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Dynamic multi-objective, multi-period optimisation of a hydrogen supply chain in the Gulf Cooperation Council (GCC) region: A Saudi Arabia case study

Valentina Olabi [a], Abdulrahman Alhajeri [a], Heba Ghazal [b], Hussam Jouhara [a,c,*]

[a] Heat Pipe and Thermal Management Research Group, College of Engineering, Design and Physical Sciences, Brunel University London, UB8 3PH, UK
[b] School of Life Sciences, Pharmacy and Chemistry, Kingston University London, KT1 2EE, UK
[c] Vytautas Magnus University, Studentu Str. 11, Akademija, Kaunas Distr., LT-53362, Lithuania

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ABSTRACT

Home to some of the highest solar radiation levels globally and a strategic export location, Saudi Arabia ranks among the top countries for green hydrogen potential. However, widescale deployment remains constrained by the challenge of designing a supply chain that can effectively balance trade-offs between economic, environmental, and safety/risk objectives. This study presents a multi-objective, multi-period optimisation model for the design of a green hydrogen supply chain (HSC) network in the Northwestern region of Saudi Arabia, considering various production technologies (electrolyser types), storage options, and transportation modes. A novel dynamic framework is developed to simultaneously optimise cost, carbon footprint, and safety/risk. Within this framework, a hybrid AHP–MILP approach is integrated to capture stakeholder preferences and their evolution over time through time-dependent weightings, enabling the relative importance of economic, environmental, and safety criteria to adapt across planning periods in line with changing stakeholder priorities. Four planning periods are considered in this study: establishment phase (T1); early operations phase (T2); steady operations phase (T3) and mature system (T4) - with low, medium, and high demand scenarios analysed in each period. Results showed that as hydrogen demand increases, production technologies converge in performance because their individual strengths and weaknesses counterbalance each other, while storage and transportation technologies diverge as scale amplifies the advantages of various criteria.

1. Introduction

Since the Paris Agreement of 2015, the international community has been making significant efforts to reduce emissions and limit the global temperature rise to below 2 °C above pre-industrial levels, with an ambition to cap it at 1.5 °C [1]. To achieve this target, countries have increasingly committed to finding alternatives to fossil fuels, particularly in the transport sector. In this respect, hydrogen has been gaining significant attention due to its potential as a zero-emission fuel. ‘Green’ hydrogen, in particular, refers to hydrogen produced using renewable energy sources (such as solar and wind), via electrolysis [2]. In the electrolysis process, electricity generated from renewables is used to split water into hydrogen and oxygen, resulting in no subsequent emissions [3]. Consequently, countries with abundant solar resources, like those in the Gulf Cooperation Council (GCC) region, are ideally positioned to become key players in the emerging hydrogen economy.

Saudi Arabia is actively investing towards developing its national hydrogen economy. The nation's sovereign wealth fund, the Saudi Public Investment Fund (PIF) for example, has allocated an investment of $10 billion towards green hydrogen development [4]. Complemented by national strategic plans like ‘Saudi Vision 2030’, which aims to diversify the country's economy beyond oil [5], there is a harmonised national commitment towards developing the country's hydrogen sector. Saudi Arabia's announced target is to produce 1.2 million tonnes per annum (mtpa) of green hydrogen by 2030, which would result in capturing 10% of the global market [6]. In addition to advancing national diversification targets, this hydrogen ambition presents a major strategic export

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* Corresponding author. Heat Pipe and Thermal Management Research Group, College of Engineering, Design and Physical Sciences, Brunel University London, UB8 3PH, UK.

E-mail address: hussam.jouhara@brunel.ac.uk (H. Jouhara).

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Abbreviations

GCC = Gulf Cooperation Council
HSC = Hydrogen Supply Chain
MILP = Mixed Integer Linear Programming
AHP = Analytic Hierarchy Process
MCDM = Multiple Criteria Decision Making
SMR = Steam Methane Reforming
CCS = Carbon Capture and Storage
LCOH = Levelized Cost of Hydrogen
MTPA = Million Tonnes Per Annum
BCM = Billion Cubic Metres
KW = Kilowatts
NPV = Net Present Value
CF = Carbon Footprint
AEM = Anion Exchange Membrane
PEM = Proton Exchange Membrane
PIF = Public Investment Fund

opportunity. With an annual solar radiation of 2200 kWh/m^2 [7], Saudi Arabia is placed well above the global average range of 640–2400 kWh/m^2 [8]. As a result of this abundance, the country has the natural capacity to become a leading exporter of green hydrogen. In contrast, regions such as Europe and Far East Asian countries like South Korea and Japan, face limited renewable energy potential and are expected to rely on imports for their future hydrogen supply [9]. Saudi Arabia's central geographic position between these two markets offers efficient trade flows to both regions, placing the country in an advantageous position to capture substantial economic benefits from future hydrogen ecosystems [10]. Despite this potential however, designing a hydrogen supply chain that balances cost, environmental, and safety/risk objectives requires careful planning and modelling that can capture changes in the performance of the supply chain over time. In the current literature, there are numerous studies that assess hydrogen supply chains (HSCs). Dagdougui [11] for example, conducted a review on existing planning and design systems for hydrogen supply chains. This study found that the majority of existing work utilises mathematical optimisation methods for the design of HSCs, as they are the most effective for planning future infrastructure design. However, most of the work was found to use single-objective optimisation focusing on the minimisation of either costs or emissions when optimising a HSC, with fewer works addressing the issue of safety/risk. A similar trend was observed in Riera et al. [12], where hydrogen supply chain optimisation predominantly targeted minimising cost, with some consideration of environmental objectives, and less emphasis on safety/risk. Although each objective function is critical for the design and planning of a HSC, focusing solely on one is likely to require a sacrifice in the performance of the others. For example, focusing solely on the cost objective is likely to result in a supply chain that is more environmentally degrading or less safe, and vice versa [12]. Almansoori and Shah [13] noted a similar point. Their study determined that exclusive emphasis on a single objective (i.e. cost) is likely to require a trade-off between cost and the performance of the other objectives. Other studies have also investigated the implications of varying demand on the optimal design of hydrogen supply chain networks. In a further study, the authors Almansoori and Shah [14] designed a multi-period HSC in Great Britain focusing on cost minimisation considering hydrogen produced via steam methane reforming (SMR). In this study, it was found that at lower demand, the optimal HSC configuration consisted of dedicated, centralised production plants supplying hydrogen to distributed storage facilities of varying sizes. As hydrogen demand increased, production was satisfied through a combination of small and large-scale plants allocated according to regional demand density. Similar findings were noted in Refs. [15–17], where demand variations exerted a very strong impact on the overall system.

This work focuses on the design of a green HSC network for the Northwestern region of Saudi Arabia. The Northwestern region encompasses the provinces of Al Jawf, Tabuk, Hail, and Al Madinah, spanning a total length of 1809 km and a total area of 477,089 km^2 [18,19]. One of the main motivations for evaluating a hydrogen economy in this region is the region's vast importance to a large number of stakeholders (investors, decision-makers etc.) due to the area being home to Saudi Arabia's famous NEOM Green Hydrogen Project, which aims to become the world's largest commercial hydrogen facility focusing entirely on renewable-based, green hydrogen [20]. Another reason is that the Northwestern region is located directly along the coast of the Red Sea, where currently ~14% of global maritime trade and 30% of global containerised trade transit annually [21]. With the establishment of a hydrogen supply chain, the region could benefit from facilitated exports via these well-established export corridors.

The novelty of this study (discussed in greater detail in the subsequent sections) lies in the design of a fully green hydrogen supply chain in Northwestern Saudi Arabia, supported by a novel dynamic mathematical optimisation framework that integrates a hybrid multiple-criteria decision making (MCDM) approach to capture evolving stakeholder preferences through time-dependent weighting of economic, environmental, and safety criteria.

The remainder of this paper is structured as follows: Section 2 covers the literature review; Section 3 outlines the problem definition and chosen methodology; Section 4 covers the Saudi Arabia-specific case study and Section 5 discusses the results and recommendations.

2. Literature review

HSC design problems are frequently solved using mathematical mixed-integer linear programming (MILP) models. These problems may focus on a single objective, such as cost minimisation, or involve multiple objectives-i.e. the minimisation of cost and carbon footprint.

2.1. Single-objective optimisation

Single-objective optimisation remains the most commonly used approach to design and model HSCs in the literature. In Almansoori and Shah [13], an MILP model was developed to design a hydrogen supply chain network focusing on minimising total costs. Results found that the delivery of hydrogen via tube trailers became cheaper than liquid hydrogen transport as technologies developed. This resulted in the overall most cost-competitive HSC configuration being a gaseous hydrogen-based network, also because of the low production cost of compressed hydrogen gas. As previously referenced in Section 1, the authors further developed this model in a subsequent study [14] to account for the availability and logistics of energy sources (natural gas), as well as varying hydrogen demand in the long run. In this work, it was found that the optimal HSC configuration followed a similar structure to that of existing petroleum supply chains, where optimal production occurred in dedicated, centralised plants, optimal storage occurred in facilities of different sizes and optimal distribution occurred via a combination of trucks, railway tank cars and pipelines. Camelo et al. [22] used MILP for the optimisation of a green hydrogen supply chain network in North-East Brazil, also focusing on the minimisation of the cost objective. Results found that production and storage had the biggest effect on supply chain costs, but that when demand grew, production costs decreased due to economies of scale. The study also found that an optimised configuration decreased costs per kg/H_2 produced by36% between pessimistic and optimistic scenarios, again highlighting the influence of demand on HSC performance. Ibrahim and Mohannadi [23] used MILP to minimise the cost objective in a HSC under varying CO_2 emission mitigation policies. In this work, it was found that the lowest levelized cost of hydrogen (LCOH) naturally arose when there was no emission target ($3.41/kg$H_2$) but that at a 50% emission offset, green hydrogen actually became more cost effective than blue hydrogen due to the additional costs incurred by the natural gas required to generate heat for carbon capture and storage (CCS).

2.2. Multi-objective optimisation

While single-objective approaches focus on optimising one objective function, other studies have highlighted the importance of simultaneously considering multiple objectives (e.g. cost and environmental impact) to effectively manage trade-offs in hydrogen supply chain design. Hugo et al. [24] used MILP for a bi-objective optimisation model of a HSC considering both the cost and environmental objectives. Results found that, naturally, a cost-optimal hydrogen supply chain favoured production from natural gas, while an environmentally optimised configuration favoured renewable and biomass-based routes. However, the Pareto analysis showed that an environmentally focused supply chain could also remain cost-competitive with some integration of biomass gasification and renewable electrolysis, highlighting that the minimisation of trade-offs between different objectives is possible. Other studies [25–27] also investigated bi-objective MILP considering the cost and environmental objective functions. In Ogumerem et al. [25], an interesting finding was that even when the environmental objective was optimised, in a scenario where oxygen co-produced with hydrogen during electrolysis was further processed for sale instead of discarded, electrolysis became an economically viable option because of the added revenue. Again, this shows that the trade-off between conflicting objectives can be minimised with strategic HSC design. Another interesting observation was made in Amjath et al. [27]. In this study, it was found that unsatisfied demand incurred the greatest cost on the HSC in the long run, while implementing an emissions cap within the optimisation model actually minimised emissions-related costs. This finding, along with those in Refs. [14,22], highlight that demand remains a critical factor influencing HSC performance across both single and multi-objective optimisation frameworks. An important point to note is that the aforementioned studies all focused on bi-objective optimisation, while this study focuses on tri-objective optimisation considering the cost, environmental and safety/risk objectives. As for the mathematical modelling of the MILP problem, the ε-constraint method is the most commonly used approach in the literature. In this method, one objective function is optimised while converting the remaining objectives into constraints, each bound by a specified threshold (ε), allowing for the exploration of the Pareto trade-offs [28]. Another less commonly used method is the weighted sum approach, which aggregates multiple objectives into a single objective function by assigning weightings to each, thereby capturing trade-offs in HSC performance based on predefined preferences [29]. This study uses the weighted sum method but extends the traditional approach by introducing a dynamic, time-dependent formulation within the MILP framework, allowing the relative importance of objectives to evolve across planning periods.

