Front. Energy 2025, 19(6): 1129–1142
https://doi.org/10.1007/s11708-025-1041-1

RESEARCH ARTICLE

Techno-economic and life-cycle assessment comparisons of hydrogen delivery options

Alessandro Arrigoni (✉), Tatiana D'Agostini, Francesco Dolci, Eveline Weidner

Joint Research Centre (JRC), European Commission, Westerduinweg 3, 1755 LE, Petten, The Netherlands

Abstract This paper presents a techno-economic assessment (TEA) combined with an environmental life cycle assessment (LCA) of various hydrogen delivery options within Europe, aiming to identify the most sustainable and cost-effective methods for transporting renewable hydrogen. Five hydrogen carriers—compressed hydrogen, liquid hydrogen, ammonia, methanol, and a liquid organic hydrogen carrier—are compared, assuming that hydrogen is produced via renewable electrolysis in Portugal and transported to the Netherlands by either ship or pipeline. The findings align with much of the existing literature, indicating that the most economically and environmentally sustainable options for long-distance hydrogen delivery are shipping liquid hydrogen and transporting compressed hydrogen via pipeline. Chemical carriers tend to involve higher costs and environmental impacts, largely due to the additional energy and materials (e.g., extra solar panels) required in hydrogen conversion steps (i.e., packing and unpacking). While the findings offer valuable insights for policymakers, further research is needed to address the limitations of multi-criteria assessments for emerging hydrogen technologies, particularly the uncertainties associated with the early development stages of processes along the hydrogen value chain. Future research should also focus on extending the scope of sustainability assessments and enhancing model reliability, especially for underrepresented environmental and social impact categories.

Keywords hydrogen delivery, hydrogen transportation, hydrogen supply, techno-economic assessment (TEA), life cycle assessment (LCA)

1 Introduction

The European Union (EU) has identified hydrogen as a key component in achieving carbon neutrality by 2050. Hydrogen has the potential to replace fossil fuels in several applications, such as transportation and heavy industry. However, greenhouse gas (GHG) emissions reductions can only be achieved when hydrogen is produced via specific low-carbon pathways, such as water electrolysis powered by renewable electricity. Consequently, the EU's hydrogen strategy prioritizes increasing the production of renewable hydrogen and developing a hydrogen market in sectors such as transport, industry, and buildings [1]. The REPowerEU initiative sets a target for the EU to produce 10 million tonnes (Mt) and import an additional 10 Mt of renewable hydrogen by 2030 [2]. These strategies foresee that hydrogen may have to be transported within Europe and imported via corridors involving neighboring countries.

It is thus important to determine: (1) whether it is economically viable and sustainable to import renewable hydrogen from regions with low-cost renewable electricity and then transport it to customers, and (2) which delivery options offer the best economic and environmental performance. Although numerous studies have explored this topic, their conclusions vary widely (see Section 2). Nevertheless, there is a general consensus that, under certain conditions, transporting renewable hydrogen can be more cost-effective and environmentally beneficial than producing it locally where it is used.

To address these questions, the Joint Research Centre (JRC) of the European Commission has performed a comprehensive techno-economic assessment (TEA) [3] and life cycle assessment (LCA) [4] of renewable hydrogen delivery chains. The objective is to assess and compare the costs and environmental impacts of different hydrogen delivery options, aiming to provide relevant information to policymakers, stakeholders, and the public

Received Oct. 3, 2024; accepted Aug. 22, 2025; online Sept. 30, 2025

Correspondence: Alessandro Arrigoni, alessandro.arrigoni-marocco@ec.europa.eu

on the economic and environmental sustainability of transporting hydrogen over long distances. This paper combines findings from both the TEA and LCA to identify the most sustainable hydrogen import pathways, balancing costs and environmental impacts. Additionally, it conducts a literature review on hydrogen delivery to identify research gaps and benchmark the findings against those of previous studies.

2 Literature review

A substantial body of literature has explored the costs associated with hydrogen delivery, but only a limited number of studies have addressed its environmental impacts. A search on the Web of Science in 2024 using the keywords "hydrogen delivery" or "hydrogen supply" in the title, and "cost" as a topic, identified 334 papers published since 2015. In contrast, replacing "cost" with "life cycle assessment" or "greenhouse gas emissions" resulted in only 34 and 44 papers, respectively. The literature on costs revealed significant variations across studies, largely due to differing scenarios and assumptions, including variables such as transport distance, hydrogen volume, and availability of existing infrastructure. Depending on these assumptions, different hydrogen delivery options emerged as the most cost-effective.

This systematic review focuses on the underexplored area of environmental impacts associated with hydrogen delivery, with particular attention to studies that evaluate both environmental and economic performance. Literature focusing solely on costs has been extensively covered elsewhere [5–7], and is therefore not included here. However, Section 5 compares the results of the present study with selected works that consider both cost and environmental impacts.

Table 1 summarizes LCA literature on hydrogen delivery, categorizing studies by scope: those evaluating only GHG emissions and those encompassing a broader range of environmental impact categories (denoted as "LCA" in Table 1). Table 1 also details the specific hydrogen carriers examined, geographical locations of hydrogen production and delivery, transportation distances, life cycle stages considered, and whether a cost analysis was included. From the initial list of papers, studies that lacked a comparative GHG or LCA evaluation of different hydrogen delivery options or that lacked sufficient details were excluded. Ultimately, 16 studies were retained, featuring case studies from across the world.

Liquid hydrogen was the most frequently assessed carrier, followed by compressed hydrogen, liquid organic hydrogen carriers (LOHCs), and ammonia. Methanol received less attention. Approximately half of the studies analyzed the impact of transporting hydrogen over long distances by ship, while the remainder focused on relatively short distances using trucks and pipelines. Only

Table 1 Literature review of life cycle environmental impact and GHG emissions from hydrogen delivery

Reference	$C\text{-}H_2$	$L\text{-}H_2$	NH_3	LOHC	MeOH	Life cycle stage			Location		Distance	Type of analysis		
						Pack	Transport	Unpack	Production	Use	10^3·km	GHG	LCA	Cost
Akhtar et al. [24]	x	x	x	x		x	P, T	x	AU	N.A	0.1–0.4		x	
Al-Breiki & Bicer [19]		x	x		x	x	S		QA	N.A	9.3–37	x		
Di Lullo et al. [21]	x	x	x	x			P, T		CA	N.A	0.1–3.0	x		x
Frank et al. [18]	x	x				x	P, T	x	US	US	0–1.5	x		x
HYSTOC [10]	x	x		x		x	T	x	DE, FI	DE, FI	0.3		x	x
Ishimoto et al. [16]		x	x			x	S	x	NO	NL, JP	2.5–23.4	x		x
Lee et al. [15]		x	x	x	x	x	P, S	x	AU	KR	5.8	x		x
Li et al. [9]	x	x			x	x	P, S, T	x	CN	CN	1.0–6.0		x	x
Noh et al. [14]	x	x	x	x		x	S	x	AU, KR	KR	0.1–10		x	
Ozawa et al. [17]		x	x	x		x	P, S	x	AE, AU, NO	JP	12–20	x		
Ren et al. [20]	x	x				x	P, S, T	x	CN	CN	0.1–6.0	x		
Wulf et al. [12]		x		x		x	T	x	DE	DE	0.4		x	x
Wulf et al. [11]	x			x		x	P, T	x	DE	DE	0.1–0.4		x	
Zhu et al. [23]			x		x	x	T		CN	CN	1.5	x		
Shin et al. [22]		x	x	x		x	S	x	MY	JP	4.7	x		
Kaiser et al. [8]	x	x		x		x	P, S	x	AU, MA	DE	2.8–18		x	x
Ortiz et al. [3], Arrigoni et al. [4]	x	x	x	x	x	x	P, S	x	PT	NL	2.5–10		x	x

Notes: P: pipeline, S: ship, T: truck and/or train; N.A.: not available.

