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A techno-economic evaluation and SWOT analysis of various hydrogen energy carriers: Production to distribution

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ABSTRACT

The transition from fossil fuel dependency to low-carbon pathways is dependent on efficient energy transportation methods. Hydrogen (H_2) stands as a key player in achieving carbon-neutral targets by 2050. However, large-scale H_2 transport presents technological and economic challenges. This study provides a techno-economic evaluation (TEE) and SWOT analysis of hydrogen energy carriers (HECs) for export from natural gas-rich countries, comparing four different pathways: liquid hydrogen (LH_2), ammonia (NH_3), methanol (MeOH), and dimethyl ether (DME). NH_3 emerges as the most cost-effective option, with the lowest specific energy consumption (SEC) of 7.67 kWh/kg-H_2 and a levelized cost of hydrogen (LCOH) at US$4.76/kg-$H_2$. SWOT analysis reveals strong infrastructure and regulatory support for NH_3, while LH_2 is ranked higher on specific factors. Although NH_3 faces safety challenges, it remains favorable for sustainable transportation. However, significant research is needed to ensure the technological and economic feasibility of these pathways for large-scale implementation.

Abbreviations

AHP	Analytical hierarchy process
BOG	Boil off gas
CC	Carbon capture
CO_2	Carbon dioxide
CAPEX	Capital expenditure
CHECs	Circular hydrogen energy carriers
CGH_2	Compressed gaseous hydrogen
DME	Dimethyl ether
HECs	Hydrogen energy carriers
HLP	H_2 liquefaction process
HPP	H_2 precooling process
LCOH	Levelized cost of hydrogen
LH_2	Liquid hydrogen
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
MeOH	Methanol
MCDM	Multi-criteria decision-making
MCDA	Multi-criteria decision analysis
NH_3	Ammonia
O & M	Operational and maintenance
OPEX	Operating expenditure
PSA	Pressure swing adsorption
PESTEL	Political, economic, social, technological, legal and environmental
Q-Chem	Qatar chemicals
QAFCO	Qatar fertilizer company
QAFAC	Qatar fuel additives company
SEC	Specific energy consumption
SMR	Single mixed refrigerant
SWOT	Strengths–weaknesses–opportunities–threats
TEE	Techno-economic evaluation
TPD	Tons per day

1. Introduction

Large-scale hydrogen (H_2) production facilities, which are centralized and utilize diverse energy sources, are currently in operation. However, the transportation of H_2 from these production sites to distribution points poses a challenge, especially when the energy source is situated in a distant site [1]. H_2 can be transported via pipeline, road or ocean in the form of liquid, gas, or metal hydride. For short distances and smaller quantities, especially when dealing with CGH_2, road transport is feasible. However, pipelines prove to be a more effective

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option for transporting large amounts of H_2 over larger distances. Particularly, liquid hydrogen (LH_2) can be effectively transported through road or ocean over extensive distances. On the other hand, H_2 stored in metal hydrides in low pressure is constrained to shorter distances and less volume [2].

Fig. 1 illustrates the various pathways for H_2 transportation and distribution across extensive distances. The supply chain of H_2 encompasses seven key phases: hydrogen production, conditioning, storage and loading, transportation, unloading and storage, re-conditioning, and end-use distribution [3]. It should be noted that the import and export terminal storage procedures are a part of the loading and unloading phases. Section 2.3 provides a detailed explanation of each stage, examining its strengths, weaknesses, opportunities, and threats (SWOT). The transportation of liquid hydrogen (LH_2) via road or ocean provides a range of options in the realm of H_2 transport. For shorter distances, utilizing trucks for compressed gaseous hydrogen (CGH_2) emerges as particularly cost-efficient. Various research studies have recognized CGH_2 pipelines and LH_2 trailers as the economically feasible options for transportation of H_2 for long distances over land. Furthermore, these investigations have affirmed that shipping of LH_2 presents itself as the most economically viable approach for transporting hydrogen across oceans, closely followed by the shipping of liquid organic H_2 carriers (LOHC) as the best economical alternative [4].

In the pathway of liquid H_2, it undergoes a regasification and compression process for its transportation as compressed H_2. This can be accomplished through either tube trailers or pipeline systems. Tube trailers are configured to transport hydrogen within the pressure range of 200–500 bar, accommodating varying payload capacities ranging from 300 to 1100 kg, contingent upon the specific carrier employed. Tube trailers present a pragmatic solution particularly well-suited for scenarios characterized by demand and transportation distances of around 160 km. Alternatively, the utilization of tanker trucks instead of CGH_2 emerges as a viable option offering potential cost advantages attributed to the high density of LH_2. However, a notable technical challenge of boil-off gas (BOG) losses is common loss associated with LH_2. Conversely, the deployment of pipelines stands out as the most financially feasible solution for extensive H_2 transportation necessitating long distances and catering to substantial demand. While the establishment of pipelines demands considerable capital investment but the operational and maintenance (O&M) expenditures of these pipelines are less, rendering them economically attractive over an extended operational lifespan of around 40 years [3].

Table 1 Compares different methods of H_2 transportation. Overall, pipelines and cryogenic tankers demonstrate the maximum benefits among the different choices for transportation. However, substantial initial investments and transmission costs are required. As depicted in Table 1, the costs associated with transporting and distributing liquid hydrogen (LH_2) are noticeably less than those for compressed gaseous hydrogen (CGH_2). Additionally, Table 1 emphasizes that pipelines can become the most cost-effective solution for conveying CGH_2 when large quantities of H_2 need to be transported over considerable distances.

However, the large-scale transportation of H_2 poses notable challenges in technological and economic dimensions, that must be tackled within current energy infrastructures. Consequently, this research investigates and compares four distinct modes of HECs: LH_2, NH_3, MeOH, and DME. The comparison of techno-economic evaluations (TEE) of these hydrogen transportation pathways is numerically conducted to advance the cost-effectiveness and expansive development of HECs. There is a lack of studies as per authors' knowledge within the open literature that conducts both a TEE and a quantitative SWOT analysis for these four HECs. The SWOT analysis serves as a valuable tool to offer a comprehensive understanding of the current landscape of HECs in Qatar. It equips decision-makers with insights into the prevailing SWOT, enabling them to navigate the challenges and leverage the opportunities that lie ahead. Furthermore, previous TEEs of hydrogen pathways predominantly emphasized economic feasibility, often neglecting environmental impacts, particularly for H_2 or NH_3 exclusively. Therefore, the primary contribution of this research is bridging the gap by conducting a TEE for various HECs from the Qatar to various regions. It evaluates their 3E (energetic, economic, and environmental) indicators along with a quantitative SWOT analysis.

2. Methodology

In this research, two different approaches are investigated to evaluate the techno-economically feasible, safe and sustainable option for hydrogen energy carriers (HECs). First, a techno-economic evaluation (TEE) method is used to evaluate a feasible option. Second, a SWOT analysis is used to examine a strengths, weaknesses, opportunities, and threats for HECs. The goal of this study is to combine the methodologies of SWOT analysis and roadmap enhancement to build strategic plans for hydrogen utilization. The study will highlight the advantages of establishing a hydrogen economy in Qatar and provide examples of strategic plans for hydrogen utilization. The evaluation of SWOT of HECs in this study is based on a two-step approach. First selection of criteria was identified from an extensive literature review, industry reports, and best

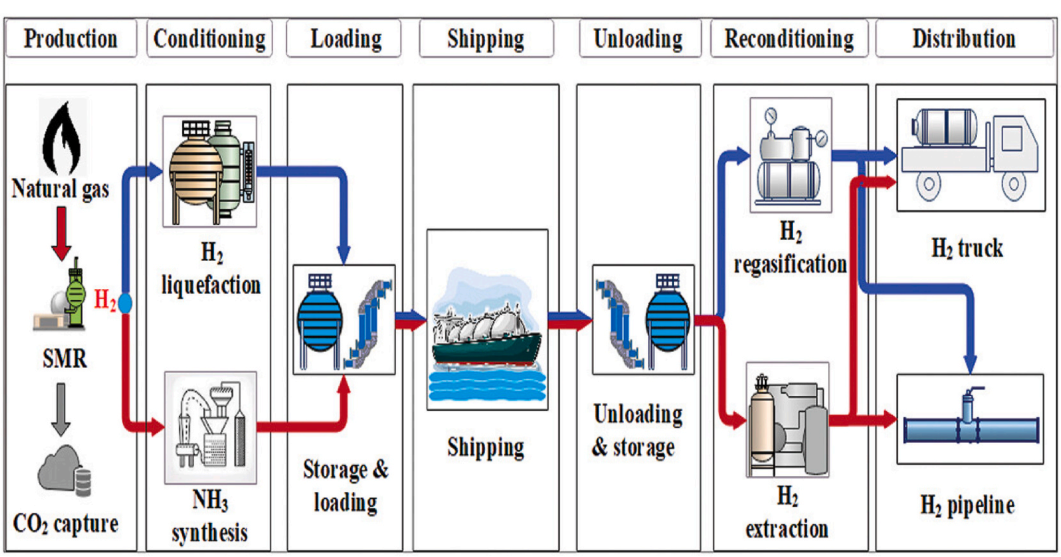

Fig. 1. LH_2 and NH_3 supply chain flow diagram [3].

Table 1
Comparison of various H_2 transportation modes [4–8].

