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Decision support system for sustainable hydrogen production: Case study of Saudi Arabia

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ABSTRACT

The global energy sector is undergoing a transition towards sustainable sources, with hydrogen emerging as a promising alternative due to its high energy content and clean-burning properties. The integration of hydrogen into the energy landscape represents a significant advancement towards a cleaner, greener future. This paper introduces an innovative decision support system (DSS) that combines multi-criteria decision-making (MCDM) and decision tree methodologies to optimize hydrogen production decisions in emerging economies, using Saudi Arabia as a case study. The proposed DSS, developed using MATLAB Web App Designer tools, evaluates various scenarios related to demand and supply, cost and profit margins, policy implications, and environmental impacts, with the goal of balancing economic viability and ecological responsibility. The study's findings highlight the potential of this DSS to guide policymakers and industry stakeholders in making informed, scalable, and flexible hydrogen production decisions that align with sustainable development goals. The novel DSS framework integrates two key influencing factors technical and logistical by considering components such as data management, modeling, analysis, and decision-making. The analysis component employs statistical and economic methods to model and assess the costs and benefits of eleven strategic scenarios, while the decision-making component uses these results to determine the most effective strategies for implementing hydrogen production to minimize risks and uncertainties.

Introduction

The global energy sector is experiencing a significant shift towards sustainable energy sources, with hydrogen emerging as a promising alternative due to advances in production and distribution technologies (IRENA, 2022). Despite its potential, the transition to a hydrogen-based economy faces several challenges, including complex planning, international agreements, and the need for efficient production and distribution systems (Abdullah et al., 2011; Kaheel et al., 2023). Various hydrogen production methods, such as steam methane reforming, solar-integrated reforming with carbon capture, and electrolysis using renewables and ammonia, have been reported (Okonkwo et al., 2021). However, the adoption of hydrogen technology remains in its early stages (DOE, 2020; Troncia et al., 2023). Therefore, there is a need for strategic decision-making in hydrogen production which should consider technical, economic, and environmental criteria before establishment. Blue ammonia production and export are currently the most promising approach (Shabaneh et al., 2020), while green hydrogen is expected to catch up and become competitive (Yu et al., 2021). The lack of a combine strategic decision framework for the implementation of hydrogen technology has been extensively reviewed and reported in (Kaheel et al., 2023). The carbon footprint of several approaches to the generation of hydrogen has been analysed in (Y. Li et al., 2023; Sarrakh et al., 2020), and ways to cut down emissions has been reviewed in (Kovač et al., 2021). More study is required to determine the strategies that will result in the most rapid economical construction and implementation of a hydrogen infrastructure (Kovač et al., 2021; Machado et al., 2022).

Several research reported uncertainty in demand, storage networks and lack of reliable distribution systems as a key challenge in hydrogen implementation (Agyekum et al., 2022; Ren, Dong, et al., 2020; Younas et al., 2022). To accelerate hydrogen development, a comprehensive policy approach and rigorous regulatory analysis are necessary (Alsulaiman, 2024). The infrastructure investments required for large-scale hydrogen production and distribution networks further underscore the need for robust automated decision-making system (Thacker

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et al., 2019). Energy supply security, climate change, local air pollution, and increasing energy service prices, absent of worldwide policymaking are also challenges. Further research is needed to enhance the efficiency and dependability hydrogen-based technologies. Additionally, research has emphasized the need for robust decision-making frameworks that can incorporate uncertainties and evaluate trade-offs in complex energy systems (Majid et al., 2021). Similarly, (Kaheel et al., 2023) provides an insightful review of hydrogen energy development systems, challenges in optimizing their deployment, and their implementations as shown in Fig. 1. Technical factors include hydrogen transportation, supply-demand dynamics, industrial use, technology advancements, environmental concerns, and supply chain intricacies. Logistical factors include regulatory policies, stakeholder roles, economic considerations, financial efficiency, and private sector involvement. The collective challenges can be mitigated by adopting a comprehensive policy approach and conducting rigorous regulatory analyses using a decision-making strategy to expedite and contribute to a more sustainable energy security.

The development and utilization of hydrogen are significantly influenced by policies, standards, legislation, and advanced technologies. Key challenges include ensuring economic profitability, secure storage, and transportation, as well as the reliability and efficiency of hydrogen technology (Agyekum et al., 2022; Younas et al., 2022). Effective decision-making is crucial, but without a centralized decision support system (DSS), the process risks inefficiency, higher costs, and missed opportunities (Matsuo et al., 2020; Podvesovskii et al., 2021). The global shift towards clean energy underscores the importance of hydrogen in the energy transition (Aziz et al., 2024; Dincer & Acar, 2018; Lee & Kim, 2021; Suleman et al., 2016; Tarkowski, 2019). MATLAB-based decision tree models, widely used for optimizing hydrogen production, have proven effective by integrating machine learning and predictive analytics (Bastos, 2022; Kim & Kim, 2017; B. Li & Li, 2021; Nadler, 2019; Ren, Li, et al., 2020). However, traditional approaches often lack adaptability to dynamic market conditions (Chen et al., 2018; Liang et al., 2017). (Chen et al., 2018)This research seeks to develop a technology-driven decision matrix to support Saudi Arabia's hydrogen potential, focusing on optimizing renewable hydrogen supply systems by considering factors ranging from technical to logistical. The proposed DSS will offer strategic guidance to policymakers and stakeholders, with validation ensuring the system's robustness and accuracy (Pamucar et al., 2021; C. Zhang, Song, et al., 2022). The research identifies a significant gap in the integration of Decision Support Systems (DSS) for optimizing hydrogen production and distribution, particularly in fast-growing markets like Saudi Arabia. Despite advances in hydrogen production technologies, existing literature primarily addresses challenges in isolation, such as production costs, supply chain issues, and regulatory complexities, without providing a comprehensive and adaptable solution. This research addresses this gap by developing a centralized DSS framework tailored to optimize hydrogen production. By taking Saudi Arabia as a case study, this research aims to provide strategic decision-making support to stakeholders, thereby improving efficiency, cost-effectiveness, and the successful implementation of hydrogen infrastructure. The contribution of this study can be summarized as follows.

I. Development of a centralized DSS framework for optimizing hydrogen production and distribution.
II. Proposed integrated decision-making system to improve the effectiveness of hydrogen implementations including factors such as economic, environmental, technical and regulatory factors.
III. Investigate a case study application to validate the effectiveness of the proposed DSS.
IV. Provided a strategic guidance for stakeholders to improve efficiency, reduce costs, and address uncertainties in hydrogen production and market integration.

The structure of the article is as follows: Section 1 provides a focused introduction to the challenges and opportunities in hydrogen energy transition, narrowing down to the specific implementation factors. Section 2 discusses the DSS framework and methodology, with a detailed examination of Saudi Arabia's hydrogen energy landscape. Section 3 presents the results of the DSS application in a case study, and Section 4 outlines future research directions. Finally, Section 5 concludes the paper by summarizing the key findings and implications.

Methods

A Hydrogen Decision Support System (H_2DSS) has been developed to guide decision-making in hydrogen production and export for Saudi Arabia. This system considers technical, economic, environmental, political, and social factors to assist in comprehensive analysis. Previous studies have shown the effectiveness of decision trees in strategic hydrogen planning as reported in (Dagdougui et al., 2011; Elshurafa et al., 2022). (Elshurafa et al., 2022)The integration of dynamic decision trees and machine learning enhances accuracy in complex scenarios, as demonstrated by (García-Nieto et al., 2023). The H_2DSS prioritizes sustainability and economic optimization, aligning decisions with environmental impact assessments and financial outcomes. It is particularly suitable for emerging economies, like Saudi Arabia, with