7 studies considered environmental impacts beyond GHG emissions, and 8 included a cost analysis.

Due to the variation in system boundaries and delivery pathways, drawing definitive conclusions on the most environmentally sustainable option remains challenging. Most LCAs adopted a cradle-to-gate approach, where the "gate" refers to either a hydrogen refueling station or final storage, excluding the use phase of hydrogen. Typically, these studies cover hydrogen production, conversion into a transportable carrier ("packing"), transportation, and reconversion to hydrogen ("unpacking"). However, some studies expanded the boundary to include additional conversion steps at the delivery site [8], while others excluded stages such as unpacking (where the carrier is used directly) [9], or hydrogen production [10].

The studies covered a diverse range of production locations—most often Australia, Europe, and China—and transportation distances ranging from less than 100 to over 30000. LCA outcomes were influenced by the chosen pathway, scope, assumptions, and environmental metrics. Transport distance and mode were critical factors. Compressed or liquid hydrogen often emerged as more environmentally favorable [8,10–14], with compressed hydrogen via pipelines usually displaying an advantage at shorter distances [8–10,13,14]. For example, Wulf et al. [11] found that truck-delivered compressed hydrogen produced more than double the GHG emissions compared to pipeline delivery over a 400 km distance.

The "unpacking" stage also plays a critical role. Li et al. [9] and Akhtar et al. [13] found that chemical carriers such as methanol and ammonia outperform liquid and compressed hydrogen when utilized directly without reconversion. However, because the dehydrogenation step is not considered, it is not possible to make a direct comparison with studies that deliver pure hydrogen. LOHCs were generally among the least favorable options due to their high energy demands for both hydrogenation and dehydrogenation [8,10–14], regardless of the chosen organic molecule [12,14]. Still, emissions could be lowered by using a portion of the transported hydrogen [12–13] or waste heat [8] to assist dehydrogenation. Switching from grid to renewable electricity at the delivery site also significantly decreased GHG emissions and improved the performance of LOHC pathways [14].

Contrasting findings were reported in studies that considered both GHG emissions and costs. Lee et al. [15] identified a LOHC (toluene-methylcyclohexane, TOL-MCH, not considered in the present study but discussed in Section 5) as having the lowest GHG emissions, followed by ammonia and liquid hydrogen. Conversely, Ishimoto et al. [16] found liquid hydrogen to consistently outperform ammonia in GHG terms. The role of shipping in GHG emissions also differed: Lee et al. [15] considered it negligible, while Ishimoto et al. [16] found it significant, particularly for long-distance ammonia transport powered by marine fuel, where for comparable carrier capacities, the assumed fuel consumption per day of the ammonia ship in Ishimoto et al. [16] nearly doubled [15]. It should be noted that for liquid hydrogen, Ishimoto et al. [16] only considered liquid hydrogen ships powered by the hydrogen they carry. In terms of costs, Lee et al. [15] projected LOHC (TOL-MCH) to be the most economical in both 2020 and 2050, while Ishimoto et al. [16] favored liquid hydrogen over ammonia.

Only a few studies examined environmental impacts beyond GHG emissions, and only one presented a single score for overall environmental impact [9], although it did not include unpacking. When multiple environmental impact categories were considered, the findings were less clear. For example, using renewable electricity at the delivery site significantly reduced GHG emissions for chemical carriers, but increased burdens in other impact categories [14].

Definitions of "GHG emissions" also varied. Of the 9 studies focused only on GHGs, two considered solely CO_2 (Ishimoto et al. [16] and Ozawa et al. [17], though the latter did include upstream CH_4 emissions during mining). Three others included CH_4 and N_2O [18–20], while four did not specify the gases considered but provided results in CO_2-equivalents [15, 21–23].

Overall, the review highlights a major research gap: few studies assess hydrogen delivery pathways from a multi-criteria perspective. Only four studies conducted both robust environmental and cost analysis. The present study seeks to address this gap by presenting a harmonized assessment of cost and environmental performance through a comprehensive, multifaceted case-based study to support decision-making. Section 3 outlines the methodology, Section 4 presents the results, Section 5 compares them with existing literature, and Section 6 concludes with key findings.

3 Methods

3.1 Case study

The objective of this case study is to compare the costs and environmental impacts of various hydrogen delivery options, with the aim of informing policymakers and stakeholders about sustainable transport pathways. The scope of the assessment is outlined in this section.

The case study is inspired by hydrogen import proposals connecting southern and northern Europe, such as the H2Sines.RDAM project [25]. It uses the same geographical endpoints—Portugal as the hydrogen supplier and the Netherlands as the recipient—with a transport distance of 2500 km. However, it increases the hydrogen volume to 1 Mt per year and introduces a range of transportation options. A sensitivity analysis considers an extended transport distance of 10000 km, representative of routes such as those from the Persian Gulf to northern Europe via the Suez Canal. Hydrogen end-users, such as large industrial clusters, are assumed to be located near the port, eliminating the need to model further hydrogen distribution. The delivery is expected to occur post-2030 and consists of three segments: ① packing–preparation of hydrogen for transport, ② transport–via ship or pipeline, and ③ unpacking–preparation of hydrogen for end-use.

The assessment follows a cradle-to-gate approach, starting with hydrogen production and ending at the point of entry into an industrial facility. A simplified flow chart of the key processes is presented in Fig. 1. Two transport modes (ship and pipeline) and five hydrogen carriers are considered: compressed hydrogen (C-H_2), liquid hydrogen (L-H_2), ammonia (NH_3), methanol (MeOH), and LOHC. Additionally, on-site hydrogen production via renewable electrolysis is included as a baseline for comparison.

Processes along the delivery chain were selected based on their potential for low GHG emissions and reasonable technological maturity. Fossil fuel-based options were excluded where possible, and circular solutions, such as using CO_2 from direct air capture (DAC)—were prioritized for chemical carriers. Hydrogen is assumed to be fully renewable, in line with the EU Hydrogen Strategy [1], RePowerEU [2] and Clean Planet for All [26]. It is produced via water electrolysis (50 kWh/kg H_2), powered by photovoltaic (PV) electricity with a GHG intensity of 20 g CO_2e/kWh [27]. While this projected GHG intensity is significantly lower than current state-of-the-art levels [28], it aligns with 2030 projections for high-efficiency single-crystal silicon PV technology in southern Europe [29]. All processes at the hydrogen production site are powered by off-grid renewable PV electricity, with a capacity factor of 17% (i.e., 1500 full-load hours per year) [27]. In contrast, processes at the delivery site and during pipeline transport use projected 2030 grid electricity mixes for the Netherlands and Europe, respectively [30].

Additional renewable hydrogen is produced to cover heating demands in the delivery chain, particularly for dehydrogenation of the chemical carriers. After each step of the delivery chain (i.e., hydrogen production, packing, transportation, unpacking), storage facilities (salt caverns for gaseous hydrogen and tanks for liquid hydrogen and chemical carriers) are assumed to enable a smooth transition. For the delivery of compressed hydrogen, the entire production volume is assumed to be stored in salt caverns before being transported by ship. For other carriers, only 1% passes through salt caverns, with the rest going directly to the packing stage. After packing, all carriers are stored in aboveground tanks before transportation.

Shipping is assumed to be powered by biodiesel, as large electric or hydrogen- fueled vessels are unlikely to be commercially available by 2030. Alternative fuels such as ammonia, methanol, or SNG may emerge as viable shipping fuels in the future. A sensitivity analysis is therefore conducted to investigate the environmental impact of different ship fuel options.

