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Designing a sustainable hydrogen supply chain network in the Gulf Cooperation Council (GCC) region: Multi-objective optimisation using a Kuwait case-study

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ABSTRACT

Located in the Arabian Gulf, Kuwait is a renewable-abundant country ideal for producing hydrogen via solar energy (green hydrogen). With a global transition away from fossil fuels underway due to their adverse environmental impacts, hydrogen is gaining significant traction as a promising clean energy alternative for the transport sector. Despite this, there are still various challenges associated with implementing a hydrogen supply chain, particularly with regard to the conflicting objectives of minimising cost, environmental impact and risk. This study determines the feasibility of implementing a green hydrogen supply chain in Kuwait based on a multi-objective design, to determine which combination of production (electrolysis type), storage method and transportation method is the most optimal for Kuwait. Three objective functions were considered in this study: the hydrogen supply chain cost, environmental impact, and safety/risk. A mathematical formulation based on mixed integer linear programming (MILP) was used, involving a multi-criteria approach where the three considered objectives must be optimised simultaneously, i.e., cost, global warming potential and safety/risk. The multi-objective optimisation approach via the weighted sum method was applied in this study and solved via GAMS. To account for the ranking of multi-objective criteria, a hybrid AHP-TOPSIS approach was used. Results showed that medium and high demand scenarios better reflect the comparative advantages of each considered method in terms of their multi-objective trade-offs. In particular, it was found that higher hydrogen demand amplifies the impact of higher efficiency and operational savings within several production, storage and transportation methods, and that despite higher initial capital investments, these costs are at some point offset by superior operational efficiency as hydrogen production volumes increase. Conversely, using highly efficient electrolysers or transportation methods at low demand was found to limit their performance.

1. Introduction

As the agenda of low-carbon economies continues to gain global momentum, hydrogen is receiving significant attention as the potential replacement for conventional fossil fuels. 'Green' hydrogen specifically, which describes hydrogen powered entirely from renewable energy sources (such as solar and wind), has been subject to vast consideration due to its zero-emissions nature. Green hydrogen is produced via water electrolysis by using an electric current to split water into hydrogen and oxygen, with no resulting greenhouse gas (GHG) emissions [1]. As a result of these immense potential environmental advantages, several countries are actively investing in green hydrogen related policies and infrastructure, particularly in the Gulf Cooperation Council (GCC) region, which is widely known for its abundant solar resources.

Kuwait is already allocating substantial investments towards national clean energy deployment, with $ 6.3 billion worth of clean energy projects ongoing nationally since 2022 [2]. National plans have also been announced for Kuwait to reduce its carbon emissions by 7.4 % by 2035 (in a business-*as*-usual scenario), by harnessing the country's solar energy potential and improving efficiency to accommodate increasing demand [3]. According to the U.S. Energy Information Administration (EIA), Kuwait aims to source 15 % of its power supply, estimated at around 4.5 GW, from renewable energy by 2030, and is aiming to

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Abbreviations

GCC =	Gulf Cooperation Council
HSC =	Hydrogen Supply Chain
MILP =	Mixed Integer Linear Programming
TOPSIS =	Technique for Order of Preference by Similarity to Ideal Solution
AHP =	Analytic Hierarchy Process
MCDM =	Multiple Criteria Decision Making
PV =	Photovoltaic
GW =	Gigawatts
MW =	Megawatts
CF =	Carbon Footprint
GHG =	Greenhouse Gas
GWP =	Global Warming Potential
AEM =	Anion Exchange Membrane
PEM =	Proton Exchange Membrane
OPEC =	Organisation of the Petroleum Exporting Countries
IEA =	International Energy Agency

become entirely carbon-neutral by 2060 [3]. A key national motivator for exploring hydrogen is that, if green hydrogen is able to gain a considerable market share of clean energy, numerous economic and environmental advantages will be yielded. These advantages include meeting announced decarbonisation targets, as well as advantages in fuel generation. Currently, fuel in Kuwait is highly subsidised, with the International Energy Agency (IEA) forecasting a $3.64 billion increase in subsidies for fuel and petroleum products in Kuwait between 2023 and 2024 [4]. Although this is beneficial for keeping fuel prices low, subsidies over time may cause economic strains, particularly when carbon pricing and carbon tax for conventional fossil fuels start to become globally adopted. In this case, fuel generation via green hydrogen will aid in both avoiding carbon tax and lowering the subsidies for fuel.

Besides national securities, green hydrogen presents a highly attractive export opportunity for Kuwait. The Arabian Gulf is located centrally between Europe and Far-East Asian markets, giving the region a strategic location for international exports. Particularly, given Kuwait's proximity to the Strait of Hormuz-one of the world's most critical export passages where between 20 and 30 % of total global oil trade currently occurs [5] – in the event of a hydrogen economy, the export of green hydrogen could occur via the same trade route. However, despite green hydrogen's potential and Kuwait's cost-competitive solar resources, the construction of a sustainable supply chain network that includes production sites, storage facilities, and transportation options still presents a universal challenge. To fully compete with the fossil fuel economy, a strategic hydrogen supply chain (HSC) should consider all of cost-minimisation, environmental aspects, and safety. In the current literature, there are various papers assessing HSCs. Li et al. [6] for example, conducted a review of existing literature for modelling and optimising hydrogen supply chains. In their study, different models were classified based on their abilities for decision-making and optimisation in each stage of the hydrogen supply chain. It was found that most models followed a single objective, which was the minimisation of the total cost of the supply chain network. Almansoori and Shah [7] expanded on this issue and argued that total focus on cost optimisation could compromise other critical aspects of the supply chain, such as environmental impact and safety. Several works [6,8,9] have also addressed the issue of demand uncertainty. In Ref. [6], a key observation made was that in the majority of analysed supply chains, transportation links were installed between regions of lower hydrogen demand rather than constructing a new production facility, as this is universally cheaper. Although this helps with cost minimisation, the global warming potential (GWP) will be higher, and safety indexes lower, due to the increased risk of hydrogen combustion and leakage during transport [10]. This study aims to address the trade-offs between cost, environmental impact, and safety through the use of multi-objective optimisation and multi-criteria decision making (MCDM), discussed in Section 2. Elaborating on this work's choice of solar energy, to optimise a hydrogen supply chain network, it is also critical to consider natural comparative advantages that can facilitate green hydrogen deployment commercially. Kuwait is home to an annual solar radiation of 2200 kWh/m^2 [11], lying in the higher end of the global range of 640–2400 kWh/m2 [12]. Meanwhile, solar PV installation costs have dropped significantly from $4731/kw to $883/kw in 2021 [13]. In short, a HSC that harnesses a country's already existing natural comparative advantages (in this case Kuwait's solar abundance), is likely to be more sustainable due to the energy source always being available, but also more commercially attractive to all involved stakeholders for practical implementation.

To the authors' knowledge, no current studies have designed a green hydrogen supply chain network entirely producing hydrogen via solar energy. Motivated by these factors, this study presents a multi-objective optimisation model for a green HSC network in Kuwait.

The rest of this paper is structured as follows: Section 2 provides a literature review of the optimisation methods used in this work, as well the problem description; Section 3 outlines the chosen methodology for optimal HSC network configuration; Section 4 discusses the Kuwait case study and country-specific considerations, and Section 5 discusses the various results.

2. Literature review

The problem of hydrogen supply chain networks is frequently solved using mixed integer linear programming (MILP) models. These problems either have a single (mono) objective, e.g. cost minimisation, or multiple objectives, e.g. the minimisation of cost and GHG emissions.

2.1. Mono-objective optimisation

Mono-objective optimisation remains a highly utilised approach for designing hydrogen supply chains. An important point to note however, is that the optimisation of a supply chain from a single objective, e.g. cost, doesn't usually consider other objectives such as environmental and risk (and vice versa). Almansoori and Shah [7], used MILP to determine the optimal design of a hydrogen supply chain network using a demand-driven method to minimise the total cost. In their study, they used a scenario-based optimisation approach to capture the long-term uncertainty of hydrogen demand in Britain. The authors expanded on this work in Ref. [14], to consider the availability and logistics of energy sources (natural gas, coal etc.), as well as the variation in hydrogen demand over a long-term period. This approach aimed to develop the correct infrastructural requirements (e.g. production plants of different sizes). In both studies, only the cost objective was considered, as opposed to GHG emissions or risk. In Ref. [15], a multi-period optimisation model was used for planning a hydrogen supply chain network in New Jersey. This study considered the stochasticity of hydrogen demand using a macro, country-level view, and aimed for cost minimisation of the supply chain network with uncertain demand. Han and Kim [16], used MILP to plan and analyse strategic investment for the design of an integrated renewable energy source-based hydrogen supply chain in Korea. Their study used optimisation to determine the investment timing and allocation to the underlying energy supply system, including the type and quantity of renewable sources used, as well as the number and location of energy facilities installed.

2.2. Multi-objective optimisation

Multi-objective optimisation models considering two or more objective functions have also been widely adopted in the literature. Kim and Moon [17] used MILP to consider the trade-off between the cost and safety objectives of a hydrogen supply chain in Korea. In their study, the effects of demand uncertainty were also analysed by comparing deterministic and stochastic solutions. In a further study by Li et al. [18], MILP was used for a bi-objective optimisation between the cost and global warming potential of hydrogen, in order to obtain a Pareto optimal solution (discussed in 2.3) between the two objectives. Their study concluded that the Pareto front obtained by solving the bi-objective model provides a holistic view of the supply chain network and can provide decision-makers with the quantification and visualisation of the trade-off between costs and emissions. In Hugo [19], multi-objective MILP was used to design a hybrid photovoltaic (PV)-hydrogen renewable energy system considering the minimisation of total life costs and the loss probability of power supply. Ogumerem et al. [20], used a multi-objective, multi-period MILP model to maximise the net present value (NPV) and minimise GHG emissions of the hydrogen supply chain in the state of Texas. A promising discovery in this work found that the further processing of oxygen produced for sale instead of discarding it made electrolysis an economically competitive technology option for hydrogen production. Other studies [21,22], utilised MILP to determine the most effective ways of designing hydrogen supply chains to account for both monetary value and emissions. As for literature considering multiple (>2) objective functions, Guillén-Gosálbez [23] used MILP for a sustainability analysis to assess the limitations of multi-objective optimisation in minimising several environmental indicators of concern. This study concluded that several metrics of the same objective (i.e. environmental) can behave in a non-conflicting manner, making it feasible to reduce the dimension of multi-objective MILP optimisation without losing critical information. In this work, three objectives are considered: total cost, environmental impact and safety/risk. An important point to note is that, in all these works, the objective functions were optimised via the ε-constraint method. However, in this work, a weighted sum method is used. Unlike ε-constraint, which optimises one objective function at a time while modelling the other two objectives as constraints, weighted sum simultaneously optimises the three objectives by combining them into a single objective function. This means that the trade-offs between the three objectives are considered together in one unified model.

2.3. Multiple-criteria decision-making: AHP-TOPSIS

The key difference between mono and multi-objective optimisation is that with mono-objective, there is a single optimal solution; whereas, with multi-objective, different objectives (cost, environment, risk), are likely to conflict [24]. As a result, multi-objective optimisation utilises a set of trade-off solutions, known as Pareto optimal solutions. Most of the aforementioned literature considers Pareto solutions. A Pareto optimal solution, in short, represents the best possible solution for multiple conflicting objectives. In the literature, it is defined as a set of 'non-inferior' solutions in the objective space, which defines a boundary beyond which none of the objectives can be improved without sacrificing at least one of the other objectives [25]. In conjunction with obtaining Pareto optimal solutions, this work uses a hybrid of two multiple-criteria decision making (MCDM) tools; analytic hierarchy process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). AHP aids decision-makers by breaking down the criteria in a complex objective, in this case a hydrogen supply chain, into a hierarchy of criteria, based on a Pairwise matrix that ranks the importance of the criteria against each other [26]. In Ref. [27], AHP was used to rank criteria in a plastics manufacturing supply chain in India. According to the findings, 'government support and policies' were ranked as the most important criteria. Another study by Badea et al. [28] used AHP to determine how to mitigate supply chain crises. This study found that 'collaborative efforts' are a key contributor in aiding managers to develop strategies for supply chain crisis prevention. An important point to note is that in both studies [27,28], the criteria being analysed are subjective, rather than objective. In utilising AHP alongside a mathematical MCDM tool like TOPSIS, an objective supply chain design can be achieved considering the preferred ranking of criteria according to nuanced stakeholder preferences.

TOPSIS on the other hand is becoming an increasingly utilised tool in the literature for multi-criteria decision making, particularly for nascent technologies such as hydrogen supply chains. In Reyes-Barquet et al. [29], TOPSIS was used to determine the optimal design of a HSC powered with agro-industrial wastes from the sugarcane industry in Mexico. In their study, it was found that in an optimal case, hydrogen used in the transport sector is likely to contribute to 23 % of total annual emissions of CO_2-eq. Goh et al. [30] used TOPSIS to optimise a solar-biomass hybrid renewable energy system for industrial hydrogen supply in Malaysia. In their study, it was found that when TOPSIS was incorporated into the supply chain, a total annual operational cost minimisation of up to $10 million was possible, while also reducing energy waste. Azadnia et al. [31], used TOPSIS for a green hydrogen supply chain risk analysis in the hard to abate sectors of the European Union. In this work, it was highlighted that high capital investments for green hydrogen production coupled with the lack of regional electrolyser capacity were the highest-ranked risk factors preventing hydrogen development.