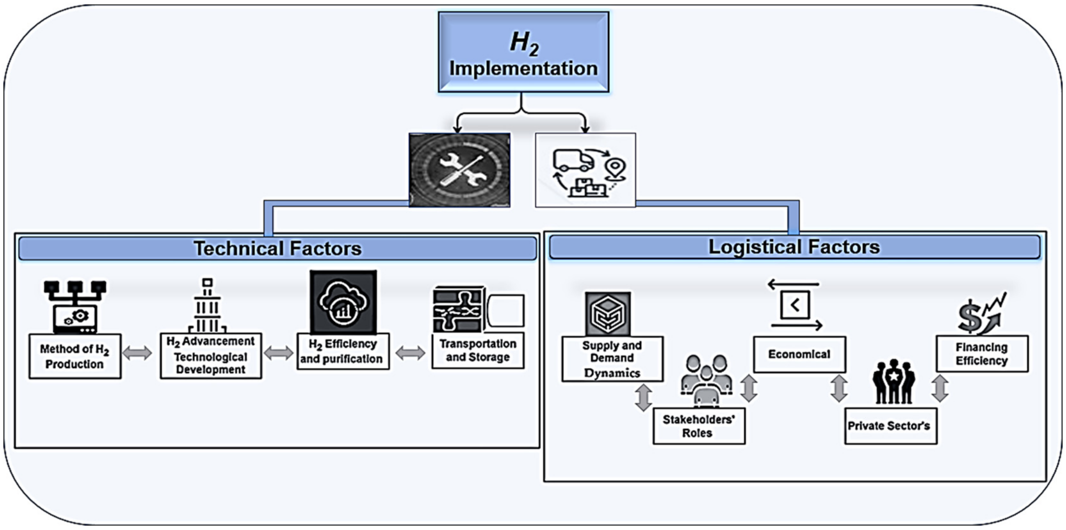


Fig. 1. The implementation factors of hydrogen energy.

significant energy resources and global market influence. Built with MATLAB Web App Designer, the H_2DSS evaluates supply-demand dynamics, economic feasibility, policy implications, and environmental impacts, aiming to balance economic growth with environmental stewardship. This approach is adopted in our research to provides a comprehensive framework that integrates environmental and financial considerations, ensuring the sustainability and economic viability of hydrogen projects. The H_2DSS system is suitable for emerging economies, where energy choices have profound long-term socio-economic implications. Saudi Arabia, with its vast energy reserves and strategic global energy role has been selected as a case study to demonstrate the feasibility of the H_2DSS. The aim is to make a balance between economic growth and environmental stewardship aligning with the global agenda for sustainable energy transition. Since a clear, explicit, and long-term strategy is needed for hydrogen's role in the energy transition. H_2DSS would be to decision-makers by providing a pathway for optimised decision to offer clarity by breaking down factors based on scenarios.

Employing the influencing factors into the proposed H_2DSS

The strategic decision making in energy sector relies on scientific and empirical insights to balance economic viability with environmental sustainability. This approach is essential for navigating the complexities of technological advancements, market dynamics, regulatory frameworks, and societal expectations. A key decision in this context is the choice between natural gas and hydrogen energy, informed by lifecycle assessments and cost analyses. Aligning production with market needs is crucial to avoid imbalances and optimize resource use. In the decision tree structure for evaluating green hydrogen production, as illustrated in Fig. 2, both logistical and technical factors play a critical role in shaping final decisions. These factors determine whether to prioritize local consumption or export, directly impacting the feasibility and profitability of hydrogen production. Understanding the demand-supply balance helps identify market opportunities and guide capacity planning, while evaluating production and distribution costs ensures economic viability. Additionally, trade policies and stakeholder engagement shape operational strategies. On the technical side, assessing production capacity and regulatory compliance is vital for infrastructure readiness and adherence to environmental standards, particularly for green hydrogen. Technology reliability influences operational efficiency and product quality, while environmental impact assessments guide sustainable resource use. The complete framework can be represented in Eq. (1). Where H represent the overall influence on hydrogen energy utilization and implementation, E represent economic factors, P represent regulation and legislation policy, S represent supply & demand., T represent technology, research and development, O represent oil & gas factors, R represent private sector involvement, K represent stakeholder role & facilitation, C represent supply chain factors, F represent financing efficiency and D represent technological development.

$$H = f\,(E, P, S, T, O, R, K, C, F, D) = f(\lambda) \tag{1}$$

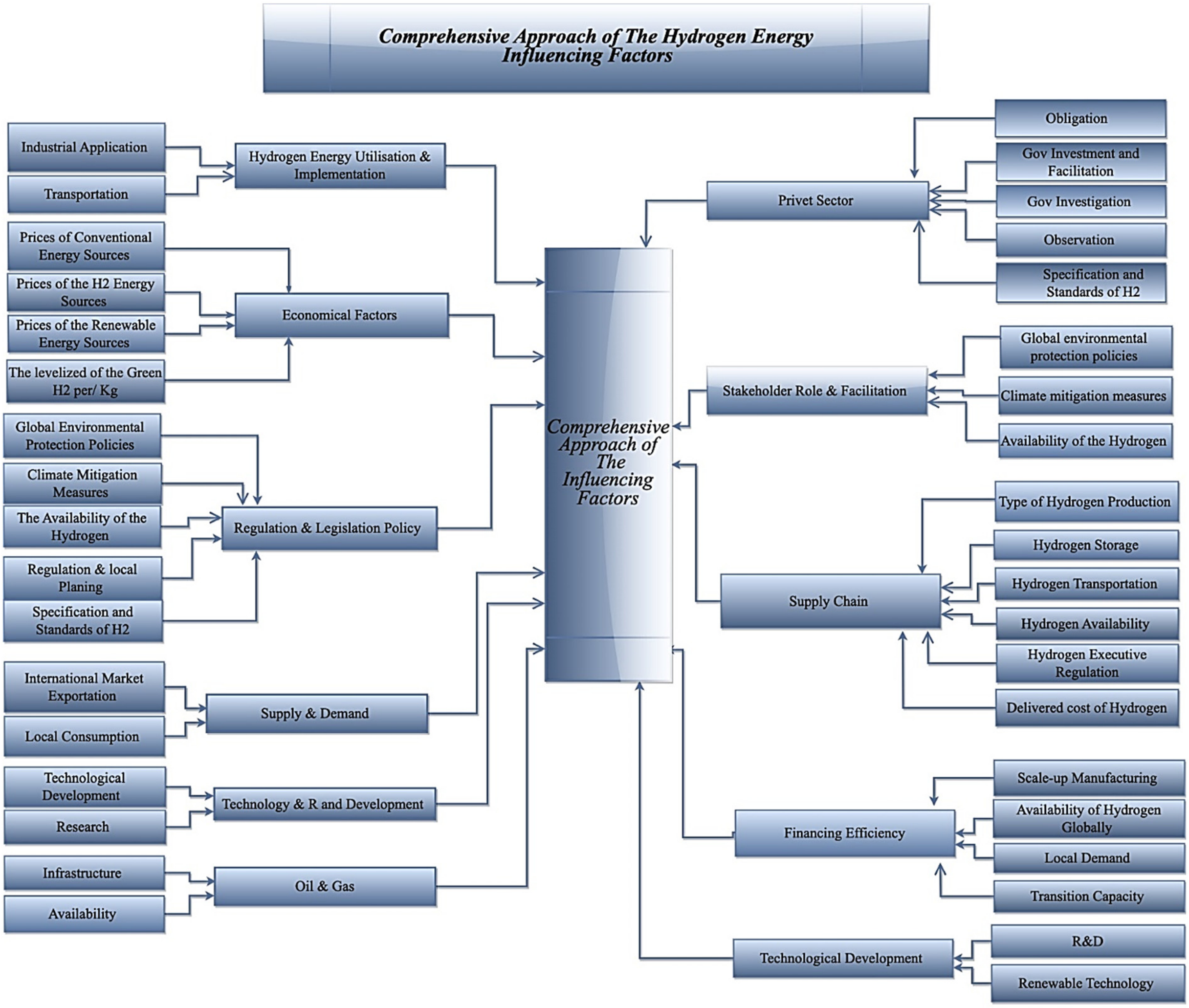


Fig. 2. A comprehensive approach to the hydrogen energy influencing factors.

If λ is any of the influencing factor, then $\lambda = f(x_1, x_2, x_3, \ldots x_n)$, meaning each of the influencing factors can be further broken down into equations based on their specific sub factor branches, contributions, interactions, and weights. λ is derived from empirical data or expert specific knowledge.