Hydrogen and carrier losses throughout the delivery chain are accounted for based on values from the literature and internal assumptions. Specific loss rates for each process are detailed in the inventory section of the Electronic Supplementary Material (ESM). For an in-depth sensitivity analysis on this topic, readers are referred to the original LCA report [4].

The functional unit for the assessment is the delivery of 1 kg of hydrogen (at 30 bar, 99.97% purity) at an industrial site in the Netherlands, assuming an annual delivery volume of 1 Mt post-2030. The approach is both prospective (for expected deliveries beyond 2030) and attributional (restricted to contrasting different delivery options instead of disclosing environmental consequences). In multifunctional processes (i.e., when an activity provides multiple co-products with different functions), environmental impacts are allocated using the ecoinvent cut-off system model primarily based on economic allocation [31]).

The LCA includes 16 environmental impact categories, following the Environmental Footprint (EF) impact assessment method of the European Commission [32]. As mandated by the EF method, absolute impacts in each category are normalized relative to the global impact on a per capita basis, and then multiplied by a set of weighting factors to derive a single score (in “points”). These weighting factors are designed to represent the relative importance of each environmental category, while also considering their robustness [33]. The specific weighting

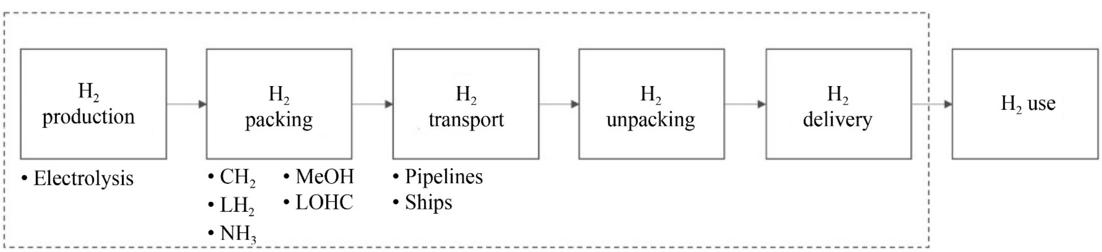

Fig. 1 System boundary of the assessment (Only the processes within the dotted lines fall within the scope of the analysis).

factors used are detailed in Table S14 of the ESM. Although ISO standards on LCA do not endorse the use of normalization and weighting, these steps help communicate findings more effectively and support informed decision-making [34]. To ensure clarity and transparency, both normalized and weighted results, as well as the absolute impacts, are presented to provide a comprehensive understanding of the environmental impacts.

The EF method was adapted to include indirect global warming potential (GWP) from hydrogen emissions [35], incorporating the latest GWP value published in a peer-reviewed journal (11.6 kg CO_2e/kg H_2 for a time horizon of 100 years [36]).

Life cycle inventory data were sourced from the literature and ecoinvent version 3.9 (cut-off model) [37]. Additional inventory details are available in the ESM. For a complete overview of assumptions and methodologies employed, refer to Arrigoni et al. [4] and Ortiz Cebolla et al. [3].

3.2 Delivery pathways

This section provides a concise overview of the hydrogen delivery pathways considered. A detailed description of the individual processes involved and complete inventories is available in the original JRC reports [3, 4]. The life cycle inventory used for the LCA is summarized in the ESM, and a CSV file compatible with SimaPro is publicly available on Zenodo at 10.5281/zenodo.13928195.

3.2.1 Compressed hydrogen (C-H_2)

After electrolysis, hydrogen is stored in a salt cavern and then compressed either into gas cylinders at 250 bar for shipping or into a pipeline at 70 bar. Thirty ships are calculated to be needed to transport 1 Mt of compressed hydrogen, or alternatively, a steel pipeline with an outer diameter of 86.4 cm and a wall thickness of 3.2 cm. If transported by ship, hydrogen is assumed to be stored in a salt cavern at the delivery site. The end user is expected to withdraw the hydrogen either from the storage cavern or directly from the pipeline, depending on the transport method used.

3.2.2 Liquid hydrogen (L-H_2)

The L-H_2 delivery chain comprises hydrogen liquefaction, storage in double-hulled cryogenic tanks, maritime transportation, storage at the delivery site, and subsequent evaporation and compression for the final use. Transporting liquid hydrogen through pipelines was considered technically unfeasible within the timeframe assessed. A hydrogen loss of 1.6% was estimated during liquefaction [38], 0.21% during storage (based on the average of values reported in Refs. [39–40]), and 0.2% per day during transportation [3]. No losses were assumed at the delivery site, as any boil-off is assumed to be used directly by the end user.

3.2.3 Ammonia (NH_3)

Ammonia is assumed to be synthesized from hydrogen and nitrogen (extracted from air) using only renewable electricity generated at the hydrogen production site. The ammonia is stored in refrigerated tanks and transported either via ships or pipelines. During shipping, ammonia losses are assumed to be minimal (0.02%), as boil-off gases are captured, cooled, and re-liquefied. At the delivery site, ammonia is cracked into hydrogen using local grid electricity. The resulting hydrogen is assumed to have a purity of 99.97% and a pressure of 240 bar [41], eliminating the need for further purification or compression in final delivery stages.

3.2.4 Methanol

The methanol pathway involves combining renewable hydrogen with carbon dioxide for delivery. Carbon dioxide is assumed to be sourced via direct air capture, using additional renewable electricity and a portion of the produced hydrogen to meet the energy demand. Methanol synthesis is assumed to be fully electrified, with heating and cooling provided by an electric boiler operating at 95% efficiency. The resulting methanol is stored in steel tanks prior to transportation.

At the delivery site, heat is required for the dehydrogenation of methanol. It is assumed that the methanol itself supplies the necessary energy for this process, and the CO_2 released during hydrogen separation is vented to the atmosphere. Following dehydrogenation, the hydrogen is further compressed from 10 to 30 bar to meet the delivery specifications.

3.2.5 LOHC

The LOHC considered for the study is dibenzyltoluene (DBT), with production inventory from Wulf et al. [6]. DBT is assumed to be reused over a lifespan of approximately 30 years. After production, the DBT is stored in steel tanks, hydrogenated, and stored again before being transported by either ship or pipeline. Upon arrival, the hydrogenated DBT is stored in containers at the port before being sent to a dehydrogenation unit.

A dehydrogenation efficiency of 98.8% is assumed. The heat required for dehydrogenation is provided by hydrogen, with 0.5% of the hydrogen assumed to leak into the atmosphere during the process. The resulting hydrogen then undergoes purification and additional compression to meet the final delivery specifications.

3.2.6 On-site production

Hydrogen production at the delivery site, hereafter referred to as “on-site” production, was assumed to be achieved through water electrolysis powered by wind-generated electricity. The cost of wind electricity in the Netherlands for 2030 is 0.12 €/kWh, with an associated global warming impact of 10 g CO_2e per kWh [27].

4 Results

Figure 2 presents the cost, environmental impact, and GHG emissions (global warming impact) of the different hydrogen delivery pathways divided by life cycle stage:

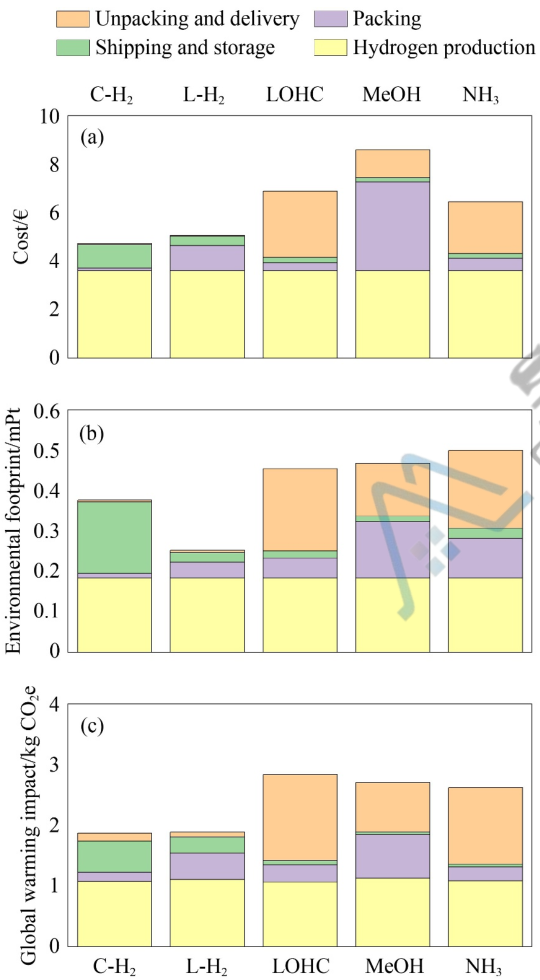

Fig. 2 Cost and environmental impact of each delivery option per kilogram of hydrogen delivered, by life cycle stage.

