy. For instance, the impact of location-specific conditions on hydrogen costs is evidenced by causes such as geographical constraints or the distribution of the resources [119]. They influence not only the costs of the hydrogen supply but also the market development (e.g., industry clusters). However, this variation in costs receives limited attention in the design and planning of the hydrogen infrastructure. Besides, the OpEx of the infrastructure or equipment is primarily considered as a percentage of the CapEx in the reference papers, which may lead to an inaccurate estimation of the OpEx. More detailed considerations of the OpEx, such as labor costs, energy costs, LOHC return cost, and maintenance costs, should be included in the cost calculations. Increasing the accuracy and transparency would provide researchers, policymakers, and system operators better insights into the key factors that influence storage and transportation costs, aiding in the identification of suitable hydrogen supply chains. Therefore, they should be addressed in future research to increase the feasibility and accuracy of the designed supply chains.

Lastly, low commercial readiness levels are a significant concern for the hydrogen storage and transportation stages during hydrogen deployment and the realization of a large-scale hydrogen economy. The barriers that may contribute to this issue include but are not limited to the lack of policies and regulations for facility construction and operations and the lack of construction and operational experiences of large-scale facilities. This encompasses infrastructure such as salt caverns, CGH_2 and LH_2 tanks, hydrogen pipelines, hythane pipelines, and overseas shipping. These findings suggest that the development of large-scale hydrogen systems requires addressing these barriers, for instance, the development of standardized regulations and policies to support the development of safe and efficient hydrogen supply chains, to enhance commercial viability, and to promote the broader development of large-scale storage facilities and transportation networks. Currently, factors such as policy and regulation development and government incentives are not considered in the sample. Potentially, this is due to the fact that the quantification of their cost impact is challenging, particularly because of their dynamic development. However, policies and regulations are evidenced to play a crucial role in energy transition and new technology adoption. With the increasing stability of policies and regulations, it is crucial to integrate these factors in quantified ways into the supply chain development in future research.

CRediT authorship contribution statement

Xing Lu: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Anne-Charlotte Krutoff:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Mona Wappler:** Writing – review & editing, Validation, Supervision. **Anja Fischer:** Writing – review & editing, Validation, Supervision.

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.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.01.196.

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