The Identifying the influencing factors in the hydrogen industry, or any energy-related field, is crucial for informed decision-making. Therefore, considering all relevant factors whether financial, political, technical, logistical, or related to climate change is essential for understanding the dynamics that affect the hydrogen industry. The proposed H_2DSS integrates these various influencing factors into its decision-making processes. This includes economic considerations, environmental impacts, regulatory requirements, stakeholder preferences, technological constraints, and market dynamics. The system collects inputs from users and provides analyses using a complex decision tree model, which is designed to represent the relationships between these influencing factors and potential decision outcomes. Continuous improvement of the H_2DSS is necessary to ensure its effectiveness in supporting decision-making. By incorporating these influencing factors into the model, organizations can enhance their decision-making processes, improve resource allocation, mitigate risks, and achieve outcomes that are better aligned with their objectives and stakeholders' interests, as highlighted in several studies (Imanina et al., 2016; Komarova et al., 2021; Tian & Lin, 2019).

H_2DSS framework description

A comprehensive decision tree is employed to facilitate optimal decision making by considering all relevant factors in the strategic planning and analysis of hydrogen energy projects, as illustrated in Fig. 3. This figure is structured as a flowchart, outlining the sequential steps and criteria crucial for evaluating and deciding on hydrogen energy initiatives. The process begins with the project initiation block, followed by logistic considerations, which are further divided into sub-blocks corresponding to steps 1 through 5. The flowchart then progresses to technical aspects, covering steps 6 through 11. These include selecting the energy source, assessing supply chain efficiency, ensuring regulatory compliance, verifying technology reliability, evaluating production capacity, and considering political stability. The decision tree model provides a clear rationale for the decisions made, which is essential for operational use. This method offers a straightforward and easily interpretable representation of the decision-making process, enabling stakeholders to comprehend the reasoning behind the final decisions.

The methodology begins with logistic considerations, including demand and supply evaluation, off-take agreements, market growth assessment, market analysis and profit margin calculation, trade policy assessment, and stakeholder engagement evaluation. Following this, the focus shifts to technical considerations, encompassing energy source selection, supply chain efficiency, compliance with environmental regulations, technology reliability, production capacity evaluation, and political stability assessment. The DSS integrates these analyses to support strategic decision-making, offering a holistic view of the project's market viability, economic profitability, and environmental sustainability. The decision-making process follows a logical sequence of evaluations, with each step building upon the insights and analyses derived from the preceding steps. The final decision block represents the culmination of all preceding analyses, serving as a pivotal decision point were conditional paths lead to different outcomes, such as proceeding with the project or reconsidering alternatives. Table 1 provides detailed descriptions of each step in the decision sequence.

Case study

Saudi Arabia (SA) represents an ideal case study for optimizing hydrogen production through a Decision Support System (DSS), given its status as one of the world's largest oil producers. The Kingdom provides critical insights into the challenges and opportunities that major oil-producing nations face as they transition towards sustainable energy solutions, decarbonization, and net-zero targets. Moreover, SA is actively restructuring its energy strategy to incorporate renewable sources, with the goal of reducing economic dependence on oil. In this context, the implementation of a DSS is crucial for facilitating informed

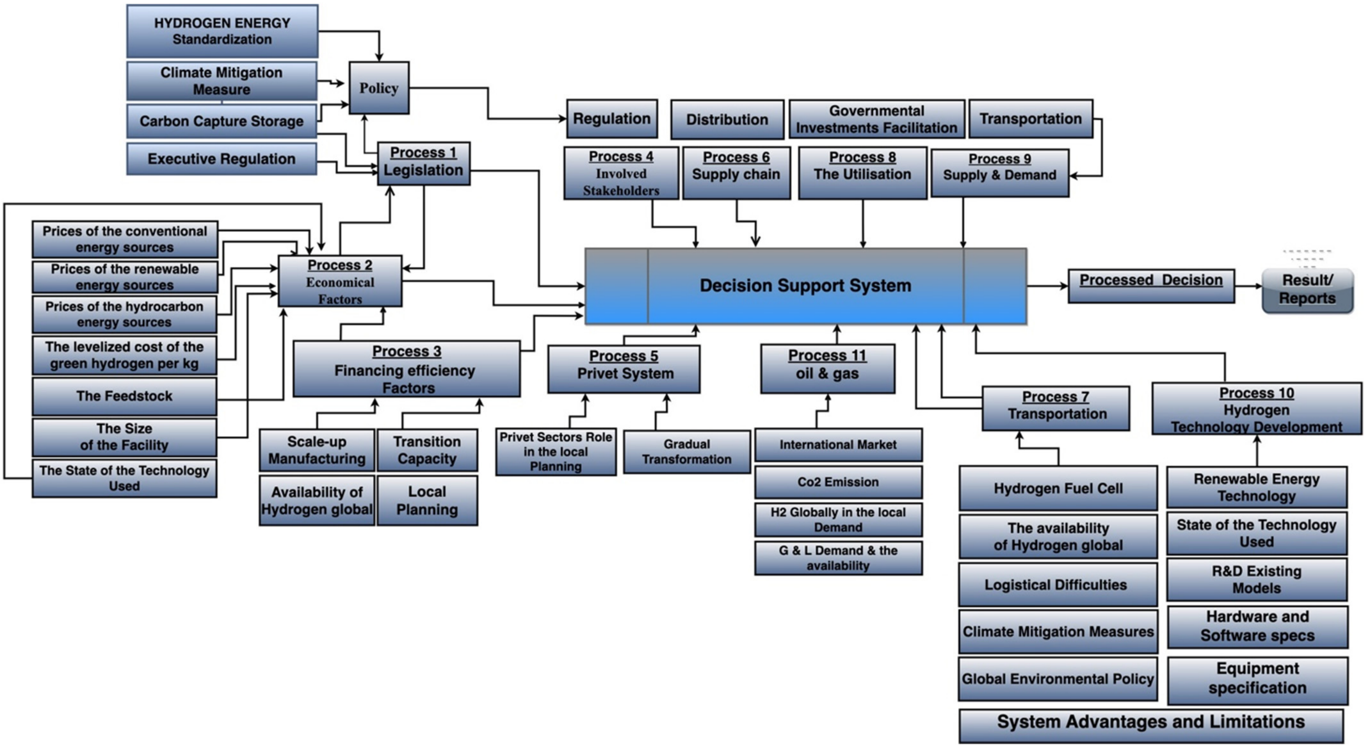


Fig. 3. Comprehensive hydrogen decision support system including the influencing factors.

Table 1
Description of the decision sequences steps.

Step	Concept	Decision criteria	Description
1	Logistic	Demand & Supply Evaluation with Off-take Agreements	Adjust demand based on off-take agreements.
2	Logistic	Market Growth Evaluation	Assess market growth potential.
3	Logistic	Market Analysis & Profit Margin Calculation	Include green hydrogen premium in profit margin.
4	Logistic	Trade Policy Assessment	Evaluate trade policy impacts.
5	Logistic	Stakeholder Engagement Evaluation	Assess engagement levels.
6	Technical	Energy Source Selection	Choose energy source based on scores.
7	Technical	Supply Chain Efficiency Assessment	Evaluate supply chain efficiency.
8	Technical	Regulatory Compliance Check	Ensure compliance with emissions regulations.
9	Technical	Technology Reliability Verification	Assess technology reliability.
10	Technical	Production Capacity Evaluation	Confirm capacity meets demand.
11	Technical	Political Stability Assessment	Evaluate political stability.
12	Integration	Comprehensive Market and Economic Viability Analysis	Integrate market and technical analyses.
13	Integration	Environmental Impact Consideration	Evaluate environmental benefits.
14	Final Decision	Strategic Decision Making	Make the final decision based on evaluations.

decision-making across all phases, from initial conceptualization to the comprehensive deployment of renewable energy projects. Reported a collaboration between Saudi Arabia and Japan in hydrogen production and supply, demonstrating Saudi Arabia's commitment to international cooperation in energy transition and decarbonization. The adoption of hydrogen technology in Saudi Arabia is relatively recent, with many essential factors still in the planning and development stages. Therefore, making informed decisions and outlining a strategic perspective on transforming green hydrogen into a viable decarbonization solution are critical steps towards achieving the goals of the Saudi Green Deal and establishing the New Energy Industrial Strategy. The approach to developing the H_2DSS and implementing the case study of Saudi Arabia involves considering energy capabilities and potentials of energy resources. Additionally, characteristics such as the abundance of fossil fuels, as well as economic and geographical capabilities are also considered for choosing KSA. Several research have been reported on Saudi hydrogen energy transition in (Alturki, 2022; Aziz et al., 2024; Hassan et al., 2024, 2023; Khondaker et al., 2015). The decarbonization strategy plan of Saudi Arabia can be summarized as shown in Fig. 4 based on the following references (A. Balabel et al., 2023; Al-Sharafi et al., 2017; Demirbas et al., 2016; Elshurafa et al., 2022; Hajimineh & Moghani, 2023; Hasan & Shabaneh, 2022; Hassan et al., 2024).