(a) Cost; (b) environmental footprint; (c) global warming impact (hydrogen production refers to the production of 1 kg of hydrogen, which is the same for all delivery options; the cost and impact of generating additional hydrogen to compensate for losses along the delivery chain being attributed to the specific life cycle stage where the loss occurs).

hydrogen production, packing, shipping and storage, and unpacking and delivery. The environmental impact is expressed in milli-points (mPt) per kilogram of hydrogen delivered, aggregating results across 16 environmental categories according to the normalization and weighting steps required by the EF method. Detailed LCA results per category are available in Table 2 where “S” indicates transportation by ships, and “P” transportation by pipeline. For further information on the units considered for the different impact categories, refer to the EF method [32].

In terms of costs, the techno-economic assessment shows that no single delivery pathway is optimal in all scenarios [3]. Costs depend heavily on distance and existing infrastructure. However, compressed and liquid hydrogen, especially via pipelines, are the most cost-effective within Europe, particularly where existing natural gas pipelines can be repurposed. Chemical carriers (ammonia, LOHC, methanol) become more competitive as distance increases. For the reference case (2500 km), importing renewable hydrogen was generally more economical than on-site production, except for the LOHC pathway.

In terms of environmental impact, on-site hydrogen production using renewable electricity remains the most sustainable option. However, affordable renewable sources are not always accessible at the delivery site. Among import options, liquid hydrogen delivered by ship and compressed hydrogen by pipeline prove to be the most favorable choices. Energy and resources required to pack and unpack hydrogen into more convenient chemical carriers for transportation, such as ammonia, LOHC, and methanol, make these options less attractive. Specifically, for methanol, the packing stage is particularly detrimental due to the high cost and energy demand associated with direct air capture. Direct air capture is chosen to align with EU goals of minimizing additional CO_2 emissions to the atmosphere, but this technology may not yet be an economically feasible option for large-scale implementation in 2030. Alternative sources of CO_2, such as CO_2 capture from an industrial site, may reduce costs and energy demand, but will eventually lead to an increase in CO_2 in the atmosphere unless the CO_2 is captured and stored when methanol is unpacked. For ammonia and LOHC, the main drawback is the additional energy required for dehydrogenation at the delivery site to dehydrogenate the carrier.

The transportation stage has a relatively negligible impact on the environmental impact of delivered hydrogen, regardless of the fuel used. The exception is the compressed hydrogen pathway, wherein transportation accounts for 27% of the overall climate impact due to large volumes transported. The fuel used for shipping significantly influences the GHG emissions of this pathway: using heavy fuel oil instead of biodiesel

Table 2   Life cycle impact assessment results of the 16 environmental impact categories of the EF method, per kilogram of hydrogen delivered, for the different delivery options

Category	Unit	$C\text{-}H_2$		$L\text{-}H_2$	LOHC		MeOH		NH_3	
		S	P	S	S	P	S	P	S	P
Acidification	mol H+ eq ($\times10^{-3}$)	36.3	10.7	12.1	25.9	23.7	36.3	10.7	12.1	25.9
Climate change	kg CO_2 eq	1.88	2.22	1.89	2.84	3.33	1.88	2.22	1.89	2.84
Ecotoxicity, freshwater	CTUe	11.2	11.3	10.8	18.7	20.3	11.2	11.3	10.8	18.7
Particulate matter	Disease incidence ($\times10^{-9}$)	151	103	104	183	192	151	103	104	183
Eutrophication, marine	g N eq	11.4	2.02	2.56	6.11	5.16	11.4	2.02	2.56	6.11
Eutrophication, freshwater	g P eq	1.24	1.18	1.11	1.81	1.95	1.24	1.18	1.11	1.81
Eutrophication, terrestrial	mol N eq ($\times10^{-3}$)	127	20.2	26.0	55.7	44.7	127	20.2	26.0	55.7
Human toxicity, cancer	CTUh ($\times10^{-9}$)	1.69	2.43	2.34	4.11	5.23	1.69	2.43	2.34	4.11
Human toxicity, non-cancer	CTUh ($\times10^{-9}$)	43.0	50.4	48.6	80.4	86.3	43.0	50.4	48.6	80.4
Ionising radiation	kBq U-235 eq ($\times10^{-3}$)	110	665	114	384	729	110	665	114	384
Land use	Pt	306	167	188	280	267	306	167	188	280
Ozone depletion	µg CFC11 eq	252	276	265	435	453	252	276	265	435
Photochemical ozone formation	g NMVOC eq	28.5	6.83	8.10	19.0	17.1	28.5	6.83	8.10	19.0
Resource use, fossils	MJ	20.2	33.3	17.0	40.1	52.1	20.2	33.3	17.0	40.1
Resource use, minerals and metals	mg Sb eq	45.1	49.0	49.9	81.7	84.5	45.1	49.0	49.9	81.7
Water use	L deprived	36.3	10.7	12.1	25.9	23.7	36.3	10.7	12.1	25.9

increases GHG impact by 81%, whereas utilizing a fuel derived from renewable hydrogen could reduce it by up to 15% [4].

Storage also has a relatively low environmental impact: in terms of climate change, which is the impact category most affected by this life cycle stage due to hydrogen losses, the impact is approximately 0.14 kg CO_2e/kg H_2. This accounts for around 15% of the overall climate impact for the compressed hydrogen case, but significantly less for the other options, where only 1% of the hydrogen is assumed to pass through the cavern. A sensitivity analysis was conducted, and assuming 10% of the hydrogen would undergo storage, the impact would increase negligibly in most categories. Climate change would remain the most affected category, with an increase of 1%–2% due to hydrogen losses. Notably, the majority (75%) of the climate impact associated with storage is attributed to hydrogen losses, while electricity consumption and the production of lost hydrogen contribute to the remaining impact.

The increased environmental impact of hydrogen delivered via chemical carriers is primarily due to the need for additional renewable electricity at the production site, necessitating an expansion of solar capacity and consequently more panels. Considering the significant environmental burden associated with manufacturing PV panels, this leads to a heightened overall environmental impact.

It is important to note that a comprehensive approach was taken in this study to assess the environmental impact, including categories such as resource depletion and land use, which can be particularly relevant for renewable electricity generation. By selecting locations that optimize the use of renewable infrastructure, such as those with favorable solar irradiation and wind conditions, the overall environmental impact of the produced hydrogen can be minimized. Additionally, including a battery storage system to increase the plant's capacity factor may further minimize this impact. However, it is worth noting that this assessment is based on relatively optimistic assumptions regarding the GHG intensity of renewable power generation.