Transportation mode	Pressure (MPa)	Capacity (Maximum)	BOG	CAPEX (US$)	OPEX (% CAPEX US$)/year	Transport cost US$/kg/100 km
Pipelines	2–3	100 tons/h	0.8%/100 km	0.2–1 million/km	4-4.7%	0.10 - 1.0
CGH_2 trailer	20–50	400 kg	6%/100 km	0.3 million/trailer	2%	0.50 - 2.0
LH_2 trailer	0.1- 0.4	400 kg	6%/100 km	0.3 million/trailer	2%	0.50 - 2.0
Tankers	0.1-0.7	4000 kg	1%/100 km	0.3 – 0.m Million/trailer	16634K + 4%[a] CAPEX	0.30 - 0.50
Shipping	0.1-0.7	10,000 tons	0.3%/day	465 - 620 million/ship	10553746 + 4%[a] CAPEX	1.80 - 2.0

[a] +4% represents a percentage adjustment factor of CAPEX.

practices in hydrogen energy research. These parameters include technical, economic, safety, and environmental factors. Second, the selected parameters were assessed using Aspen HYSYS simulations for techno-economic factors (e.g., specific energy consumption, efficiency, costs), while non-simulated parameters (e.g., infrastructure readiness, safety considerations) were ranked based on established literature and industry reports.

The following sub-sections first describe the various energy carriers, TEE and the SWOT framework.

2.1. Hydrogen energy carriers (HECs)

Hydrogen energy carriers (HECs) refer to methods of storing and transporting hydrogen, either in chemically bonded forms such as NH_3, MeOH, and DME, or as liquefied hydrogen (LH_2). Through chemical conversion, storage and transportation of H_2 are anticipated to be enhanced. Depending on the carrier and its reaction kinetics, conversion process can either be reversible or irreversible. In irreversible systems, H_2 undergoes conversion into another chemical carrier to serve as a primary fuel source. Conversely, reversible systems involve temporary bonding of hydrogen to a carrier, allowing for a reverse reaction to release the hydrogen when needed. Liquid organic hydrogen carriers (LOHCs), formic acid (CH_2O_2), methane (CH_4), methanol (MeOH), dimethyl ether (DME), and ammonia (NH_3) are some of the most promising hydrogen carriers [9]. The primary characteristic of the LOHC system is its temporary bonding of H_2 to a chemical structure, which is released when the carrier chemical returns to the production. However, H_2 can also undergo reactions with other chemicals to yield end products such as MeOH, DME, NH_3, and CH_2O_2. These chemicals hold potential for dissociation to regenerate H_2 or can be directly utilized at the destination as end products. In such instances, the process becomes irreversible bypassing the energy-intensive step. These carriers are referred as circular hydrogen energy carriers (CHECs) due to the recycling of the carrier in lean form (N_2 or CO_2). While LOHCs and formic acid (CH_2O_2) are considered as potential hydrogen carriers, but these are not considered in the detailed analysis in this study due to relatively low maturity for large-scale applications, higher associated costs, and limited infrastructure availability compared to the four selected carriers (LH_2, NH_3, MeOH, and DME). Therefore, this study focuses on hydrogen energy carriers (HECs) that are currently more feasible for large-scale deployment, particularly in the context of Qatar's hydrogen economy and export strategies. Table 2 provides the comparative properties of these HECs.

2.1.1. Liquid hydrogen (LH_2)

Liquid hydrogen (LH_2), which maintains a saturated liquid state at 1 bar and -253 °C, has a density of 70.8 kg/m^3, making it highly suitable for applications requiring greater storage capacities compared to gaseous forms. This increased density of LH_2 is especially advantageous for large-scale transportation and storage, as it offers a cost-efficient solution with higher energy density. For example, large-scale ocean transportation can be efficiently conducted using storage tankers with capacities exceeding 10,000 m^3. Similarly, inland transportation options include trailers with tank capacities of 30–60 m^3 or rail containers holding approximately 115 m^3 [12]. Future demand for liquid hydrogen (LH_2) is predicted to rise significantly on a worldwide scale as its role in addressing the growing need for low-emission fuels becomes more prominent. LH_2 is particularly suited for applications requiring high energy density and long-distance transport, making it a key player in the global energy transition [13,14]. However, several key technical hurdles still impede widespread adoption, particularly concerning hydrogen liquefaction. These challenges include the high cost associated with the process with significant energy of 13.8 kWh/kg-H_2 approximately [15], and significant hydrogen BOG loss ranging from 1 to 3% per day during the conditioning process [16]. Such losses occur primarily due to heat ingress into cryogenic storage tanks, which causes a portion of the liquid hydrogen to evaporate. Modern storage systems use advanced insulation technologies, such as vacuum-jacketed tanks with multi-layer insulation, to minimize heat transfer and reduce BOG losses. Higher losses may occur if storage systems are not properly maintained, or during operational events such as loading and unloading, which can lead to transient increases in heat exposure [17,18]. Many research teams are currently working to reduce the BOG losses and optimize specific energy consumption (SEC) and improve process efficiency in order to address these challenges [19]. To meet industrial demand, researchers are exploring a range of hydrogen-liquefaction processes, including innovative refrigeration techniques and thermodynamic cycles with mixed refrigerants.

Table 2
Comparative properties of various HECs [9,10,11].

Properties	Hydrogen (H_2)	Ammonia (NH_3)	Methanol (CH_3OH)	Dimethyl Ether (DME)
Density[a] (kg/m^3)	70.8 at -253 °C and 1 atm	682 at -33 °C and 1 atm	792 at 25 °C and 1 atm	665 at 20 °C and 6 atm
Dynamic viscosity (Pa. s)	8.8×10^{-6}	9.9×10^{-6}	5.94×10^{-3}	1.22×10^{-5}
Energy density (MJ/l)	8.5 (LH_2)	15.6	22	19.3
Lower heating value (MJ/kg)	120	18.80	19.92	27.6
Laminar burning velocity (m/s)	3.51	0.07	0.36	4.4
Minimum ignition energy (mJ)	0.011	8.000	0.140	0.29
Auto-ignition temperature (°C)	500–575	657	439	350
Octane number	>100	130	119	35
Gravimetric hydrogen density (wt%)	100.0	17.8	12.5	13

[a] Densities are reported under the typical storage and transportation conditions for each carrier to allow for a fair comparison.

2.1.2. Ammonia (NH_3)

Ammonia (NH_3) holds a pivotal role in both agriculture and industry with considerable interest as a prospective HEC within the growing hydrogen economy. Its primary benefits are ease of transportation, substantial H_2 storage capacity, and straightforward reconditioning process. NH_3 can be liquefied at room temperature under low to medium pressures of approximately 10 bar, presenting a less energy-intensive solution for energy storage and transportation [9]. NH_3 stands as the second most-produced chemical globally, boasting a capacity exceeding 200 million tons per year. Its importance to the agricultural sector is profound, as nearly 40% of food production relies on NH_3 synthesis. Notably, NH_3 exhibits a high H_2 content, comprising 17.6 wt%. Its versatile applications include use in gas turbines, combustion processes, NH_3 fuel cells, and as a fertilizer feedstock [20,21,22,23]. Traditional NH_3 production methods consume approximately 2% of the global fossil energy, leading to emissions exceeding 420 MT of CO_2. Consequently, the adoption of the green NH_3 route holds the potential to substantially reduce CO_2 emissions [24,25]. Ammonia (NH_3) is typically synthesized using the Haber-Bosch process (Eq. (1)). To maximize ammonia (NH_3) yield in the Haber-Bosch process, the reaction is typically conducted at temperatures of 300–500 °C and pressures ranging from 100 to 300 bar, depending on the specific reactor design and catalyst efficiency [26,27]. Despite the exothermic nature of the reaction, the energy demand stands at 1.5 MJ/kgNH_3, roughly equivalent to 6.5% of NH_3 lower heating value (LHV). A significant portion of this energy is allocated to compressing hydrogen and nitrogen to the reaction pressure. Addressing these challenges requires intensive research on catalyst development. NH_3 is a crucial chemical for various industries, including chemicals, food, and agriculture. While the H–B process is globally employed, current NH_3 synthesis techniques are optimized for CH_4, making them less suitable for renewable H_2 utilization. Hence, further research is imperative to enhance process efficiency in this context.

$$N_2 + 3H_2 \rightarrow 2NH_3 \tag{1}$$

NH_3 exists in the gaseous state under ambient conditions. For large-scale storage, liquefying ammonia by cooling to -33 °C at 1 bar is the preferred method due to its higher storage capacity and energy efficiency. At this condition, ammonia achieves a liquid density of approximately 682 kg/m^3, enabling significant volumes to be stored in insulated, atmospheric-pressure tanks. This method is widely adopted in industrial settings where large-scale refrigeration infrastructure is available. Alternatively, ammonia can be stored by compressing it to 10 bar at 25 °C, achieving a liquid density of around 610 kg/m^3. This method is suitable for smaller-scale applications or locations where maintaining cryogenic temperatures is impractical. However, the higher energy requirements for compression and the reduced storage capacity make it less favorable for large-scale storage [28,29]. While NH_3 is technically a flammable gas, and high toxicity along with its extremely high vapor pressure which can pose safety concerns during handling. Additionally, NH_3 is corrosive in nature towards materials like zinc alloys, copper, and brass further complicates its usage. Despite having an established infrastructure due to its widespread supply, there are doubts about whether the existing infrastructure can adequately support a large-capacity NH_3 system [30,31].