2.3. Multiple-criteria decision making (MCDM)

Beyond technical optimality, the realisation of a hydrogen supply chain relies also on stakeholder preferences, as stakeholders will ultimately be the ones driving its real-world establishment. To incorporate these preferences into the HSC design as well as their evolution over time, this study employs multiple criteria decision making (MCDM), specifically the analytic hierarchy process (AHP) method. AHP describes a method of measurement where the importance of criteria relies on stakeholder judgement through pairwise matrices-i.e. each criterion is assigned a weighting based on how important it is to stakeholders relative to the other criteria [30]. This is done via three main steps. First, the decision goal is specified, in this case the three objectives (cost, environmental and risk), whereas the subsequent lower levels represent the breakdown of the decision criteria, sub-criteria and the alternatives for reaching the decision goal (see Figs. 5–7 for reference). Following this, the pairwise matrices are completed by the respective stakeholders (industry experts) for their opinion regarding the respective importance of each criterion and sub-criterion across the multiple objectives. In this matrix, the criteria are not independently ranked, but rather are ranked against each other. For example, in the economic objective, two criteria could be 'CAPEX' and 'efficiency'. If CAPEX is found to have a 'strong importance' over efficiency, it is given a numerical ranking of 5; conversely, efficiency will be given a weighting of 1/5 with respect to CAPEX. The same approach is followed across all criteria in each of the objective functions. The pairwise comparisons are based on a nine-point scale, which can be found in the Appendix. Following this, normalisation is performed by dividing each matrix element by the sum of its column, producing dimensionless values from which the relative priority weights are calculated. Finally, the last step for AHP is verification of consistency. Although expert judgment is critical for determining the relative importance of each criterion, because AHP remains subjective, the consistency of rankings is not automatically guaranteed. Therefore, consistency verification is performed via the computation of consistency ratio (CR) [30]. At this stage, the normalised matrix is used to derive the priority vector by averaging each row, producing the relative criterion weights. The weights are subsequently normalised such that their total sum equals 1. The maximum eigenvalue is then calculated to determine the consistency index (CI) and consistency ratio (CR). If the CR exceeds the acceptable threshold of 0.1, the pairwise comparison judgments are reconsidered and revised until acceptable consistency is achieved (i.e. $CR < 0.1$). If this is not the case and $CR > 0.1$, initial stakeholder judgements are revised. After all of the necessary pairwise comparisons, and revisions have been made, and the consistency ratio has also been found to be less than 0.1, the rankings are accepted as final and in the case of this study, integrated into the MILP for analysis. Manafzadeh et al. [31] used AHP for the determination of cost-optimal clean HSC pathway configurations. In this study, criteria such as 'feedstock cost' and 'resource availability' were the most important factors determining the optimal HSC pathways. This resulted in different optimal configurations for domestic consumption (blue hydrogen using existing natural gas infrastructure) versus export scenarios (green hydrogen based on solar energy to meet international clean hydrogen demands). Another study by Ransikarbum et al. [32] used AHP to evaluate the policy implications and sourcing decisions for HSCs in Thailand. Results from this study revealed that 'political acceptance' was considered the most important criterion for HSC development, and natural gas was found to be the most likely source for hydrogen production. Ren et al. [33] also used AHP in the context of HSCs. In this work, AHP was used to develop a method for prioritising and classifying the sustainability of hydrogen supply chains to assist decisionmakers in China. An important finding from this study was that SMR emerged as the preferred hydrogen production method across scenarios. However, from a technical standpoint, SMR is one of the least favourable options for hydrogen production in China due to the limited availability and high cost of natural gas [33]. This highlights a key limitation of relying solely on AHP, which primarily reflects subjective stakeholder preferences. While AHP is extremely valuable for incorporating qualitative insights into decision-making, its subjectivity emphasises the need to integrate it with mathematical MCDM tools to ensure that technical feasibility and objective performance criteria are also adequately captured in the assessment of hydrogen supply chains.

While previous studies have explored hydrogen supply chain optimisation, few have comprehensively addressed the temporal evolution of stakeholder priorities or system configurations. This study contributes to filling this gap via the following: criteria weightings are automatically adjusted across four planning periods (2025, 2035, 2045 and 2060) based on AHP–derived priorities and integrated into the dynamic weighted sum MILP to allow the model to endogenously reflect shifting stakeholder emphasis on cost, carbon footprint, and safety/risk criteria. A multi-period framework is considered to assess how the optimal supply chain configuration evolves under varying conditions over time, and multiple demand scenarios (low, medium, high) are considered in each time period to evaluate the impact of hydrogen demand uncertainty on the optimal configuration. The focus is on an entirely green hydrogen supply chain comparing electrolyser performance to leverage Saudi Arabia's natural advantages in solar-based hydrogen production. This assessment is achieved via a multi-objective optimisation framework that simultaneously minimises three objective functions: cost (in $), carbon footprint (in kgCO_2e), and safety/risk (index) via the introduction of a dynamic MILP-based weighted sum methodology that links the optimisation framework directly to stakeholder preference evolution, highlighting another novelty of this work.

2.4. Sensitivity analysis

To test the robustness of mathematical models, a sensitivity analysis can investigate how variations in input parameters influence resulting outputs [34]. Within the context of HSCs, this method can identify the criteria that most strongly affect the supply chain performance and assess the configuration's dependability under altering conditions. Kim et al. [35] used a sensitivity analysis on an MILP framework to analyse biomass supply chain networks. In this study, it was found that the availability and yield of feedstock were the most significant sources of uncertainty affecting profitability and optimal configuration. Similarly, Kim et al. [36] incorporated a sensitivity analysis into a bi-level optimisation model for HSC design. In this study, results indicated that the optimal configuration was found to be influenced by economies of scale, while high capital investment in hydrogen production and delivery technology were identified as the highest risk factors. Another interesting finding from this study was that renewable energy price uncertainty was found to impact net present value (NPV) by up to 20-30%, while discount rate variations were found to impact NPV by more than 15%. Other studies have used a sensitivity analysis in conjunction with MCDM to assess how changes in weighting factors or evaluation criteria influence the ranking and selection of supply chain alternatives. In Mangla et al. [37] for example, a sensitivity analysis was used alongside AHP for a risk analysis in green supply chains. This work found that specific high-priority risks for implementing and managing green supply chains included 'lack of government incentives', 'lack of top management commitment', and 'supplier unwillingness to participate in green initiatives. Other studies [32,38] also employed a sensitivity analysis in conjunction with TOPSIS to assess the robustness of alternative rankings in hydrogen supply chain design under different criteria weighting scenarios. In Ref. [32], it was found that the final ranking of renewable energy sites was most affected by changes in the weightings given to geographic and environmental criteria, such as wind speed and solar radiation.

3. Methodology

3.1. Problem definition and study contributions

This study focuses on designing a multi-period, multi-objective green HSC network for the Northwestern region of Saudi Arabia, encompassing three main echelons: production, storage, and transportation. The model aims to simultaneously minimise three conflicting objectives: cost ($), carbon footprint (kg$CO_2$e), and safety/risk (index). Four planning periods are considered in this study (2025-2060), with gaps of 10 years between T1-T2 and T2-T3 and a gap of 15 years between T3-T4. According to various sources [39–41], most green hydrogen supply chains are projected to be fully mature systems by 2060, explaining the authors' choice to increase the time gap between T3-T4. Low, medium, and high demand scenarios are analysed for each time period based on the projected penetration rate of green hydrogen in the transport sector at these times, discussed in greater detail in Section 4. A sensitivity analysis is then conducted to test the robustness of the optimal configuration. A key methodological novelty of this work lies in the introduction of a dynamic MILP-based weighted sum formulation that automatically updates criteria weightings in the MILP model over time in response to evolving stakeholder priorities. These preferences are quantified using an integrated AHP–MILP framework, which informs the optimisation model by assigning time-dependent weightings to the criteria across cost, environmental, and safety/risk objectives. This integration enables the model to adaptively reflect the temporal evolution of decision-maker priorities, providing a more realistic representation of long-term system planning. The weight changes across the planning periods are derived from the AHP pairwise comparisons, reflecting expected shifts in stakeholder priorities as hydrogen markets evolve. Here, early-stage decision making prioritises economic feasibility, while later stages increasingly emphasise environmental performance and safety considerations. The consistency of the AHP matrices was verified using the CR. Additionally, a sensitivity analysis was conducted by varying the criteria weights within predefined ranges to evaluate the robustness of the optimal supply chain configuration and to confirm that the main technology selection trends remain stable under moderate variations in stakeholder preferences. Fig. 1 presents the full methodological framework used in this study.

While a direct comparison with a conventional static multi-objective MILP was not performed in this study, the dynamic MILP approach is expected to offer advantages in capturing evolving stakeholder priorities over time. Unlike static models with fixed weightings, the proposed framework can adapt criteria weightings in each planning period to reflect changes in demand, risk perception, and environmental priorities, providing a more realistic representation of long-term hydrogen supply chain planning.

Because of Saudi Arabia's aforementioned comparative advantages in solar-based hydrogen production [7–10], solar energy is adopted as the sole energy source in this study, with the focus instead placed on production (electrolysers), storage, and transportation. For production, the electrolysers considered in this study are anion exchange membrane (AEM), proton exchange membrane (PEM), and alkaline water. For storage, compressed gas tanks, salt caverns, and cryogenic tanks are analysed, while the transportation options consist of compressed gas trucks, pipelines, and cryogenic trucks. These methods were selected as they represent the most technically feasible and commercially viable options for green hydrogen supply chain design [42–44]. Fig. 2 presents a schematic of the production, storage, and transportation methods analysed in this study, along with the objective functions and planning periods considered.

A previous study by the authors Olabi et al. [45] designed a multi-objective green HSC network in Kuwait focusing on a single period (2050). This work extends the previous analysis to a multi-period context for Saudi Arabia. In the Kuwait study, hydrogen demand was found to significantly influence the optimal configuration, particularly for production, as technically efficient electrolysers such as PEM only became advantageous once demand exceeded a certain threshold. Motivated by the geographic proximity of Saudi Arabia to Kuwait (they share a border), this study investigates whether similar HSC configurations could be adopted across the GCC. Accordingly, the study aims to answer the following key questions.

- How does the optimal HSC configuration evolve across multiple planning periods?
- How do different demand scenarios (low, medium, high) affect the optimal configuration over time?
- How do evolving stakeholder preferences influence optimal supply chain decisions over time?

3.2. Mathematical model

The mathematical model first developed by Almansoori and Shah [14] is employed in this study and extended to multi-objective optimisation through the addition of environmental and risk objective

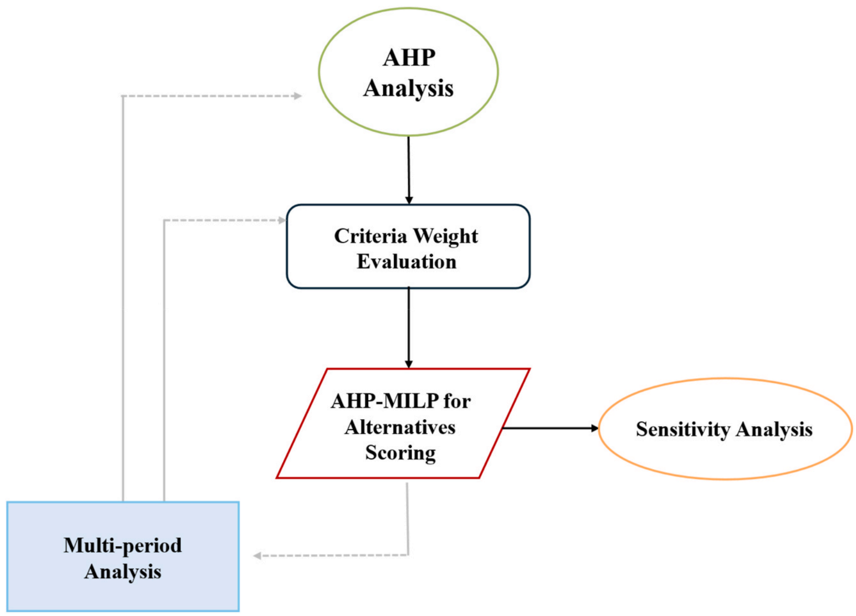

Fig. 1. Methodological structure for hydrogen supply chain network design.

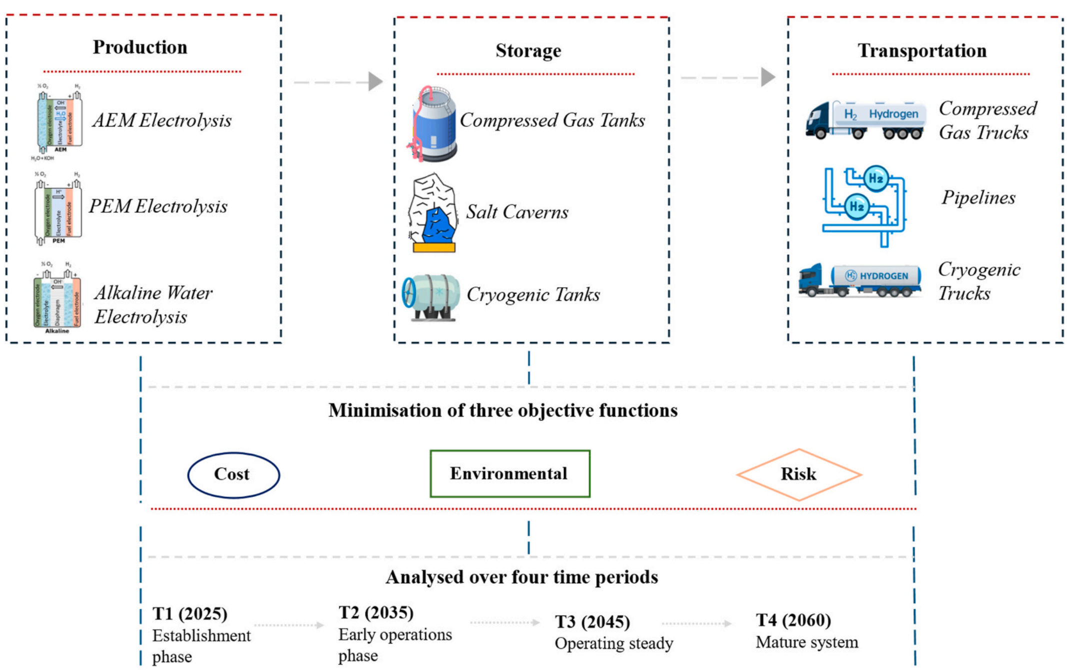

Fig. 2. Schematic of the hydrogen supply chain network, objectives, and planning periods.

functions. Following this, the traditional weighted sum method for multi-objective optimisation is described, followed by a presentation of the novel dynamic weighted sum approach. This new approach automatically updates objective weightings across multiple planning periods in response to evolving stakeholder priorities.