The difference between AHP and TOPSIS is that AHP assigns weightings to the assessed criteria based on their relative importance to stakeholders. In the case of multi-objective optimisation, this determines the weight of each criterion per objective (cost, environmental impact, risk). Conversely, TOPSIS ranks the Pareto optimal solutions by evaluating their closeness to an ideal solution (the best possible outcome for each criterion) and their distance from the worst solution (the worst possible outcome) [32]. In this work, a hybrid AHP-TOPSIS approach is used to leverage the strengths of both methods. To the authors' knowledge, no current literature has developed a hybrid AHP-TOPSIS MCDM tool for a HSC network optimisation, highlighting another novelty of this work.

2.4. Sensitivity analysis

Sensitivity analysis describes an analytical technique used to assess the robustness of mathematical models by evaluating how variations in input parameters influence results [33]. In the case of hydrogen supply chains, a sensitivity analysis can identify key factors or criteria that significantly impact the supply chain performance and ensure whether it remains reliable under different conditions. Mao et al. [34] for instance, incorporated a sensitivity analysis into an MILP-optimised supply chain to determine the sensitivity of hydrogen producing technologies compared to the levelized cost of hydrogen. In their study, it was found that electrolysers were about 33 % more sensitive to solar electricity price than CAPEX, while low-carbon technologies like carbon capture were found to be highly sensitive to fuel costs but not very sensitive to efficiency. In Kim et al. [35], a sensitivity analysis was incorporated into MILP optimisation to explore the relationship between the levelized cost of hydrogen and lead time. Their study found that the levelized cost of hydrogen increased by about 6.3 % with each one-week increment in lead time. Other studies incorporated sensitivity analysis into TOPSIS to determine the potential variations in the optimal solutions when different weights were assigned to the criteria. In Goh et al. [30], a sensitivity analysis was also used for the TOPSIS-optimised solar-biomass-based hydrogen supply chain. In the analysis, it was found that when the reduction of loss of power supply was excessively prioritised, the optimal solution shifted from an increased production capacity of the electricity generator to enlarged solar panel sizes and maximum capacity of more expensive water electrolysis systems. Another interesting finding of this work was that the capacity of hydrogen storage systems should be marginally increased to minimise the production of excessive unused energy in cases where potential energy waste probability is highly prioritised. In this work, the sensitivity analysis was integrated into the TOPSIS model by varying individual criterion weights in all of production, storage and transportation, while evenly distributing the weights of the other criteria.

2.5. Problem definition/objectives and contribution of the study

The primary objective of this work is to design a three-stage green hydrogen supply chain network (production, storage and transportation) for Kuwait using multi-objective optimisation to simultaneously minimise three objective functions: cost, environmental impact and safety/risk. More specifically, this work aims to answer the following questions, considering all objectives.

(1.) What is the most effective type of electrolysis for green hydrogen production in Kuwait?
(2.) What is the most effective hydrogen storage method in Kuwait?
(3.) What is the most effective hydrogen transportation method in Kuwait?

The green hydrogen supply chain analysed in this work is presented in Fig. 1. In terms of energy source, green hydrogen is produced via solar energy, given Kuwait's climatic conditions [11]. As for the production, storage, and transport methods, a previous study conducted by the authors Olabi and Jouhara [36] compared the advantages and disadvantages of each method in greater detail. In this study, a green hydrogen supply chain is modelled based on the previous comparative study to determine which combination of production, storage, and transport methods are the most optimal given Kuwait's natural environment. To summarise, hydrogen can be produced via three principal types of electrolysis: anion exchange membrane (AEM); proton exchange membrane (PEM), and alkaline water electrolysis [36] and can be stored and transported via all methods presented in Fig. 1. For more detail regarding the universal advantages and disadvantages of each method of hydrogen production, storage and transport, see Ref. [36].

The second objective is to determine if the optimal HSC network configuration changes when nuanced stakeholder preferences are considered in the AHP-TOPSIS approach. First, a 'no-priority' MILP supply chain is configured, where all analysed criteria are given an equal weighting. Following this, a sensitivity is conducted to test the impact of incremental weight changes on the supply chain outcomes. Lastly AHP rankings are integrated into the original model to determine whether the optimal supply chain changes based on explicit stakeholder priorities. This aims to design the most well-defined green hydrogen supply chain, considering a more structured and multifaceted evaluation process of the complex HSC. Fig. 2 illustrates the structural outline for the design of the hydrogen supply chain optimisation model, considering both the multi-objective, MILP framework and the AHP-TOPSIS MCDM tool used in this work.

3. Methodology

3.1. Mathematical model

The design of a green hydrogen HSC in Kuwait is considered, according to all feasible hydrogen production, storage and transportation methods available (Fig. 1). As previously mentioned, there are three objective functions to be minimised simultaneously: (1.) cost-which covers the facility, maintenance, and operational costs of running the HSC (in $); (2.) environmental-which covers the carbon footprint (kg CO_2e) and risk, which covers safety (measured as an index). For the time period analysed, this study focuses on a HSC network considering a 2050 scenario (i.e. 1 period). Future studies may focus on a multi-period extension to account for the medium-term (2030–2040).

The mathematical model, first developed by Almansoori and Shah [14] is used in this study and extended to multi-objective optimisation via the addition of environmental and risk objective functions. Following this, the weighted sum method is used for the simultaneous optimisation of the three objective functions.

3.1.1. Economic objective function

The first echelon to be optimised is the economic objective function, defined as the total cost (TC) of the hydrogen supply chain. This combines the capital and operational cost terms from production, storage, and transportation:

$$TC = \sum \frac{FCC + TCC}{\alpha CCF} + FOC + TOC + ESC \tag{1}$$

where, total cost (TC) (in $) is equal to the sum of facility and transportation capital costs, (FCC) and (TCC) divided by the network operating period (α) and the annual capital charge factor-payback period (CCF). This is then added to the facility (FOC) and transportation (TOC) operating costs, and the energy transportation costs (ESC).

3.1.2. Environmental objective function

The environmental objective defines the total carbon footprint

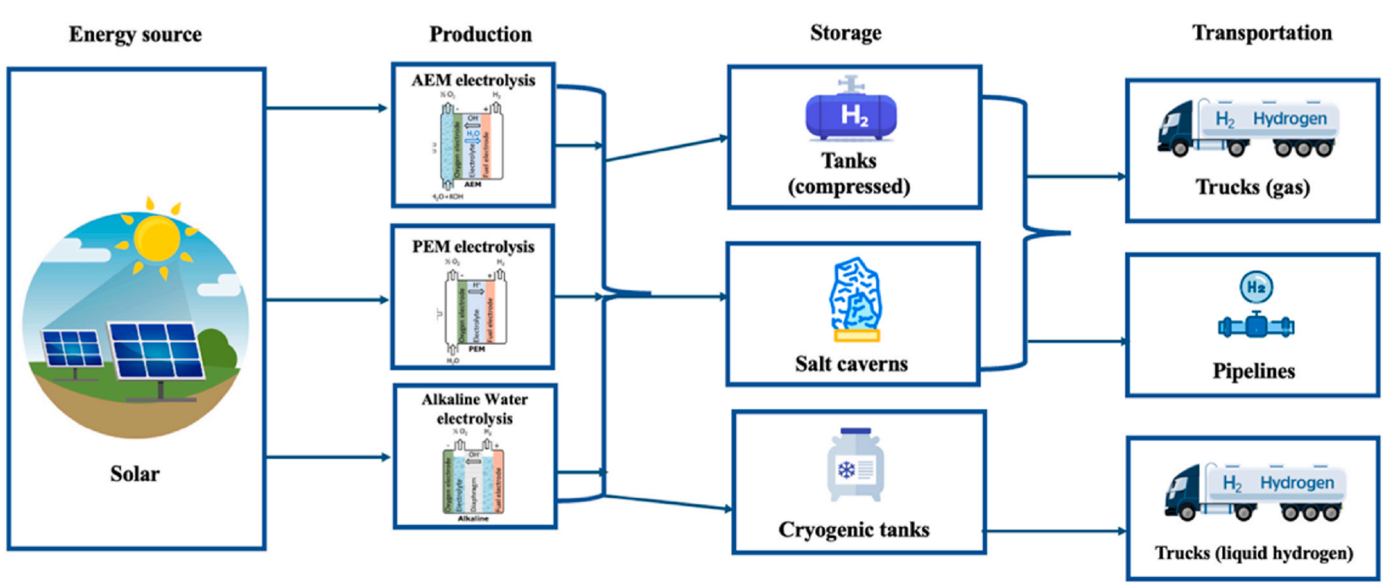

Fig. 1. Green hydrogen supply chain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

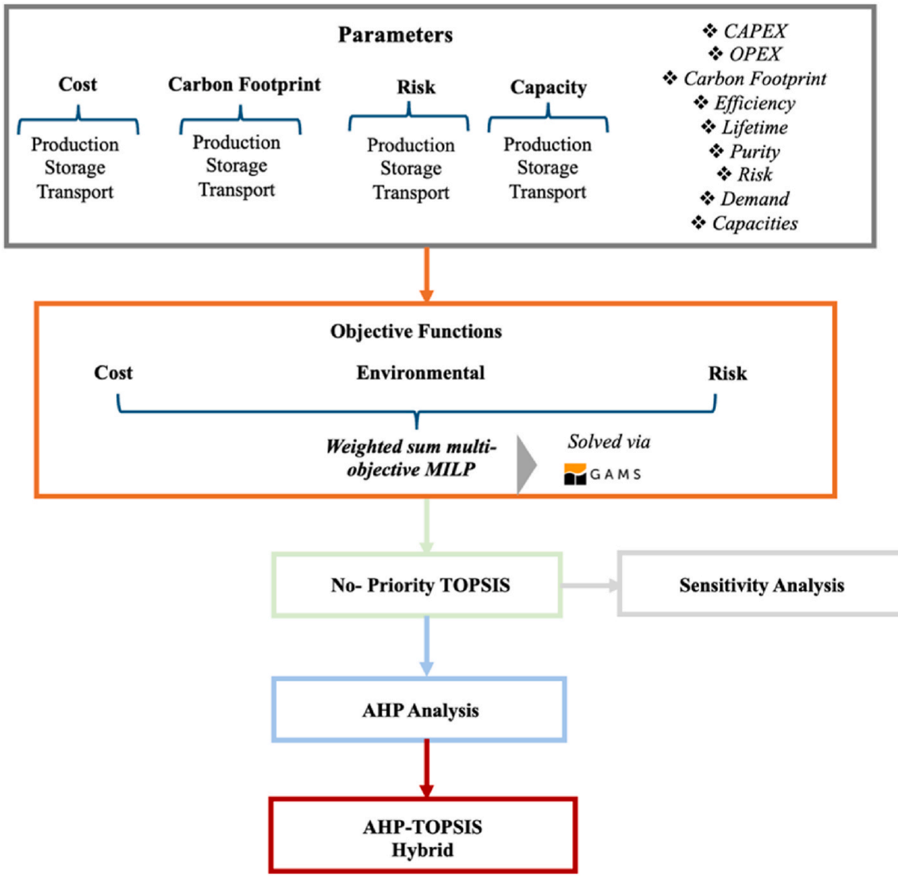

Fig. 2. Structural outline for HSC network design.

(measured in kg CO_2e). This consists of the total carbon footprint in production, storage and transportation:

$$CFtot = PCF + SCF + TCF \tag{2}$$

where, total carbon footprint (CF*tot*) is equal to the sum of the total carbon footprint in production (PCF), the total carbon footprint of storage facilities (SCF) and the total carbon footprint of transportation facilities (TCF). For conciseness, the equations for achieving total CF in production, storage and transportation are not included in the main body of this paper; for these equations, see Ref. [37].

3.1.3. Risk objective function

The risk objective defines the total risk (TR) in production, transportation and storage and is measured by an index, following the approach used in Ref. [35], originally developed in Ref. [17]:

$$TR = TPR + TSR + TTR \tag{3}$$

where, total risk (TR) is equal to the sum of risk in production (TPR) plus the risk of storage (TSR) and the risk of transport (TTR). The risk of each stage of the HSC (also determined by an index), is also calculated following the approach used in Ref. [38].

3.1.4. Weighted sum method

As previously mentioned, in the weighted sum method, the three objectives are combined into a single objective by multiplying each objective by a specific weight. The objectives are first normalised by adjusting the values of the objectives so that they have defined constraints that lie on a common scale between 0 and 1. Once the units are standardised, a combined objective function is constructed by summing the weighted normalised objectives. The problem is then converted into a single objective optimisation problem, as follows:

$$\min Z(x) = w_1 .Z_1(x) + w_2 .Z_2(x) + w_3 .Z_3(x) \ldots\ldots + w_n .Z_n(x) \tag{4}$$

where, (Z_n) represents objective function 'n' and (w_n) represents the respective weight of the objective function. For the objectives optimised in this work, the combined single objective is as follows:

$$\min \; w_1 . TC + w_2 . TCF + w_3 . TR \tag{5}$$

3.1.5. TOPSIS method

Like in the weighted sum method, in TOPSIS, the criteria are normalised on a scale between 0 and 1, as follows:

$$X_{n,ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \tag{6}$$

where $(X_{n,ij})$ represents the normalised criterion, (n) represents the total number of alternatives, (i) represents the row number, and (j) represents the column number in the pairwise decision matrix.