The impact categories contributing the most to the single-score environmental impact of the hydrogen delivered result to be resource use, climate change, and water use. In terms of resource use, the higher consumption of minerals and metals for chemical carriers is directly linked to the need for more PV panels. Additionally, higher fossil resources are consumed not only to produce the panels but also during the unpacking process at the delivery site. Given that fossil fuels are likely to remain a significant part of grid electricity in 2030, their use at the delivery site contributes to the higher impact of chemical carriers. The climate change impact category results are consistent with those for fossil resources. However, hydrogen leakage during transport partially offsets the climate benefits of shipping hydrogen in liquid or compressed form, as opposed to using chemical carriers. Current loss estimates for the liquid hydrogen pathway are considerably higher than those for other pathways. However, these estimates are expected to decrease in the coming years [35]. If reductions are not achieved, the global warming impact of the liquid hydrogen pathway could be as significant as that of chemical carriers. Finally, the main contributors to water use impact are the electrolysis process, electricity generation, and cooling processes. The impact is highly dependent on the location from which water is sourced; processes that consume water in regions with limited freshwater availability, such as Portugal in the case study, have a greater impact. Chemical carriers, such as ammonia and methanol, result to be particularly water-intensive due to the cooling requirements during their production in Portugal.

Figure 3 presents the integrated results from the techno-economic and life-cycle assessment, illustrating costs versus environmental impacts for hydrogen transport over distances of 2500 and 10000 km. Figures 3(a) and 3(b) show total environmental impact, while Figs. 3(c) and 3(d) display global warming impact. Absolute impacts for the other impact categories are available in Arrigoni et al. [4].

Liquid and compressed hydrogen emerge as better options in terms of costs and environmental impacts compared to chemical carriers for a distance compatible with European territory (2500 km). When longer distances are considered (10000 km), compressed hydrogen becomes a less attractive option, due to increased demand for vessels and fuel necessary for transport, while liquid hydrogen maintains its advantage.

For the chemical carriers, the variations in environmental impact and cost are not markedly distinct. Nevertheless, for shorter distances, LOHC emerges as the preferable choice among the carrier options. For longer distances, ammonia stands out as the best carrier alternative. Ammonia proves to be more economical than local production, even over longer distances. LOHC exhibits comparable costs to local production, whereas methanol is associated with higher costs.

When the analysis is limited to GHG emissions, some variations in the results are observed. Specifically, the impact of compressed hydrogen and ammonia decreases relative to the other carriers, since the environmental impacts of biodiesel production and ammonia emissions

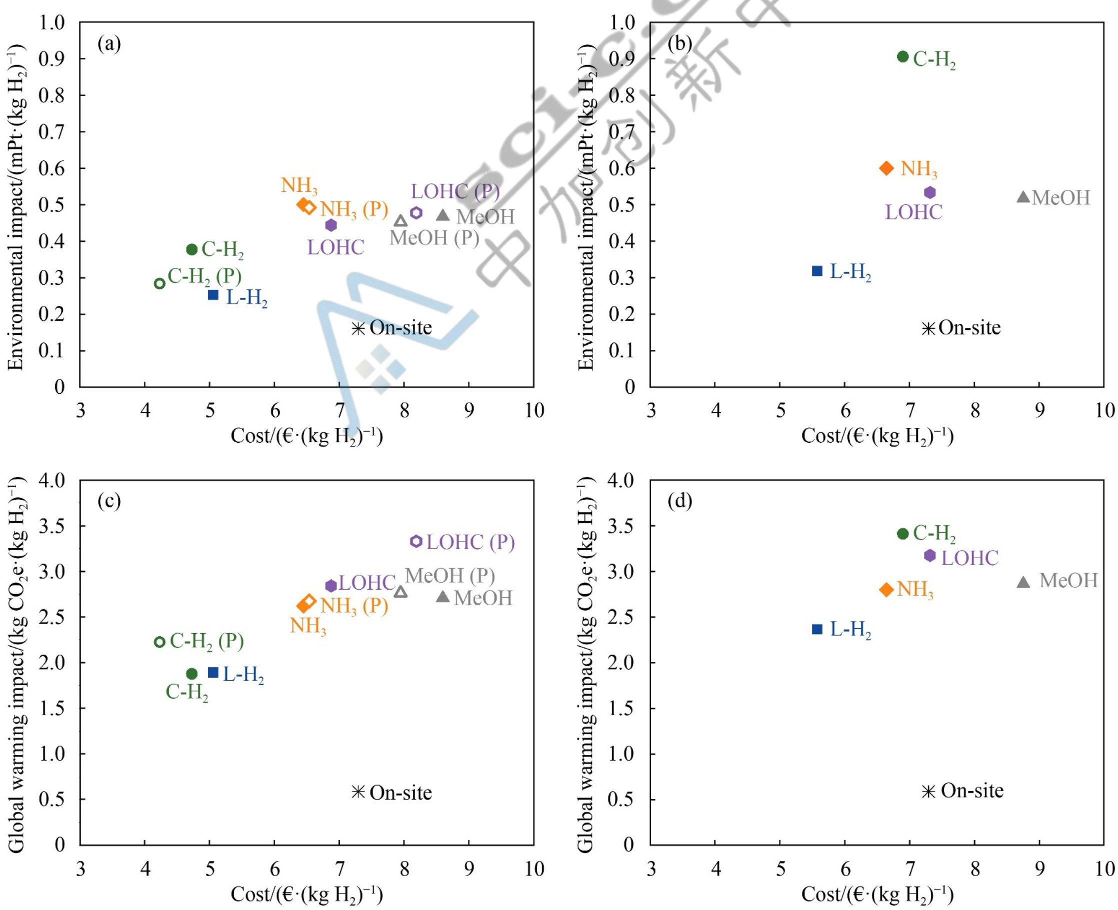

Fig. 3 Cost versus environmental impact of each delivery option per kilogram of hydrogen delivered.

(a) Cost versus aggregated environmental impact for 2500 km; (b) cost versus aggregated environmental impact for 10000 km; (c) cost versus global warming impact for 2500 km; (d) cost versus global warming impact for 10000 km (the points marked with a “P” corresponding to pipeline delivery; other points corresponding to delivery by ship).

are not fully captured by solely considering GHG emissions.

Finally, it is important to emphasize that these results reflect the aggregated outcomes from the baseline scenarios detailed in prior JRC reports [3–4]. Extensive sensitivity analyses in those studies demonstrate that different assumptions across the delivery chain can lead to divergent results.

5 Discussion

A direct comparison between the present results and those in the existing literature is challenging due to differences in the scenarios, assumptions, and methodological choices. Nevertheless, such a comparison can still provide valuable insights. This section provides a comparative analysis with existing literature in terms of costs (Section 5.1) and environmental impacts (Section 5.2). Additionally, key limitations of the study and future research directions are provided (Section 5.3).

5.1 Cost comparison

Concerning costs, the IEA Future of Hydrogen report [42] evaluated various hydrogen delivery pathways, including C-H_2, LOHC (TOL-MCH) and NH_3. According to the report, for transport distances below 1500 km, pipelines are expected to be the most cost-effective delivery option. Beyond this range, shipping hydrogen as NH_3 or LOHC becomes more economical. The IEA study estimated that the cost of conversion and delivery of hydrogen over 1500 km by ship as an LOHC is 0.6 \$/kg H_2, as ammonia 1.2 \$/kg H_2, and as liquid hydrogen 2 \$/kg H_2. In comparison, for the same distance, the present study finds higher costs for LOHC (3.3 €/kg H_2) and ammonia (2.94 €/kg H_2) but a significantly lower cost for L-H_2 (1.39 €/kg H_2). The discrepancy can be partially explained by methodological differences. Notably, the IEA excluded cracking and dehydrogenation costs for ammonia and LOHC, which account for more than half of the total costs in this study. Furthermore, this assessment assumes larger-scale infrastructure for liquefaction and storage, yielding cost reductions through economies of scale.