3.2.1. *Economic objective*

The economic objective function calculates the total cost (TC, in \$) of establishing and operating the hydrogen supply chain, including production, storage, and transportation across all planning periods. It incorporates both operational costs and investment decisions.

$$TC=\sum_{t}\Bigg[\sum_{p,g}P_{p,g,t}\cdot FOC_{p,g}+\sum_{s,g}S_{s,g,t}\cdot SOC_{s,g}+\sum_{l,g,g'}H_{l,g,g',t}\cdot TOC_{l,g,g'} + \sum_{p,g}\frac{FCC_{p,g}\cdot Y_{p,g,t}}{\alpha\cdot CCF}+\sum_{s,g}\frac{SCC_{s,g}\cdot Z_{s,g,t}}{\alpha\cdot CCF}+\sum_{l,g,g'}\frac{TCC_{l,g,g'}\cdot X_{l,g,g',t}}{\alpha\cdot CCF} + \sum_{l,g,g'}H_{l,g,g',t}\cdot ESC_{l,g,g',t}\Bigg] \tag{1}$$

Here, the total cost (TC, in \$) is calculated by annualising the capital costs of facilities (FCC) and transportation (TCC) over the network's operating period (α) using the capital charge factor (CCF). The resulting annualised capital cost is then added to the operating costs of facilities

(FOC) and transportation (TOC), as well as the energy costs for transportation (ESC), to determine the overall TC.

3.2.2. Environmental objective

The environmental objective describes the total carbon footprint (in kg CO2e) of production, storage and transportation:

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

Here, total carbon footprint (CF*tot*) is equal to the sum of the total carbon footprint in production (PCF), storage (SCF) and transportation (TCF).

The total production carbon footprint (PCF) is equal to the amount of hydrogen produced at each production plant p in grid g (P_{pjg}) multiplied by the carbon footprint per kg H_2 produced in that specific plant (GP_p):

$$PCF = \sum_{p,j,g} GP_p \tag{3}$$

Storage follows a similar calculation, where storage carbon footprint (SCF) is determined by multiplying the quantity of hydrogen stored using technology s in grid g (S_{sg}) by the carbon footprint per kg H_2 stored for that technology (GS_s):

$$SCF = \sum_{s,g} S_{sg} GS_s \tag{4}$$

The transportation carbon footprint (TCF) accounts for the emissions associated with hydrogen transport between grids, considering distance, transport mode, and flow quantity. It is calculated by summing hydrogen transportation modes (l) and origin-destination grid pairs (g, g'), multiplying the amount of hydrogen transported ($H_{lgg'}$) by the carbon footprint per kg/H_2 per km for that specific transportation mode (GT_l, in kg Co_2e/kg per km) and the distance between grids ($AD_{lgg'}$):

$$TCF = \sum_{l,g,g'} H_{lg\,g'} GT_l AD_{lg\,g'} \tag{5}$$

3.2.3. Safety/risk objective

The risk objective encapsulates the total risk (TR) in production, transportation and storage, and is measured by an index, following the method used in Kim et al. [36]:

$$TR = TPR + TSR + TTR \tag{6}$$

Here, 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). For briefness, these equations have not been included in the main body of this paper but can also be found in the Supplementary Materials document.

In general, the safety/risk objective function follows a similar structure to the carbon footprint formulation, where production risk is determined by the operational and technological hazards at each facility, storage risk is linked to the quantity and type of storage technology employed, and transport risk depends on the mode, distance, and volume of hydrogen moved between locations.

3.2.4. Traditional weighted sum method

As mentioned in Section 2, the weighted sum method requires three objective functions being combined into a single objective by multiplying each objective by a specific weighting. 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, the merged objective function is constructed by summing the weighted normalised objectives. The problem is then converted into a single objective optimisation problem, as follows:

$$\min Z(x) = w_1 .Z_1(x) + w_2 .Z_2(x) + w_3 .Z_3(x)\ldots\ldots + w_n .Z_n(x) \tag{7}$$

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

$$\min\ w_1 .\ TC + w_2 .\ TCF + w_3 .\ TR \tag{8}$$

3.2.5. Dynamic weighted sum method

Unlike the traditional weighted sum method, in the novel dynamic weighted sum method proposed in this study, the weightings are no longer static. Instead, they are automatically updated for each planning period based on the derived stakeholder preferences using the integrated AHP-MILP framework. The weightings of each objective function are time-dependent, reflecting the evolution of stakeholder priorities and system conditions across multiple planning periods. The single-objective function for period t is expressed as:

$$\min Z(t) = \sum_{n=1}^{n} w_n(t)\ .\ Z_n\ (x) \tag{9}$$

Here, Z_n (x) represents objective function (n) (i.e. economic, environmental or risk), w_n (t) represents the weighting assigned to objective n at planning period t, updated dynamically for each period and N represents the total number of objectives.

The time-dependent weighted sum objective thus becomes:

$$\min Z(t) = w_1 .Z_1(x) + w_2 .Z_2(x) + w_3 .Z_3(x)\ldots\ldots + w_n .Z_n(x) \tag{10}$$

4. Saudi Arabia: Case study

4.1. Grid-based spatial assessment

The Northwestern region of Saudi Arabia, presented in Fig. 3, is divided into 40 grids for sufficient spatial representation. The grid allocation was weighted by the relative land area of each province, presented in Table 1, and resulted in the following distribution: Tabuk (12 grids), Al Madinah (12 grids), Hail (10 grids), and Al Jawf (6 grids). The grid distribution is presented in Fig. 4. All grids represent areas where hydrogen can be produced via all electrolyser types (AEM, PEM, and alkaline water), stored in compressed gas tanks, salt caverns or cryogenic tanks and transported via gas or liquid trucks and pipelines. For storage, Saudi Arabia presently has no known salt caverns. However, the Northwestern region is home to the extensive Saq Aquifer, a deep, laterally continuous aquifer [46]. Aquifers present substantial potential for hydrogen storage, particularly in the GCC [47], and parts of the deep, confined Saq Formation meet the depth (~1100 m) and pressure (~300 bar) conditions suitable for porous-media hydrogen storage [48]. By analogy with typical aquifer storage evaluations, this study assumes that about 10% of the total 65 billion cubic metres (BCM) volume of the Saq Aquifer [49] is designated for hydrogen storage-i.e. 6.5 BCM.

In the subsequent results section, four case studies are presented, representing each time period analysed (T1: establishment phase), (T2: early operations phase), (T3: steady operations) and (T4: mature system). In each of these periods, a low-demand scenario, a medium-demand scenario and a high-demand scenario are analysed. The demands in each period are calculated according to the projected hydrogen fuel cell vehicle (HFCV) penetration rate during these years. For T1-2025, Saudi remains in the early demonstration phase of HFCV development. Presently, there are about 10 known hydrogen vehicles operating in Saudi Arabia [50–52]. The production of 1kg/H_2 fuel for each vehicle via electrolysis requires 60 kWh of electricity, with each vehicle granting a consistent driving operation of 400 km [53]. In this study, demand values expressed in kW represent the average equivalent power required to produce the corresponding hydrogen demand via electrolysis on an annual basis. Converted to kW per vehicle, this yields a high demand scenario of 9 kW, so total high demand for T1 is accepted as 90 kW. Medium demand is considered 50% of high demand (45 kW for 2025) and low demand is considered 20% of high demand (18 kW). In T2 (2035), Saudi Arabia is aiming for a green hydrogen production of 4 MTPA, with about 5% to be used for domestic consumption [54]. The

Province	Area (in km²)
Al Jawf	85,212
Tabuk	136,000
Hail	103,887
Al Madinah	151,990

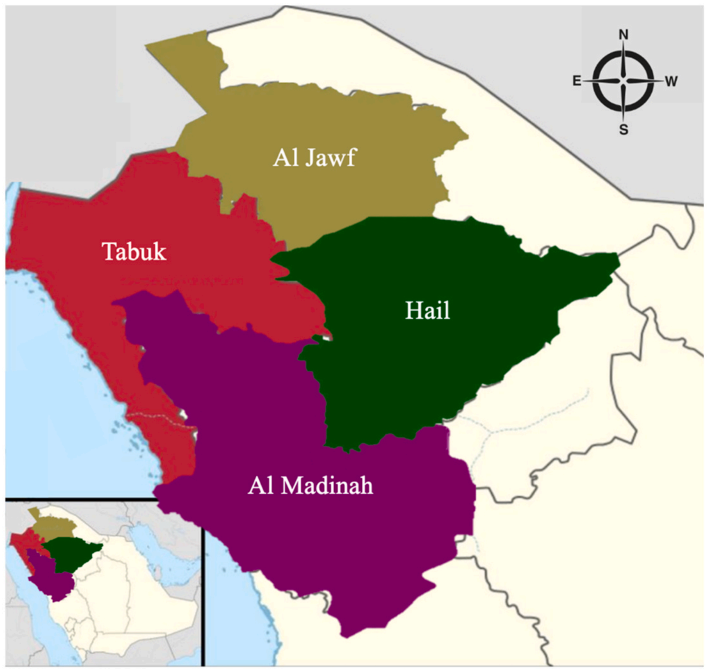

Fig. 3. Northwestern Saudi Arabia provinces.

Table 1
Area by province.

Province	Area (in km^2)
Al Jawf	85,212
Tabuk	136,000
Hail	103,887
Al Madinah	151,990

reported values represent the equivalent average power demand required annually to produce the hydrogen allocated to the transport sector via electrolysis. This yields a high demand of 760,000 kW for 2035. Using the same 50%, 20% breakdowns for medium and low demands this yields demands of 380,000 kW (medium) and 152,000 kW (low) for 2035, respectively. T3 and T4 were calculated following the same approach, accounting for Saudi Arabia's targeted hydrogen production in these years, and the share going towards domestic HFCVs in 2045 and 2060. The full demand values for T1-T4 are presented in Table 2.

Aside from the aquifer conversion for hydrogen storage, other considerations were made to reflect Saudi Arabia's natural conditions. Due to Saudi Arabia's arid climate (>30 °C) and freshwater scarcity, operational and maintenance costs were marginally increased to reflect the cooling requirements and higher costs of water due to desalination requirements. This is a similar approach to that used in the previous Kuwait study [45]. Regarding transportation, hydrogen takes about four times more energy to move through a retrofitted natural gas pipeline than natural gas [44]. As such, this study assumes that a new pipeline infrastructure would need to be established for hydrogen to be transported via pipelines. According to the literature, hydrogen pipeline installation costs about 68% more than a natural gas pipeline [55]. In Saudi Arabia, the Master Gas System (MGS) pipeline is the nation's largest natural gas pipeline system, which costs ~$1.9 million per km [56]. Considering the 68% inflated cost for hydrogen pipelines and the Northwestern region's 1809 km length, a capital investment of $3.44 billion is assumed for the construction of the pipeline network.

For parameters related to risk throughout production, storage, and transportation, these were classed as either ‘low risk’ ‘moderate risk’ or ‘high risk’ and were evaluated according to the risk assessments conducted in Refs. [57–59]. These are presented in Table 3.

For the AHP analysis, Figs. 5–7 present the schematic charts for each of the economic, environmental and safety/risk criteria assessed in this study. A total of 31 criteria are compared across production, storage and transportation throughout T1-T4. For the criteria weightings (i.e. relative importance), the normalisation (scaling between 0 and 1) is first conducted to include the time-dependent weightings $w_n(t)$ and standardise differing units among the criteria. The normalised objective function, including the time-dependent weightings, is presented in equation (15), as follows:

$$\min\ w_1.(t)\left(\frac{TC - TC_{min}}{TC_{max} - TC_{min}}\right) + \min\ w_2.(t)\left(\frac{TCF - TCF_{min}}{TCF_{max} - TCF_{min}}\right) + \min\ w_3.(t)\left(\frac{TR - TR_{min}}{TR_{max} - TR_{min}}\right) \quad (15)$$

After obtaining the normalised objective function, the next step is to derive the criteria priority weightings by computing the principal vectors of the normalised pairwise-comparison matrix. This yields the

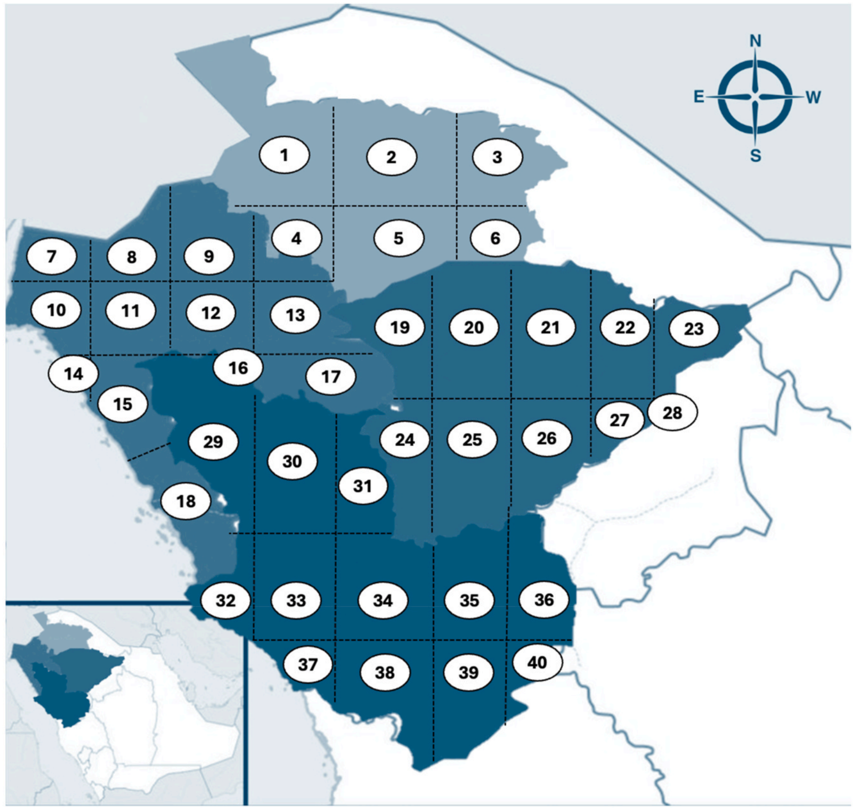

Fig. 4. Northwestern Saudi Arabia grid distribution.

relative importance of each criterion, which is then validated through a consistency check (CI and CR) to ensure the judgement matrix is acceptable. Four separate AHP evaluations were conducted for periods T1-T4, resulting in the time-dependent weighting vectors $w(t_1)$, $w(t_2)$, $w(t_3)$ and $w(t_4)$. These dynamic weightings were then integrated directly into the optimisation model in equation (10). The pairwise matrices for all four time periods, as well as the AHP criteria weightings can be found in the Appendix.