Then, the weighted normalised matrix is constructed, which involves multiplying the weights by the normalised data, as follows:

$$V_{ij} = X_{n,ij} \times W_j \tag{7}$$

where, (V_{ij}) represents the weighted normalised value, $(X_{n,ij})$ represents the normalised data and (W_j) represents the criterion weight. After constructing the weighted normalised matrix, the best and worst values are determined considering the weighted normalised data for each assessed criterion. These values can be either the maximum or minimum, depending on the best and worst values of the criterion. If the assumption is that a criterion has a negative impact, then the 'best' value will be the minimum obtained value between the different alternatives. Following this, the distances between the data of each alternative and the best and worst values are calculated, as shown in equations (7) and (8), respectively:

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2} \tag{8}$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2} \tag{9}$$

where, (S_i^+) represents the distance from the best value, (S_i^-) represents the distance from the worst value, (m) represents the number of criteria, (V_{ij}) represents the weighted normalised value, (V_j^+) represents the best value, and (V_j^-) represents the worst value.

Lastly, the final step involves evaluating the score of each alternative (P_i), which represents the ratio of the distance from the worst value to the summation of both distances. The alternatives' rankings are determined by this score, such that higher scores correspond to higher rankings, as follows:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{10}$$

4. Case study: Kuwait

Kuwait is divided into 15 grids as per Fig. 3, accounting only for the mainland area (excluding Bubiyan and Az Zawr islands). In all grids, green hydrogen can be produced via all types of electrolysers (AEM, PEM, and alkaline water), stored in compressed gas tanks, salt caverns and cryogenic tanks and transported via pipelines, and trucks (gas or liquid).

In Fig. 3, the green areas highlight the known available oil fields, where depleted areas can be converted into salt caverns for hydrogen storage. The three objective functions (total cost, carbon footprint and risk) are simultaneously optimised via the weighted sum method. In the results section below, three case studies are presented, with each of the case studies including low-demand, medium-demand and high-demand scenarios. Case study (1) is the weighted-sum MILP HSC network following a 'no-priority' approach (i.e. no criteria ranking); Case study (2) is the no-priority TOPSIS and Case study (3) is the AHP-TOPSIS HSC network. The three different demand scenarios (low, medium, high) are analysed considering three scenarios for 2050 hydrogen fuel cell vehicle (HFCV) demand. According to the International Energy Agency (IEA), hydrogen demand in the transport sector is expected to amount to 25 % of total demand across all industries by 2050 [39]. Meanwhile, another analysis conducted by McKinsey and Company [40], determined that by 2050, green hydrogen is expected to dominate the hydrogen market, with a share between 50 and 65 % of total hydrogen demand. Other works [41–43] have also concluded that at least 60 % of global hydrogen demand by 2050 will come from green energy sources. Based on these sources, this work assumes a 25 % hydrogen demand in the transport sector by 2050, but because green hydrogen is analysed, the demand range is as follows: in a low-demand scenario: 12.5 % (i.e. 50 % of 25 %); medium-demand scenario: 13.8 % (55 % of 25 %) and high-demand scenario: 16.3 % (65 % of 25 %). The hydrogen demand (in kWh) and penetration rates are presented in Table 1.

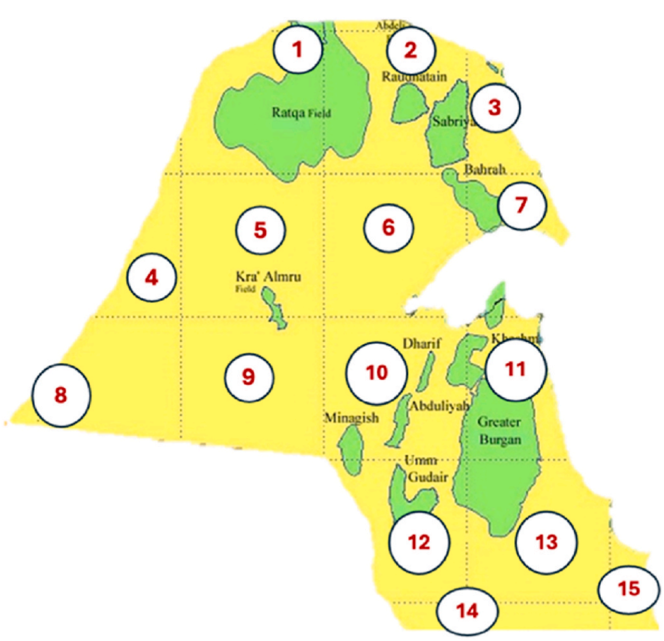

Fig. 3. Kuwait HSC network and grids.

Figs. 4–6 present the criteria compared in the pairwise matrices for each of hydrogen production, storage and transportation. To account for Kuwait's natural environment, the following considerations were accounted for: operational and maintenance costs were slightly adjusted upwards to reflect the higher costs of water (especially if desalination is needed) and potential cooling requirements due to Kuwait's high ambient temperatures. Meanwhile, for storage, Kuwait at present has no known salt caverns, but depleted oil reservoirs can be converted into salt caverns for hydrogen storage. As previously mentioned, the green areas in Fig. 3 highlight Kuwait's major oil fields. According to a study by Höök et al. [44], the oil field depletion rate for Organisation of the Petroleum Exporting Countries (OPEC) fields is ~5 %. As such, this work assumes that 5 % of Kuwait's oil fields can be converted to salt caverns for potential hydrogen storage. For transportation, an important consideration lies within pipelines. In the case that hydrogen is transported via pipelines, the likely scenario is that a new pipeline network would need to be constructed because of existing natural gas pipes being less efficient for hydrogen transport [45]. Hydrogen pipelines cost about 3–5 times higher than natural gas pipelines [46] and natural gas pipelines cost on average \$3.32 million per km [47]. Kuwait's total area is 17,820 km^2 (or 133.5 km) [48]. As such, an upfront capital investment of \$2.2 billion is assumed for the construction of a new pipeline network.

For risk, parameters related to production, storage, and transportation were evaluated according to the risk assessments conducted in Refs. [49–51], and in the subsequent analysis are ranked as either 'low' 'medium' or 'high'. The safety rankings for each method of hydrogen production, transportation and storage are presented in Table 2.

To solve both the MILP optimisation problem and the TOPSIS MCDM hydrogen supply chain network, GAMS software is used.

5. Results and discussion

5.1. Case study 1: no-priority multi-objective optimisation based on weighted-sum method

In this case, all objectives are combined into one singular function, as per equation (5).

Before determining the weights, the normalisation (scaling between 0 and 1) is conducted to standardise the differing units. The normalised objective function, shown in equation (11), is as follows:

Table 1
Projected green hydrogen demand 2050.

Penetration rate		Green hydrogen demand (kWh)
Low	12.5 %	15,000,000
Medium	13.8 %	20,000,000
High	16.3 %	25,000,000

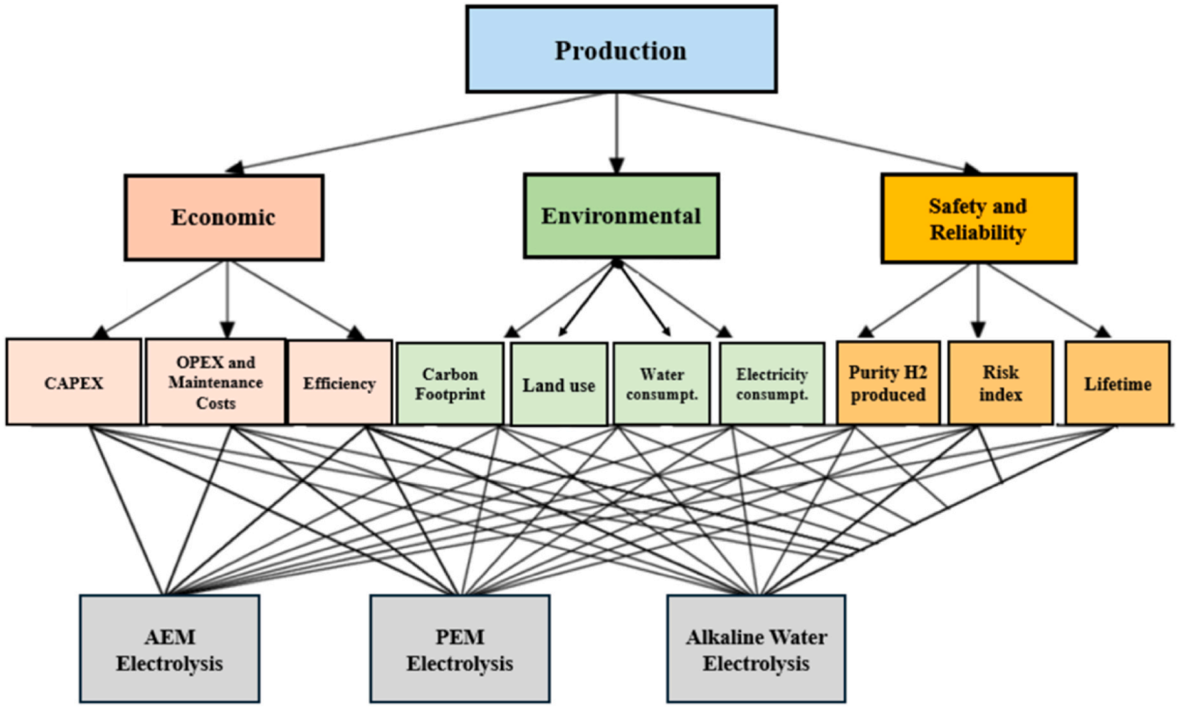

Fig. 4. AHP flowchart for green hydrogen production. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

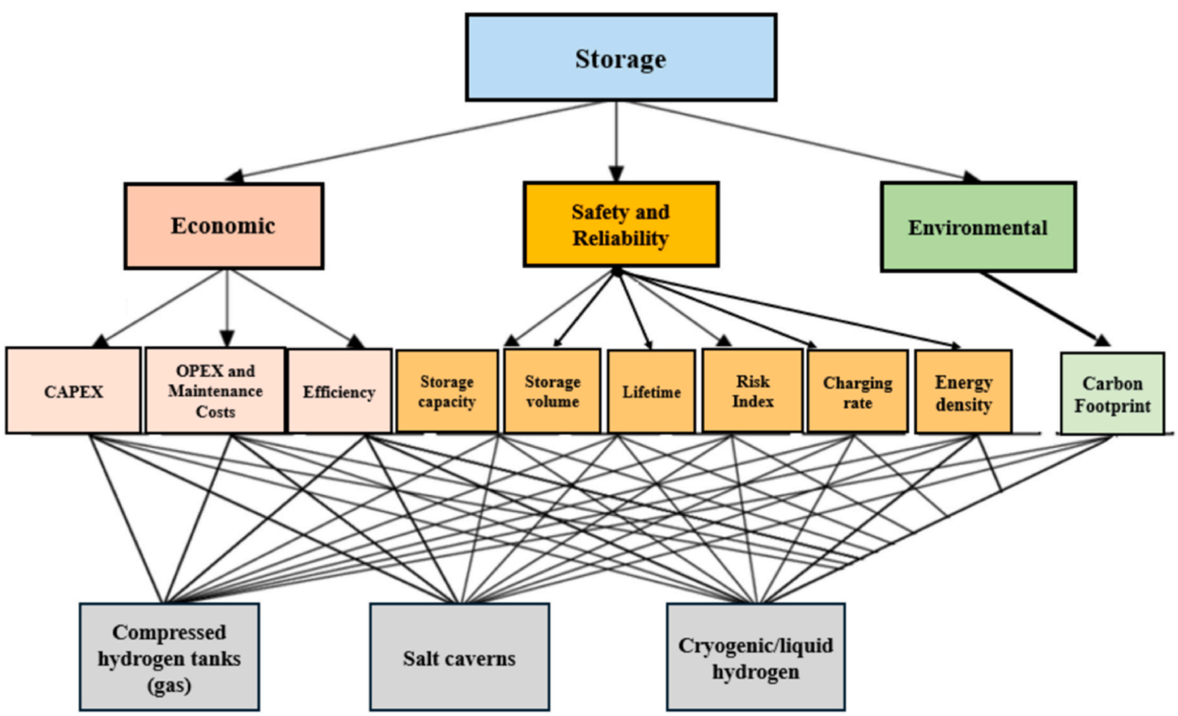

Fig. 5. AHP flowchart for green hydrogen storage. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$\min\ w_1 \cdot \left(\frac{TC - TC_{min}}{TC_{max} - TC_{min}}\right) + \min\ w_2 \cdot \left(\frac{TCF - TCF_{min}}{TCF_{max} - TCF_{min}}\right) + \min\ w_3 \cdot \left(\frac{TR - TR_{min}}{TR_{max} - TR_{min}}\right) \tag{11}$$

In the no-priority MILP scenario, the weights of each criterion are equal. For production and storage, each method had 10 criteria analysed, so in the normalisation matrix, these criteria were assigned a weighting value of (0.1). Meanwhile, for transportation, 11 criteria were analysed, giving each criteria the decimal value equal to (1/11). This generates the unbiased Pareto solutions across all three objectives. The results are presented in Figs. 7–9 for each of the demand (low, medium and high) scenarios, while Table 3 presents the scores obtained, as well