A study by Hank et al. [43] assessed various hydrogen delivery pathways and found that L-H_2 and NH_3 were the most cost-effective options for transporting 42500 t H_2/a from Morocco to northern Europe, both with delivery costs around 1.70 €/kg H_2. This aligns with the L-H_2 cost found here (1.56 €/kg H_2), but diverges for NH_3, which reaches 3.0 €/kg H_2 in the present study. Hank et al. [43] also reported LOHC as the most expensive option, largely due to high cost of purchasing dibenzyltoluene (DBT). In contrast, the current assessment assumes logistical optimizations to reduce the required amount of DBT, lowering overall costs.

The IRENA report [44] also compared NH_3, L-H_2, LOHC, and hydrogen pipeline transport, finding that, apart from pipelines, ammonia shipping was the cheapest option, with costs being 7%–23% lower than the alternatives. The IEA study shows higher costs for hydrogen transportation by pipeline (2 \$/kg H_2 for 3000 km) compared to the present and other studies, such as Galimova et al. [45], which report pipeline costs below 1 €/kg H_2. This difference may be due to the lower hydrogen throughput considered in the IEA study (360 vs. 1000 kt/a here), as well as differences in pipeline diameter, utilization rates, and compression strategies.

Several studies highlight LOHC as a costly option, primarily due to the energy required for dehydrogenation. However, the Roland Berger report [46] found LOHC to be the most economical option for multi-modal transport over medium distances and comparable in cost to NH_3 for long distances (> 10000 km), estimating a cost of 2.2 €/kg H_2, compared to around 4 €/kg H_2 for a similar distance in the present study. LOHC (toluene) performed better than L-H_2 in terms of cost of delivery in the paper by Wulf and Zapp [12] for short distance road delivery with supply costs close to 6 €/kg H_2, though their case is not directly comparable.

Lee et al. [15] also found LOHC (TOL-MCH) to be the most cost-effective option, at around 3 \$/kg H_2, compared to LOHC (DBT) at around 6 \$/kg H_2. The present study estimates a cost of around 4 €/kg H_2 for DBT over 10000 km. For L-H_2, Lee et al. [15] also reported costs to be over three times higher than those in the present study (6.3 \$ vs. 2 €/kg H_2), primarily due to much higher assumed liquefaction costs, with an electricity demand close to 14 kWh/kg H_2 assumed for liquefaction, whereas we assumed 6.5 kWh/kg H_2. On the other hand, for dehydrogenation of LOHC, although the energy demand for packaging is higher than that assumed in the present study (18.5 vs. 13.5 kWh/kg H_2), Lee et al. [15] used natural gas, which was not considered in the present study due to the associated GHG emissions.

Ishimoto et al. [16] found L-H_2 to be more cost-effective than NH_3 for hydrogen transport from Norway to Rotterdam, consistent with the findings of the present analysis. Furthermore, for longer distances, such as delivering to Tokyo, L-H_2 has either comparable or lower costs than the NH_3 route, depending on conservative or optimistic estimates about L-H_2 processing and handling expenses. The L-H_2 transportation cost to Rotterdam is 2.27 € for a distance of 2539 km, which is significantly higher than the findings of the present study (1.46 €). This discrepancy can be attributed at least partly to the higher L-H_2 infrastructure costs assumed in the Ishimoto et al. [16] study.

In conclusion, while meaningful comparisons can be made, they are inherently limited by differing assumptions across studies—particularly regarding throughput, technology maturity, energy sources, and infrastructure scale. Cost estimates remain sensitive to these parameters, and projections of future costs are subject to substantial uncertainty.

5.2 Environmental impact comparison

Comparing environmental impacts across studies presents significant challenges, as most studies present category-specific results by individual impact category rather than using a single aggregated score. Single-score assessments require normalization and weighting steps, which can vary significantly between methodologies and can potentially influence outcomes [34]. While the ISO standard on LCA (ISO 14044) advises caution with single-score reporting [47], the EU's EF methodology incorporates normalization and weighting to support comparison, interpretation and communication of results [48].

In the present study, GWP, resource use and water use emerged as the most relevant environmental impact categories, whereas the literature review revealed that these categories were not covered comprehensively by other studies. For instance, Li et al. [9], who used the CML 2001 method developed by the Institute of Environmental Science at Leiden University, included only five impact categories, excluding several considered crucial in the present analysis.

In terms of GHG emissions, the findings in the present paper are broadly consistent with those of other studies [8,10–14], which consistently identify compressed and liquid hydrogen as the least carbon-intensive delivery options. As shown in Fig. 3, the performance gap between compressed and liquid hydrogen widens with increasing transport distance, an observation consistent with Noh et al. [14].

Very few studies compare longer-distance delivery of compressed hydrogen with that of liquid hydrogen. Most focus on distances below 1000 km (see Table 1) or compare short-distance pipeline delivery with longer-distance shipping or trucking methods [8,9]. Noh et al. [14] modeled fully electrified production using offshore wind power, attributing GHG differences primarily to the ship phase. Their results agree with the current study in that compressed hydrogen produces higher CO_2 emissions than liquid hydrogen during transport due to its low density. Similarly, ammonia produces slightly lower CO_2 emissions than liquid hydrogen during the transport phase.

While only considering distances up to 1500 km, Frank et al. [18] compare pipeline delivery of compressed hydrogen with truck delivery of both compressed and liquid hydrogen. Their results suggest that there is a crossover point at longer distances where the truck delivery of compressed hydrogen produces higher emissions than that of liquid hydrogen, but the pipeline delivery of compressed hydrogen seems to always lead to the lowest emissions. When the results are extrapolated to longer distances, the transportation by pipeline of compressed hydrogen shows similar GHG emissions to those obtained in the present study. In contrast, Lee et al. [15] identified ammonia as being more beneficial in terms of GHG emissions than liquid hydrogen in both 2020 and 2050 scenarios, with an LOHC (MCH-TOL) having the lowest GHG emissions in 2020. For this scenario, the ammonia and LOHC packing and unpacking processes were partially powered by natural gas, while hydrogen liquefaction is powered by electricity. As the assumed carbon intensity of electricity today is higher than that of natural gas, liquid hydrogen resulted in higher emissions than ammonia and MCH-TOL, even when the latter processes show higher energy requirements. These results agree with those presented here in that the packing and unpacking of ammonia (and the LOHC) are more energy intensive than hydrogen liquefaction. However, the present study assumes fully electrified ammonia (and LOHC) processing. It should also be noted that the assumed energy consumption of these processes is significantly higher in Lee et al. [15]. In the 2050 scenario, multiple improvements were made, including integration with SOFC in the case of processes requiring heat. Because of this, the energy requirements of liquid hydrogen remained the same as the 2020 scenario, while that of ammonia and MCH-TOL decreased significantly.

These examples illustrate the many choices that can be made in process design that may lead to differing results. Nevertheless, the body of literature on life-cycle analyses for hydrogen delivery relies on a limited set of sources, with many studies [8,10–13] referencing the life cycle inventories developed by Wulf et al. [11–12] and Reuß et al. [49]. Therefore, there is a need for more independent data on the delivery processes.

5.3 Limitations and future research

In terms of informing policy-making, while findings from the present study and those from other sources [15–16] suggest that the least costly options also tend to be environmentally preferable, other studies indicate the opposite [10,12]. This divergence highlights the need for a more nuanced approach in policy design. In regions such as the EU, where ambitions for hydrogen imports and carbon emissions are high, it is crucial to strike a balance between cost efficiency and environmental performance.

Mechanisms like the Carbon Border Adjustment Mechanism (CBAM) represent a constructive step toward integrating environmental criteria into economic decision-making. However, for such instruments to be fully effective, their scope should be expanded to encompass the entire hydrogen delivery chain and consider a broader set of environmental impact categories beyond climate change alone. Moreover, there is a pressing need for the refinement of data quality and the enhancement of assessment methodologies across life cycle assessments. More comprehensive studies are necessary that integrate environmental impacts with economic metrics to ensure more holistic evaluations.