5. Results and discussion

5.1. Case study 1- Establishment phase (T1: 2025)

In the subsequent results Figures 8–11, the green bar represents the highest-scoring alternative, yellow represents the second-best and red represents the least-optimal. For production in the establishment phase (2025), alkaline water electrolysers performed the most optimally. In general, this suggests that because of CAPEX's high weighting, they scored the highest due to having the lowest cost. However, pipelines also ranked the highest in transportation despite having the highest cost between the transport options, so there is more that needs to be considered. With respect to electrolysers, the interplay between production capacity utilisation and efficiency becomes evident at this stage. In T1, efficiency is a highly weighted criterion, and alkaline water is technically the ‘least’ efficient of the electrolysers. This result highlights that during the early deployment stage of a hydrogen supply chain, economic feasibility tends to dominate technology selection, as investment risks and capital availability strongly influence infrastructure development decisions. However, the dynamics between capacity utilisation and efficiency show that alkaline water electrolysers can operate efficiently in moderate-load ranges and tolerate being used at under-capacity without significant efficiency losses, whereas PEM and AEM experience sharper efficiency penalties when running below their optimal capacity utilisation. This finding suggests that technologies with higher operational flexibility can outperform theoretically more efficient alternatives when system demand is still developing, and utilisation levels remain uncertain. Another interesting observation lies within safety/risk. In the aforementioned risk-level evaluation, alkaline water is classed as a high-risk electrolyser but scored the highest despite risk's high weighting. This presents an underlying dynamic between how risk interacts with efficiency. As shown by the efficiency/production capacity dynamic, alkaline water electrolysers can tolerate partial loads better and endure smaller efficiency drops when underutilised. This is important because low demand equates to low electrolyser utilisation. So, although alkaline water electrolysers have a higher ‘theoretical’ risk index, their operational stability under low-demand conditions offsets some of the risk penalty in practice. For storage, salt caverns displayed net optimality across the demand scenarios. Unlike electrolysers, which are more sensitive to capacity utilisation, salt caverns do not face major trade-offs, even at low demand. In this case, CAPEX presents as cost per storage option per unit, not per kg actually used in that moment, so salt caverns are not penalised for being underutilised, conversely to electrolysers. As such, for storage technologies, salt caverns with very high capacity at very low normalised CAPEX score extremely well, regardless of whether the full capacity is exploited. This also reflects the strategic value of large-scale geological storage in hydrogen systems, where long-term buffering capacity can support future demand growth without requiring immediate full utilisation. Similarly, for transportation, pipelines scored the highest despite CAPEX being the highest weighted criterion for 2025. This is due to their overall system-level advantages accumulating across multiple high-weighted operational criteria, such that their high CAPEX disadvantage is mitigated by superior performance in efficiency, risk, lifetime, and throughput-related metrics. Unlike storage, this outcome is not driven by dominance in a single criterion, but by alignment with how transportation value is created across pipelines' CAPEX relative to their high efficiency and lower risk. Another important point to consider is efficiency. Although cryogenic trucks (60%) have a slightly higher numerical efficiency than pipelines

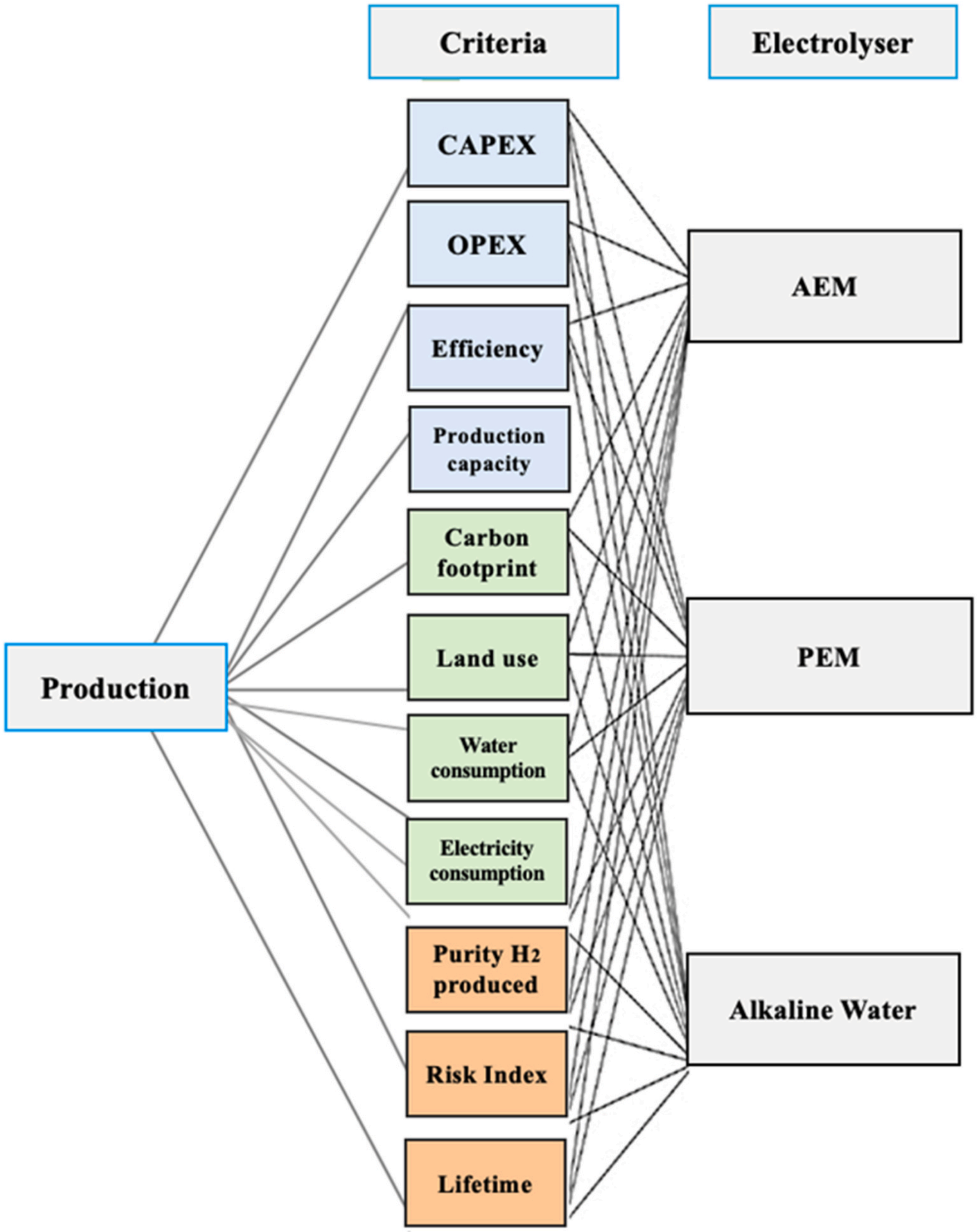

Fig. 5. AHP schematic for hydrogen production criteria.

(57%), as with electrolysers, the efficiency works in tandem with other criteria. Transport efficiency fundamentally favours pipelines because pipelines achieve high, stable efficiency without continuous energy input, while cryogenic trucks require persistent energy for liquefaction and boil-off management. Consequently, pipelines score highly without triggering these penalties that trucks at this demand level do not avoid.

5.2. *Case study 2- Early operations phase (T2: 2035)*

For production, similarly to T1, alkaline water remained the optimal electrolyser across demand scenarios. Unlike T1 however, where overall demand was lower, alkaline water's economies of scale in production become evident in 2035. When demand increases to the T2 levels, alkaline water electrolysers can deliver larger absolute hydrogen volumes per unit, reducing the need for multiple smaller units. In turn, this improves CAPEX, thus encouraging alkaline water's already existing cost advantage. This suggests that as hydrogen demand begins to scale, technologies capable of supporting larger production capacities become increasingly advantageous within supply chain optimisation frameworks. Alkaline water's higher production capacity (20 MW) also allows for better integration with intermittent renewable supply, allowing alkaline water electrolysers to maintain near-optimal efficiency at elevated demand. This compatibility with variable renewable generation is particularly important in the GCC region, where solar resources dominate and flexible hydrogen production technologies can help stabilise energy supply fluctuations. Another underlying relationship that becomes evident is that between efficiency and lifetime. PEM has a slightly higher technical efficiency (75%) than alkaline water (70%), and efficiency is the highest-weighted criterion in 2035 (0.154). However, alkaline water's longer operational lifetime compared to PEM's (90,000 h $>$ 70,000 h) spreads both CAPEX and OPEX across more production hours. This becomes increasingly important at higher demand, because units move closer to full utilisation. Although PEM becomes closer in performance at higher demand due to being used closer to its optimal capacity, running PEM at this higher capacity stresses maintenance schedules - and in turn, OPEX - thus slightly reducing its

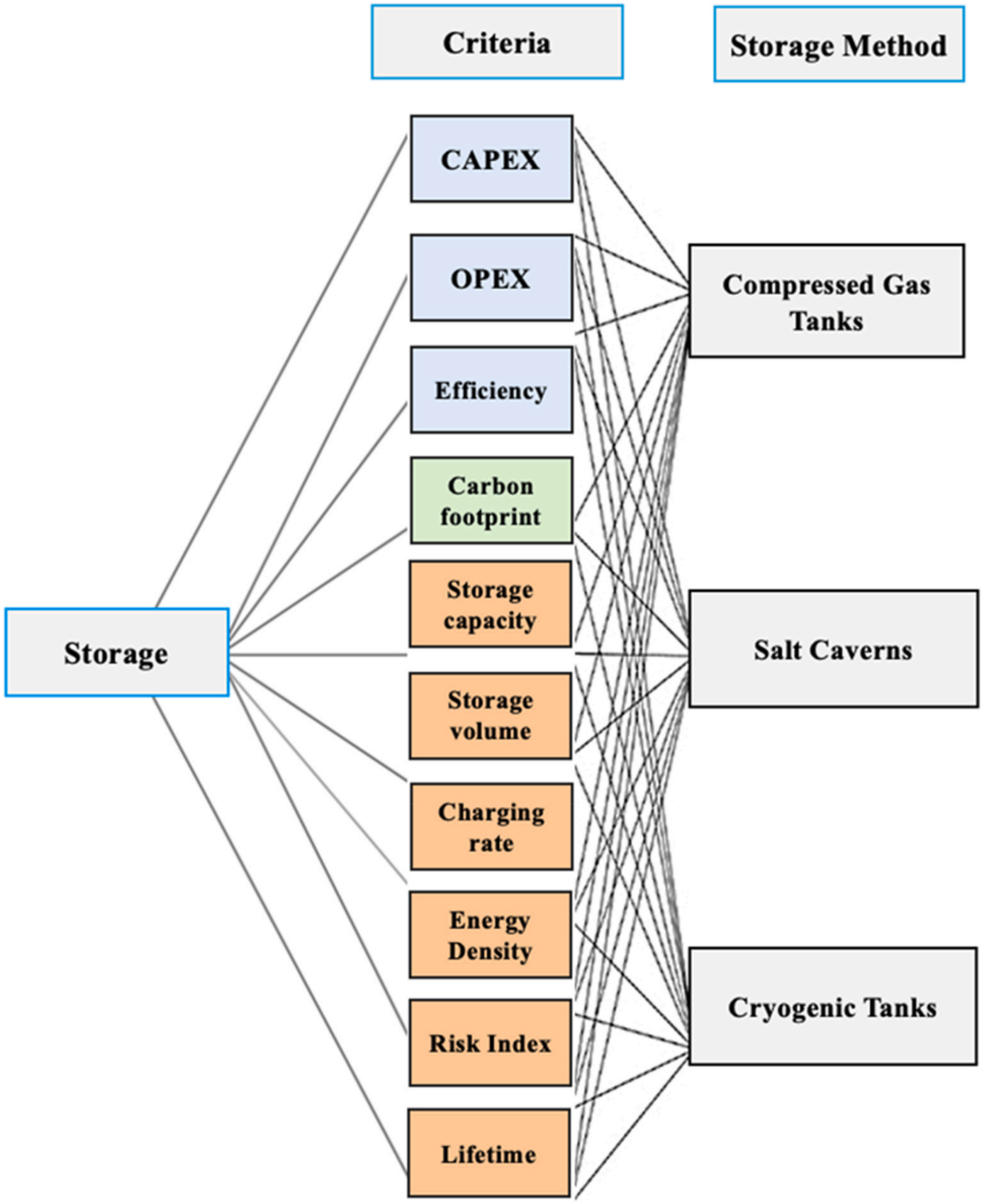

Fig. 6. AHP schematic for hydrogen storage criteria.