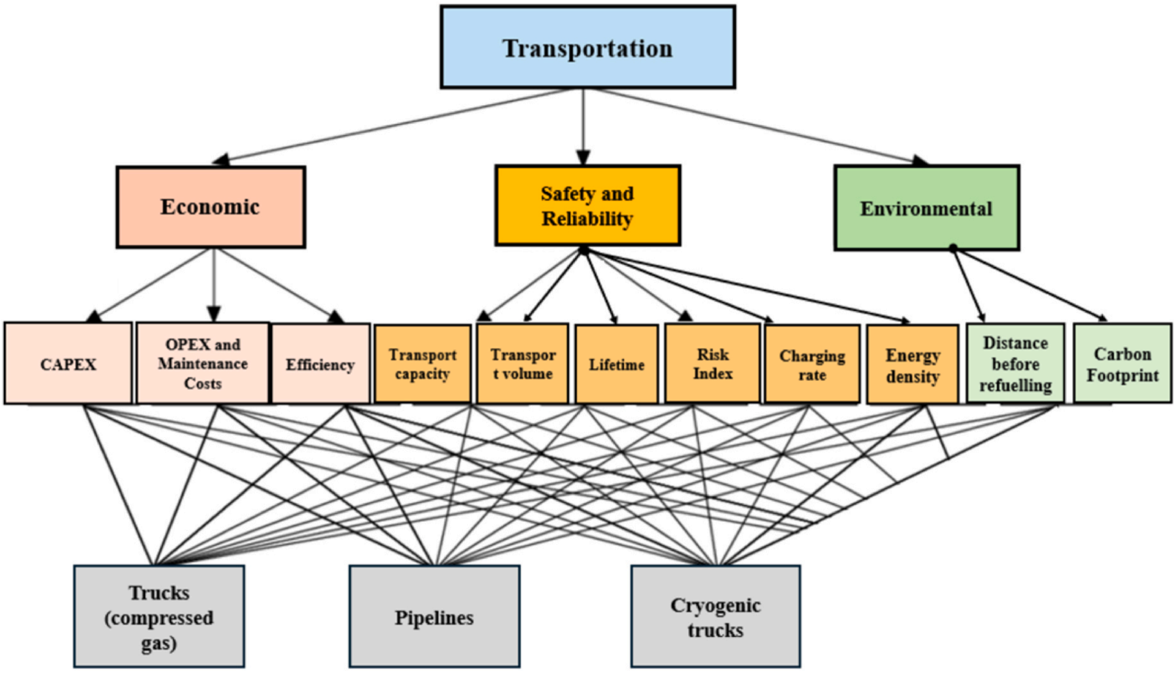

Fig. 6. AHP flowchart for green hydrogen transportation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

as the ranking for each method of hydrogen production, storage and transportation in each demand scenario analysed.

In the low-demand scenario, alkaline water electrolysis presented as the optimal hydrogen production method and cryogenic trucks presented as the optimal transport method. Meanwhile, in the medium-demand scenario, AEM electrolysis appeared as the optimal production method and pipelines the optimal transport method. In the high-demand scenario, alkaline water again presented as the optimal production method, while pipelines again presented as the optimal transportation method. Salt caverns emerged as the optimal storage method in all three demand scenarios. From these results, it can be understood that the selection of hydrogen production technology is likely to be the most sensitive to demand variations. Since alkaline water electrolysis is optimal in most scenarios (2 out of 3), it can generally be considered as the best choice for green hydrogen production. However, electrolysers commonly have optimal efficiency ranges, usually between 60 and 87 % that are linked to their capacity utilisation. AEM electrolysers have an efficiency of about 79 %, while PEM can reach as high as 86 %. In the case of low demand, running an electrolyser below its capacity can decrease its efficiency, lowering the overall score of the electrolyser. Conversely, in a high demand scenario, running the electrolyser at full capacity can also impact efficiency and subsequently, operational and maintenance costs. An important point to consider, however, is the actual difference in the scores in each demand scenario. For storage, in all three scenarios, salt caverns had a much higher difference in score than the second-best alternative (2.83 in the low demand; 3.05 in medium demand and 3.2 in high demand), showing a robust consistency in optimal performance. Meanwhile for production, the difference between the electrolyser scores didn't vary much across scenarios, with the difference in scores between the first and third rankings being 0.35 in low demand, 0.29 in medium demand and 0.21 in high demand. These minor <0.5 differences in the electrolyser scores indicate that in a no-priority case, there isn't a clear-cut optimal choice. All electrolyser options being compared are closely matched in performance. This high sensitivity indicates that changes in demand, cost, or operational conditions could easily shift the preference from one electrolyser type to another. For example, slight variations in electricity costs, efficiency under specific demand levels, or capital costs might make the second-best option more attractive in certain scenarios, as proven in the medium-demand scenario. For transportation, the results obtained were less demand-sensitive than production, but more demand-sensitive than storage. In the low demand scenario, cryogenic trucks presented as the optimal method, scoring 0.94 higher than the third ranked option (compressed gas trucks). However, the difference between cryogenic trucks and pipelines is only 0.08. This can likely be explained by the lower initial capital costs required for cryogenic trucks compared to a pipeline network installation. In the medium and high demand scenarios, pipelines were the highest ranked, scoring 0.24 higher than cryogenic trucks in medium demand, and 0.41 in high demand. Despite the higher initial capital costs, pipelines scoring the highest in the medium and high demand scenarios suggests economies of scale-i.e., this system can become cost-effective with a high, steady demand. Although, as with the electrolysers, the minor score differences suggest demand sensitivity in transportation, pipelines are likely to fit as the optimal hydrogen transportation method from a practical perspective when considering the entire supply chain, due to the production and storage methods favouring hydrogen gas over liquid hydrogen. Carbon footprint and risk index were incorporated into the analysis but remained constant in each demand scenario for each production, storage and transportation method. With this being the case, they were unlikely to contribute to altering rankings between scenarios.

5.2. Case study 2: no-priority TOPSIS

Like in the no-priority MILP, production and storage, in the no-priority TOPSIS each had 10 criteria analysed (Figs. 4 and 5), each with an assigned weighting value of (0.1) in the normalisation matrix. Transportation also remained the same, analysing 11 criteria (Fig. 6) with decimal weighting values of (1/11) each.

The results obtained in the no-priority TOPSIS, presented in Figs. 10–12 are generally consistent with the no-priority MILP in terms of the optimal configuration for hydrogen production, storage and transportation Table 4 presents no-priority TOPSIS scores and rankings. For production, in the low and high demand scenarios, again alkaline water electrolysis emerged as the optimal hydrogen production method. The major difference between MILP and TOPSIS lies in the

Table 2
Hydrogen supply chain risk levels.

Production	Risk level	Description	
AEM	Moderate	• Works in a highly diluted alkaline environment, making it safe to handle.	[52]
PEM	Moderate	• Gas cross-permeation between hydrogen and oxygen can cause ignition.	[53]
Alkaline water	High	• The chemical modification of the solid polymer electrolyte or use of catalytic H_2/O_2 recombiners can maintain crossover values at a safe level.	[54]
		• Like with AEM, there is the potential risk of ignition from the hydrogen/ oxygen gas crossover.	[55]
		• Low performance caused by the thick membrane used increases the electrical resistance and subsequently, the risk for ignition caused by a potential hydrogen/oxygen gas crossover.	[56]
Storage			
Compressed hydrogen (tanks)	High	• In its gaseous state, hydrogen is stored at high pressures (350–700 bar), resulting in a higher risk of explosion in the event of road accidents or fires.	[57]
Salt caverns	Low	• Salt caverns offer safe and efficient possibilities for underground hydrogen storage.	[58]
Cryogenic/ liquid hydrogen	Moderate	• Underground rock salt formations are generally impermeable, meaning that the gas cannot escape and is not exposed to external influences that could contaminate it.	[59]
		• Depending on their depth, salt caverns may be operated at pressures up to 200 bar, allowing for large-volume hydrogen storage to be safely stored under pressure.	[60]
		• Adequate ventilation will help reduce the possible formation of flammable mixtures in the event of a hydrogen leak or spill and helps to eliminate the potential hazard of asphyxiation.	[61]
		• Nonetheless, there still lies the potential risk of both.	[62]
		• Liquid hydrogen evaporates almost immediately upon release, due to the rapid increase in temperature above its boiling point (−252.8 °C). Ignited releases can result in flash fires, pool fires, and deflagrations (primary and secondary).	[63]
			[63]
Transportation			
Trucks (compressed gas)	Moderate	• Like compressed storage, hydrogen gas trucks operate at very high pressure (350–700 bar), making this system susceptible to potential fire hazards, due to the two risk factors of high pressure and medium ignitability.	[64]
Pipelines	Low	• However, these risks only present in the unlikely failure of a hydrogen fuel system and the ignition of the subsequently released compressed hydrogen.	[65]
Cryogenic trucks	Moderate	• Correct infrastructural developments for hydrogen pipelines can prevent and mitigate risks when accounting for human, environmental and financial parameters.	[66]
		• Liquefied hydrogen in poorly insulated or uninsulated tanks can liquefy the surrounding air in the event of a leakage.	[67]
		• If there is a gas leak in a cryogenic hydrogen storage tank the liquid hydrogen will turn into gaseous hydrogen due to boil-off, which adds the risks of fire hazards present in hydrogen gas trucks.	[68]

interpretation of the results. In TOPSIS, negative values are not obtained as this optimisation method ranks solutions based on their distance to an ideal point, rather than directly optimising the weighted sum as in the case of MILP. Conversely, in MILP, the 'best' solution is the one with the least negative value. This difference in optimisation technique can explain why PEM was considered the optimal electrolyser in the medium demand scenario. In this case, PEM had one or more criteria values closer to the ideal point. However, an important point to note is again the score difference. Like in the MILP scenarios, the difference between the electrolyser scores is minimal, where in the low demand scenario, the difference between the most and least optimal is 0.26, in the medium 0.12 and in the high, 0.22. This further confirms the high demand-sensitivity of electrolysers. For storage, salt caverns were the net optimal storage method, suggesting that they are a consistent and robust hydrogen storage method considering Kuwait's natural conditions. When comparing to the MILP results, the rankings of the second and third-best options for storage altered between scenarios, which can again be explained by the different approaches each model uses for optimisation. Transportation rankings were the same as MILP across all three demand scenarios. This consistency again suggests that cryogenic trucks are optimal when demand is low, likely due to their lower capital costs, whereas pipelines display economies of scale due to their lower unit costs and higher volumes, despite a higher initial capital cost. In terms of decision-making, the consistency between the MILP and TOPSIS results suggests that for transportation, there is a clear and predictable transition point where pipelines start outperforming cryogenic trucks as demand rises, making it easier to plan for infrastructural requirements based on demand projections. The overall uniformity between the optimal (first-ranked) MILP supply chains and the optimal TOPSIS supply chains can reduce uncertainty in planning, due to the robustness of the choices under different modelling assumptions. In turn, this can provide reassurance to decisionmakers for infrastructural planning.

5.3. Sensitivity analysis: no-priority TOPSIS

To determine how variations in individual criterion weights impact the final rankings in the no-priority TOPSIS model, a sensitivity analysis was conducted to assess ranking stability and identify the most influential criteria. Although the AHP analysis already introduces a systematic weighting variation based on stakeholder preferences, in the case of a one-period model, the weightings are static, so the impact of incremental weight changes on the supply chain outcomes is not explicitly tested. As such, the sensitivity analysis was conducted in the no-priority TOPSIS, where all criteria were initially considered equally important, to evaluate how ranking outcomes shift under different weighting scenarios. Here, each criterion for production, storage and transportation was analysed individually with 10 altering weights between 0 and 1, while the remaining weight in each case was evenly distributed among the other criteria. For example, in the case of hydrogen production, while investigating the sensitivity of electrolysers to CAPEX, if the weighting of CAPEX was 0.3, then the weighting of each of the other criteria was equal to (1–0.3)/10. The same applies for the 11 criteria in transportation; if one criterion was analysed at a weighting of 0.4, then the remaining criteria had equal weightings of (1–0.4)/11. The sensitivity analysis score tables and criteria weightings for each of production, storage and transportation can be found in the Appendix, while the

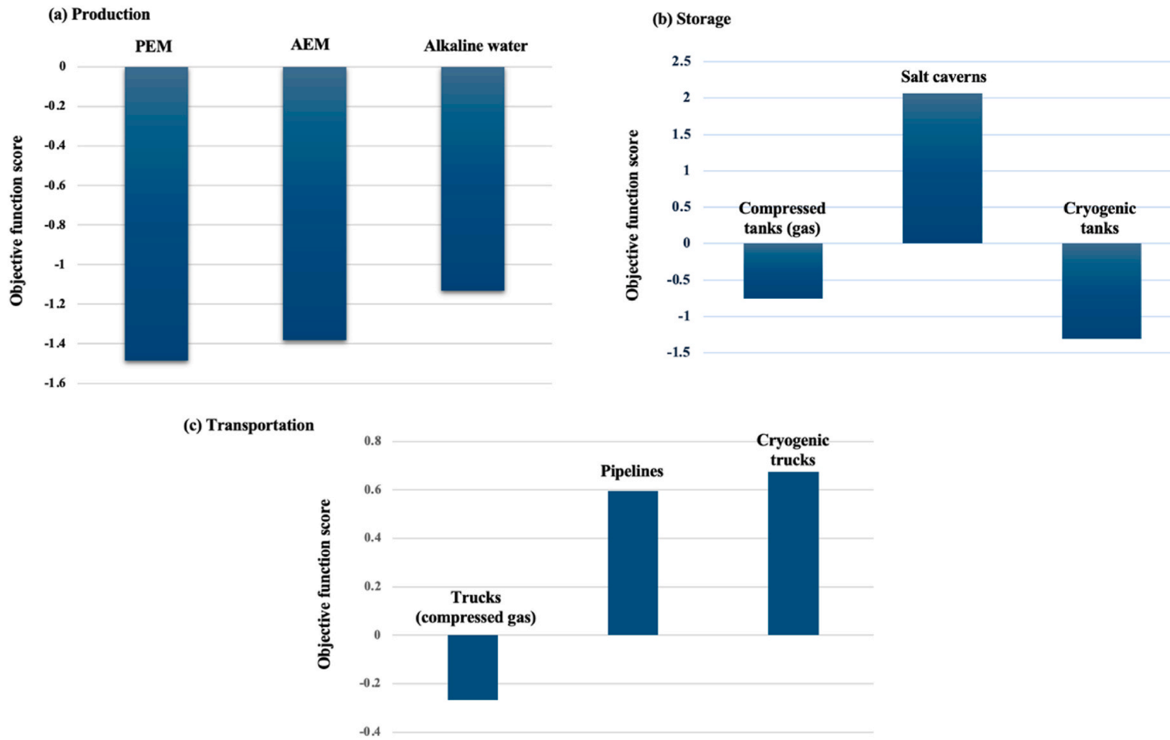

Fig. 7. Low demand scenario-no-priority MLP hydrogen supply chain network results.