2.1.3. Methanol (MeOH)

Methanol (MeOH) is primarily produced from coal or natural gas (CH_4) through syngas resulting in its abundant availability worldwide. MeOH is a hazardous substance with significant toxicity if ingested, inhaled, or absorbed through the skin, posing risks to both human health and the environment. In 2023, global methanol demand reached 88 million metric tons, and it is projected to grow at a compound annual growth rate of approximately 3%, representing an increase of over 14 million metric tons over the next five years. It is important to note, that MeOH may also be made without the use of fossil fuels by obtaining CO_2 from the carbon capture pathway and H_2 from the water electrolysis method [32]. Indeed, when the energy used for its production is entirely renewable energy, the resulting product is known as "green MeOH". This study uses natural gas as the feedstock for methanol production, leveraging Qatar's abundant reserves and established infrastructure. With the capacity to store 12.5 wt% H_2 and an energy density of 4.94 kWh/liter, methanol emerges as an excellent H_2 carrier suitable for the end-use applications [33]. The hydrogenation reaction of CO_2 to methanol, as described by Eq. (2), is accompanied by a simultaneous water-gas shift (WGS) reaction, as outlined in Eq. (3). However, if the WGS reaction undergoes incomplete conversion, it can result in the undesired by-product of CO [34].

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{2}$$

$$CO + 3H_2O \rightarrow CO_2 + H_2 \tag{3}$$

The technique of producing MeOH from CO_2 hydrogenation is a proven method that is used commercially. Producing MeOH from collected CO_2 and renewable H_2 is a widely applicable process due to its advanced technological state. According to recent research, MeOH may be the most economical supply chain route for exporting H_2 when compared to other options like liquefaction, compression, or NH_3 conversion. MeOH is a versatile substance due to its wide liquid range (−98 °C–65 °C under standard atmospheric pressure of 1 atm) and thermophysical characteristics, which include high boiling and low melting temperatures. Dynamic viscosity of MeOH is lower than gasoline and diesel, and it can be easily blended with other fuels, allowing it to adapt easily to existing infrastructure. However, it is important to note that MeOH has a low flash point of around 9.7 °C and extremely high vapor pressure compared to other carriers. Despite similarities to gasoline in terms of safety features, appropriate precautions must be taken.

2.1.4. Dimethyl ether (DME)

Dimethyl ether (DME) is a molecule that is neither carcinogenic nor toxic. Its chemical and physical characteristics are quite similar to those of liquefied petroleum gas (LPG). DME is mostly used as an aerosol propellant replacing the chlorofluorocarbon compounds which are believed to be a one of the factor in the ozone depletion [11]. In recent decades, focus on DME as an alternative liquid fuel to both diesel and LPG is increased. DME among various LOHCs stands out for its potential to significantly impact society, especially when integrated into supply chains involving CO_2 capture and utilization. This integration can effectively mitigate environmental issues without contributing to the carbon footprint. DME is usually manufactured in two steps from syngas conversion in industrial applications as given in Equations (4) and (5). In this method, methanol is first produced in one reactor, and it is then condensed into DME in another reactor. But instead of using syngas as a feedstock combination, hydrogenation of CO_2 has gained more attention during the past decade. This strategy is seen to be a more appealing way to produce methanol since it makes it possible to recycle CO_2 efficiently, which helps to reduce emissions into the atmosphere.

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{4}$$

Subsequently, in the second stage, methanol is dehydrated on an acid catalyst to form DME.

$$2CH_3OH \leftrightarrow CH_3OCH_3 + H_2O \tag{5}$$

The reverse water gas shift (WGS) has an impact on the DME synthesis in addition to processes (4) and (5), as indicated by the reaction as stated in Eq. (6):

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{6}$$

A unique approach to CO_2 hydrogenation research is the viability of a direct procedure for DME production. This method combines the synthesis of MeOH with its dehydration to produce DME in a single step. The net reaction in the one step CO_2 hydrogenation process is as follows in Eq. (7).

$$2CO_2 + 6H_2 \rightarrow CH_3OCH_3 + 3H_2O \quad (7)$$

2.2. Techno-economic evaluation (TEE)

This section presents the energy, economic, and environmental data and models to assess the HECs pathways. Each stage of the supply chain is evaluated based on its specific energy consumption (SEC), the levelized cost of hydrogen (LCOH), and CO_2 intensity. The specific energy consumption (SEC) values reported in this study represent the total energy requirements in equivalent electrical energy values across the different stages of hydrogen supply chain. In this study, the techno-economic evaluation (TEE) was performed for HECs transportation from Qatar to the Asia-Pacific and European markets. The TEE method in this study has an estimated error of ±10%, reflecting uncertainties in capital expenditure (CAPEX) and operating expenditure (OPEX) due to regional and technological variations. This range aligns with industry practices for techno-economic evaluations at the conceptual design stage. Also, the accuracy of ±10% in this study is based on energy calculations performed using Aspen HYSYS, a simulation platform that provides precise thermodynamic modeling and process simulation. Unlike generalized cost-function methods, such as the Guthrie method, which has an accuracy of ±30% for broad feasibility studies in Ref. [35,36]. The approach in this study inherently reduces uncertainties and supports the narrower accuracy range. This margin provides a reliable comparative basis for analyzing HECs within a reasonable range of precision, supporting strategic decision-making.

2.2.1. Technical and economic parameters

For the TEE, the transportation distance from Qatar (Ras Laffan port) to the target countries was estimated at a vessel speed of 15 knots (as a low conservative value similar to that of oil tankers [37]). Then, after careful examination of the data available in the literature about the energy consumption, costs, and CO_2 intensity of each stage in the supply chain, conservative input parameters were used in the assessment process, which are listed in Table 3. The TEE of the HECs are carried out at a baseline hydrogen production capacity of 600 TPD. SMR with carbon capture technology is considered for the hydrogen production stage and the energy consumption of the CO_2 capture process has been fully accounted in the analysis. For the production stage, the SEC was calculated based on natural gas consumption used to drive the hydrogen production and carbon capture processes.

2.2.2. Modeling equations

This section presents the modeling equation to assess the various pathways. The three parameters including specific energy consumption (SEC), levelized cost of H_2 (LCOH), and CO_2 emission intensity are investigated to assess each step of the hydrogen supply chain. For the H_2 production, SMR integrated with carbon capture (CC) is assumed in this study. The SEC for the production of H_2 is calculated based on the amount of natural gas consumed for H_2 production and CO_2 capture. Eqs. (8)–(10) are considered to evaluate the effect of CC on the capital expenditure (CAPEX), operating expenditures (OPEX) and CO_2 intensity [3,38,39,42]. CO_2 intensity is defined as the amount of CO_2 emissions per kilogram of hydrogen produced, accounting for emissions from each stage and energy inputs. In addition to these parameters, other correlations and parameters were used to complete the TEE model of the supply chain, which are presented in the supplementary data (Appendix A) [3]. Appendix shows the detailed steps for the development process of these correlations.

Table 3
Technical and economic parameters of the HECs from the production to the storage and loading stage [38-41].

Stage	Parameter	Unit	Value
Production	Capacity of plant	TPD	600
	Feedstock (natural gas)	GJ/kg-H_2	0.12
	Fuel (natural gas) for heating process	GJ/kg-H_2	0.10
	Capacity factor[a]	%	90
	Lifetime of plant	years	25
	Discount rate[c]	%	10
	Price of electricity [38]	US$/MWh	58
	Fuel price[a] [38]	US$/MWh	16
Conditioning	Capacity of LH_2 and NH_3 plants	TPD	600 and 3300
	Capacity factor	%	100
	Lifetime of plant	years	30
	Equivalent CO_2 intensity[c]	Kg-CO_2/kWh	0.544
Loading and storage	Storage duration[b,d]	days	15
	Specific volume of LH_2	m^3/kg-H_2	0.014
	Specific volume of NH_3	m^3/kg-NH_3	0.0015
	Boil-off rate[d]	%/day	0.10
	Electricity consumption for LH_2	kWh/kg-H_2	0.198
	Electricity consumption for NH_3	kWh/kg-H_2	0.080
	Storage tank size for LH_2	m^3/tank	3500
	Storage tank size for NH_3	m^3/tank	50000
	Storage tank cost for LH_2	Million US $/tank	9.95
	Storage tank cost for NH_3	Million US $/tank	66.30
Shipping	Capacity for LH_2	m^3/ship	80000
	Capacity for NH_3	m^3/ship	85000
	Boil-off rate for LH_2	%/day	0.2
	Vessel speed	Knots	15
	Loading/unloading time	days	4
	Cost of carrier fuel	US$/ton	436
	Total port fees	US$	97000
	Total passage fees[e]	US$	291684
	Ship hiring cost[e]	US$/voyage day	90300
Unloading and storage	Boil-off rate[d]	%/day	0.10
	Electricity consumption for LH_2	kWh/kg-H_2	0.182
	Electricity consumption for NH_3	kWh/kg-H_2	0.080
	Size of LH_2 storage tank	m^3/tank	3500
	Size of NH_3 storage tank	m^3/tank	50000
Reconditioning [40,41]	Electricity consumption for LH_2	kWh/kg-H_2	0.20
	CAPEX of H_2 regasification	Million US $/TPD	0.07
	OPEX of H_2 regasification	% From CAPEX	4
	NH_3 cracking plant capacity	Ton-NH_3/h	120
	Cracking ratio of NH_3	%	99.9
	Electricity consumption for NH_3	kWh/kg-NH_3	0.40
	CAPEX of NH_3 cracking	Million US $/TPD	0.63
	OPEX of NH_3 cracking	% From CAPEX	4
Distribution [40,41]	Maximum LH_2 pipeline capacity	TPD	600
	Maximum capacity for NH_3	TPD	3300
	Transportation distance	km	200
	Lifetime of pipeline	years	40
	Lifetime of compressor	years	10
	CAPEX of pipeline	Million US $/cm/day	0.31
	OPEX of pipeline	% From CAPEX	0.00001

[a] The capacity factor represents the ratio of the actual output of a facility to its maximum possible output over a specific period, typically expressed as a percentage.