long-term availability and impacting its efficiency relative to its lifetime. This results in alkaline water once again scoring the highest due to its combined lifetime and capacity being able to deliver better total system cost-efficiency, outweighing marginal efficiency differences. These findings indicate that long-term operational durability can become a decisive factor in hydrogen infrastructure planning, particularly in systems expected to operate continuously at higher utilisation levels. For storage, salt caverns again emerge as the net-optimal storage choice. Here, the dynamic between efficiency and energy density and their resulting impact on OPEX become critical factors reinforcing salt caverns' dominance. Salt caverns have an efficiency of 95% and an energy density of 7 kg/m^3. Conversely, cryogenic tanks excel in energy density (70.8 kg/m^3) and have an efficiency of 60%. Although cryogenic tanks excel in energy density, their lower efficiency and high OPEX offset this advantage, especially when energy losses over large volumes are accounted for. Salt caverns provide high storage efficiency, which becomes increasingly valuable as production and consumption rates scale, ensuring minimal energy losses for system-level hydrogen balancing. This indicates that for large-scale hydrogen systems, storage technologies that minimise energy losses over long durations can provide greater overall system value than technologies prioritising compactness or high energy density alone. The dynamic between lifetime and storage capacity also favours salt caverns. Salt caverns' advantageous lifetime and storage capacity allow them to absorb the growing demand in 2035 without additional investment. Cryogenic tanks conversely have shorter lifetimes and require ongoing costs for refrigeration infrastructure, in turn increasing their OPEX and lowering their overall score. For transportation, a very interesting finding presents in the 2035 results. Although pipelines again score the highest, the score difference between pipelines and cryogenic trucks increases (0.08) compared to 2025 (0.02), despite CAPEX having the highest weighting in 2025. At lower overall demand (i.e. 2025), cryogenic trucks' key strengths, namely high energy density and long driving ranges are not fully exploited because hydrogen flows are small and intermittent. As such, liquefaction and boil-off losses disproportionately penalise efficiency at this stage. By contrast, pipelines at low demand benefit from low risk, high reliability, and continuous flow, even at low utilisation. However, by 2035, the increased demand reduces penalty asymmetry,

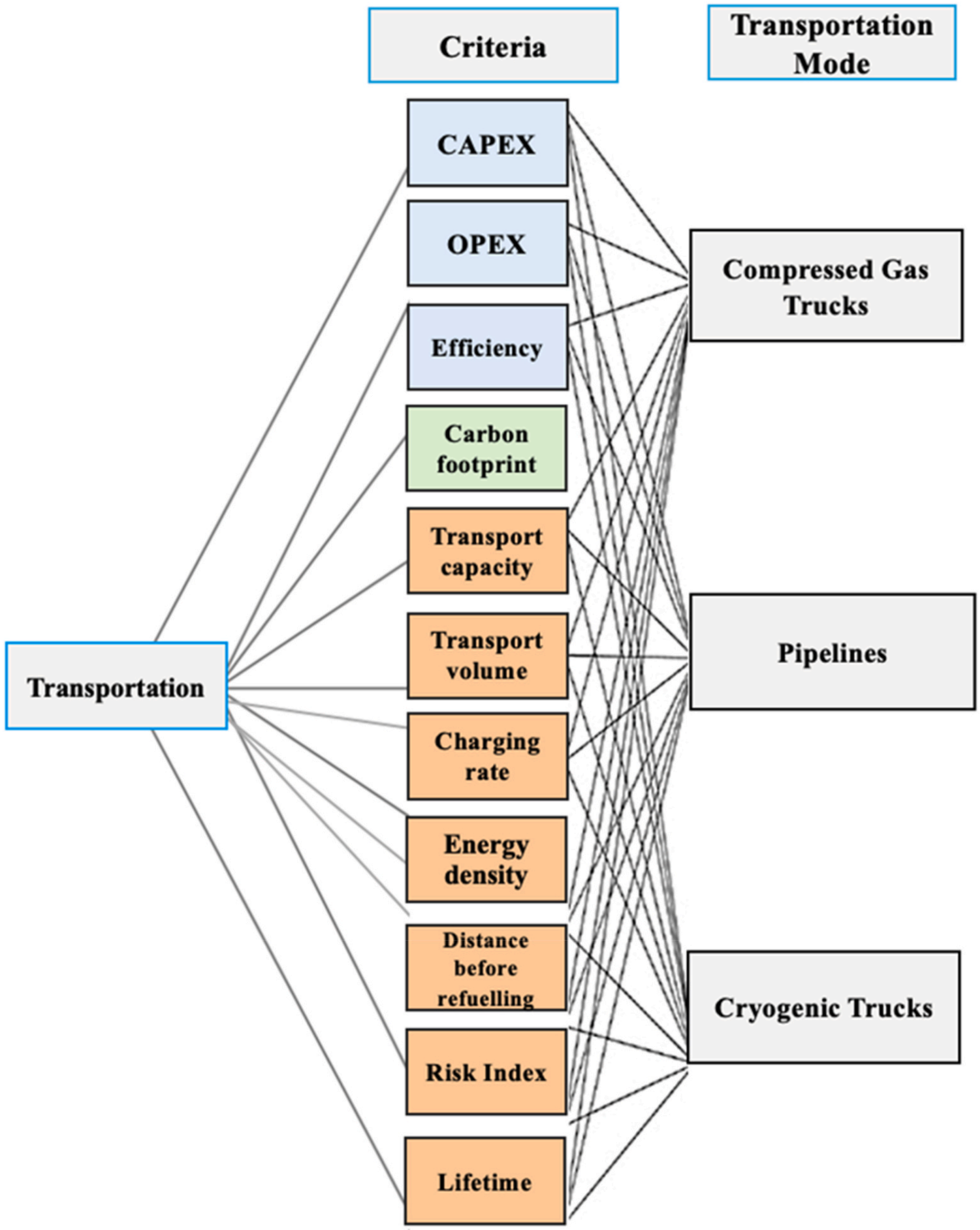

Fig. 7. AHP schematic for hydrogen transportation criteria.

Table 2
Green hydrogen demand projections in the transport sector (2025-2060).

Time period	Low (kW)	Medium (kW)	High (kW)
T1 (2025)	18	45	90
T2 (2035)	152,000	380,000	760,000
T3 (2045)	209,000	522,500	1,045,000
T4 (2060)	562,800	1,407,000	2,814,000

shrinking the performance gap and allowing cryogenic trucks to compete better.

5.3. Case study 3- Steady operations (T3: 2045)

In T3, again alkaline water emerged as the optimal electrolyser across demand scenarios. Here, production capacity becomes structurally decisive. By 2045, because hydrogen demand is large, continuous, and industrially anchored, the alkaline water electrolyser's high unit capacity (200 MW) reduces system complexity (i.e. fewer stacks) and improves system availability. This indicates that at mature stages of hydrogen system development, technologies that support large-scale centralised production become increasingly advantageous in maintaining operational stability and reducing infrastructure complexity. However, the gap between alkaline water and PEM narrows (0.03 difference) in 2045. This is important to consider as it is not caused by a 'weaker' performance of alkaline water electrolysers, but rather by changing marginal values of key criteria (risk and carbon footprint) under very high demand. Risk becomes a more binding factor at 2045 demand levels. Unlike T1, where alkaline water's higher risk was mitigated by less usage, in T3, alkaline water operates closer to its 200 MW production capacity. Consequently, the risk penalties become more binding, thus narrowing the gap as PEM is a lower risk electrolyser closer to its full capacity. This reflects how operational risk considerations become more critical as hydrogen infrastructure scales, particularly when large facilities operate near maximum capacity for extended periods. Another key reason for the gap narrowing is not carbon footprint in itself, but the

Table 3
Risk level evaluation of HSC.

Electrolyser	Risk level	Reasoning
AEM	Moderate	Ignition risk between H_2/O_2
PEM	Moderate	Ignition risk between H_2/O_2
Alkaline water	High	Thick membrane increases ignition risk between H_2/O_2
Storage methods		
Compressed gas tanks	High	High pressure required to store hydrogen in its gaseous state (350-700 bar), increasing risk of explosion
Salt caverns	Low	Underground salt formations are impermeable (no runoff or contamination)
Cryogenic tanks	Moderate	Requires ventilation to avoid asphyxiation
Transportation modes		
Compressed gas trucks	Moderate	High pressure required to transport H_2 in gaseous state (350-700 bar) increases risk of explosion if transport accident occurs
Pipelines	Low	No major risks if infrastructure is solid
Cryogenic trucks	Moderate	Boil-off due to gas leaks can lead to fire hazards

intertwined relationship that presents between carbon footprint and risk. Carbon footprint (0.135) is the other highest weighted criterion in 2045 aside from risk (0.136). Although PEM (6.07 kg CO_2e/kg H_2) has a higher carbon footprint than alkaline water (2.41 kg CO_2e/kg), alkaline water electrolyser's low carbon footprint strongly incentivises its deployment at very large scales, since emissions savings accumulate proportionally with hydrogen output. However, this same scale amplification intensifies the consequences of operational failure, making risk and carbon footprint intertwined. The lower carbon intensity encourages larger, more centralised alkaline installations, in turn increasing safety exposure. As a result, low carbon footprint, which makes alkaline water electrolysers attractive on environmental grounds simultaneously activates its risk disadvantage, giving PEM an advantage. This finding highlights a critical trade-off in large-scale hydrogen system design, where technologies that deliver superior environmental performance may simultaneously introduce greater operational risk at scale. For storage, salt caverns dominate in 2045 (0.512), significantly outperforming compressed gas tanks (0.225) and cryogenic tanks (0.262). Here, storage capacity becomes a system constraint. With a weighting of 0.124 (highest among storage criteria), and salt caverns' storage capacity of 20,000 tonnes when demand reaches 2045 levels, salt caverns are the only option capable of absorbing demand fluctuations and decoupling continuous production from variable consumption. Although more prominent at 2045 levels, this is also proven in the lower demands (2025 and 2035). If storage were tightly coupled to consumption, the high and low demands would favour flexible, modular tanks (i.e. cryogenic) or penalise capacity as in the case of electrolysers. Instead, salt caverns dominate independently of demand, which is only possible if the storage technology absorbs demand variability rather than responding to it. Another important consideration for storage here is risk. The 2045 results reveal that risk doesn't scale with consumption variability because risk with salt caverns remain constant across demand scenarios. Tank-based systems on the other hand become riskier as throughput increases. Like the demand absorption, this asymmetry "breaks" the production/consumption link, fortifying salt caverns' dominance. For transportation, pipelines again present as the optimal-performing transport mode in 2045. In this scenario, performance, continuity, and risk dominate, solidifying pipelines' optimal performance. Like in T2, the score gap between pipelines and cryogenic trucks again increases in T3 compared to 2025 when CAPEX was highly weighted. This is caused by an increasing efficiency penalty on cryogenic trucks as demand increases. At 2045 levels, because of the additional liquefaction and boil-off management requirements cryogenic

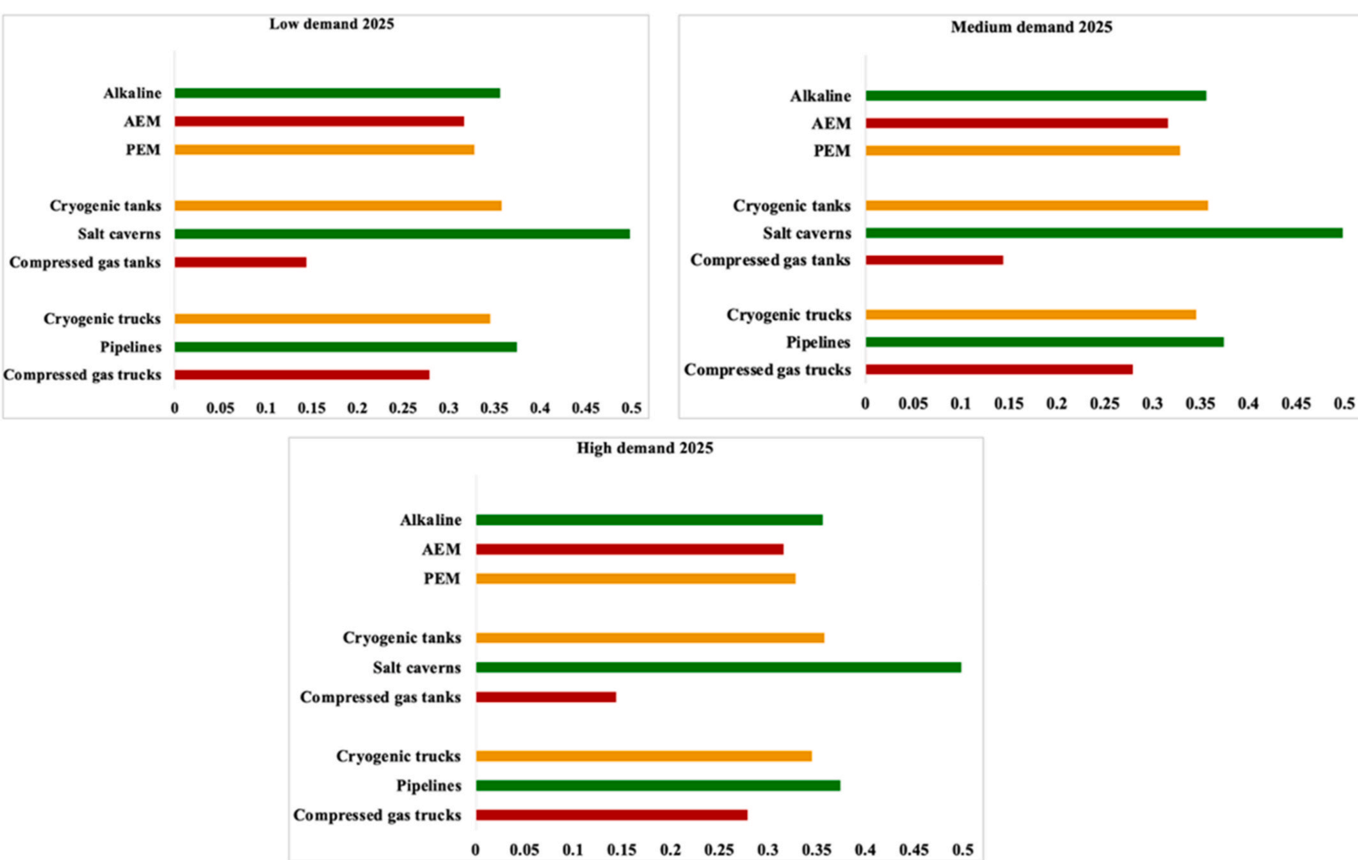

Fig. 8. T1 2025: Dynamic MILP low, medium and high demand results.