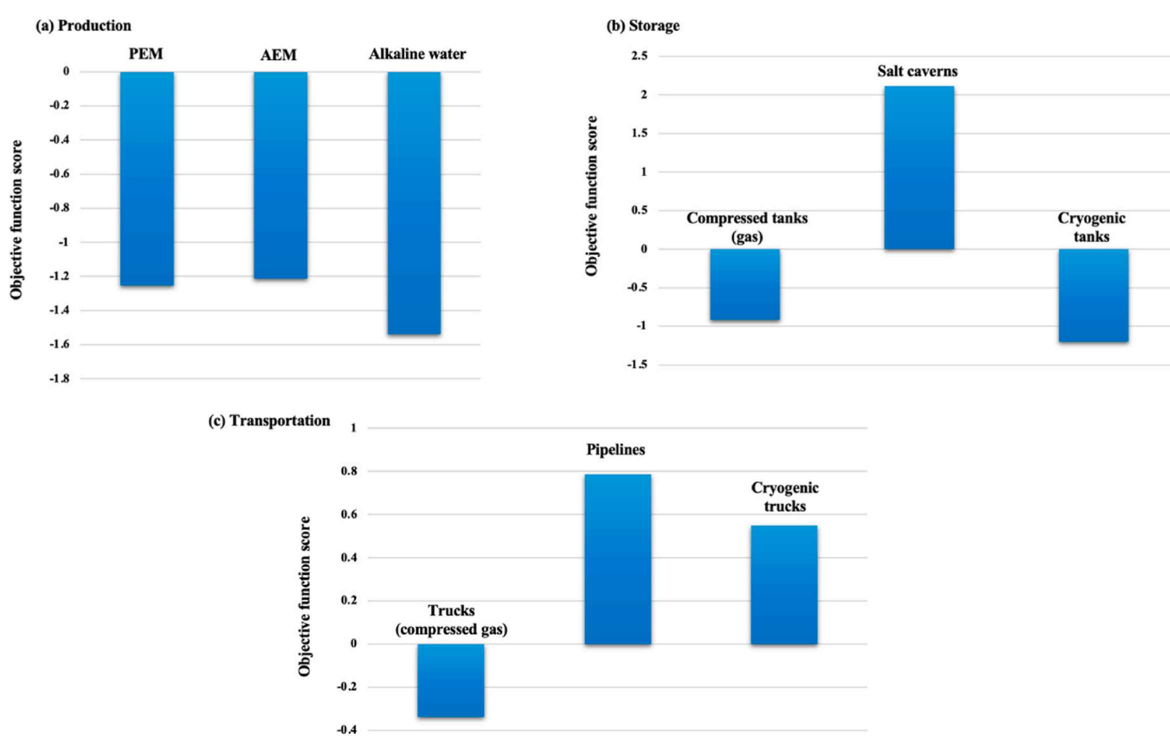

Fig. 8. Medium demand scenario-no-priority MILP hydrogen supply chain network results.

impact of weight variations is illustrated in Figs. 13–15. The analysis was conducted for the high-demand scenario as a stress test, since this represents the conditions where the supply chain operates at peak performance and maximum capacity. Under these conditions, limitations and constraints are most pronounced, making the HSC more susceptible to shifts in criteria weightings.

The results obtained in the AHP-TOPSIS, are presented in Figs. 16, 17 and 18. Table 5 shows AHP-TOPSIS hybrid scores and rankings. While alkaline water electrolysis emerged as the optimal production method in the no-priority cases, the sensitivity analysis revealed some important underlying dynamics that challenge its long-term viability under shifting priorities. The most notable trend is the consistent performance of AEM across multiple criteria, where it generally improved as the weighting factors increased. From this, it is understood that although

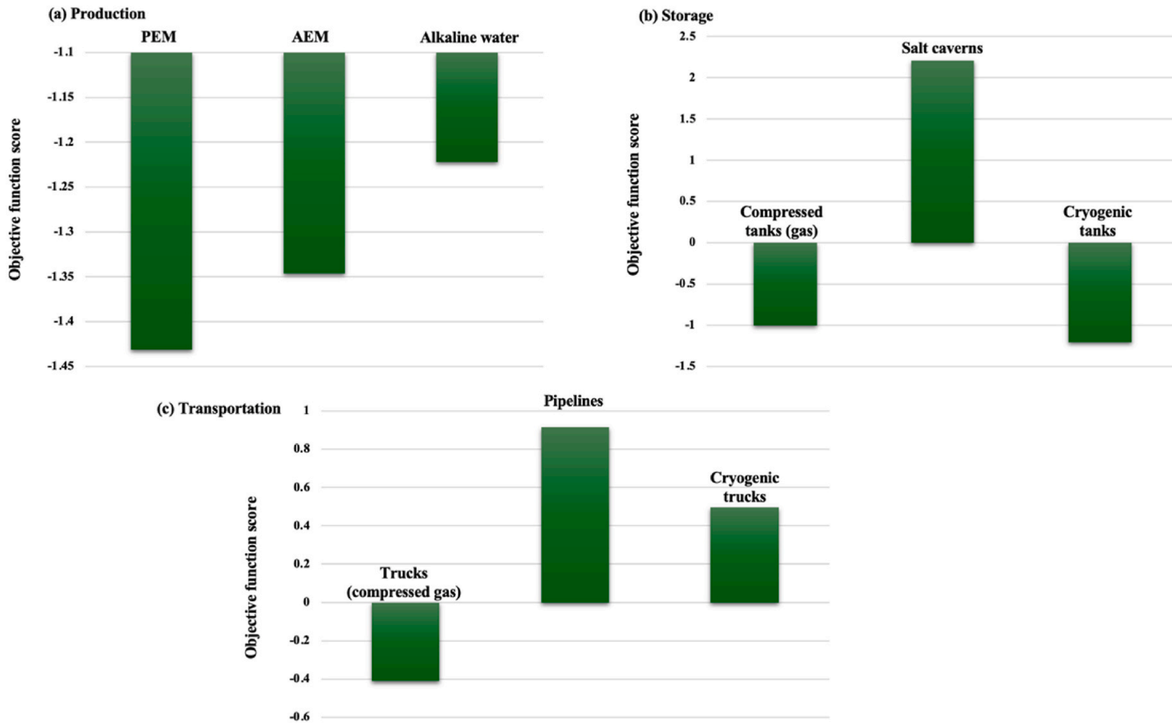

Fig. 9. High demand scenario-no-priority MILP hydrogen supply chain network results.

Table 3
No-priority MILP scores and rankings.

Demand	Low		Medium		High	
Production	Score	Ranking	Score	Ranking	Score	Ranking
PEM	−1.48	3	−1.25	2	−1.43	3
AEM	−1.38	2	−1.21	1	−1.35	2
Alkaline water	−1.13	1	−1.54	3	−1.22	1
Storage	Score	Ranking	Score	Ranking	Score	Ranking
Compressed gas (tanks)	−0.76	2	−0.93	2	−0.99	2
Salt caverns	2.07	1	2.12	1	2.21	1
Cryogenic tanks	−1.31	3	−1.20	3	−1.21	3
Transportation	Score	Ranking	Score	Ranking	Score	Ranking
Trucks (compressed gas)	−0.27	3	−0.34	3	−0.41	3
Pipelines	0.59	2	0.79	1	0.91	1
Cryogenic trucks	0.67	1	0.55	2	0.50	2

*Scores were rounded to two decimal places.

alkaline water presents as an overall more balanced choice, AEM becomes a stronger contender when specific decision-making priorities are applied. A key point to note is the relationship observed between electricity use and efficiency. Alkaline water has the lowest electricity use of the electrolysers, yet its sensitivity results indicated the greatest drop in performance when this criterion was prioritised. From this, it is understood that despite an electrolyser having the lowest electricity consumption in absolute terms, actual electricity use depends on how efficiency shifts at scale. As previously mentioned, PEM efficiency can reach as high as 86 %, while AEM's efficiency stands at about 79 %. Alkaline water's efficiency is lower at about 65 %; as such, this type of electrolyser requires more electricity per unit of hydrogen at higher production volumes, meaning that although its electricity use is lower, it becomes disproportionately impacted as demand scales up. Another interesting observation is the implication between efficiency and electricity cost. AEM and PEM are more efficient than alkaline, yet they are more sensitive to electricity price variations. This suggests that higher-efficiency electrolysers are actually more exposed to operational cost fluctuations. Because their total cost structure is more dependent on electricity, whereas alkaline has a larger fixed CAPEX component that dampens this sensitivity, higher efficiency does not necessarily translate to economic stability but rather it depends on the weighting of electricity price fluctuations. Both carbon footprint and risk didn't drastically alter rankings, suggesting that for hydrogen production there is not actually a trade-off between economic, environmental and risk objectives. Instead, the majority of trade-offs come from the cost-energy-performance dynamics of the electrolysers. For storage, like in the no-priority cases, salt caverns dominated across all criteria, confirming the strong performance of this storage method regardless of the weighting factor applied to the criteria. Here, the key observations are seen in cryogenic tanks. Cryogenic tanks revealed to be highly sensitive to energy density changes, meaning their viability is tied to high energy storage efficiency rather than cost-effectiveness. However, when energy density was weighted, cryogenic tanks performed much better compared to their general ranking. The same occurred for storage capacity, where cryogenic tanks demonstrated the biggest improvement in ranking, surpassing compressed gas and narrowing the gap with salt caverns. This indicates that cryogenic tanks are viable in low demand scenarios but lose favour when other cost and efficiency factors are considered. As such, in the case of a real-world scenario requiring high-

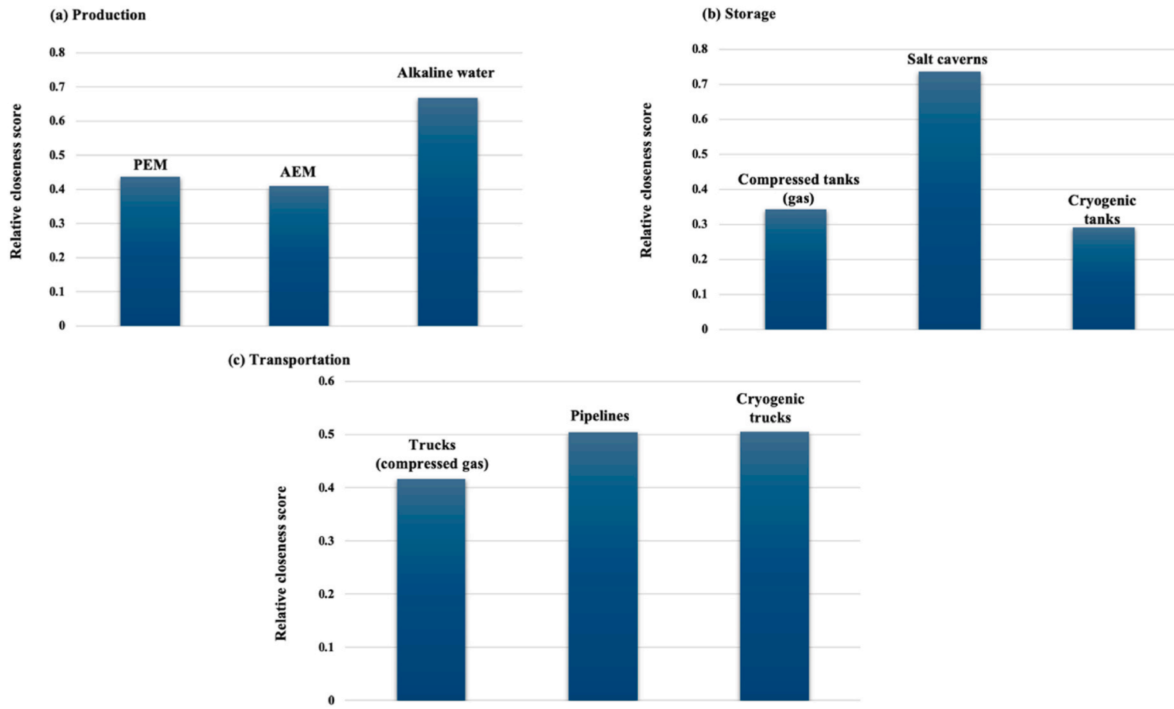

Fig. 10. Low demand scenario-no-priority TOPSIS hydrogen supply chain network results.