Saudi Arabia's socio-political landscape plays a crucial role in shaping its energy policies, particularly in the context of hydrogen production. As the world's largest oil producer, the Kingdom faces both challenges and opportunities in transitioning to green hydrogen. The Vision 2030 initiative aims to diversify the Saudi economy and reduce reliance on oil by promoting renewable energy, including hydrogen. However, the shift towards hydrogen is complex, influenced by tribal affiliations, regional politics, and the central authority of the monarchy, which can affect decision-making and resource allocation for hydrogen projects. Regional competition within the Kingdom may impact the location of hydrogen production facilities, leading to potential disparities in development. Additionally, while Saudi Arabia is generally politically stable, regional geopolitical tensions can threaten the security of energy infrastructure and market stability, influencing the scalability and sustainability of hydrogen production. As a leading member of OPEC, Saudi Arabia's energy policies, including those related to hydrogen, are also shaped by broader geopolitical considerations.

Economically, the transition to hydrogen is driven by the need to diversify revenue streams in anticipation of a post-oil future. The Kingdom's financial resources, derived from oil wealth, provide the capital necessary for significant investments in hydrogen infrastructure, such as the NEOM project, which aims to be the world's largest green hydrogen facility. However, the global hydrogen market is still nascent, and the economics of hydrogen production are currently less favorable than traditional energy sources. The success of Saudi Arabia's hydrogen initiatives will depend on maintaining political stability, managing regional tensions, and effectively allocating resources. Economic factors, including production costs, investment availability, and workforce development, will also be critical. This holistic approach not only

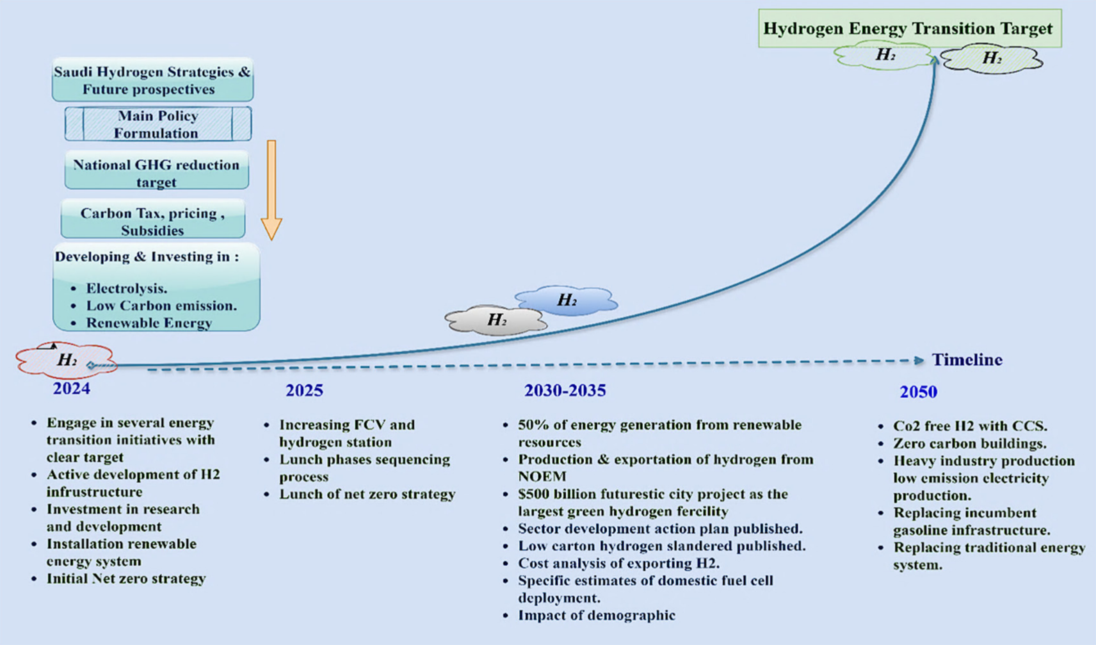


Fig. 4. Kingdom of Saudi Arabia hydrogen energy transition.

supports the Kingdom's domestic energy transition but also enhances its position in the global hydrogen market, contributing to international efforts to combat climate change and promote sustainable energy solutions.

Saudi Arabia hydrogen energy landscape

Research on Saudi Arabia's hydrogen energy production, CO_2 emission reduction plans, and future goals have been reported around natural gas potential (Demirbas et al., 2016), future energy forecast (Hassan et al., 2024, 2023; Mohammed et al., 2021), demand and supply dynamics (Hasan & Shabaneh, 2022; Khondaker et al., 2015), economic analysis (Al-Sharafi et al., 2017; Sarrakh et al., 2020), and decarbonisation (Sarrakh et al., 2020; Shabaneh et al., 2020). The systematically evaluation of parameters to derive actionable insights is needed, and decision trees present an effective approach. Decision trees, with their branched logic, offer an organized approach to multi-faceted decision-making scenarios. In the context of production and distribution, it becomes imperative to leverage such methodologies to optimize outcomes while adhering to constraints. Table 2 provide a summary of various strategic aspect of Saudi Arabia's hydrogen energy production, CO_2 emission reduction plan based on the following references (A. Balabel et al., 2023; Alghassab, 2023; Amran et al., 2020; Aziz et al., 2024; Demirbas et al., 2016; Elshurafa et al., 2022; Hajimineh & Moghani, 2023; Hasan & Shabaneh, 2022; Hassan et al., 2024, 2023; Khondaker et al., 2015). It has been shared with the experts and decision-makers in Ministry of Energy in Saudi Arabia. It is important to involve experts and gather their feedback from industry perspectives. Data from practitioners who have a long experience in the energy and hydrogen industry would ensure a strategic framework of the decision support system based on a real-world case. Therefore, data from the Ministry of Energy in Saudi Arabia was used. These is because accuracy of the data used in prediction percentage will contribute to proving the validity, feasibility, and impact of the scientific contribution.

Fig. 5 illustrate an input data for the decision-making process within the H_2DSS user interface (UI). Six scenarios are considered for the H_2DSS test considering the influencing factors and sequence highlighted in Fig. 3 and Table 1 respectively. Each factor, along with its respective unit and example value, contributes to the comprehensive analysis conducted by the H_2DSS app. The data inputs play a crucial role in driving informed decisions regarding green hydrogen production and market strategies. The projected demand for the hydrogen and the available supply are fundamental in assessing market dynamics and determining production levels. Additionally, factors such as the selling price and total production costs directly influence revenue generation and profitability calculations. Pre-existing agreements for purchasing hydrogen (Off-Take Agreement) provide insights into revenue stability, while adjustments based on market trends (Adjustment Factor) facilitate dynamic demand forecasting. Understanding sales volume (Quantity Sold) and whether the hydrogen meets green standards (Is Green) are essential for pricing strategies and market positioning. Assessing market growth potential (Market Growth Evaluation) and understanding trade policy impacts (Trade Policy Impact) guide long-term strategic planning. Stakeholder engagement (Engagement Level) and environmental considerations (Actual Emissions, Allowed Emissions, High Environmental Benefit) shape project sustainability and regulatory compliance. By inputting and analysing these factors, stakeholders gain actionable insights into market dynamics, economic viability, environmental sustainability, and regulatory compliance. This approach ensures that decisions align with financial objectives while promoting environmental stewardship in the green hydrogen industry.