Despite aiming to contribute to this broader understanding, the present study is subject to several limitations. These include the forward-looking nature of the study, the uncertainties associated with early development stage of many technologies, and the low robustness of certain environmental impact assessment models. Additionally, the unique characteristics of each delivery pathway and geographical context make generalization difficult.

Ongoing international initiatives, such as the IEA Technology Collaboration Programmes' Task 50 [50] and ISO 19870 [51], offer promising avenues to improve the consistency of hydrogen supply chain models and underlying assumptions, thereby enhancing the accuracy of cost and environmental impact estimates.

It is also important to acknowledge the limitations of environmental and economic assessments. The practical implementation of hydrogen delivery infrastructure is highly dependent on policy support and infrastructure investments. Initiatives such as the EU Hydrogen Backbone and carbon pricing mechanisms, including financial subsidies for specific hydrogen carriers, may significantly influence delivery costs. Furthermore, strategic decisions must consider the trade-off between short- and long-term strategies. For instance, substantial investments in ammonia-based hydrogen transport infrastructure may delay or hinder the future development of more efficient or sustainable direct hydrogen transport infrastructure.

Therefore, policymakers and industry stakeholders must carefully consider these factors when making decisions about hydrogen transportation. Moreover, environmental assessments and cost analyses cannot capture the safety risks and social impacts of emerging technologies. Although the findings of the present study indicate that chemical carriers generally incur higher expenses and environmental burdens, they present certain benefits when compared to less developed alternatives like liquid hydrogen. Advantages include compatibility with existing infrastructure and established familiarity in safely handling these substances, potentially leading to lower training costs and greater societal acceptance of the inherent risks.

A more detailed examination of the safety and practical constraints associated with each hydrogen carrier, including the challenges of high-pressure storage, boil-off losses, and infrastructure development, is necessary to fully assess their real-world applicability and feasibility, particularly in the context of large-scale deployment.

Social considerations are critical and warrant more thorough evaluation through dedicated social impact assessments. In this context, JRC conducted a social life cycle assessment (S-LCA) to evaluate the social implications of the hydrogen delivery chain [52]. The results of the S-LCA indicated that producing renewable hydrogen locally in Northern Europe outperforms import-based scenarios across most social indicators, primarily due to the simpler value chain and reduced labor intensity for delivering the same amount of hydrogen. This study focused exclusively on compressed hydrogen as the transport solution, based on its favorable techno-economic and environmental performance.

Future work should aim to compare various carriers for potential social impacts and risks. To support such efforts, the JRC has proposed a framework for evaluating and monitoring social risks and impacts associated with hydrogen technologies and their supply chains [53]. This framework defines a set of social dimensions and corresponding indicators tailored to the hydrogen sector, which could be used to identify the social impacts associated with various hydrogen carriers, including both the advantages of using molecules already handled at scale and the societal risks posed by potential hazards within the delivery chain.

Ultimately, incorporating these insights into a broader sustainability assessment which considers economic, environmental, and social dimensions would ultimately offer a more holistic understanding of the long-term sustainability of hydrogen delivery pathways.

6 Conclusions and recommendations

This study aimed to compare the costs and the environmental life cycle performance of different hydrogen delivery options within Europe after 2030. Five hydrogen carriers were assessed: compressed hydrogen, liquid hydrogen, ammonia, dibenzyltoluene (LOHC), and methanol, assuming that hydrogen was produced via renewable electrolysis in Portugal and delivered to the Netherlands by either ship or pipeline. Local on-site production was included as a reference case.

The results indicate that producing hydrogen locally using renewable sources is likely to be the most environmentally sustainable option. However, it may not be the most cost-effective option, especially where affordable renewable electricity is not available at the point of use. Among the hydrogen delivery options, shipping liquid hydrogen and transporting compressed hydrogen via pipeline emerge as the most cost-effective and environmentally sustainable options for long-distance delivering. In contrast, chemical carriers incur higher costs and environmental impacts, largely due to the additional energy and materials required in hydrogen conversion steps such as hydrogenation and dehydrogenation—often necessitating additional renewable electricity and infrastructure like PV panels.

These findings are consistent with much of the existing literature on hydrogen delivery. However, previous studies have focused mainly on economic costs or GHG emissions, often neglecting other important indicators for large-scale hydrogen import deployment. Moreover, many studies typically depend on a narrow set of data sources. This study broadened the assessment scope by integrating both cost assessment and a wider range of environmental impacts, using the EF method of the European Commission. Results suggest that future development should prioritize delivery methods with lower combined costs and environmental impacts, specifically shipping liquid hydrogen and pipeline transport of compressed hydrogen, while also focusing on improving the efficiency of energy-intensive conversion processes, such as hydrogen liquefaction and the dehydrogenation of chemical carriers.

Despite the value of these insights for policymakers, the analysis is subject to several limitations, such as the geographic specificity of the case study, the uncertainties inherent in forward-looking assessments, the early maturity of some technologies, the limited robustness of certain impact assessment models, the subjectivity of methodological choices such as weighting factors and the handling of co-products [54], and the omission of safety considerations and social impact assessment.

To strengthen future assessments and better support policymaking, the following recommendations are proposed:

• Promote multi-criteria assessments to avoid shifting impacts from one sustainability dimension to another;

• Refine assessment methodologies, emphasizing underrepresented environmental impact categories and social indicators. Additionally, address fundamental methodological issues in LCA, such as prospectivity and multifunctionality in life cycle assessments;

• Enhance the quality, reliability, and transparency of life cycle inventory data for hydrogen technologies [55].

Implementing these recommendations can help yield more robust and precise assessments, thereby ultimately facilitating more informed and balanced decision-making for the large-scale deployment of hydrogen imports.

Competing Interests The authors declare that they have no competing interest.

References

1. European Commission. A Hydrogen Strategy for a Climate-Neutral Europe. Brussels, Belgium, 2020
2. European Commission. REPowerEU: Joint European Action for More Affordable, Secure and Sustainable Energy. Brussels, Belgium, 2022
3. Ortiz Cebolla R, Dolci F, Weidner E. Assessment of hydrogen delivery options: Feasibility of transport of green hydrogen within Europe. Joint Research Centre, European Commission, 2022
4. Arrigoni A, Dolci F, Ortiz Cebolla R, et al. Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe. Joint Research Centre, European Commission, 2024
5. Nicita A, Squadrito G, Maggio G. Life-cycle cost (LCC) applied to hydrogen technologies: A review. International Journal of Life Cycle Assessment, 2024, 29(1): 46–79
6. Schuler J, Ardone A, Fichtner W. A review of shipping cost projections for hydrogen-based energy carriers. International Journal of Hydrogen Energy, 2024, 49: 1497–1508
7. Apostolou D, Xydis G. A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. Renewable and Sustainable Energy Reviews, 2019, 113: 109292
8. Kaiser S, Siems F, Mostert C, et al. Environmental and economic performance of CO_2-based methanol production using long-distance transport for H_2 in combination with CO_2 point sources: A case study for Germany. Energies, 2022, 15(7): 2507
9. Li J, Zhu X, Djilali N, et al. Comparative well-to-pump assessment of fueling pathways for zero-carbon transportation in China: Hydrogen economy or methanol economy? Renewable & Sustainable Energy Reviews, 2022, 169: 112935
10. HYSTOC. Deliverable 8.1—Business Development and LCA Potential Environmental Implications of LOHC Concepts. HYSTOC Project (Horizon 2020 GA 779694), 2018
11. Wulf C, Reuß M, Grube T, et al. Life cycle assessment of hydrogen transport and distribution options. Journal of Cleaner Production, 2018, 199: 431–443
12. Wulf C, Zapp P. Assessment of system variations for hydrogen transport by liquid organic hydrogen carriers. International Journal of Hydrogen Energy, 2018, 43(26): 11884–11895
13. Akhtar M S, Dickson R, Niaz H, et al. Comparative sustainability assessment of a hydrogen supply network for hydrogen refueling stations in Korea—A techno-economic and lifecycle assessment perspective. Green Chemistry, 2021, 23(23): 9625–9639
14. Noh H, Kang K, Seo Y. Environmental and energy efficiency assessments of offshore hydrogen supply chains utilizing compressed gaseous hydrogen, liquefied hydrogen, liquid organic hydrogen carriers and ammonia. International Journal of Hydrogen Energy, 2023, 48(20): 7515–7532
15. Lee J S, Cherif A, Yoon H J, et al. Large-scale overseas transportation of hydrogen: Comparative techno-economic and