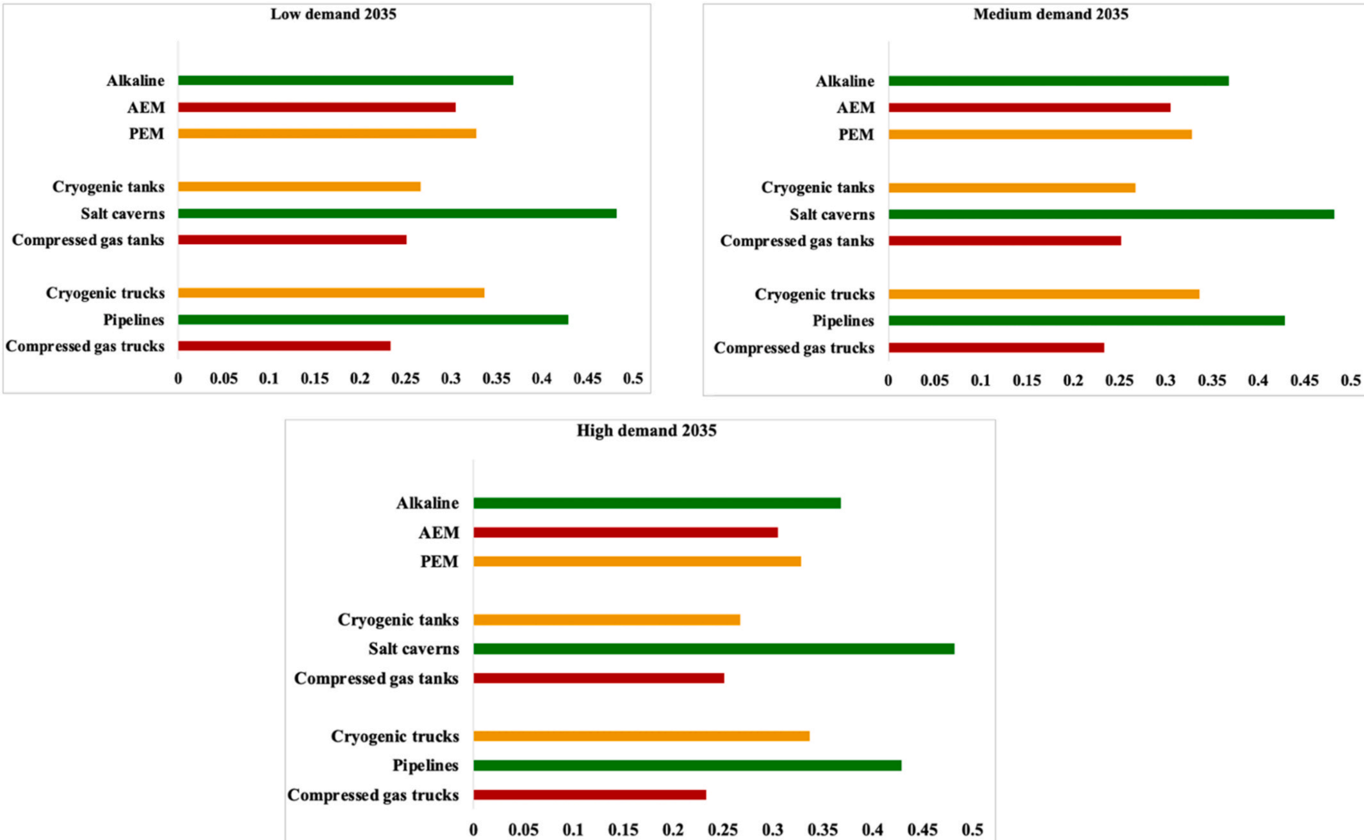

Fig. 9. T2 2035: Dynamic MILP low, medium and high demand results.

trucks need, a persistent energy penalty is imposed, causing cryogenic trucks to perform below pipelines when efficiency is highly weighted. This also has a domino effect on carbon footprint. The lower efficiency means that cryogenic trucks require more input energy per kg/H_2 delivered, which in turn results in a higher associated CO_2 per kg transported. Pipelines on the other hand benefit from the opposite dynamic: the higher efficiency results in a lower CO_2 per kg transported, which widens the gap. As such, at 2045 levels, the economies of scale of pipelines become evident despite their higher capital investment.

5.4. Case study 4- Mature system (T4: 2060)

A change in ranking is established in 2060 for production. Unlike T1-T3, 2060 sees PEM overtaking alkaline water to become the optimal electrolyser. Unlike the earlier periods (2025–2045), hydrogen demand in 2060 is high enough for PEM's efficiency to no longer be limited by part-load operation, allowing it to achieve its technically optimal efficiency (~82%). In the earlier 2035 results, PEM is pushed towards higher utilisation before the system is fully optimised, thereby resulting in increased maintenance intensity and OPEX. By 2060, both demand scale and technological maturity are sufficient to support optimally sized, continuously operated PEM installations. This effectively eliminates the transitional penalty, allowing efficiency improvements to translate directly into higher overall performance. This indicates that as hydrogen markets mature, technologically advanced electrolysers that prioritise efficiency and modularity may progressively outperform lower-cost but less flexible alternatives. While still efficient, the alkaline water electrolyser at this level does not gain any additional efficiency with higher load, so PEM closes the previous undercapacity/efficiency gap. Furthermore, unlike at lower demands where alkaline water's lower realised operational risk was linked to lower capacity utilisation, in 2060 risk becomes a critical factor penalising alkaline water. At large scale, the alkaline water electrolyser operates at its full capacity (500 MW). This large-scale operation amplifies the consequences of failure, increasing the effective impact of the risk index. On the other hand, PEM at this level benefits from modular, lower-risk stacks. This suggests that modularity and system redundancy become increasingly valuable characteristics in large-scale hydrogen production infrastructure. The carbon footprint/risk dynamic at 2060 levels also favours PEM. As in the case of 2045, alkaline water's low carbon footprint encourages large, centralised deployment, but again, this causes the interplay between carbon footprint and risk to activate, thus penalising alkaline water due to the increased risk exposure. By 2060, grid decarbonisation and improvements shift the balance towards PEM, due to the combination of lower risk, true efficiency and the efficiency/carbon footprint dynamic. These results highlight how long-term energy system decarbonisation can alter technology preferences within hydrogen supply chains by reducing the relative importance of cost-driven choices and increasing the importance of performance and system resilience. For storage in 2060, again salt caverns solidify their optimal performance. An interesting point to note here is the difference between how electrolysers perform in time versus storage methods. Storage technologies face structural asymmetries that amplify with scale, while production technologies face operational trade-offs that converge with scale. The score differences between salt caverns and cryogenic tanks over the 4 periods (0.14 in 2025) and (0.22 in 2060) confirm this. In the production scores, the variance collapses across time (0.04 to 0.01 score difference from 2025 to 2060), while for storage, the score spread widens, proving that highly weighted criteria move in the same direction over time and that larger demand amplifies these differences, rather than compressing them. Here, the mutually reinforcing efficiency/carbon footprint dynamic is evident again. At 2060 levels, salt caverns achieve 99.5% efficiency (minimal losses, no refrigeration) and 0.2 kg CO_2e/kg H_2 (no active energy input). In turn, this creates a positive feedback loop: the

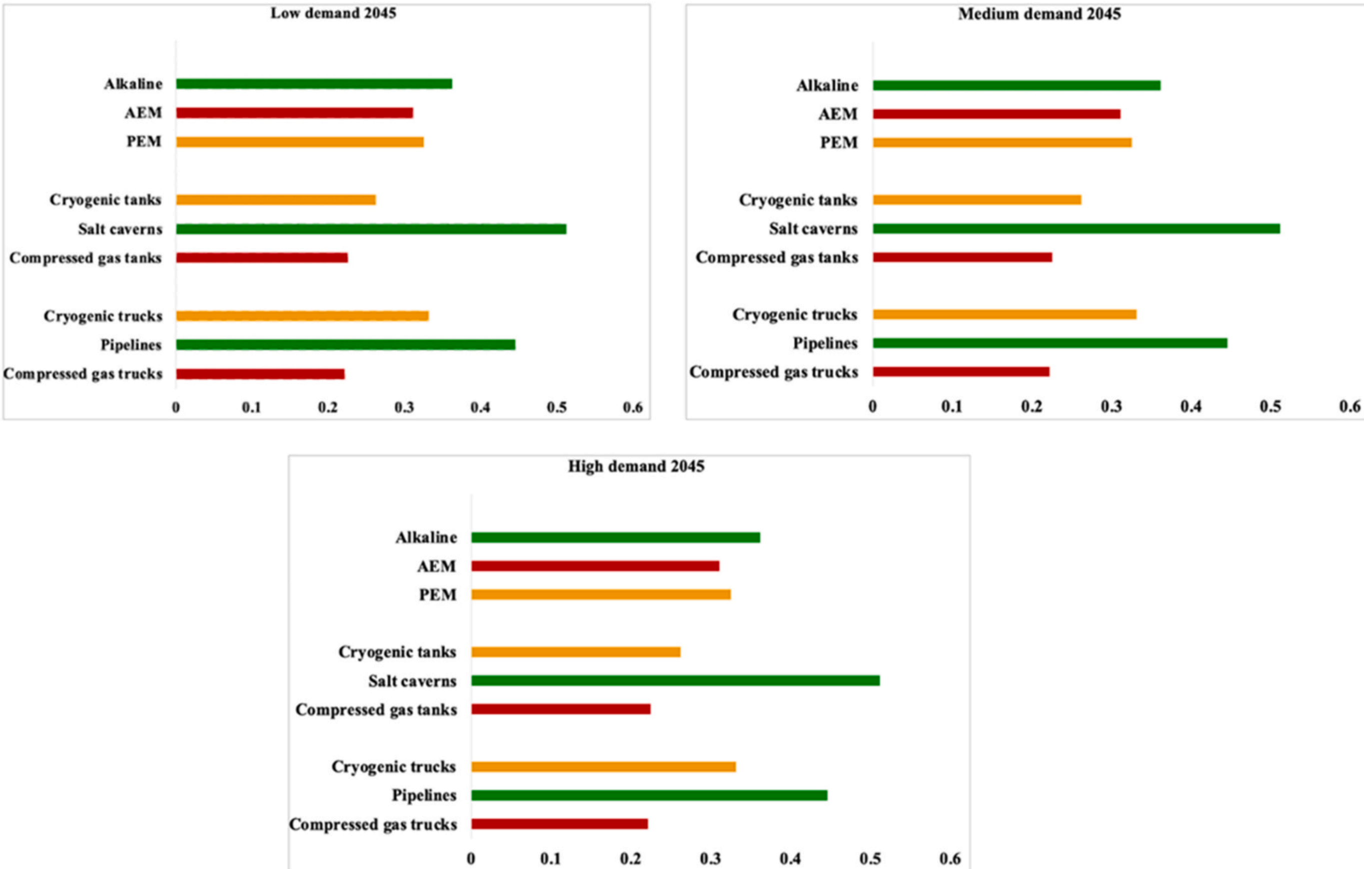

Fig. 10. T3 2045: Dynamic MILP low, medium and high demand results.

higher efficiency results in minimal energy input, which results in minimal emissions suitable for large-scale, long-duration storage. Cryogenic tanks on the other hand suffer the opposite: active refrigeration requirements lead to boil-off losses which lead to persistent energy demand. Thus, cryogenic tanks are penalised twice: once for lower comparative efficiency (78%) and again for higher carbon footprint (2.8 kg CO_2e/kg H_2). In practical terms, cryogenic tanks become increasingly costly and carbon-intensive over time and present as unsuitable for long-duration or low-turnover storage and perform better in short-duration, high-throughput niches, rather than as backbone infrastructure. Salt caverns on the other hand enable seasonal and strategic storage, as they stabilise the entire hydrogen system by decoupling production from demand without compromising costs, emissions, or efficiency. For transportation, pipelines again dominate at 2060 levels, scoring 0.1 over cryogenic trucks and 0.2 over compressed gas trucks. Again, this is a higher score difference than 2025 when CAPEX should have penalised pipelines. This widening score gap in 2060 demonstrates that like in the case of storage technologies, performance-based criteria activate reinforcing advantages. As with salt caverns, 2060 sees a positive feedback loop present itself for pipelines. As there is no continuous energy input, no boil off and a passive steady-state operation in place, pipelines' high efficiency is activated, leading to lower carbon footprint, lower risk and longer lifetime. As such, pipelines' advantages compound simultaneously, rather than the success of one criterion requiring sacrificing the performance of another. Cryogenic trucks remain relatively close due to their advantages like high energy density (76 kg/m^3), long distance before refuelling (1800 km) and reasonable efficiency (70%). However, the opposite dynamic to pipelines (negative feedback loop) presents itself again for cryogenic trucks at 2060 levels, allowing pipelines to remain ahead. At this level, cryogenic trucks suffer a double structural penalty: active liquefaction and refrigeration require continuous energy demand, resulting in higher carbon footprint and consequently, higher risk. Again, this highlights the efficiency/carbon footprint relationship which penalises cryogenic trucks at higher demand levels. Even with technology developments, this loop is unlikely to dissipate due to liquefaction being fundamentally energy intensive. As such, pipelines become structurally dominant at this level.