Table 2

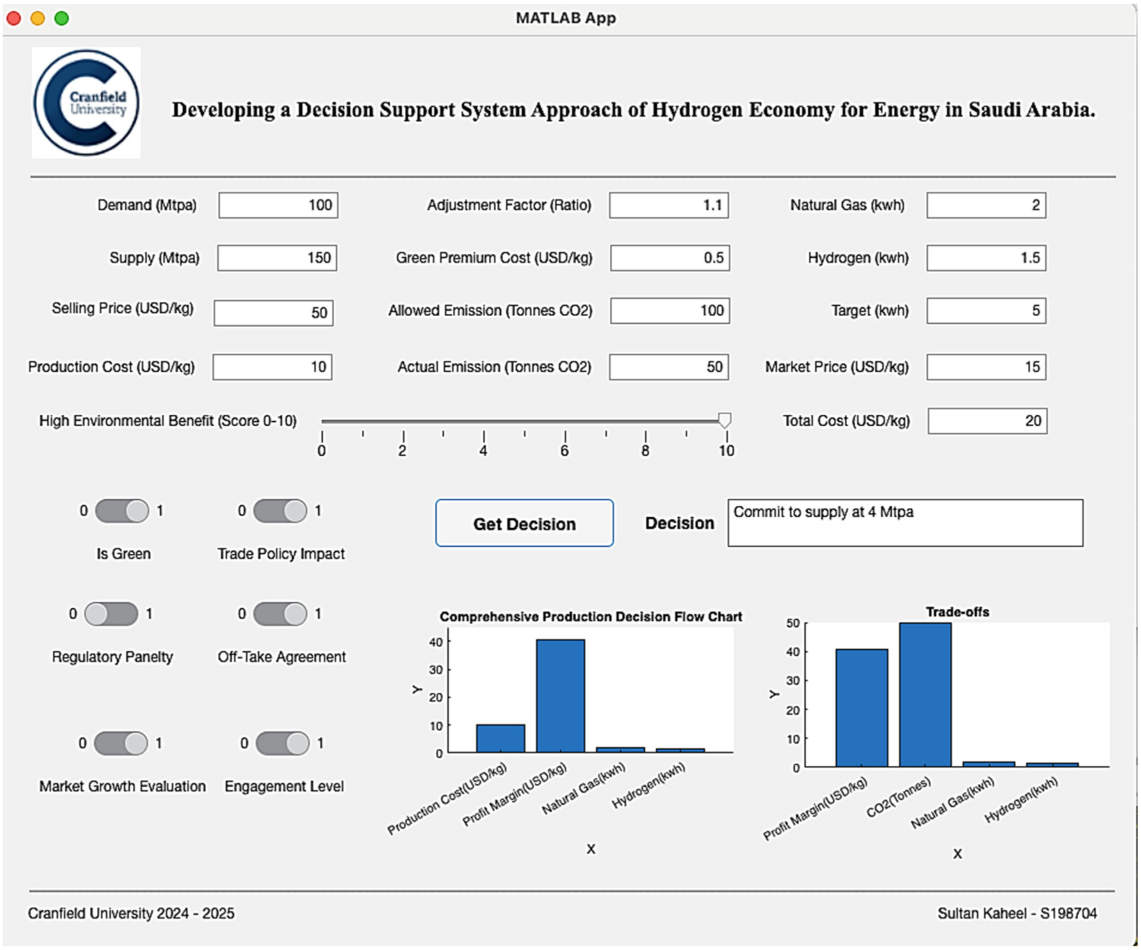
Saudi Arabia's hydrogen energy production, CO_2 emission reduction plans, and future goals.

Aspect	Details
Production Targets (Hydrogen)	2.9 million tons per year by 2030, 4 million tons per year by 2035
NEOM Green Hydrogen Project	World's largest green hydrogen production facility
Location	NEOM, Saudi Arabia
Joint Venture	Acwa Power, Air Products, NEOM
Area	Over 300 km^2
Solar Panel Count	Approximately 5.6 million
Solar Energy Production	Up to 2.2 GW
Financial Investment	USD 8.4 billion
Production by 2026	600 tons per day of carbon-free hydrogen using 4 GW of solar energy
CO2 Emission Goals	Net zero emissions by 2060 through the Circular Carbon Economy approac
CO2 Emission Reduction Targets	Reduce carbon emissions by 278 Mtpa by 2030
Future Energy Projects	17 renewable energy projects under development, with a total capacity of 13.76 GW
Afforestation and Land Rehabilitation	Plant 10 billion trees over the coming decades, rehabilitating 40 million hectares of land; 600+ million trees, including 100 million mangroves, to be planted by 2030
Wildlife Conservation Efforts	1200+ endangered animals rewilded across 15 different locations in 2022; 30 % of Saudi Arabia's land and sea under protection by 2030 (644,000+ km^2)
Overall Green Economy Goal	Become the world's largest hydrogen producer; facilitator of a global energy transition with a focus on blue hydrogen and renewables-based hydrogen, particularly in Neom

Decision tree construction

A decision tree is a structured method for constructing and evaluating decisions, organized into nodes and branches to systematically guide the decision support system's function. The decision tree model operates like a branching tree, incorporating multiple parameters, including economic factors (such as demand, supply, selling price, quantity sold, and costs) and regulatory factors (such as emissions limits and energy sources like natural gas and hydrogen), to optimize decisions on production and supply.

Fig. 6 illustrates the decision tree process used for strategic hydrogen production, specifically addressing whether to produce, export, or consume locally. The process begins at the start node, where key factors such as demand, supply dynamics, cost considerations, and environmental impacts are assessed. The first step evaluates market demand relative to supply, identifying opportunities for market expansion. Depending on the demand-supply gap, different production levels are considered: minor adjustments for small gaps (e.g., 2 Mtpa), moderate increases for medium gaps (e.g., 4 Mtpa), and maximum capacity for large gaps (e.g., 8 Mtpa). Next, the decision tree branches into a cost analysis node, where profit margins are calculated by subtracting production and distribution costs from potential revenue based on market prices. This step determines the economic feasibility of expanding production. A break-even analysis further refines the financial viability of different production levels. Following this, the environmental impact assessment node evaluates compliance with local and international emissions regulations and considers potential environmental benefits or credits from green hydrogen production, which is critical if the product is marketed as sustainable. The assessments are then integrated into a market and economic viability analysis, comparing the profitability and strategic benefits of selling hydrogen locally versus internationally, while considering domestic needs, international market prices, and the effects of trade policies and tariffs. Finally, the strategic decision node synthesizes this information to determine the best course of action. If the analysis favours higher returns from international markets and environmental impacts are manageable, exporting at higher production levels may be preferred. Conversely, if local market demand is sufficient and profitable, with fewer complexities from exporting and environmental constraints limiting production scale, focusing on local consumption at lower or moderate production levels may be more



Developing a Decision Support System Approach of Hydrogen Economy for Energy in Saudi Arabia.

Demand (Mtpa): 100
Supply (Mtpa): 150
Selling Price (USD/kg): 50
Production Cost (USD/kg): 10
Adjustment Factor (Ratio): 1.1
Green Premium Cost (USD/kg): 0.5
Allowed Emission (Tonnes CO2): 100
Actual Emission (Tonnes CO2): 50
Natural Gas (kwh): 2
Hydrogen (kwh): 1.5
Target (kwh): 5
Market Price (USD/kg): 15
Total Cost (USD/kg): 20
High Environmental Benefit (Score 0-10): 10
Decision: Commit to supply at 4 Mtpa

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Fig. 5. H_2DSS user interface for KSA (Input based on scenario 6 of Table 4).

appropriate.