environmental investigation. Renewable & Sustainable Energy Reviews, 2022, 165: 112556
16. Ishimoto Y, Voldsund M, Nekså P, et al. Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. International Journal of Hydrogen Energy, 2020, 45(58): 32865–32883
17. Ozawa A, Kudoh Y, Kitagawa N, et al. Life cycle CO_2 emissions from power generation using hydrogen energy carriers. International Journal of Hydrogen Energy, 2019, 44(21): 11219–11232
18. Frank E D, Elgowainy A, Reddi K, et al. Life-cycle analysis of greenhouse gas emissions from hydrogen delivery: A cost-guided analysis. International Journal of Hydrogen Energy, 2021, 46(43): 22670–22683
19. Al-Breiki M, Bicer Y. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. Journal of Cleaner Production, 2021, 279: 123481
20. Ren L, Zhou S, Ou X. Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. Energy, 2020, 209: 118482
21. Di Lullo G, Giwa T, Okunlola A, et al. Large-scale long-distance land-based hydrogen transportation systems: A comparative techno-economic and greenhouse gas emission assessment. International Journal of Hydrogen Energy, 2022, 47(83): 35293–35319
22. Shin W J, Lee Y, Yu Y, et al. Comparative life cycle greenhouse gas analysis of clean hydrogen pathways: Assessing domestic production and overseas import in South Korea. Journal of Cleaner Production, 2023, 425: 138907
23. Zhu R, Wang Z, He Y, et al. LCA comparison analysis for two types of H_2 carriers: Methanol and ammonia. International Journal of Energy Research, 2022, 46(9): 11818
24. Akhtar M S, Dickson R, Liu J J. Life cycle assessment of inland green hydrogen supply chain networks with current challenges and future prospects. ACS Sustainable Chemistry & Engineering, 2021, 9(50): 17152–17163
25. Port of Rotterdam. Sines and Rotterdam Together in the H_2 Sines. World Port Center, The Netherlands, 2022
26. European Commission. A European Strategic Long-term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy. Brussels, Belgium, 2018
27. Hydrogen Council. Hydrogen Decarbonization Pathways. A Life-cycle Assessment. Brussels, Belgium, 2021
28. Kolahchian Tabrizi M, Famiglietti J, Bonalumi D, et al. The carbon footprint of hydrogen produced with state-of-the-art photovoltaic electricity using life-cycle assessment methodology. Energies, 2023, 16(13): 5190
29. Ferrara C, Marmiroli B, Carvalho M L, et al. Life cycle assessment of photovoltaic electricity production in Italy: Current scenario and future developments. Science of the Total Environment, 2024, 948: 174846
30. E3Modelling. Summary Report: Energy, Transport and GHG Emissions. Athens, Greece, 2021
31. ecoinvent. System Models. Zurich, Switzerland, 2022
32. European Commission, Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. Brussels, Belgium, 2021
33. Sala S, Cerutti A K, Pant R. Development of a weighting approach for the environmental footprint. Publications Office of the European Union, Luxembourg, 2018
34. Roesch A, Sala S, Jungbluth N. Normalization and weighting: The open challenge in LCA. The International Journal of Life Cycle Assessment, 2020, 25(9): 1859–1865
35. Arrigoni A, Diaz L B. Hydrogen emissions from a hydrogen economy and their potential global warming impact. Publications Office of the European Union, Luxembourg, 2022
36. Sand M, Skeie R B, Sandstad M, et al. A multi-model assessment of the global warming potential of hydrogen. Communications Earth & Environment, 2023, 4(1): 203
37. Wernet G, Bauer C, Steubing B, et al. The ecoinvent database version 3 (part I): Overview and methodology. International Journal of Life Cycle Assessment, 2016, 21(9): 1218–1230
38. Heuser P M, Ryberg D S, Grube T, et al. Techno-economic analysis of a potential energy trading link between Patagonia and Japan based on CO_2 free hydrogen. International Journal of Hydrogen Energy, 2019, 44(25): 12733–12747
39. Decker L. Liquid hydrogen distribution technology. In: HYPER Closing Seminar, Brussels, 2019
40. Krenn A. Diagnosis of a poorly performing liquid hydrogen bulk storage sphere. AIP Conference Proceedings, 2012, 1434(57): 376–383
41. Fothergill K, Greenwood S, Makepeace J, et al. Ammonia to green hydrogen project. Science & Technology Facilities Council (STFC)/Ecuity Consulting, 2015
42. IEA. The Future of Hydrogen—Seizing Today’s Opportunities. Paris, France, 2019
43. Hank C, Sternberg A, Köppel N, et al. Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. Sustainable Energy & Fuels, 2020, 4(5): 2256–2273
44. IRENA. Global Hydrogen Trade to Meet the 1.5 °C Climate Goal: Part II – Technology Review of Hydrogen Carriers. Abu Dhabi, United Arab Emirates, 2022
45. Galimova T, Fasihi M, Bogdanov D, et al. Impact of international transportation chains on cost of green e-hydrogen: Global cost of hydrogen and consequences for Germany and Finland. Applied Energy, 2023, 347: 121369
46. Uwe Weichenhain. Hydrogen Transportation. The Key to Unlocking the Clean Hydrogen Economy. Munich: Roland Berger GmbH, 2021
47. ISO 14044:2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. Geneva, Switzerland, 2006
48. European Commission. Commission recommendation of 16.12.2021 on the use of the environmental footprint methods to measure and communicate the life cycle environmental performance of products and organisations. Official Journal of the European Union, L 471, 17.12.2021

49. Reuß M, Grube T, Robinius M, et al. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Applied Energy, 2017, 200: 290–302
50. IEA. Task 50: Cost and Carbon Intensity Analysis and Model Comparison of Hydrogen Supply Chains. Madrid, Spain 2024
51. ISO 19870:2023. Methodology for Determining the Greenhouse Gas Emissions Associated with the Production, Conditioning and Transport of Hydrogen to Consumption Gate. Geneva, Switzerland, 2023
52. Martín-Gamboa M, Mancini L, Eynard U, et al. Social life cycle hotspot analysis of future hydrogen use in the EU. The International Journal of Life Cycle Assessment, 2024, 30: 1379–1396
53. Zamagni A, Mancini L, Eynard U, et al. A conceptual framework for assessing and monitoring social risks and impacts related to hydrogen technologies and their value chains. Publications Office of the European Union, Luxembourg, 2025
54. Arrigoni A, Hurtig O, Buffi M, et al. Life cycle assessments use in hydrogen-related policies: The case for a harmonized methodology addressing multifunctionality. International Journal of Hydrogen Energy, 2024, 69: 1426–1438
55. Santucci V, Eynard U, Valente A, et al. Developing life cycle inventory datasets for the hydrogen value chain. Publications Office of the European Union, Luxembourg, 2024