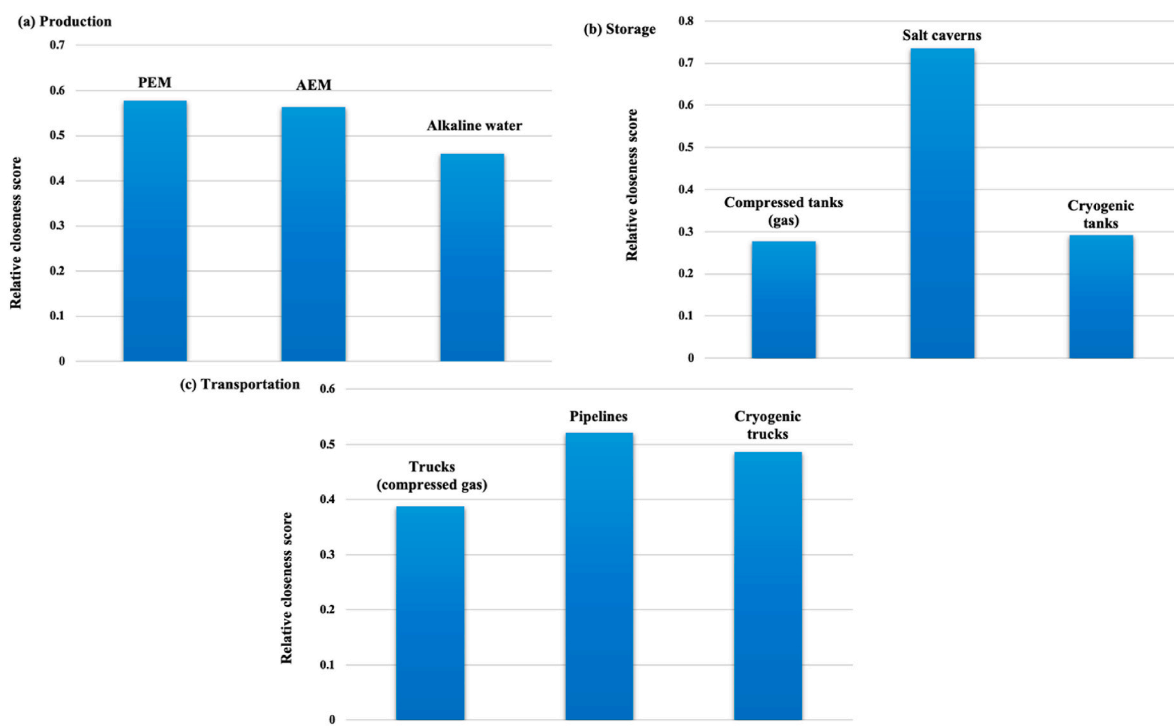

Fig. 11. Medium demand scenario-no-priority TOPSIS hydrogen supply chain network results.

capacity storage within a limited space, such as urban areas, cryogenic tanks may become the preferred storage option, despite their higher costs. For transportation, like in the no-priority cases, the economies of scale demonstrated by pipelines is evident. Pipelines' score sharply increased as CAPEX weight increased (from 0.479 at 0 CAPEX to 1 at full CAPEX), confirming that pipelines are preferred when long-term investment is prioritised over upfront affordability. Although pipelines have the highest initial CAPEX among the transportation options, this cost is distributed over long operational lifetimes, alongside low OPEX per unit transported. Cryogenic trucks maintained their competitiveness at low CAPEX due to their lower initial costs, but as the weight increased, their ranking dropped significantly. For other criteria like OPEX and efficiency, cryogenic trucks were initially favoured, with pipelines subsequently being favoured at higher weightings. Cryogenic trucks performed well under high OPEX weighting since their operational costs are lower than pipelines' for smaller-scale distribution.

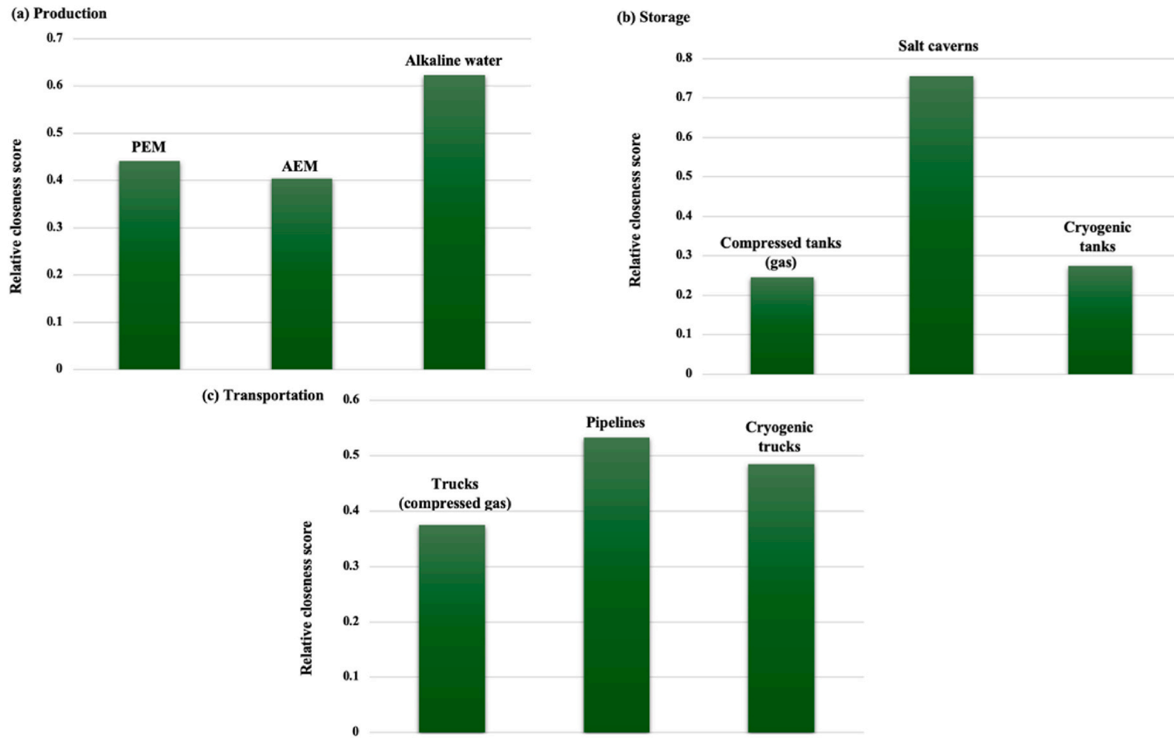

Fig. 12. High demand scenario-no-priority TOPSIS hydrogen supply chain network results.

Table 4
No-priority TOPSIS scores and rankings.

Demand	Low		Medium		High	
Production	Score	Ranking	Score	Ranking	Score	Ranking
PEM	0.44	2	0.58	1	0.44	2
AEM	0.41	3	0.56	2	0.40	3
Alkaline water	0.67	1	0.46	3	0.62	1
Storage	Score	Ranking	Score	Ranking	Score	Ranking
Compressed gas (tanks)	0.34	2	0.28	3	0.25	3
Salt caverns	0.74	1	0.73	1	0.76	1
Cryogenic tanks	0.29	3	0.29	2	0.27	2
Transportation	Score	Ranking	Score	Ranking	Score	Ranking
Trucks (compressed gas)	0.42	3	0.39	3	0.37	3
Pipelines	0.50	2	0.52	1	0.53	1
Cryogenic trucks	0.51	1	0.49	2	0.48	2

*Scores were rounded to two decimal places.

However, their ranking declined as demand scaled up, with pipelines overtaking them. As for efficiency, cryogenic trucks remained competitive at lower weightings, but their scores fell as the weighting increased, reinforcing that their advantage is tied more to operational flexibility rather than overall system efficiency. A similar trend emerged for transport capacity and volume. At lower volume weightings, cryogenic trucks prevailed where flexibility was valued over bulk transport efficiency, while pipelines gained a clear advantage as transportation capacity and volume weightings increased, again showing that their economies of scale become critical in high-demand scenarios. In cases where charging rate and energy density were heavily weighted, cryogenic trucks became the dominant choice, indicating their viability in applications requiring fast refuelling and high energy efficiency. For carbon footprint and risk, like in the case of production, these criteria had a negligible impact on the results, reinforcing the notion that the majority of trade-offs come from cost-energy-performance dynamics rather than different objectives.

Overall, the sensitivity analysis revealed critical insights for strategic, demand-responsive infrastructure planning. CAPEX has a minimal impact at low demand but becomes a decisive factor as demand scales up. This dynamic suggests that in the early stages of hydrogen infrastructure development, lower-CAPEX options (i.e. cryogenic tanks and trucks) may be favoured due to their affordability and operational flexibility. However, as demand stabilises and scales up, investments in higher-CAPEX but more cost-efficient infrastructure—such as salt caverns for storage and pipelines for transport—become justifiable. Salt caverns consistently demonstrated a strong performance, but their lower energy density allowed cryogenic tanks to compete in specific scenarios, particularly when energy density and storage capacity were highly weighted. In real-world applications, this trade-off means that while salt caverns offer the lowest-cost bulk storage solution, their feasibility depends on geographical availability. In urban or space-constrained environments, where land availability is a limiting factor, cryogenic tanks may be the preferred option despite their higher costs. Future research should integrate geographic and land use constraints to help determine optimal storage solutions considering different regions. Pipelines emerged as the dominant choice for medium to high demand due to their superior economies of scale. If a transport network must accommodate fluctuating hydrogen volumes over time, a hybrid approach may be necessary. In periods of low demand, cryogenic trucks offer flexibility and lower upfront costs, making them ideal for early-stage or decentralised distribution networks. However, as demand grows, pipelines become the preferred method due to their long-term cost advantages and ability to handle large volumes efficiently. This suggests that infrastructure planning should consider a staged transition, initially leveraging cryogenic trucks, while gradually investing in pipelines as demand stabilises. Additionally, a mixed transport network—where cryogenic trucks complement pipelines for peak demand fluctuations—could provide an optimal balance of flexibility and cost-effectiveness.

To systematically incorporate stakeholder preferences into the weighting of criteria, an AHP analysis was conducted. As previously mentioned, the AHP flowcharts and their respective criteria are presented in Figs. 4–6 above, while the pairwise comparison matrices can

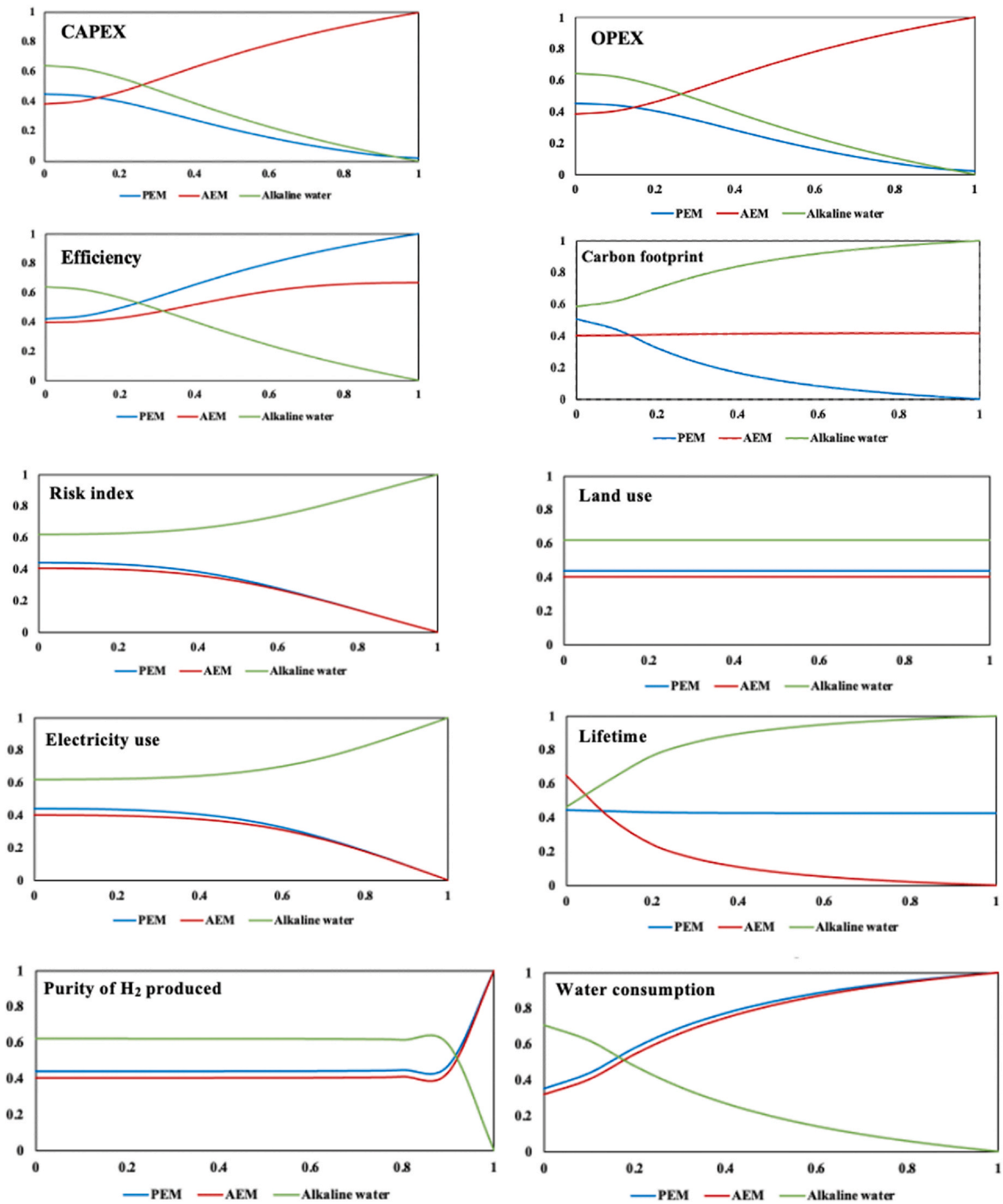

Fig. 13. Sensitivity analysis-hydrogen production criteria.

be found in the Appendix. The AHP-obtained criteria weightings were integrated with TOPSIS to refine the rankings of the supply chain components. These adjusted rankings were then applied within the original MILP framework to evaluate whether the sensitivity-driven insights align with the prioritised rankings to determine whether the solutions identified through sensitivity analysis remain robust under stakeholder-weighted criteria.