The complete decision tree can be represented in the following equations. For a given set of inputs as a function D_s to decide on hydrogen production and quantifying the relationship between demand and supply. The sufficiency of demand relative to supply is given by the following condition in Eq. (2).

$$Sufficiency = \begin{cases} True, if\ D_s \geq 0 \\ False, if\ D_s < 0 \end{cases} \tag{2}$$

Where $\boldsymbol{Ds}$, is the difference between demand and break-even quantity. If $\boldsymbol{Ds} \geq 0$, the process proceeds otherwise, a re-evaluation is necessary, as the economic viability of the process may need reassessment. With successful sufficiency, the profit margin (*PM*) is computed as a function of selling price $\boldsymbol{S_p}$, production cost $\boldsymbol{P_{cost}}$, distribution cost $\boldsymbol{D_{Cost}}$, fix cost $\boldsymbol{F_{cost}}$and target quantity $\boldsymbol{Q_t}$ to be sold as given in Eq. (3).

$$PM = \frac{(S_p \times Q_t) - (P_{cost} + D_{Cost} + F_{cost})}{(S_p \times Q_t)} \tag{3}$$

Eq. (3) can be further simplified such that $(\boldsymbol{S_p} \times \boldsymbol{Q_t})$ = Target revenue, and $(\boldsymbol{P_{cost}} + \boldsymbol{D_{Cost}} + \boldsymbol{F_{cost}})$ = Total costs. The condition for profit margin evaluation can be represented in Eq. (4). While the evaluation of the technical (***TF***) and logistical factor (***LF***) can be represented in Eqs. (5) and (6).

$$PM_{Evaluation} = \begin{cases} True, if\ PM > 0 \\ False, if\ PM \leq 0 \end{cases} \tag{4}$$

$$\begin{aligned} TF = {} & (w_{tf1} \times Energy\ Sources) + (w_{tf2} \times Hydrogen\ Energy) \\ & + (w_{tf3} \times Natural\ Gas\ Energy) + (w_{tf4} \times Environmental\ Impact) \end{aligned} \tag{5}$$

$$LF = (w_{Lf1} \times Transportation) + (w_{Lf1} \times Storage) \tag{6}$$

Where $\boldsymbol{w_{tf1}}$, $\boldsymbol{w_{tf2}}$, $\boldsymbol{w_{tf3}}$, $\boldsymbol{w_{tf4}}$ represent the weights of technical factors, and $\boldsymbol{w_{Lf1}}$, $\boldsymbol{w_{Lf2}}$ represent the weights of logistic factors. The policy and regulation (***PR***) factor depend on ***TF*** and ***LF*** represented by Eq. (7). $\boldsymbol{w_{pr1}}$ and $\boldsymbol{w_{pr2}}$ are weights representing the importance of technical and logistic factors in regulatory decisions. Economic viability is assessed by determining whether the combined technical, logistic, and regulatory factors support a profitable outcome. As shown in Eq. (8), if the outcome is not economically viable, the process should undergo re-evaluation to explore alternative strategies or adjustments. In addition, if engagement is inadequate, the project may require re-evaluation to address the deficiencies in support.

$$PR = (w_{pr1} \times TF) + (w_{pr2} \times TF) \tag{7}$$

$$\boldsymbol{Economically\ Viability} = \begin{cases} \boldsymbol{True, if\ PR \geq Economical\ target} \\ \boldsymbol{False, if\ PR < Economical\ target} \end{cases} \tag{8}$$

The reduction in CO_2 emissions due to the use of green or more efficient technologies compared to a baseline conventional emission can be evaluated using Eqs. (9) and (10), respectively. Where *i* represent a specific define process which leads to the emission, $\boldsymbol{E_i}$, $\boldsymbol{E_{green\_i}}$, are energy usage, and $\boldsymbol{E_{fi}}$, $\boldsymbol{E_{fgren\_i}}$ are emission factors, respectively. The emission factor represents the rate at which the process *i* emit CO2 to the

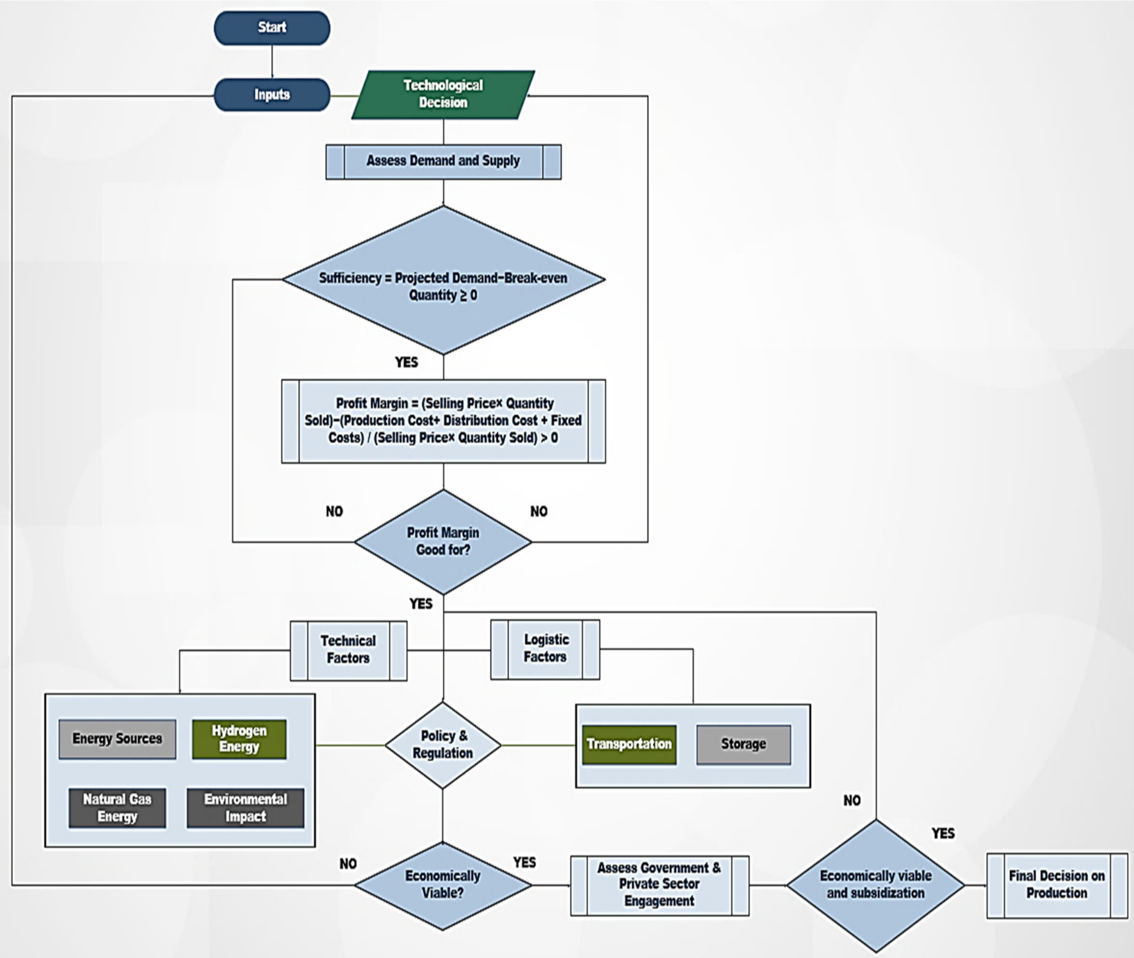


Fig. 6. Hydrogen energy production decision tree.

environment. Carbon emissions are quantified by comparing baseline conventional emissions ($E_{Green\ Emissions}$) with emissions after implementing green technologies ($E_{Green\ Emissions}$), the emissions saved (E_{Saved}) as presented in Eq. (11).

$$E_{Baseline\ Emissions}\ (tCO_2) = \sum (E_i \times E_{fi}) \tag{9}$$

$$E_{Green\ Emissions}\ (tCO_2) = \sum (E_{green\_i} \times E_{fgren\_i}) \tag{10}$$

$$E_{Saved}\ (tCO_2) = E_{Baseline\ Emissions}\ (tCO_2) - E_{Green\ Emissions}\ (tCO_2) \tag{11}$$

If the energy efficiency (η) is quantified as the ratio of useful energy output to total energy input as presented in Eq. (12), which influences both environmental and economic outcomes.

$$\eta = \frac{Useful\ Energy\ Output\ (kWh)}{Total\ Energy\ Input\ (kWh)} \times 100 \tag{12}$$

Eq. (12) indicates how efficiently the energy is being converted into useful work, with higher percentages signifying greater efficiency and lower environmental impact. This also leads to lower overall environmental impact as less energy is consumed for the same output. The environmental impact score (***EIS***) can be used within the DSS to compare different scenarios or strategies, highlighting which options are more environmentally friendly. Thies can be presented as Eq. (13).

$$EIS = w_{E1} \times E_{Saved}\ (tCO_2) + w_{E2} \times \eta \tag{13}$$

Where w_{E1} and w_{E2} are weights which can be adjusted based on the relative importance of emissions versus energy efficiency. To convert the ***EIS*** to a scale between 0 and 10, $w_{E1} + w_{E2} = 1$, and the normalization of the individual components of E_{Saved} and η need to be consider. For a zero-emission saving, $E_{Saved}(min) = 0$ and $E_{Green\ Emissions}\ (tCO_2) = E_{Baseline\ Emissions}\ (tCO_2)$. Then the normalization of E_{Saved} is presented in Eq. (14). Similarly, the normalization of η is presented in eq. 15, and Eq. (13) become Eq. (16).