5.5. Sensitivity analysis- Mature system: high demand (T4: 2060)

To assess the robustness of the optimisation results, a sensitivity analysis was conducted to evaluate how incremental variations in individual criterion weightings influence technology rankings across the hydrogen supply chain. Although the dynamic MILP framework incorporates time-varying AHP-derived weightings to reflect the evolving importance of criteria across planning periods, these weights remain fixed within each time period. As a result, the impact of incremental deviations from the given weightings on the resulting rankings is not explicitly captured by the core optimisation. The sensitivity analysis therefore tests whether the optimal solutions identified by the dynamic MILP remain stable when individual criteria are emphasised or de-emphasised. The analysis was conducted for the 2060 high-demand scenario, as this represents the case where production, storage and transportation technologies operate near or at full utilisation, thus representing the most demanding operating condition of the system. The weighting of each individual criterion for all of production, storage and transportation was varied incrementally between 0 and 1. For each value tested, the remaining weighting (i.e. 1-w_i) was evenly distributed among all other criteria. For example, in the case of hydrogen production, if production capacity was weighted at 0.4, the remaining 0.6 was distributed equally among the other 10 criteria for production, resulting in weightings of 0.06 for the other criteria. The same approach was used

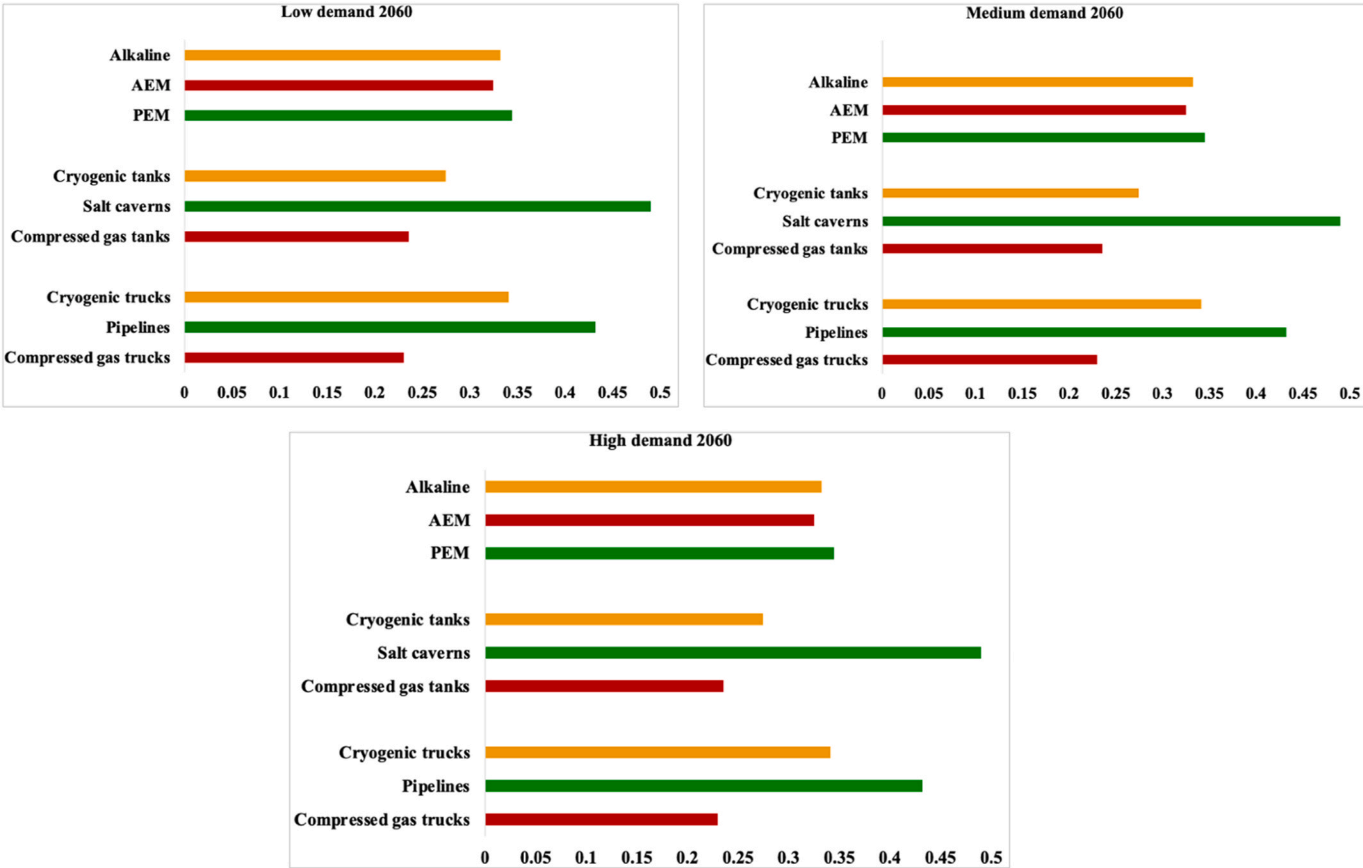

Fig. 11. T4 2060: Dynamic MILP low, medium and high demand results.

for storage and transportation. The results are presented in Figs. 12–14.

For production, the sensitivity analysis identified risk as the most influential criterion. Here, even small increments in risk weighting rapidly reduce alkaline water's score while increasing PEM's, indicating a high elasticity of the ranking to risk under 2060 conditions. This illustrates that large-scale, centralised technologies are more sensitive to operational risk than modular systems, highlighting the importance of risk mitigation strategies in future deployments. Consistent with the 2060 results and the lower-demand scenarios, alkaline water's risk disadvantage remains largely latent at low utilisation but becomes binding at near-full-capacity operation in 2060 when the system operates close to its maximum throughput. Under these conditions, alkaline water's larger and more centralised installations concentrate hydrogen inventory and production capacity, such that any single failure event carries disproportionately high system-level consequences. By contrast, PEM's modular stacks at 2060 levels limit propagation and allow them to perform optimally. Furthermore, the sensitivity analysis again supports the intertwined dynamic between carbon footprint and risk. When carbon footprint weighting increases from 0 to 1, alkaline water's score initially rises relative to PEM, confirming that in isolation, low emissions make alkaline water attractive. However, when risk weighting increases, PEM's score rises sharply, while alkaline water's drops. Again, this highlights that at high-demand, full-capacity operation, the low-carbon advantage of alkaline water is coupled with a higher operational risk - i. e. low-carbon installations exacerbate risk exposure in large-scale alkaline units. PEM's efficiency penalty when used at undercapacity is also confirmed by the sensitivity results. The slope of PEM's efficiency and production capacity curves demonstrates that if PEM were running below optimal load (like in T1–T3), it scores lower because part-load operation prevents full efficiency realisation. The fact that PEM's score increases sharply with higher efficiency and capacity weightings in 2060 confirms that its performance advantage is unlocked only when operating near optimal capacity. This demonstrates that multi-objective trade-offs are non-linear and scenario-dependent, underlining the value of dynamic weighting in capturing realistic decision-making. For storage, the sensitivity analysis confirms that, unlike production, storage rankings are highly elastic to multiple criteria, and this elasticity increases with scale. Storage capacity presents as the dominant structural criterion at 2060 levels, which is expected as the high demand requires long-duration, seasonal-scale buffering. As such, as the weighting increases, salt caverns gain an overwhelming advantage due to their geological scale capacity. Contrarily, compressed gas tanks collapse to zero as storage capacity weighting increases, meaning that at this level, they become structurally infeasible. However, an important observation lies with efficiency and energy density. In the T2 (2035) results, it was noted that salt caverns provide high storage efficiency. However, in the sensitivity results, increasing efficiency weighting steadily penalises salt caverns and favours cryogenic trucks. This contradiction arises due to efficiency being treated as a stand-alone, static performance metric, rather than a time-dependent system property within the sensitivity analysis. Cryogenic tanks perform better under this narrow definition because they enable short-term discharge rates and volumetric utilisation, despite suffering continuous boil-off and refrigeration losses. Salt caverns on the other hand incur near-zero marginal losses over time, but have a lower technical efficiency, making them inherently better suited for long-duration, high-volume storage. As a result, the sensitivity analysis reveals that when efficiency is isolated and overweighted, salt caverns are mechanically penalised, but when efficiency is evaluated in conjunction with duration, scale, and system balancing requirements, salt caverns' advantage re-emerges and strengthens with demand. This highlights a key insight that the most technically “efficient” storage may not be optimal at the system level unless scale, duration, and throughput

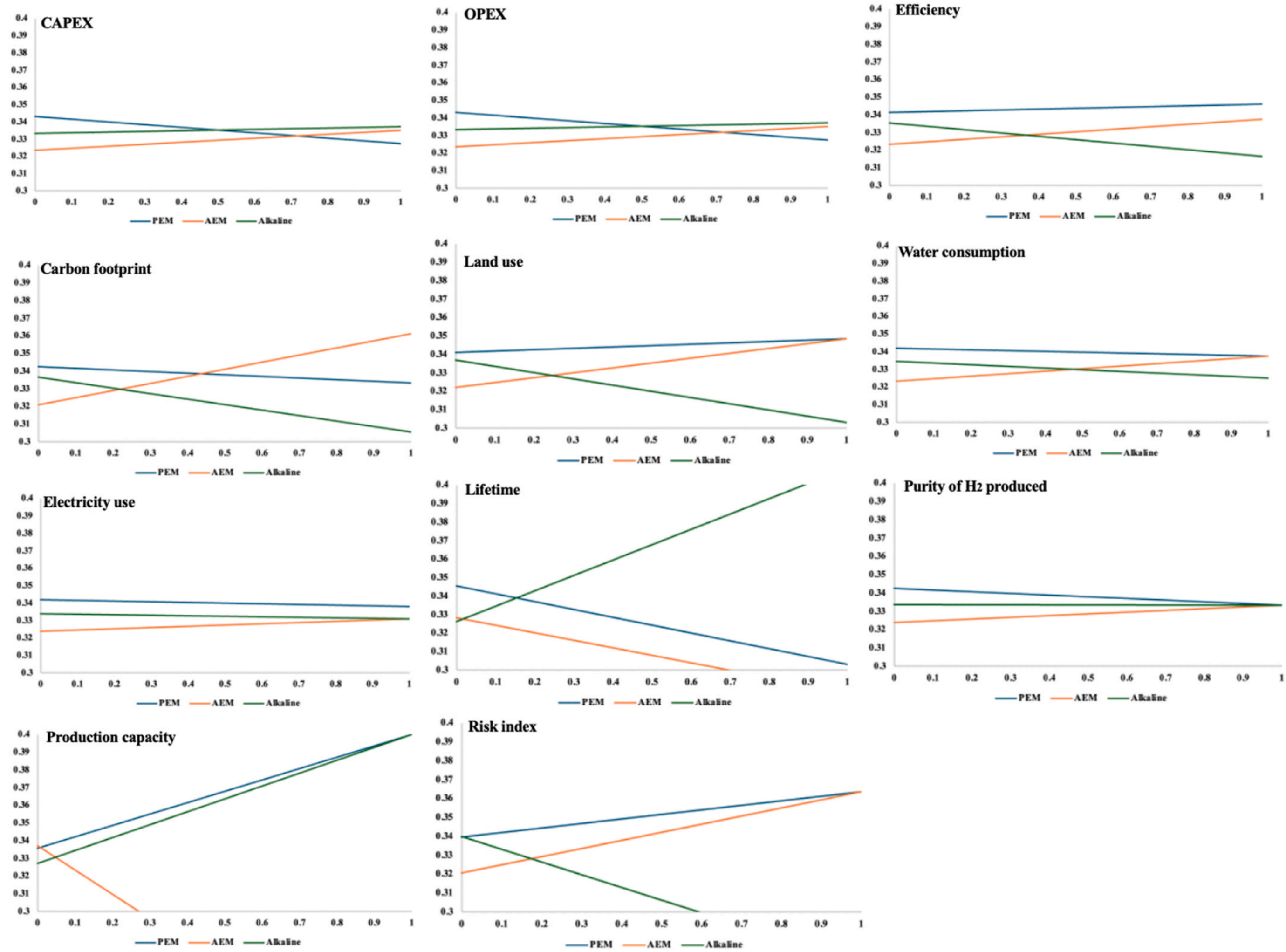

Fig. 12. Sensitivity analysis: production criteria.