5.4. Case study 3: AHP- TOPSIS hybrid

Considering the refined stakeholder preferences, the general optimal supply chains in the low and medium scenarios remained relatively similar to the no-priority cases. In the low demand scenario, like in the no-priority case, alkaline water, salt caverns and cryogenic trucks presented as the optimal configuration. Broadly, this indicates that stakeholder preferences, even when explicitly prioritised, are inherently aligned with what is technically optimal. For production, alkaline water electrolysis emerged as the optimal production method in the low-demand scenario, while AEM scored the highest in the medium and high demand scenarios. Comparing to the sensitivity analysis, the electrolysers demonstrated a similar dynamic. Like in the case of the sensitivity analysis, AEM became stronger when specific decision-making priorities were applied. Aside from the previously mentioned findings of higher-efficiency electrolysers being more exposed to

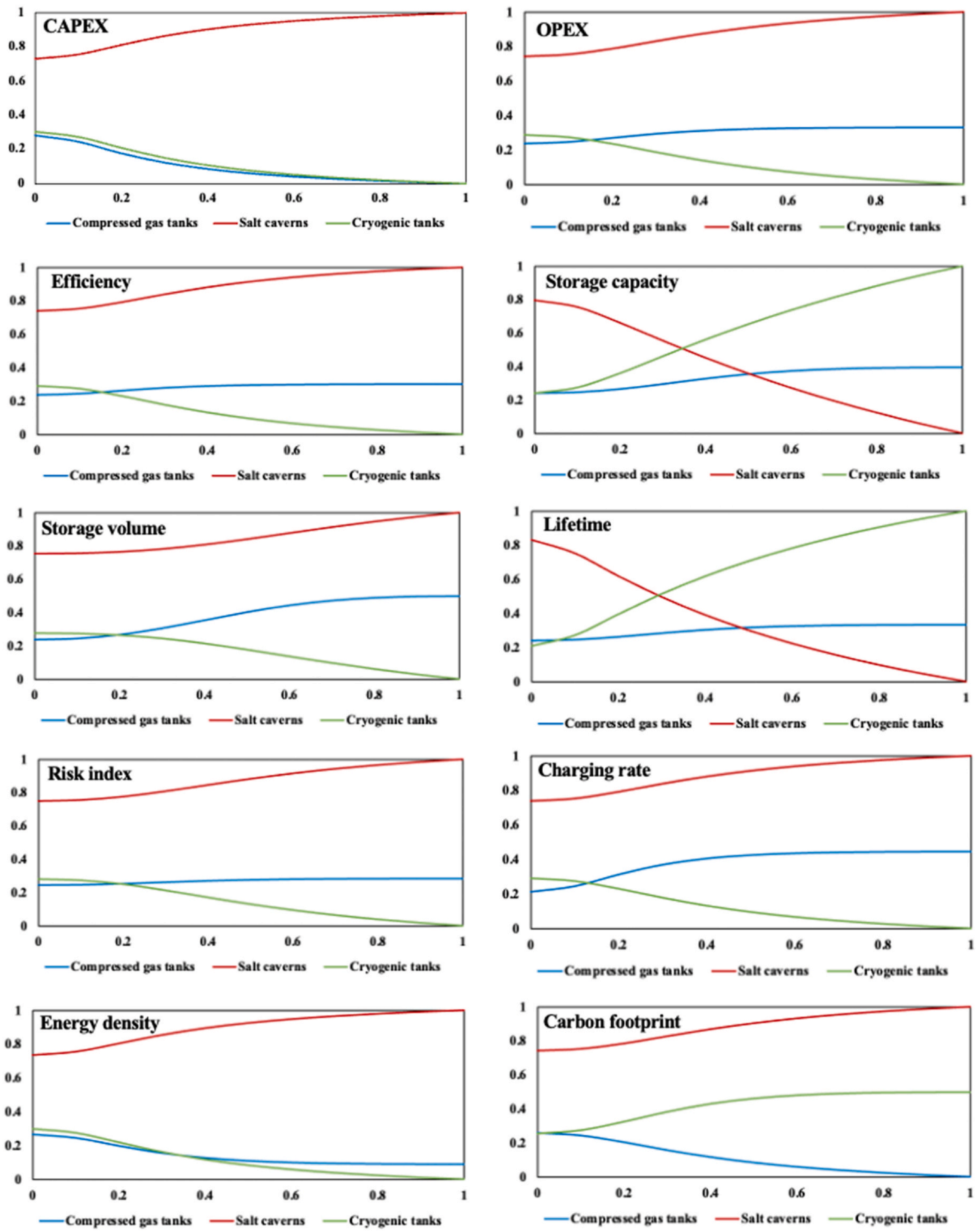

Fig. 14. Sensitivity analysis-hydrogen storage criteria.

operational cost fluctuations and the inverse relationship between electrolysers running undercapacity and efficiency, another interesting observation for production lies in the dynamic between CAPEX and demand. Alkaline water has a higher CAPEX compared to AEM, yet in a low demand scenario is considered more optimal, despite stakeholders giving CAPEX a high priority. From this, another observation is that in low-demand scenarios, fixed costs such as CAPEX alone don't necessarily impact the optimal electrolyser in terms of cost, but rather it's the underlying relationship between efficiency and electricity consumption in relation to the quantity of hydrogen produced that influences “cost”. Due to being used at undercapacity at low demand, despite a lower initial investment cost, AEM may not provide significant economic advantages in a scenario where electricity consumption is relatively small. As demand increases, the impact of higher efficiency and operational savings becomes more evident due to the larger production volumes. This shift in CAPEX sensitivity across different demand levels reinforces the point that since CAPEX is less impactful in low-demand scenarios, early investments may prioritise technologies with lower operational cost risks rather than focusing solely on minimising upfront capital expenditure. However, as demand scales up, CAPEX becomes a more

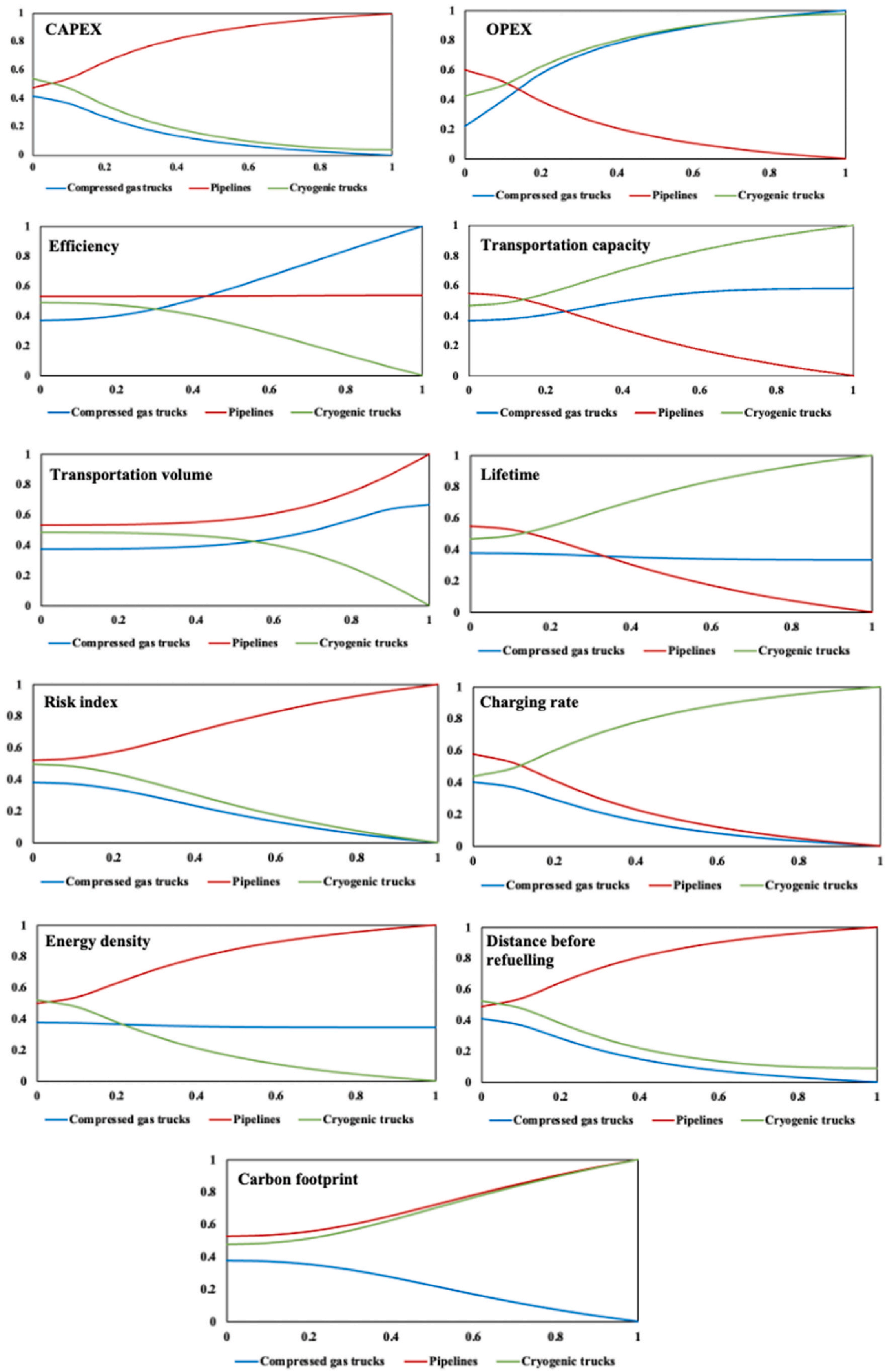

Fig. 15. Sensitivity analysis-hydrogen transportation criteria.

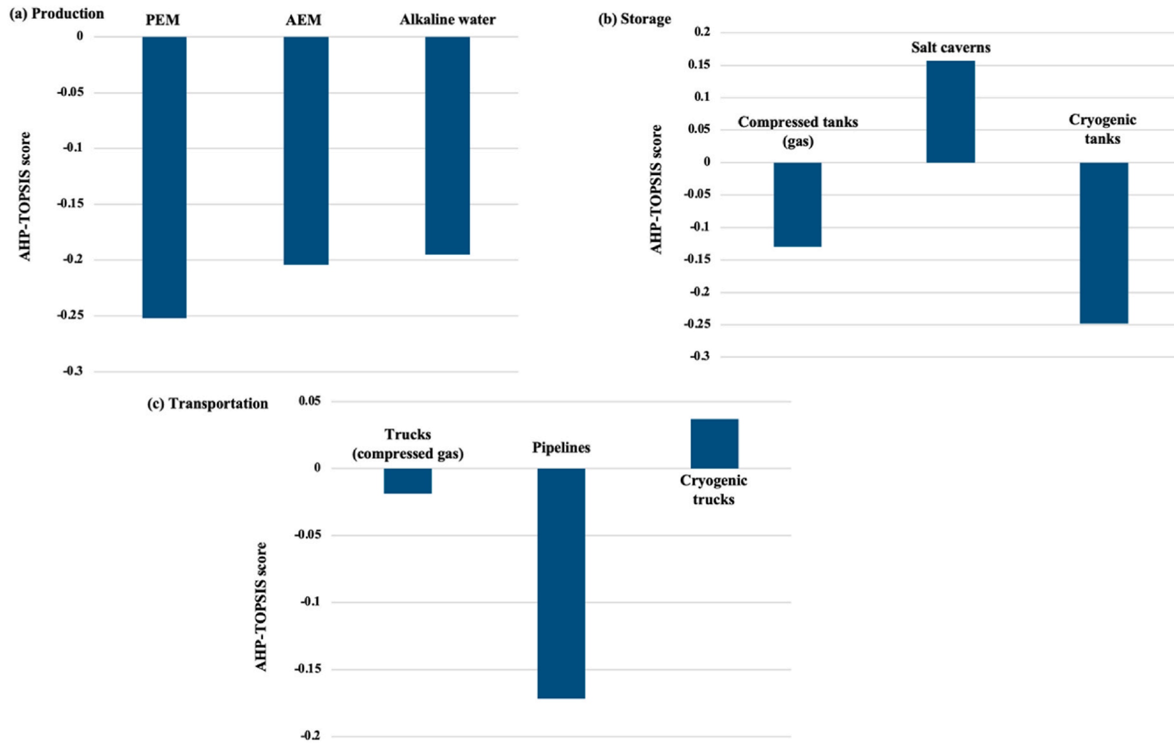

Fig. 16. Low demand scenario- AHP-TOPSIS hybrid hydrogen supply chain network results.