$$E_{Saved\ normalized} = \frac{E_{Saved} - E_{Saved}(min)}{E_{Saved}(max) - E_{Saved}(min)} = \frac{E_{Saved} - 0}{E_{Saved}(max) - 0} = \frac{E_{Saved}}{E_{Saved}(max)} \tag{14}$$

$$\eta_{normalized} = \frac{\eta - \eta_{min}}{\eta_{max} - \eta_{min}} \tag{15}$$

$$EIS = w_{E1} \times E_{Saved\ normalized} + w_{E2} \times \eta_{normalized} \tag{16}$$

The final DSS decision on production is based on the fulfillment of all conditions and considering the ***EIS*** which can be between 0 and 10. The condition for the final decision can be represented by following equation.

$$Final\ Decision = \begin{cases} Proceed\ with\ production,\ if\ all\ conditions\ are\ met \\ Do\ not\ produce,\ if\ any\ condition\ fails \\ Re-evaluation,\ if\ all\ met\ but\ not\ EIS \end{cases} \tag{17}$$

Table 3 provides a detailed overview of the decision-making framework for planning hydrogen production, organized by objectives, considerations, and expected outcomes. This structured format

Table 3
In-depth look of the decision-making.

Decision section	Objective	Considerations	Outcome
Assess Demand & Supply	Evaluate the balance between demand and supply for production planning.	Market trends, seasonal fluctuations, consumer preferences, competitive landscape.	Align production capabilities with forecasted demand to avoid overproduction and its negative impacts, including unnecessary costs, wastage, and potential brand damage.
Evaluate Cost & Profit Margin	Determine the financial viability of production based on profit margins.	Comparison of net profit per unit against market price; assessment of production, distribution, and fixed costs.	Decisions on production continuation based on profitability; if profit margins are too low, production may be halted to avoid losses.
Policy & Regulation	Ensure compliance with CO2 emissions regulations.	Current emissions levels vs. regulatory standards.	Production decisions are influenced by compliance status; if emissions exceed permissible levels, production may be halted
Maximum Production Capacity	Assess if production capacity meets the company's targets.	Maximum production capabilities from natural gas and hydrogen sources.	Ensure sufficient capacity to meet production targets; address the risks of overproduction leading to increased costs and reduced profit margins
Evaluate Profit Margin Decision	Make supply decisions based on profitability and capacity.	Profitability of supplying the product and the production capacity constraints.	Guide supply decisions to ensure no overcommitment on supply and manage costs effectively; the depth of decision nodes (up to 5) informs this process
Compare Market Prices vs Total Cost	Decide the best market for selling the product based on price comparisons.	Market price comparisons against total production costs, including the impact of economies of scale.	Determine whether exporting or local selling is more profitable, considering environmental implications of transportation emissions. Integration of economies of scale as production scale increases, affecting pricing decisions

clearly outlines the purpose, factors considered, and results of each decision-making stage, making the process straightforward to follow. The “Assess Demand & Supply” section focuses on balancing production with market demand by accounting for consumer behavior and market conditions. This alignment helps prevent overproduction and ensures that decisions meet stakeholder needs and market capacity. In the “Evaluate Cost & Profit Margin” section, the emphasis shifts to financial health, where profitability is analysed in relation to market prices and production costs, placing financial viability at the core of decision-making. The “Policy & Regulation” section ensures that production adheres to environmental regulations, integrating legal and ecological considerations. Compliance is crucial not only for meeting legal standards but also for maintaining a positive public image and aligning with sustainability goals. The “Maximum Production Capacity” segment assesses whether existing infrastructure can meet production goals efficiently, addressing technological limitations and ensuring that capacity is both necessary and sustainable. In the “Evaluate Profit Margin Decision” section, profitability assessments and capacity considerations guide supply decisions, promoting resource efficiency and minimizing environmental impact, which are vital for sustainable practices. Lastly, the “Compare Market Prices vs Total Cost” section evaluates whether selling locally or exporting is more economically advisable by comparing market prices to total production costs. This decision-making process balances potential financial gains with environmental costs, highlighting the need to weigh economic benefits against ecological impacts. Overall, this framework integrates economic, environmental, technological, and market considerations, ensuring that every decision in green hydrogen production is informed, balanced, and geared towards long-term sustainability and profitability. This approach is crucial for navigating the complexities of green hydrogen production, making the process both competitive and responsible.

Scenarios based on Saudi Arabia prospect

Decision trees in MATLAB are instrumental in addressing the global-local challenges of scaling hydrogen production. They integrate environmental impact assessments, helping to select options that align with sustainability goals, such as minimizing carbon emissions. By assessing the ecological footprint of different production scales, decision trees identify environmentally responsible choices. The use of MATLAB for decision tree modeling allows for rigorous testing and validation, leading to continuous improvement and refinement of decision models. This enhances the precision and data-driven nature of decision-making, supports risk assessment and mitigation, optimizes resource allocation, and integrates sustainability considerations. This scientific approach ensures that decisions align with both economic and environmental objectives while adapting to the evolving landscape of the hydrogen energy industry (Qyyum et al., 2021). The decision to proceed with production is based on the profit margin. If the profit margin is positive, production is deemed profitable, allowing the company to proceed. If not, the company must adjust its strategy to reduce costs or increase revenue, ensuring financial sustainability and preventing long-term harm. Therefore, strategic decisions must be based on profitability. By incorporating the concept of economies of scale, the decision tree becomes more dynamic and responsive to the nuances of hydrogen production scaling (Jian et al., 2022; Meng et al., 2021; Qyyum et al., 2021). This approach supports optimizing production levels and deciding between export and local consumption, ensuring decisions are based not only on immediate costs and market prices but also on long-term operational efficiency and profitability.

Table 4 presents eleven scenarios from the H2DSS, detailing how different input parameters influence final decisions in hydrogen production planning. Each scenario maintains consistent values for most parameters, such as Demand (100 Mtpa), Supply (150 Mtpa), Production Cost (10 USD/kg), and the Green Premium Cost (0.5 USD/kg). Variations in Actual Emission values, Market Prices, and Environmental Benefit scores primarily differentiate the scenarios and influence strategic outcomes. For instance, Scenario 0 shows no production due to favorable conditions, while Scenario 3 opts for local consumption due to lower actual emissions and moderate market prices. Scenarios 4 through 7 escalate supply commitments at varying capacities (2 to 8 Mtpa), driven by similar emissions but different market prices and target values. Scenario 8, with the lowest environmental benefit score (0), prompts a re-evaluation of strategy, demonstrating the system's sensitivity to environmental impact in decision-making. This approach highlights how the DSS integrates economic, environmental, and market dynamics to develop sustainable production strategies. Scenario 9 and 10 presents “Green Off, Emission [0].” and “Green Off” and The first chart represents the production decision, comparing variables such as production costs, profit margins, natural gas usage, and hydrogen usage. In the “Green Off” scenario, which excludes green energy measures, shows a higher profit margin but results in CO_2 emissions which leads to the decision of re-evaluation of strategy. Conversely, the “Green Off, Emission [0]” scenario leads to slightly higher production costs due leading production cost to exceed profit. This leads to the decision of re-

Table 4
H_2DSS test scenarios.