are considered simultaneously. The sensitivity analysis demonstrates that long-duration storage technologies provide structural resilience to the supply chain, buffering fluctuations in both production and demand, which cannot be replicated by short-term, modular storage solutions. For transportation, several key intertwined criteria present themselves in the sensitivity analysis. Cost and transport capacity for example reveal that trucks only become competitive when CAPEX/OPEX weighting dominates, but at high-demand production, the capacity limitation outweighs cost savings. When the weighting of CAPEX or OPEX increases, truck scores increase, while pipelines decline sharply. As such, when cost is highly prioritised, the lower capital cost of trucks makes them appear more competitive. However, when transport capacity gains weighting, pipelines rise sharply, demonstrating their reliability when system-level throughput is prioritised. Despite their cost advantage, trucks cannot handle high volumes efficiently, thus invalidating their initial cost-effectiveness when large volumes of hydrogen are required. The energy density and transport capacity dynamic reveals some other important considerations. When energy density weighting increases, cryogenic trucks improve markedly in score, reflecting their ability to transport more hydrogen per vehicle. Contrarily, when transport capacity is highly weighted, pipelines again rise sharply while cryogenic trucks decline, demonstrating that density advantages do not translate into system-level throughput. At high demand, the binding constraint is not how much hydrogen a single vehicle can carry, but how much hydrogen can be moved continuously across the network. Despite their high energy density, cryogenic trucks remain constrained by discrete trips, loading cycles, fleet size, and refuelling frequency. As a result, energy density gains cannot compensate for limited transport capacity, thus making pipelines a better option for sustained, high-volume hydrogen transport. This reinforces that transport technologies cannot be assessed on single metrics alone; continuous delivery, scalability, and efficiency under load are decisive in large-scale hydrogen networks.

Taken together, the sensitivity analysis and multi-objective results indicate that establishment-stage hydrogen systems should adopt a hierarchical and flexible architecture. Centralised alkaline electrolysers should form the production backbone due to their robust performance across most demand scenarios, low operational risk at moderate utilisation, and cost-effectiveness. PEM stacks may be selectively deployed to capture efficiency and modularity benefits at peak demand, but only if high-load operation is sufficiently certain to justify their higher CAPEX. For storage, salt caverns dominate system-level performance in high-demand scenarios because their geological scale provides near-zero marginal losses over long durations, ensuring reliable seasonal buffering. Cryogenic tanks, while offering localised flexibility and high energy density, cannot scale structurally to meet system-wide demand without incurring prohibitive cost or efficiency penalties. However, the tanks are justified in areas where geological storage is unavailable, space is constrained, or rapid, short-term access to hydrogen is required, such as urban hubs, industrial clusters, or emergency reserves. Transportation similarly requires a nuanced strategy: pipelines are the most effective means of sustaining high throughput, as their continuous delivery

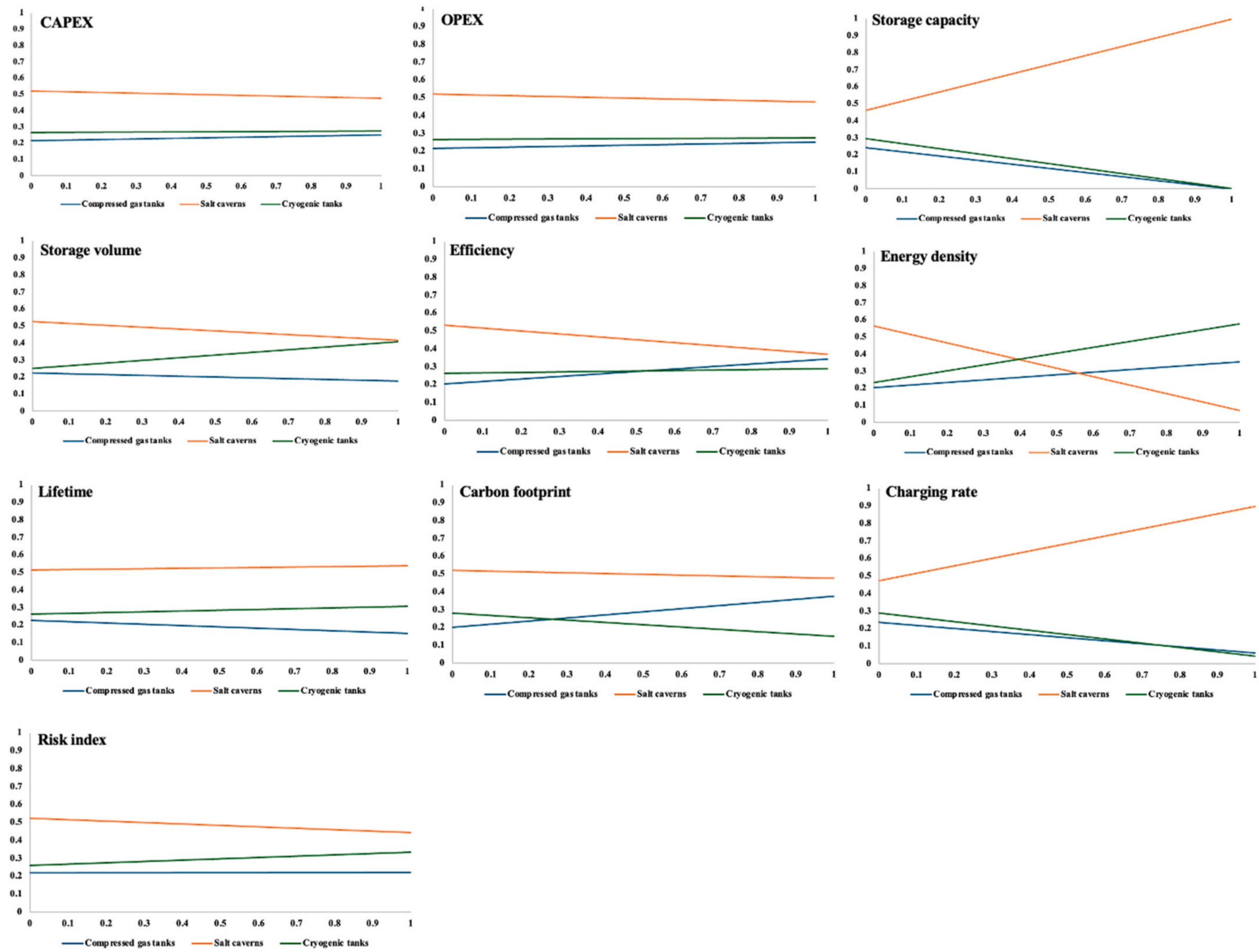

Fig. 13. Sensitivity analysis: storage criteria.

capability and non-linear energy efficiency scale with volume, whereas trucks or cryogenic vehicles are limited by discrete trips, fleet size, and refuelling cycles. Nonetheless, here again, modular transport options retain value for short-term, localised, or emergency supply, or in decentralised or remote regions where pipelines are infeasible or cost prohibitive. Overall, this hybridised approach of centralised alkaline production, targeted PEM supplementation, salt cavern storage with localised tank-based supplementation, and pipeline-based transport with modular flexibility can balance cost, efficiency, and operational risk, and aligns infrastructure investment with demand scaling. In turn, this approach can maintain resilience under uncertainty and provide a clear, analytically justified pathway for scalable hydrogen deployment.

6. Conclusion and recommendations

This work developed a multi-objective, multi-period optimisation framework for the design of a green hydrogen supply chain in Northwestern Saudi Arabia, integrating production, storage, and transportation technologies under evolving stakeholder priorities. The results reveal that production technologies converge as demand scales, with centralised alkaline water electrolysers forming a robust backbone across most scenarios, accounting for approximately 70–90% of production capacity in T1–T3, due to their cost-effectiveness, operational resilience, and moderate-load efficiency. PEM stacks are only justified at high, sustained demand in 2060, representing roughly 35–40% of production capacity in T4, suggesting selective hybrid deployment for peak-demand flexibility. For storage, salt caverns dominate system-level performance at scale, providing near-zero marginal losses, high efficiency, and long-duration buffering, while cryogenic tanks retain value in spatially constrained or rapidly responsive applications such as urban or industrial clusters, typically contributing 20–25% of the total storage volume in hybrid scenarios. Transportation exhibits a similar divergence: pipelines deliver continuous, high-throughput capacity efficiently at scale, whereas trucks and cryogenic vehicles serve as flexible supplements for localised, short-term, or remote operations, accounting for 10–20% of transport capacity depending on scenario and distance requirements. The analysis indicates that an optimally staged and hierarchical supply chain-centralised alkaline water electrolyser production, targeted PEM supplementation, salt cavern storage with selective tank-based support, and pipeline networks augmented by modular transport can balance cost, efficiency, and risk while aligning investment with evolving demand. Future work should extend this multi-period approach to integrate dynamic policy scenarios and technological learning curves to enable more precise guidance for scalable and resilient hydrogen deployment.

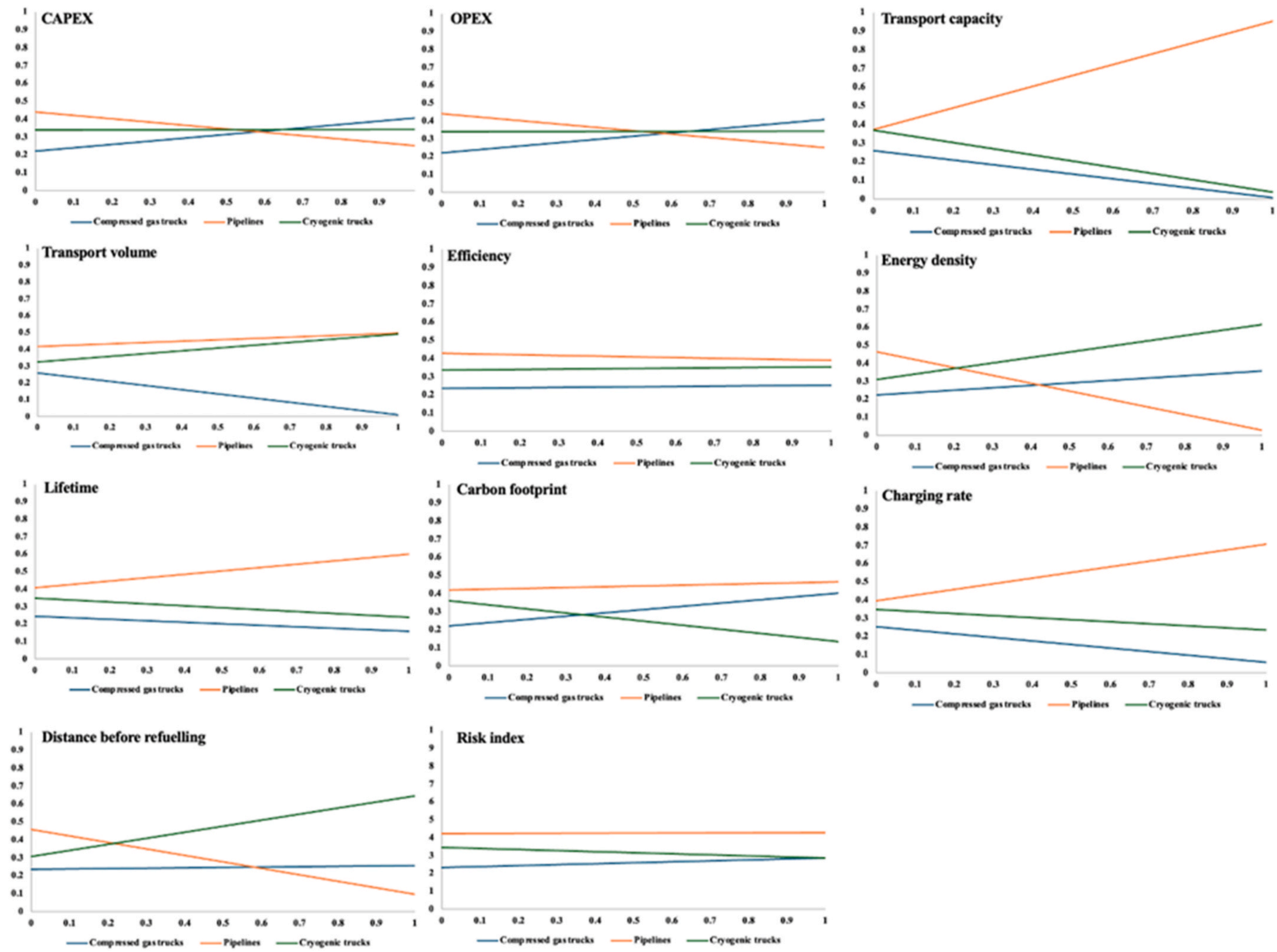

Fig. 14. Sensitivity analysis: transportation criteria.

CRediT authorship contribution statement

Valentina Olabi: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Abdulrahman Alhajeri:** Validation, Software, Data curation, Conceptualization. **Heba Ghazal:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Hussam Jouhara:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2026.154838.

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