[b] The storage duration is assumed as typical for both loading and unloading terminals. This assumption aligns with industry norms to ensure operational continuity and buffer capacity for hydrogen energy carriers.
[c] For all stages.
[d] For both loading and unloading terminals.
[e] For European countries.

$$CAPEX_{H2,generation}[million\ US\$] = Plant\ capacity\ [TPD] \times [1.014 + 0.0142 \times CC[\%]] \quad (8)$$

$$OPEX_{H2,generation}[million\ US\$ / year] = Plant\ capacity\ [TPD] \times \{0.0493 + 0.0043 \times CC[\%] \quad (9)$$

$$CO_2\ Intensity_{H2,generation}\left[\frac{kg_{CO_2}}{kg_{H_2}}\right] = 10.63 - 0.0467 \times CC[\%] \quad (10)$$

For the conditioning process (liquefication for H_2 and synthesis for other energy carriers), SEC and CAPEX are calculated using Eq. (11) and Eq. (12), respectively [38];

$$SEC_{H2,liquefaction}\left[\frac{kWh}{kg_{H_2}}\right] = 13.92 \times (plant\ capacity\ [TPD])^{-0.1} \quad (11)$$

$$CAPEX_{H2,liquefaction}[\ million\ US\$] = 9.3 \times (plant\ capacity\ [TPD])^{0.8} \quad (12)$$

The amount of storage tanks for the loading process is determined using Eq. (13) [3,83];

$$Number\ of\ Storage\ tanks = \frac{Specific\ volume\ \left[\frac{m^3}{kg}\right] \times plant\ capacity\ [TPD] \times 10^3 \times storage\ duration[days]}{Single\ tank\ capacity\ [m^3]} \quad (13)$$

The cost of H_2 shipping can be calculated using Eq. (14) [3,83];

$$Shipping\ cost\ \left[\frac{US\$}{kg_{H_2}}\right] = 0.0000286 \times shipping\ distance\ [km] + 0.158 \quad (14)$$

Similarly, the transportation cost of the pipelines is determined using Eq. (15);

$$Pipeline\ cost\ \left[\frac{US\$}{kg_{H_2}}\right] = 0.00022 \times transporation\ \ distance\ [km] + 0.00564 \quad (15)$$

The SEC of the overall chain can be calculated using Eq. (16) [3,83];

$$SEC = \sum_{r=a}^{r=g} \left[\frac{Energy\ input}{Delivered\ H_2}\right]_r \quad (16)$$

where r is the stage of pathway (a = production, b = conditioning (liquefication or synthesis), c = loading, d = shipping, e = unloading, f = reconditioning, and g = distribution).

Levelized cost of H_2 ($LCOH$) can be determined using Eq. (17);

$$LCOH = \sum_{r=a}^{r=g} \left[\frac{\sum_{t=1}^{n} (CAPEX_t + OPEX_t)(1+i)^{-t}}{\sum_{t=1}^{n} P_{H_2}(1+i)^{-t}}\right]_r \quad (17)$$

where t denotes the year. Depending on the lifespan, the beginning year of operation is regarded as 1, and the last year is regarded as n. i is the discount rate and P_{H_2} is the annual quantity of H_2 delivered.

CO_2 intensity of the overall process can be calculated using Eq. (18) [3];

$$CO_2\ intensity = \sum_{r=a}^{r=g} \left[\frac{\sum CO_2\ emissions}{Delevered\ H2}\right]_r \quad (18)$$

2.3. Strengths–weaknesses–opportunities–threats (SWOT) analysis

The aim of this analysis is to examine the internal and external environment of various hydrogen energy carriers (HECs) for the hydrogen economy in Qatar using the strengths–weaknesses–opportunities–threats (SWOT) analytical method. Based on the findings, the strategies for promoting the development of the HECs in Qatar will be prioritized. The suggested approach is general in nature and, depending on a number of variables, is also applicable to the analysis of the HECs in other parts of world.

2.3.1. SWOT framework

The Strengths–Weaknesses–Opportunities–Threats (SWOT) analytical method is widely employed for strategy formulation, serving as a critical tool for understanding the current situation of the subject under study and for designing future strategies to address existing challenges. SWOT analysis helps identify the strengths (factors to capitalize on and enhance), weaknesses (areas requiring assistance and improvement), opportunities (areas to exploit for advantages), and threats (factors that may impede the object's development) of the subject being analyzed. Strengths and weaknesses are internally determined factors, while opportunities and threats are dictated by external forces.

SWOT analysis provides a structured framework for identifying strengths, weaknesses, opportunities, and threats associated with hydrogen energy carriers (HECs). While useful for preliminary strategic analysis due to its simplicity and ability to summarize complex scenarios, SWOT is inherently semi-quantitative and influenced by subjective assessments. The approach relies on current perceptions and qualitative judgments, which introduces a level of subjectivity into the findings. Despite these limitations, the method remains widely utilized in strategic evaluations across various sectors. As summarized in Table 4, previous studies in the energy field have primarily adopted a qualitative approach, often focusing on single energy carriers. In this research, a comparative analysis of multiple HECs is presented, integrating quantitative data such as specific energy consumption (SEC),

Table 4
Summary of the previous SWOT and MCDM studies on HECs.

Author [Reference]	Year	Carrier	Scope	Method	Categories	Criteria/ Indicators
Aba et al. [45]	2024	H_2	Compares both carriers and their technologies for H_2 economy	SWOT	Energetic, technical, and environmental	4
Ishaq et al. [46]	2024	NH_3	Accelerate decarbonization using sustainable approaches	SWOT	Energetic, safety and cost	6
Yilmaz et al. [47]	2024	H_2	H_2 energy development	SWOT	Technical, social, economic and environmental	17
Yap et al. [48]	2024	H_2	Transitions to a H_2 economy	Survey and Delphi	Technical, public acceptance and economic	5
Hjeij et al. [49]	2023	H_2	Competitiveness index of countries for H_2 export	MCDM (AHP)	Resources, economic, political and regulatory status	21
Al-Breiki et al. [50]	2023	NH_3	Roadmap to an ammonia economy	Survey and SWOT	Technical, social, economic and environmental	4
Khan et al. [51]	2023	H_2	Existing problems and future scenarios of H_2 economy	SWOT	Technical, social, economic and environmental	32
Rahimirad et al. [52]	2023	H_2	Strategies for developing policies for green H_2	SWOT and MCDM	Technical, social, economic and environmental	35
Ren et al. [53]	2023	H_2	Strategies for promoting H_2 economy	PESTEL and SWOT	Technical, social, economic and environmental	12
Bednarczyk et al. [54]	2022	H_2	Analysis of the sources of financing for the H_2	SWOT/TWOS	Technical and economic	17
Oner et al. [9]	2022	LOHC	Development of a multicriteria decision support tool for evaluation	Two MCDM methods	Technology, safety, environmental and economic	9
Al-Haidous et al. [55]	2022	LNG	Risks associated with the LNG supply chain are categorized	SWOT	Political and regulatory, safety and security, environmental	4
Li et al. [56]	2022	H_2	Systemic strategies and a policy framework for green H_2	Delphi and SWOT	Strategic, policy and technology levels.	3
Okonkwo et al. [57]	2021	H_2 and NH_3	Decision-making framework is presented for H_2 production and exportation	Weighted average	Technical, economic and environmental	3

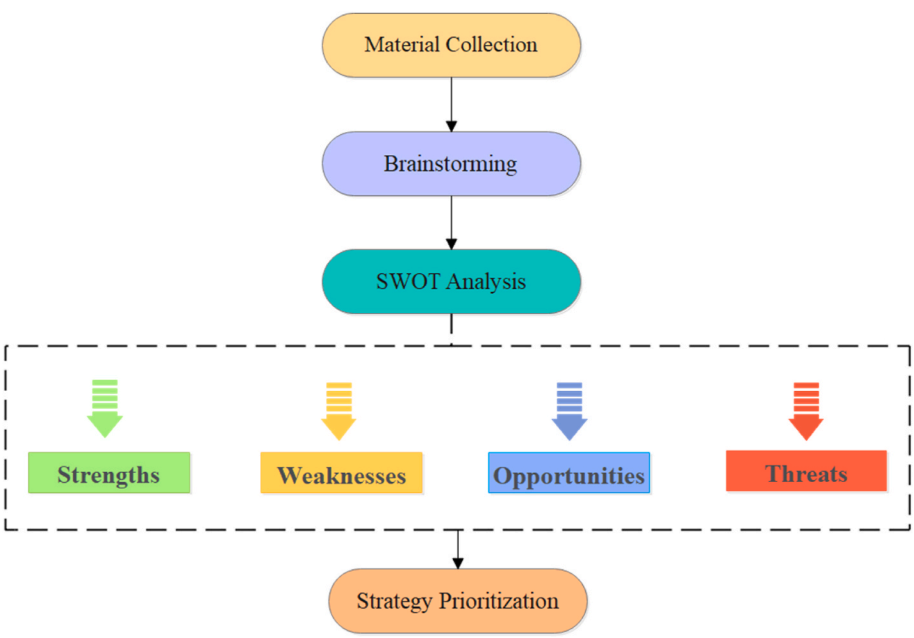

Fig. 2. The framework of SWOT method.

capital and operational costs, and safety considerations. Although the analysis incorporates these quantitative metrics to enhance rigor, it should be understood as a semi-quantitative assessment aimed at providing initial strategic insights.