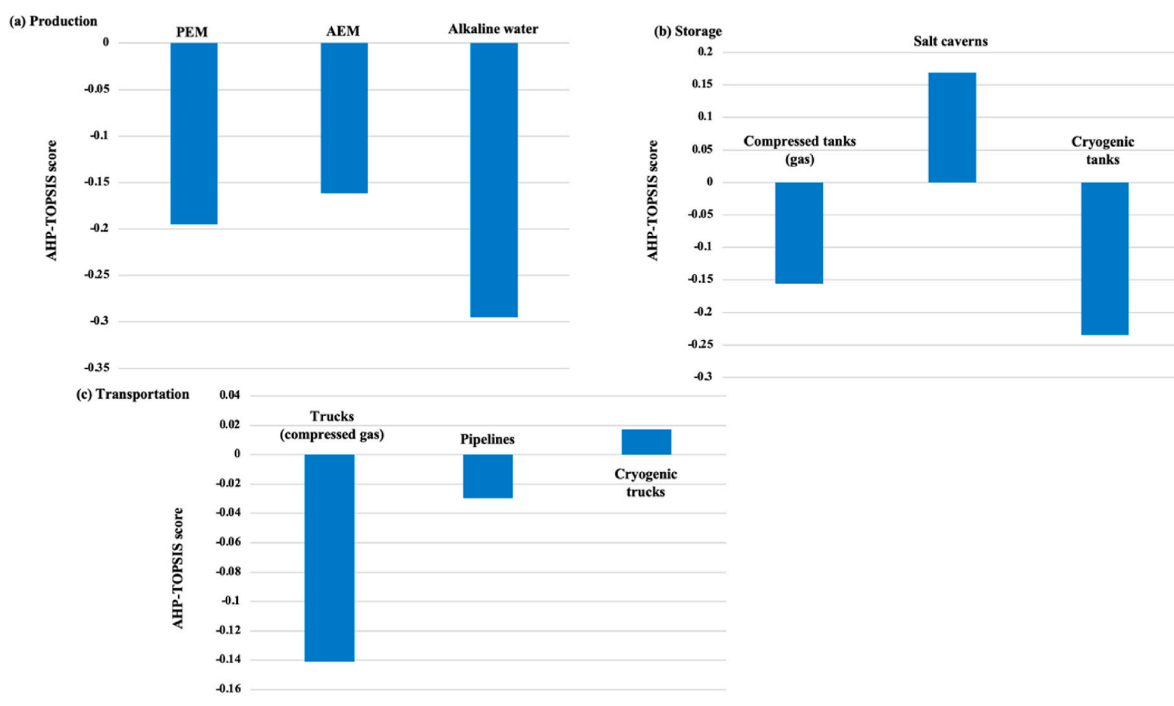

Fig. 17. Medium demand scenario- AHP-TOPSIS hybrid hydrogen supply chain network results.

critical factor. Due to a clear convergence in electrolyser performance when certain criteria, such as operational efficiency, become amplified with increasing demand, a hybrid approach may be employed to accommodate peak electrolyser performance at fluctuating demand levels, strategically leveraging alkaline water electrolysis for stability in low-demand scenarios, while integrating higher-efficiency options like AEM as demand scales to optimise cost-effectiveness across varying production conditions. For storage, again salt caverns emerged as the optimal storage method in all three demand scenarios. The consistent high performance across demand scenarios despite refined stakeholder preferences solidifies the superior performance of salt caverns. It is important to note however, that while in the no-priority cases, the score difference between salt caverns and alternative storage methods is high, in the AHP ranked scenario, the score difference between salt caverns and the lowest ranked storage method is 0.41 at low demand, 0.4 at medium and 0.41 at high. Although salt caverns dominate in the key

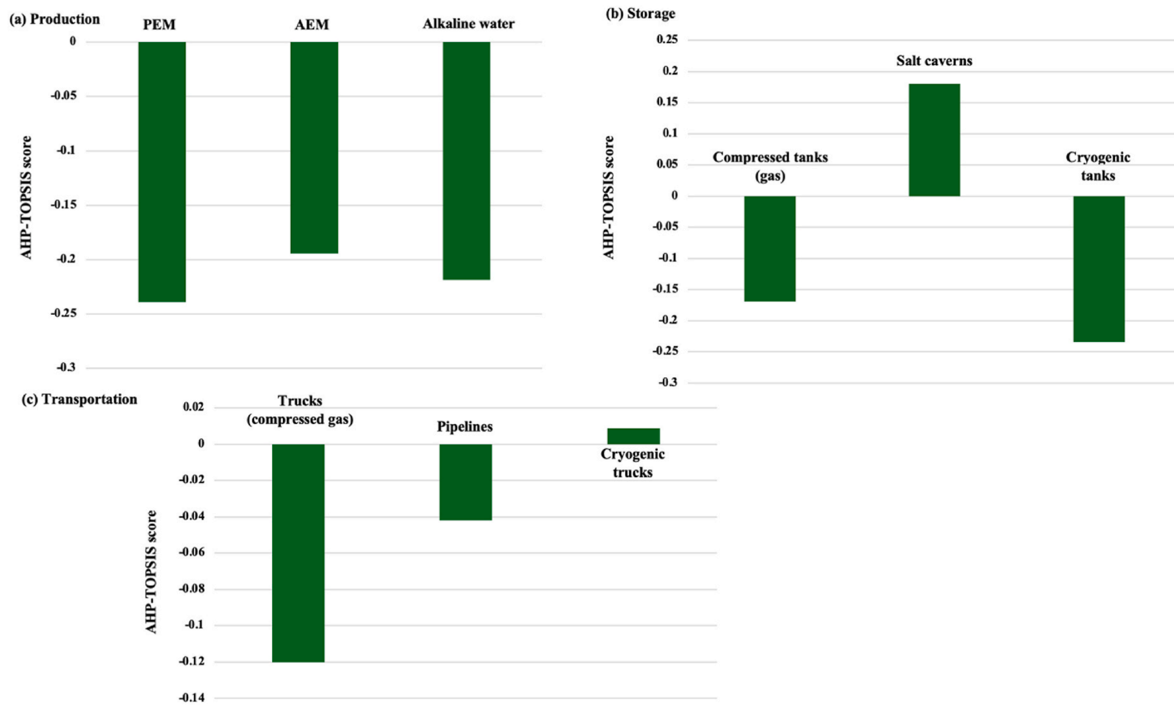

Fig. 18. High demand scenario- AHP-TOPSIS hybrid hydrogen supply chain network results.

Table 5
AHP-TOPSIS hybrid scores and rankings.

Demand	Low		Medium		High	
Production	Score	Ranking	Score	Ranking	Score	Ranking
PEM	−0.25	3	−0.19	2	−0.24	3
AEM	−0.20	2	−0.16	1	−0.19	1
Alkaline water	−0.19	1	−0.29	3	−0.22	2
Storage	Score	Ranking	Score	Ranking	Score	Ranking
Compressed gas (tanks)	−0.13	2	−0.16	2	−0.17	2
Salt caverns	0.16	1	0.17	1	0.18	1
Cryogenic tanks	−0.25	3	−0.23	3	−0.23	3
Transportation	Score	Ranking	Score	Ranking	Score	Ranking
Trucks (compressed gas)	−0.02	2	−0.14	3	−0.12	3
Pipelines	−0.17	3	−0.03	2	−0.04	2
Cryogenic trucks	0.04	1	0.02	1	0.01	1

*Scores were rounded to two decimal places.

criteria, the prioritised weighting schemes amplify secondary criteria where alternative storage methods have a competitive advantage. For example, out of all three storage methods, salt caverns have the lowest energy density, allowing compressed gas tanks and cryogenic tanks to better compete when this criterion is amplified. Consequently, this lowers salt caverns' overall dominance score wise. A similar trend was observed in the sensitivity analysis, where cryogenic tanks performed much better compared to their general ranking when this criterion was amplified. This reinforces the finding that the lower energy density of salt caverns means their feasibility depends heavily on geographical availability and higher demand volumes, so, in cases of lower demand, cryogenic tanks may be favoured. For transportation, at low demand, cryogenic trucks performed the most optimally like in the no-priority case. However, unlike in the no-priority MILP, where pipelines ranked first in the medium and high scenarios, cryogenic trucks remained the highest scoring transport method across all three demand scenarios. This is expected due to the significantly lower CAPEX for cryogenic trucks compared to pipelines. Like in the case of electrolysers, where higher efficiency can cause weaker performance at low demand, pipelines at this level cannot fully leverage their scalability benefits. This aligns with what was observed in the sensitivity analysis, where it was found that that pipelines are preferred when long-term investment is prioritised over upfront affordability. However, it is again important to consider the score differences. At low demand, pipelines' score is 0.21 lower than cryogenic trucks, while at medium and high demand, a minimal 0.05 is the score difference. Considering the fact that CAPEX was highly prioritised in the AHP, pipelines were still able to score <0.1 less than cryogenic trucks in the medium and high demand scenarios, despite initial investment costs being higher. From this, it is understood that regardless of explicitly prioritised criteria, the economies of scale in pipelines become unequivocally obvious in higher demand scenarios. In this case, efficiency and transport volume play an important role, where pipelines can transport larger volumes of hydrogen at lower energy cost per kg, as a result of their energy consumption not increasing linearly with transport volume. On the other hand, cryogenic trucks can incur increasing energy loss for each additional truck, which was similarly noticed in the sensitivity analysis.

The general consistency among the various models indicates that the technically optimal hydrogen supply chain configuration is mostly aligned with the stakeholder priorities amplified during the AHP process. As production scales up with higher demand, factors such as operational efficiency and scalability overtake initially critical factors, such as capital costs. From an environmental perspective, salt caverns and pipelines-that can store and transport the largest volume of hydrogen-are the most optimal, particularly in medium and high demand scenarios. This is largely due to the lower carbon footprint per unit of hydrogen stored and transported, especially at high volumes. Because of the higher efficiency, less energy loss occurs, in turn boosting the environmental performance of these storage and transport methods. However, it is important to consider that, although environmental performance improves with larger volumes of hydrogen stored and transported, in a real-world scenario, local energy mix or policy incentives will significantly vary the scale impacts. In regions like Kuwait, with a high solar energy capacity [11], and increasingly cost-competitive solar PVs [13], scaling up hydrogen infrastructure can enhance environmental performance, as larger volumes of renewably produced hydrogen reduce the relative emissions per kg. However, in regions with less prevalent comparative advantages, the scaling up of a hydrogen supply chain may lead to higher lifecycle emissions, thus limiting the environmental benefits of scaling. Policy incentives play a similar role. Kuwait's substantial clean energy investments [2] and ambitious hydrogen targets [3] indicate a national alignment towards green hydrogen development. As such, large-scale green hydrogen adoption is being accelerated, in turn making low-emission hydrogen pathways more financially viable. In regions with weaker incentives, smaller-scale solutions may be favoured over full-scale green hydrogen deployment. Future multi-period research should incorporate detailed life-cycle assessments and policy scenarios spanning across various regions to provide a more comprehensive understanding of the varying scale impacts based on individual regional factors, such as local energy mix and policy incentives for green hydrogen.

In terms of risk, safety considerations became more prevalent in the AHP weighted model, again largely at medium and high demand. For example, although alkaline water electrolysis is the highest risk production method, at low demand, it scored the highest. Because the AHP weights are static, other advantages of this electrolyser, such as low carbon footprint and lifetime offsetted risk at low demand, despite its high weighting. In this context, medium and high demand scenarios actually assert the impact of the high-priority criteria more. While low-demand scenarios may alter rankings by underemphasising key criteria and overemphasising secondary criteria, medium and high demand scenarios better reflect the comparative advantages of each considered method, thus better reflecting the multi-objective trade-offs. This is particularly evident with efficiency, where for all of production, storage and transportation, the relative advantages were seen in the medium and high demand scenarios. Future research should consider feasibility studies for the actual construction of a green hydrogen supply chain, considering the findings from this work.

6. Conclusion and future considerations

This work focused on the strategic design of a green hydrogen supply chain in Kuwait, through a combined model involving multi-objective optimisation tools and multiple criteria decision-making techniques to account for stakeholder priorities. The study explored varying demand scenarios, while using a simultaneous multi-objective approach to balance economic, environmental, and risk factors. The key findings revealed that electrolyser performance is highly demand-sensitive, and that there is a threshold of hydrogen demand that needs to be passed in order for comparative advantages such as higher efficiency to become apparent. Similar observations were made in the transportation methods, where pipelines' superior performance emerged at higher demands. The sensitivity analysis revealed that infrastructure planning should consider a staged transition or a hybrid system considering different systems for fluctuating demands. Initially, cryogenic tanks and trucks should be leveraged due to their higher performance at low demand, while gradually investing in salt caverns and pipelines as demand stabilises. These results highlight that the construction of a supply chain in real-time will need to align greatly with expected demand profiles, as at some point operational efficiency and scalability offset higher initial capital investments, which can actually be more cost-effective in the long run. The same stands for environmental performance and risk, where the AHP weightings overemphasised secondary criteria at low demand but levelled the criteria to a more realistic reflective level in medium and high scenarios.

While this work considered a single period focusing on the long run, future research should adopt a multi-period framework to capture temporal variations in demand, technological maturity, and cost dynamics. For example, conducting a medium-term study for 2030–2040 with a broader range of demand variability would capture the transitional dynamics between the short and long term, to determine if electrolysers or storage and transport systems can achieve their optimal performance when operating at intermediate maturity levels. In a multi-period framework, future research should incorporate dynamic re-evaluations of AHP weightings at intervals of five years to reflect evolving stakeholder priorities. Additionally, incorporating technological learning curves, policy scenarios, and detailed life-cycle assessments can offer a more comprehensive understanding of long-term hydrogen supply chain optimisation.

CRediT authorship contribution statement

Valentina Olabi: Writing – original draft, Software, Data curation, Conceptualization. **Abdulrahman Alhajeri:** Writing – original draft, Software, Data curation, Conceptualization. **Hussam Jouhara:** Writing – original draft, Supervision, Formal analysis, Conceptualization.

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

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