Several alternative methods offer different perspectives for strategic evaluation. Political, economic, social, technological, legal and environmental (PESTEL) analysis, for example, examines external factors that impact the development and feasibility of technologies. Although PESTEL is effective at analyzing the broader regulatory and market landscape, it does not account for internal operational metrics as comprehensively as SWOT [43]. Multi-criteria decision analysis (MCDA) provides a more rigorous, quantitative assessment by assigning weights to various criteria to objectively rank alternatives [44]. However, MCDA requires extensive data and complex modeling, which may be impractical for emerging technologies where data availability is limited. Despite these limitations, MCDA can be highly effective when datasets are available. Therefore, SWOT remains a practical choice for initial evaluations of HECs, particularly when the goal is to understand both internal strengths and weaknesses and external opportunities and threats. The analysis is informed by quantitative data, enhancing the framework's utility while acknowledging its inherent subjectivity. The selection of SWOT, therefore, strikes a balance between accessibility and strategic insight, serving as a valuable tool for early-stage comparative analysis.

When employing the SWOT method to assess different HECs, the initial step involves gathering and synthesizing internal and external factors that could impact the advancement of Qatar's hydrogen economy. This process is facilitated through a comprehensive literature review, encompassing regulations, reports, academic papers, legislative documents, and statistical data relevant to the research topic. The methodology comprises four distinct stages, illustrated in Fig. 2.

In the first step, Materials Collection, the focus lies on gathering pertinent data and resources related to the research topic. This includes a wide array of supplementary materials such as regulations, reports, academic literature, papers, official documents, legislations, and national statistics, all aimed at providing a comprehensive foundation for the study. Moving to Step 2, Brainstorming, the objective shifts towards structuring a framework to identify key factors pertaining to strengths, weaknesses, opportunities, and threats. This stage facilitates the formulation of strategies aimed at enhancing the status of the subjects under investigation. Step 3 involves the SWOT Analysis, where the outcomes from the preceding step are utilized to scrutinize and delineate the factors encompassing strengths, weaknesses, opportunities, and threats. Leveraging the SWOT analytical method, this phase provides a systematic approach to evaluating the internal and external dynamics impacting the research subject. Finally, Step 4, Strategy Prioritization, entails synthesizing effective strategies based on the identified strengths, weaknesses, opportunities, and threats. Through brainstorming sessions, strategies are devised to optimize strengths and opportunities while mitigating weaknesses and threats, ultimately guiding the course of action.

2.3.2. Application of SWOT analysis for various HECs

The utilization of SWOT analysis can offer stakeholders and decision-makers valuable insights into the existing state of the hydrogen economy in Qatar, enabling them to formulate strategic initiatives to foster its growth. By adhering to the SWOT methodology outlined in section 2.3.1, this approach systematically identifies key factors pertaining to strengths, weaknesses, opportunities, and threats, as illustrated in Fig. 3. This structured framework empowers stakeholders to assess the internal and external landscape comprehensively, facilitating informed decision-making and the development of targeted strategies to advance the hydrogen economy in Qatar.

Based on the above key factors, each stage of various pathways is analyzed for ranking the various carriers. In this study, quantitative ranking is taken on a scale of 1–4 (1 as low, 2 as medium, 3 as strong and 4 as high) from the obtained values of TEE and also from the open literature. For the technical key factors (Specific energy consumption, cost, CO_2 emissions, capacity and Technology readiness level), data from the results of TEE is taken for ranking from 1 to 4 based on low to high values of respective factors. However, for the other key factors (Infrastructure, social acceptance, applications, government support, safety and toxicity, regulation and standards, and lifetime), ranking for the decision matrix is done based on the various scholarly papers, government reports, annual reports of the various companies such as Qatar Fertilizer Company (QAFCO), Qatar Chemicals (QChem) and Qatar Fuel Additive Company (QFAC). From these reports, authors have investigated the internal and external influences and ranked them on scale of 1–4 based on the impact as HECs to analyze Qatar's hydrogen economy. The detailed selection of the weights for the TEE and SWOT analysis is presented in Section 3.1 and 3.2, which is part of the results and discussion section, to ensure transparency and reinforce the robustness of the analysis. Each key stage of the HEC supply chain is systematically evaluated using a structured framework, combining quantitative data from the TEE with qualitative insights from literature and industry reports. This comprehensive approach ensures that the analysis is well-supported and suitable for prioritizing viable HEC options within the context of Qatar's hydrogen economy.

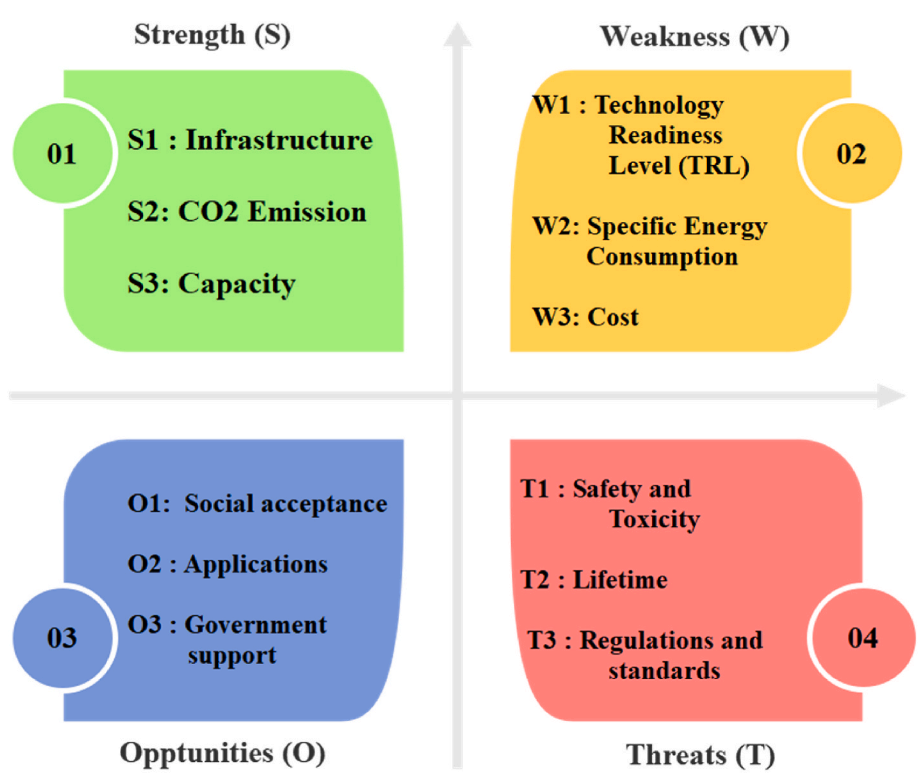

Fig. 3. Key factors of SWOT analysis.

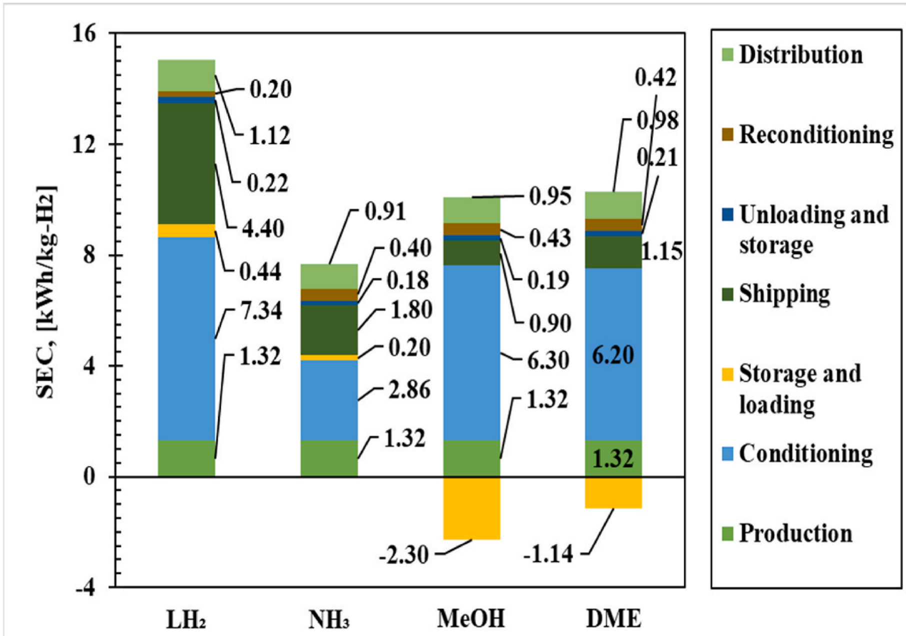

Fig. 4. Specific Energy Consumption (SEC) for all seven stages of H_2 pathways for LH_2, NH_3, MeOH and DME.

3. Results and discussion

The techno-economic evaluation (TEE) conducted in this study encompasses an assessment across three key indicators which include the specific energy consumption (SEC), levelized cost of hydrogen (LCOH), and CO_2 intensity of all four HECs (H_2, NH_3, MeOH and DME). Within the TEE framework, strategies to enhance these indicators and reduce LCOH for the most optimal pathway are outlined and analyzed. Furthermore, leveraging the insights derived from the TEE results, a quantitative SWOT analysis is undertaken. Subsequent sections delve into the detailed examination and discussion of the TEE findings, evaluating these indicators at each stage to pinpoint potential areas for enhancement (Section 3.1). Following this, the pathways undergo a SWOT analysis in Section 3.2, facilitating a comprehensive understanding of their strengths, weaknesses, opportunities, and threats.

3.1. Techno-economic evaluation

The results of TEE are presented in terms of performance parameters i.e. SEC, LCOH, and CO_2 intensity of various pathways in this section. The SEC of various pathways is illustrated in Fig. 4. It is estimated using equations defined above and input data from the literature [3,58,59]. The conditioning (liquefication and synthesis) and shipping phase have the maximum SEC compared to all other stages in the LH_2 route shown in Fig. 4. SEC for the shipping and liquefaction are 4.40 kWh/kg of H_2 and 7.34 kWh/kg of H_2, respectively. The main causes of this are the -253 °C temperature at which H_2 turns into a liquid and the significant losses incurred from H_2 boil-off during LH_2 transportation. Similar to this, the SEC of ammonia synthesis in the NH_3 process is 2.86 kWh/kg of H_2. Methanol and DME have corresponding SEC of 6.30 kWh/kg of H_2 and 6.30 kWh/kg of H_2 for methanol and DME synthesis. The negative SEC values observed in Fig. 4 for MeOH and DME for storage and loading processes represent net energy recovery or offsets that occur during certain stages. These values indicate that, under specific conditions, the process generates excess energy or utilizes heat recovery systems that reduce the overall energy consumption. The total SEC of the LH_2 approach is greater than the other methods during the whole procedure. NH_3 has a total SEC of 7.67 kWh/kg of H_2, which is less than that of other HECs. As a result, compared to the LH_2 technique, the operational costs of other methods most notably NH_3 are significantly cheaper. This shows that for LH_2 to become competitive with the other routes, improvements in reducing its energy usage are necessary.

The LCOH of various energy carriers is illustrated in Fig. 5. It is calculated using Eq. (10) and input data from the literature [3,58,59]. The LCOH for LH_2, DME, and MeOH is US$ 5.17, 7.51, and 6.52 per kg of H_2, respectively, all of which are higher than the LCOH for the NH_3 pathway, which is US$ 4.76 per kg of H_2. It should be noted that conditioning and reconditioning processes are the primary cost drivers in the LCOH for MeOH and DME. Interestingly, although the NH_3 pathway has a lower LCOH, the difference in LCOH between the NH_3 and LH_2 pathways is smaller than the difference in their specific energy consumption (SEC). This is largely due to the reconditioning costs: while LH_2 requires regasification, which is relatively inexpensive, NH_3 must undergo cracking to release H_2, adding significant expense. Given current technology limitations, directly using NH_3 as a fuel in thermal power plants and the transportation sector remains impractical due to challenges with low combustion efficiency and high NO_x emissions, which would need to be addressed for broader adoption.

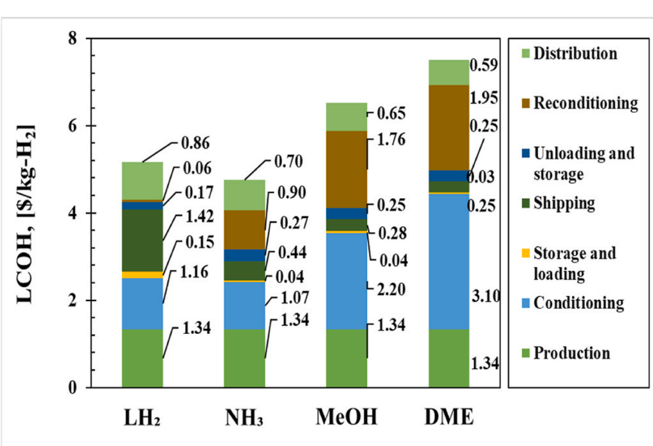

Fig. 5. Levelized cost of Hydrogen for all seven stages of H_2 pathways for LH_2, NH_3, MeOH and DME.

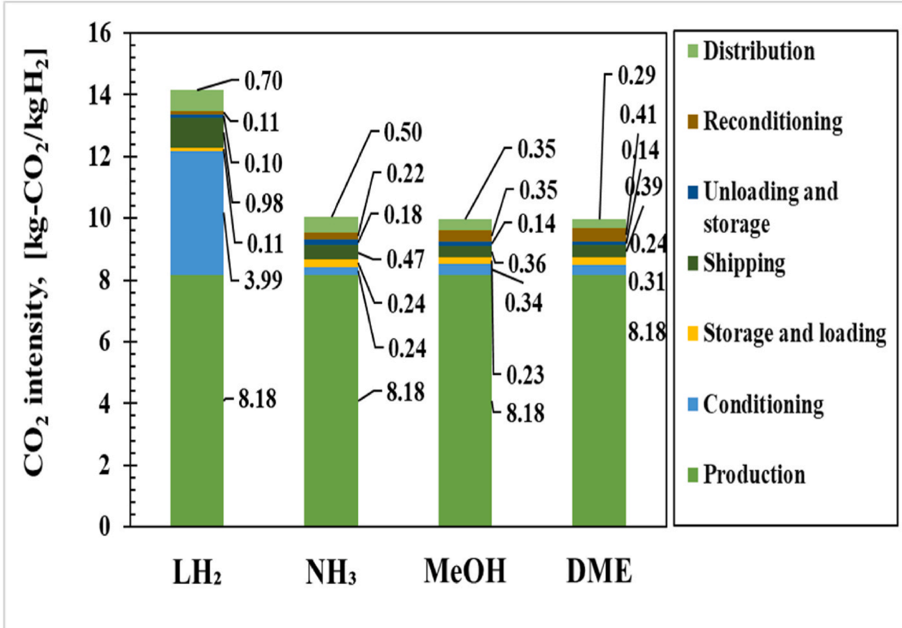

Fig. 6. CO_2 intensity for all seven stages of H_2 pathways for LH_2, NH_3, MeOH and DME.

Table 5
Improvement measures for the reduction in LCOH for NH_3 pathway.

Stage	Measures	Current Cost (US $/kg.$H_2$)	Future cost (US $/kg.$H_2$)	References
Production	Integrating the SMR, supercritical carbon dioxide (sCO2) power cycle and pressure swing adsorption (PSA)	1.34	1.10	[60,61]
Conditioning		1.07	0.71	
Shipping	NH_3 as a primary fuel including the BOG losses from NH_3 storage tankers.	0.44	0.31	[62]
Storage and loading	Invested CAPEX for the LNG terminal can be repurposed for NH3	0.04	0.02	[63]
Unloading and storage		0.27	0.13	
Distribution		0.70	0.35	

About 52% of the carbon emissions in the SMR process used to produce hydrogen are produced at the reactor unit, and 33% are produced at the reformer step [38]. Consequently, using Eq. (11) to compute the CO_2 intensity of the all HECs at a carbon capture fraction of 52% is shown in Fig. 6. It can be seen from the figure that the maximum CO_2 intensity is 8.18 kg of CO_2/kg of H_2 for the production stage, which is greater than other processes since SMR is used for generation of H_2. Moreover, because the hydrogen liquefaction process requires a substantial quantity of energy, its CO_2 intensity is 3.99 kg of CO_2/kg of H_2. However, the CO_2 intensity of the LH_2 route would decrease if the HLP was fueled by a renewable energy source that produced zero CO_2 emissions. The CO_2 intensity of the DME and MeOH routes is 9.96 kg of CO_2/kg of H_2 and 9.95 kg of CO_2/kg of H_2, respectively, which is lower than the other pathways.

From the above investigation, it is clear that the NH_3 energy carrier has SEC, LCOH, and CO_2 intensity lower in comparison to the other pathways. Further, this LCOH can be reduced more by adopting advancement measures for NH_3 pathway. Some of the measures proposed in the literature to mitigate the LCOH of NH_3 pathway are summarized in Table 5.

After incorporating the improvement measures given in Table 5 to the TEE of the NH_3 pathway as shown in Fig. 5, the LCOH will be decreased by 15.3% from 4.76 to 3.52 US$/kg of H_2 as shown in Fig. 7.

3.2. SWOT analysis and prioritization

In this section, a comprehensive SWOT analysis is systematically conducted across key stages of the HECs supply chain, providing a structured framework for prioritizing viable options. Each stage is evaluated based on specific criteria, including SEC, CO_2 emissions, capital and operating expenditures (CAPEX and OPEX), infrastructure availability, and safety standards, with rankings assigned on a 1–4 scale. These rankings are derived from insights gained in the techno-economic evaluation (Section 3.1), as well as supporting literature, industry reports, and government documents, ensuring a thorough assessment of each HECs. A detailed analysis and justification of each stage is provided in the subsections below.

3.2.1. Production

Hydrogen energy carriers (HECs) including H_2, NH_3, MeOH, and DME can be produced using various thermochemical, electrochemical, or biological methodologies [12,64-66]. The choice of production method primarily hinges on several factors, including the existing infrastructure, feedstock availability, system production capacity, and technology readiness level (TRL) [65]. Natural gas (NG) is abundant in many gas-exporting nations and it serves as a viable feedstock hydrogen production using steam methane reforming (SMR), autothermal reforming (ATR) and partial oxidation (POX). Among these, SMR stands out as an immediately scalable method, availability of existing infrastructure and well-developed technology with a Technology Readiness Level (TRL) of 9 [39,57,67]. Hence, SMR provides a direct pathway for large-scale H_2 production in Qatar. However, insights from the TEE reveal that the SMR process results in CO_2 emissions approximately 6–8 times greater than those of renewable energy-based electrolysis. Thus, integrating carbon capture with this process becomes imperative. Notably, within the SMR process, over 52% of CO_2 emissions arise during the reactor stage, with an additional 33% emanating from the reformer [68]. Therefore, SMR integrated with carbon capture (CC) is assumed in this study for the H_2 production. Hence, ranking on scale of 1–4 is allotted in Tables 6–9 based on the results of TEE from section 3.1 and literature survey according to the SMR process.

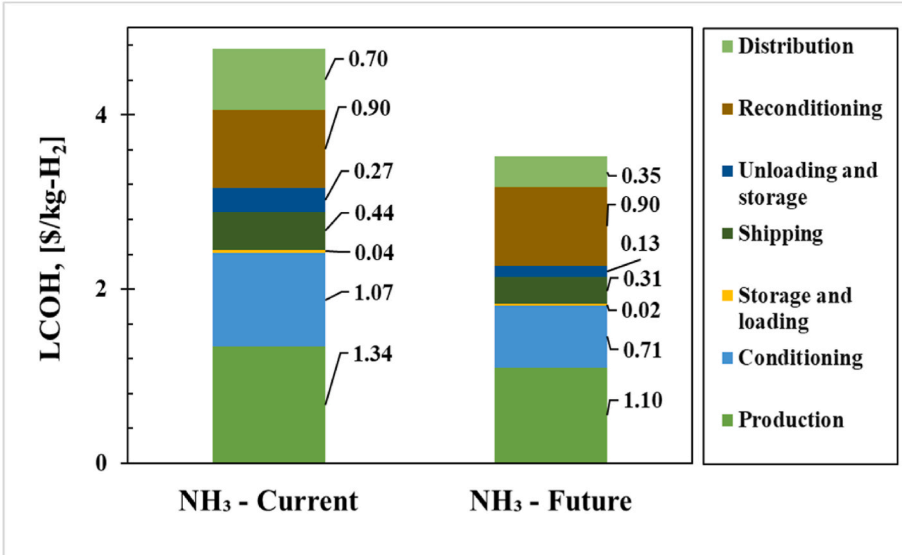

Fig. 7. Comparison between current and future reduced LCOH of the NH_3 pathway.

Table 6
Strength ranking of various HECs.

Strength	LH_2			NH_3			MeOH			DME		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
Production	4	1	4	4	1	4	4	1	4	4	1	4
Conditioning	2	1	3	4	4	4	1	2	1	1	3	1
Storage and loading	2	3	3	3	1	4	1	2	1	1	1	1
Shipping	2	1	3	3	2	4	1	4	1	1	3	1
Unloading and storage	2	3	3	3	1	4	1	2	1	1	2	1
Reconditioning	2	4	3	4	3	4	1	2	1	1	1	1
Distribution	2	1	3	3	2	4	1	3	1	1	4	1
Sum	16	14	22	24	14	28	10	16	10	10	15	10
	52			66			36			35		

S1 = Infrastructure, S2=CO_2 emissions and S3 = Production Capacity.

Table 7
Weakness ranking of various HECs.

Weakness	LH_2			NH_3			MeOH			DME		
	W1	W2	W3	W1	W2	W3	W1	W2	W3	W1	W2	W3
Production	4	4	3	4	4	3	4	4	3	4	4	3
Conditioning	3	1	3	4	4	4	2	2	2	2	3	1
Storage and loading	2	1	1	4	3	4	2	4	4	2	4	3
Shipping	3	1	1	4	3	2	2	4	3	2	3	4
Unloading and storage	3	1	4	4	4	2	1	4	3	1	2	3
Reconditioning	3	4	4	4	3	3	1	1	2	1	2	1
Distribution	3	1	1	4	4	2	1	3	3	1	2	4
Sum	21	13	17	28	25	20	13	22	20	13	20	19
	51			73			55			52		

W1 = Technology readiness level (TRL), W2 = Specific energy consumption (SEC) and W3 = Cost.

3.2.2. *Conditioning (Liquefication and synthesis)*

In the conditioning stage, hydrogen liquefication process is considered for hydrogen pathway and for other carriers it is considered as synthesis of NH_3, MeOH and DME. The H_2 liquefication process involves cryogenics to liquefy hydrogen, reducing its temperature from near ambient levels to below -253 °C. [1]. However, the hydrogen liquefication process stands out as the most energy-intensive process within the LH_2 pathway, a fact underscored by the specific energy consumption (SEC) depicted in Fig. 1. Consequently, the viability of the hydrogen liquefication process is primarily contingent upon the need to transport substantial quantities of hydrogen across considerable distances [19]. From the TEE of the H_2 liquefaction process (Section 3.1), it can be also seen that CO_2 emissions of this process is also high based on real time data of commercial H_2 liquefication process plants. However, due to the mature infrastructure and TRL [69], its cost is comparatively lower than MeOH and DME but it is bit higher than NH_3 conditioning.

Ammonia (NH_3) presents itself as a promising hydrogen carrier for large-scale transportation due to several key factors. Firstly, its higher boiling temperature simplifies storage and transportation compared to hydrogen. Secondly, existing infrastructure for NH_3 storage and transportation reduces implementation barriers. Lastly, despite requiring energy for synthesis, specific energy consumption of NH_3 is lower than that of hydrogen liquefaction [70,71]. Methanol and dimethyl ether (DME) are also viable HECs, offering distinct advantages. Its synthesis

Table 8
Opportunities ranking of various HECs.

Opportunities	LH_2			NH_3			MeOH			DME		
	O1	O2	O3	O1	O2	O3	O1	O2	O3	O1	O2	O3
Production	2	3	3	2	3	3	2	3	3	2	3	3
Conditioning	2	3	2	3	3	3	1	1	1	1	1	1
Storage and loading	2	3	2	3	3	3	1	1	1	1	1	1
Shipping	2	3	2	3	3	3	1	1	1	1	1	1
Unloading and storage	2	3	2	3	3	3	1	1	1	1	1	1
Reconditioning	2	3	2	3	3	3	1	1	1	1	1	1
Distribution	2	3	2	3	3	3	1	1	1	1	1	1
Sum	14	21	15	20	21	21	8	9	9	8	9	9
	50			62			26			26		

O1 = Social acceptance, O2 = Applications and O3 = Government support and policies.

Table 9
Threats ranking of various HECs.

Threats	LH_2			NH_3			MeOH			DME		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Production	3	4	4	3	4	4	3	4	4	3	4	4
Conditioning	3	4	3	2	4	4	3	3	2	3	2	2
Storage and loading	3	3	3	2	3	4	3	3	2	3	2	2
Shipping	3	3	3	2	4	4	3	3	2	3	3	2
Unloading and storage	3	4	3	2	4	4	3	3	2	3	2	2
Reconditioning	3	4	3	2	4	4	3	3	2	3	2	2
Distribution	3	4	3	2	4	4	3	3	2	3	2	2
Sum	21	26	22	15	27	28	21	22	16	21	17	16
	69			70			59			54		

T1 = Safety and Toxicity, T2 = Plant/Equipment Lifetime and T3 = Regulations and standards.

involves the reforming of natural gas or biomass, producing hydrogen as a byproduct, making it a versatile and readily available option. DME, on the other hand, boasts higher energy density than methanol and can be produced from various sources, including natural gas, biomass, or even CO_2 and hydrogen [64,33]. Its physical properties, such as being a gas at room temperature but easily liquefied under modest pressure, make it suitable for storage and transport. Both methanol and DME offer advantages in terms of lower flammability compared to hydrogen and can be utilized in fuel cells or internal combustion engines with minimal modifications. However, challenges include the need for carbon capture and storage to mitigate emissions from their production processes, as well as infrastructure development for widespread adoption [38,39,72].

Since 1973, Qatar has been producing ammonia (NH_3) through the QAFCO. The process involves converting natural gas into hydrogen (H_2), which then reacts with nitrogen (N_2) to produce NH_3 using the Haber-Bosch process [50]. The widely used Haber-Bosch process facilitates ammonia production, albeit with high energy demands. Operating at pressures of 15–30 MPa and temperatures of 300–600 °C, this process achieves fractional conversion rates per pass of 10%–30%. To maintain high overall efficiency, a loop-mode operation is employed, with NH_3 continuously removed while fresh gases are introduced. However, ammonia's lower hydrogen purity can pose challenges in applications that require high-purity H_2, unlike LH_2 which meets such requirements more readily. For large-scale production, Ras Laffan, Qatar, is assumed as the hydrogen production site. NH_3 or LH_2 can then be transported directly to nearby storage units, minimizing transport distance. In Qatar, methanol and dimethyl ether (DME) are primarily synthesized from abundant natural gas reserves. Methanol production involves steam reforming of natural gas to create synthesis gas, which is then converted into methanol. Major companies like Qatar fuel additives company (QAFAC) and Qatar chemical company (Q-Chem) operate large methanol facilities for global export. Similarly, DME synthesis starts with syngas production from natural gas, followed by methanol dehydration. Qatar's interest in these compounds stems from efforts to diversify energy sources and reduce carbon emissions. Research focuses on enhancing production efficiency and sustainability, including exploring carbon capture and utilization technologies. Qatar's investments in downstream industries also support methanol and DME synthesis, aligning with the country's energy transition objectives [73-75].

Similarly, based on the results of TEE from section 3.1 and above literature facts, ranking on scale of 1–4 is allotted in Tables 6–9.

3.2.3. Loading, shipping, and unloading processes

In all the HECs, the output from the conditioning stage is temporarily stored at the loading terminal before being loaded onto ships for transportation. Upon arrival at the receiving terminal, LH_2, NH_3, MeOH or DME is unloaded into temporary storage tanks prior to the reconditioning stage.

LH_2 storage faces challenges due to its extremely low boiling point (−253 °C), resulting in significant boil-off losses despite well-insulated tanks. While research suggest using boil-off gas during voyages with advanced insulation, this practice remains unimplemented. Current LH_2 tank sizes (<6000 m^3) are insufficient for large-scale storage, although some studies suggest larger capacities at loading terminals. For conservative estimates, LH_2 storage capacities are assumed to be less than 6000 m^3 [3,76]. In contrast, NH_3 benefits from mature storage technology and a global distribution network, reducing storage costs compared to LH_2. NH_3 is commonly stored in steel vessels but requires cautious handling due to its toxicity and corrosiveness. It can be stored in liquid form at atmospheric pressure and -33 °C, medium pressure and mild temperatures, or compressed at low pressure for storage in existing LPG tanks. Leveraging existing infrastructure and regulations facilitates NH_3 adoption and significantly lowers storage costs compared to LH_2, according to studies [77,78].

Similarly, methanol (MeOH) and dimethyl ether (DME) present alternative options for energy storage and transportation [79,80]. Methanol benefits from existing infrastructure and higher boiling points, simplifying storage and transport. MeOH storage typically involves its synthesis from natural gas or biomass, with the resulting product stored in tanks. Unlike LH_2, methanol does not face extreme temperature challenges during storage, simplifying the process and reducing associated costs. However, cautious handling is still necessary due to its flammability. DME is synthesized from syngas, often derived from natural gas or biomass. It is stored in tanks and offers advantages such as higher energy density compared to methanol. Physical properties of DME allow for storage at moderate pressures, facilitating handling and storage in existing infrastructure. Both MeOH and DME benefit from established storage technologies and can leverage existing infrastructure for storage and transportation, contributing to cost savings compared to LH_2 [81]. However, considerations regarding flammability and handling safety remain important during storage and transportation processes [82].

Following the findings of TEE presented in Section 3.1 and considering the literature reviewed, rankings ranging from 1 to 4 have been assigned in Tables 6–9

3.2.4. *Reconditioning and distribution*

At the receiving terminal in LH_2, NH_3, MeOH, or DME pathways, further reconditioning processes are essential before delivering hydrogen or its derivatives to end-users. In the LH_2 pathway, compression and regasification processes enable H_2 transportation as a compressed gas through pipelines or tube trailers. Trailers typically transport H_2 at pressures ranging from 200 to 500 bar, with each trailer accommodating 300–1100 kg of hydrogen, the capacity varying based on the pressure vessel specifications. Tube trailers prove efficient for low-demand and short-distance scenarios, typically up to 160 km. Tanker trucks transporting LH_2 at longer distances provide greater cost-effectiveness due to higher density. However, challenges arise from storage losses, notably boil-off gas. Alternatively, pipelines appear as the most economically advantageous option for extended distances and high demand, notwithstanding the substantial initial investments required. Nevertheless, pipelines offer the advantage of low operational and maintenance costs, with lifetime up to 40 years [3]. NH_3 can be directly used as a fuel or through decomposition indirectly. Direct uses includes applications in internal combustion engines (ICE), residential heating and cooling, power generation, and fuel cell technology. Current research focus on energy extraction from NH_3, encompassing direct combustion, NH_3 fuel cells, co-combustion and NH_3 stations. In contrast, indirect utilization entails decomposition catalyzed at temperatures surpassing 800 °C and normal pressure, constituting a highly energy-intensive process due to its endothermic nature. NH_3 decomposition may be attained through electrolysis, requiring lower voltage compared to water electrolysis, or via thermal decomposition, leveraging the same catalyst employed for NH_3 synthesis [83].

MeOH and DME also offer alternative solutions for energy storage and transportation. MeOH, synthesized from natural gas or biomass, can be stored in tanks without facing extreme temperature challenges, simplifying storage processes and reducing associated costs. However, cautious handling is necessary due to its flammability. DME, derived from syngas, often from natural gas or biomass, is stored in tanks. It claims higher energy density than MeOH and can be stored at moderate pressures, facilitating handling and storage in existing infrastructure. Both MeOH and DME benefit from established storage technologies and can leverage existing infrastructure for storage and transportation, contributing to cost savings compared to LH_2. However, considerations regarding flammability and handling safety remain vital during storage and transportation processes [84].

Based on results of TEE outlined in Section 3.1 and informed by the literature discussed above, Tables 6–9 allocate rankings on a scale of 1–4.

From the above analysis of the ranking of strength, it can be seen that the overall ranking of the NH_3 is higher than other HECs. However, ranking for the CO_2 emissions, shipping and reconditioning of LH_2 is greater than other HECs. Similarly, from the analysis of the ranking of weakness, it can be noted that the TRL, SEC and cost of the MeOH and DME are even better than the LH_2 because the liquefication of H_2 is an energy intensive process as seen from the results of the TEE. For the opportunities part, it can be concluded that there are very less opportunities for the MeOH and DME due to the lack of existing infrastructure and government policies for these HECs. However, the LH_2 is ranked equally as of NH_3 for the applications due to the shift of fossil fuel economy. Lastly, for the threats, it can be seen that the ranking of the safety and toxicity is lower for the NH_3 in comparison to the other HECs because of its toxic nature. However, for the other factors in threats, NH_3 is much better and high ranked than other HECs due to its existing infrastructure and availability of the regulations and standards.

Overall, it can be concluded from the above Tables, NH_3 outperforms the other carrier in SWOT analysis as well. Therefore, NH_3 followed by LH_2 are the safer option in terms of various factors in SWOT compared to MeOH and DME energy carrier pathways.

However, end-use considerations are critical when evaluating the practical implementation of hydrogen energy carriers (HECs). For example, Proton exchange membrane fuel cells (PEMFCs), commonly used in transportation and stationary power applications, are highly sensitive to NH_3 contamination. Even trace amounts of NH_3 can poison the catalysts within PEMFCs, significantly reducing their performance and efficiency [85]. Therefore, purity requirements are necessary when using hydrogen generated from NH_3 based systems in PEMFC applications. This limitation must be considered when designing hydrogen supply chains intended for use with PEMFCs, as additional purification steps may be required. Moreover, the safety and handling of MeOH and NH_3 present significant concerns. Both substances are toxic, and exposure poses health risks to humans and environmental hazards. MeOH can cause severe poisoning if ingested or inhaled, while NH_3 is a hazardous gas that can cause respiratory distress and other health issues. To mitigate these risks, strict safety protocols must be followed. These carriers should be kept away from public areas and managed only by trained personnel equipped with proper safety gear. Safe transport and storage infrastructure must be in place to minimize the risk of accidental exposure or environmental release, particularly in urban or densely populated regions.

4. Conclusions

This paper investigates techno-economic evaluation (TEE) and SWOT analysis of four different hydrogen energy carriers (HECs) namely LH_2, NH_3, MeOH, and DME. Each energy carrier comprises of seven phases from production to distribution. The performance indicators of TEE are specific energy consumption (SEC), levelized cost of hydrogen (LCOH), and CO_2 emission intensity. For the SWOT analysis, quantitative rankings are assigned on a scale of 1–4 (1 being low, 2 as medium, 3 as strong, and 4 being high) based on both the acquired data from TEE and relevant literature. Technical key factors such as SEC, cost, CO_2 emission intensity, capacity, and TRL are ranked on a scale of 1–4 according to the respective factor's values, ranging from low to high as determined by TEE results. The SWOT analysis is performed to provide insight into the current state of the HECs in Qatar and to understand decision-makers about the challenges and opportunities of various modes of energy transportation. The main findings of this research are:

- For the TEE, NH_3 followed by LH_2 are the most cost-effective options compared to MeOH and DME energy carrier pathways.
- The total SEC of NH_3 option is 7.67 kWh/kg of H_2 which is 51% lower than LH_2 option.
- The overall LCOH for NH_3 pathway is 4.76 US$/kg of H_2, which can be reduced to 3.52 US$/kg of H_2 (reduced by 26%) by implementing new integrated cycles and repurposing of LNG technologies.
- NH_3 outperforms the other carrier in SWOT analysis followed by LH_2. These are more safe and sustainable options in terms of various factors in SWOT compared to MeOH and DME. NH_3 ranks highest overall among the HECs analyzed, while LH_2 excels in CO_2 emissions, shipping, and reconditioning.

- MeOH and DME exhibit better TRL, SEC, and cost rankings than LH_2 due to its energy-intensive liquefaction process. Limited opportunities exist for MeOH and DME, while NH_3 and LH_2 face different threats, with NH_3 rated lower in safety but stronger in other threat factors due to existing infrastructure and regulatory standards.
- The main reason for the low LCOH of NH_3 pathway is that for MeOH and DME pathways cost of conditioning and reconditioning stages is much higher.

In the future, research is required on the commercial feasibility of H_2 transportation for a sustainable H_2 economy. NH_3 options stand out as promising alternatives for sustainable transportation for the efficient H_2 economy. While these options may entail considerable initial capital investment but as transportation distances increase it may become suitable for long-distance transport needs.

CRediT authorship contribution statement

Laveet Kumar: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ahmad K. Sleiti:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Wahib A. Al-Ammari:** Writing – review & editing, Software, Formal analysis.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.03.125.

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