Parameter	Scenarios										
	0	1	2	3	4	5	6	7	8	9	10
Demand (Mtpa)	200	100	100	100	100	100	100	100	100	100	100
Supply (Mtpa)	150	150	150	150	150	150	150	150	150	150	150
Selling Price (USD/kg)	50	50	20	50	50	50	50	50	50	50	50
Production Cost (USD/kg)	10	10	10	10	10	10	10	10	10	10	10
Adjustment Factor (Ratio)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Green Premium Cost (USD/kg)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Allowed Emission (Tonnes CO2)	100	100	100	100	100	100	100	100	100	100	100
Actual Emission (Tonnes CO2)	50	150	50	50	50	50	50	50	50	0	50
Total Cost (USD/kg)	20	20	20	20	20	20	20	20	20	20	20
Natural Gas (kwh)	4	4	4	4	4	1	2	4	4	2	2
Hydrogen(kwh)	2.5	2.5	2.5	2.5	2.5	0.5	1.5	2.5	2.5	1.5	1.5
Target (kwh)	7	7	7	4	7	2.5	5	7	7	5	5
Market Price (USD/kg)	25	25	25	25	25	15	15	15	15	15	15
Is Green	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	OFF (0)	OFF (0)
Trade Policy Impact	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)
Regulatory Penalty	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)	Off (0)
Off-Take Agreement	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)
Market Growth Evaluation	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)
Engagement Level	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)	ON (1)
High Environmental Benefit (Score 0–10)	10	10	10	10	10	10	10	10	0	10	10
Decision	Don't Produce	Don't Produce	Don't Produce	Don't Produce	Consume locally	Commit to supply at 2 Mtpa	Commit to supply at 4 Mtpa	Commit to supplyat 8 Mtpa	*Re-evaluate strategy*	Re-evaluate strategy	Re-evaluate strategy

evaluation of strategy. Both scenarios highlight the balance between economic gains and environmental sustainability, demonstrating that zero-emission strategies align with environmental goals but reduce profitability.

The bar charts in Fig. 7 offer a structured analysis of key decision-making factors in hydrogen production and supply. Each scenario is assessed based on parameters such as demand, supply, costs, emissions, energy consumption, and market conditions. Scenario 0 highlights a significant demand/supply gap with a production cost of $10/kg and emissions of 50 t CO2, well within the 100-t allowance. Scenario 1 presents a similar cost structure but with emissions exceeding the limit, potentially leading to regulatory challenges. Scenario 2 demonstrates a sharp decline in selling price, impacting profitability. Scenarios 3 through 8 depict high selling prices and controlled emissions, with energy consumption notably decreasing in Scenario 5. The decisions range from not producing in Scenarios 3 and 4, focusing on local consumption in Scenarios 5 and 6, to increasing supply commitments in Scenarios 6–8. Scenario 8 requires a strategy re-evaluation due to scaling or market changes. Energy consumption and environmental metrics vary across scenarios, reflecting different levels of production efficiency and technology use. Environmental scores remain high across scenarios, except for Scenario 8, indicating the critical role of environmental considerations until a strategic reassessment is warranted.

Fig. 8 illustrate key aspects of hydrogen production under different scenarios 9 “Green Off with Emission [0]” and scenarios 10 “Green [Off]”. The first chart represents the production decision, comparing variables such as production costs, profit margins, natural gas usage, and hydrogen usage. In this chart, the “Green Off” scenario which, no emission is saved condition based on Eq. (11). Conversely, the “Green Off, with emission saved [0]” scenario achieves zero emissions saving and slightly higher production costs which led reduced profitability. The second chart illustrates the trade-offs, focusing on how the profit margin, CO_2 emissions, natural gas usage, and hydrogen usage vary between the two scenarios. While the “Green Off” scenario offers slightly higher profitability, it comes with environmental costs, whereas the “Green Off, Emission [0]” scenario prioritizes environmental sustainability with zero emissions but compromises on profitability. Both charts highlight the balance between economic gains and environmental sustainability, demonstrating that zero-emission strategies align with environmental goals but reduce profitability.

Tradeoff between environmental impact and economic impact

The trade-offs between environmental and economic impacts of different hydrogen production methods green, blue, and grey offer a nuanced perspective on their alignment with sustainability goals and economic viability. Each method presents distinct advantages and challenges (Hauglustaine et al., 2022; Owusu & Asumadu-Sarkodie, 2016). Green hydrogen is the most environmentally friendly, using water and renewable energy to achieve zero carbon emissions. However, it incurs high production costs due to the expense of renewable energy infrastructure and electrolyzer systems. While green hydrogen supports a sustainable energy transition, it requires substantial upfront capital and policy support (Osman et al., 2022; Zachary Hurwitz, 2023). Blue hydrogen, which captures and stores CO2, reduces carbon emissions but does not eliminate them. Its cost is generally lower than green hydrogen but higher than grey hydrogen, due to the added expenses of carbon capture and storage technology. Blue hydrogen serves as a transitional method, offering reduced environmental impact with moderate economic costs. In contrast, grey hydrogen, which relies on fossil fuels without carbon capture, contributes significantly to greenhouse gas

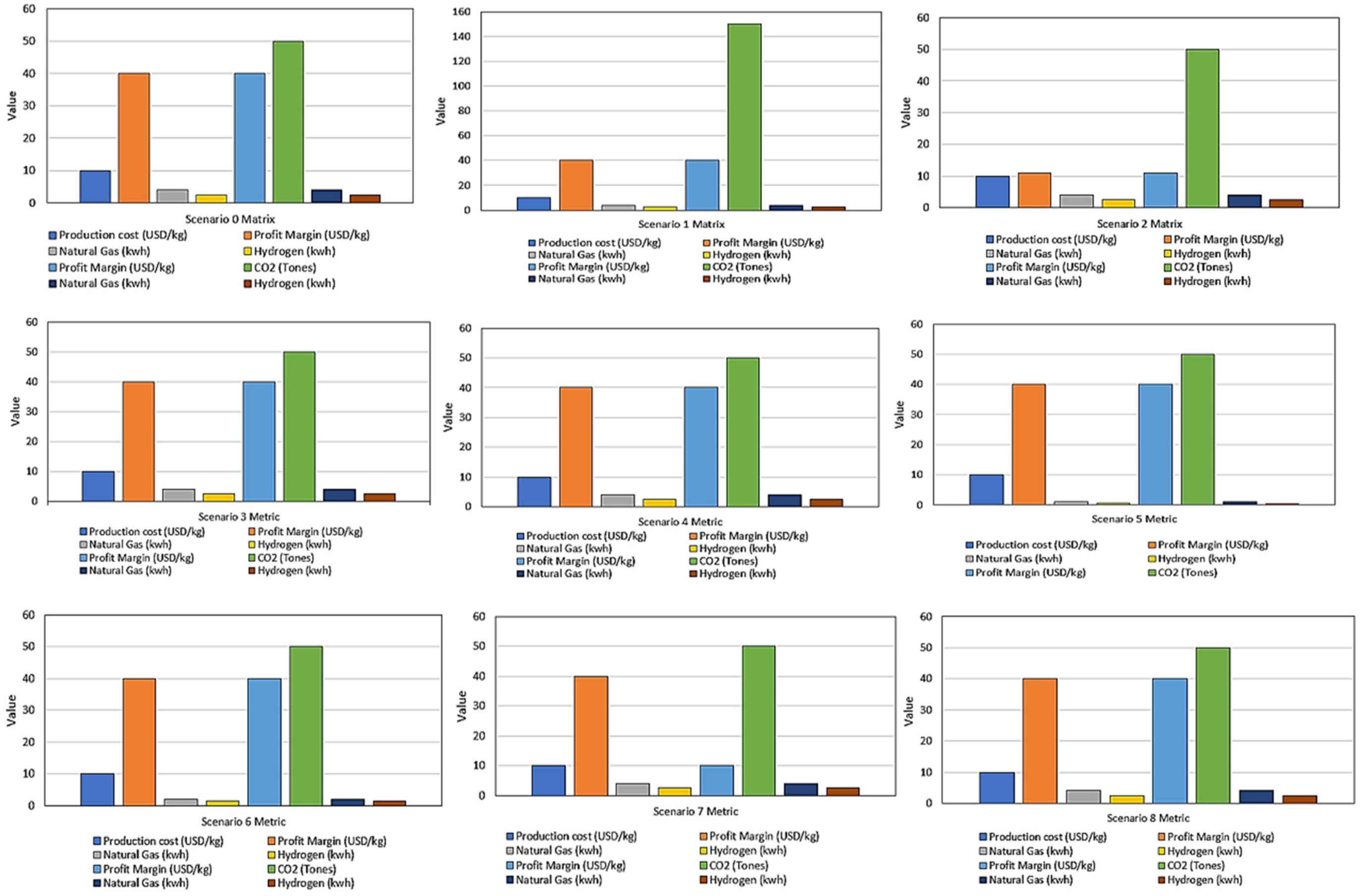


Fig. 7. Metrices analysis of test scenarios.

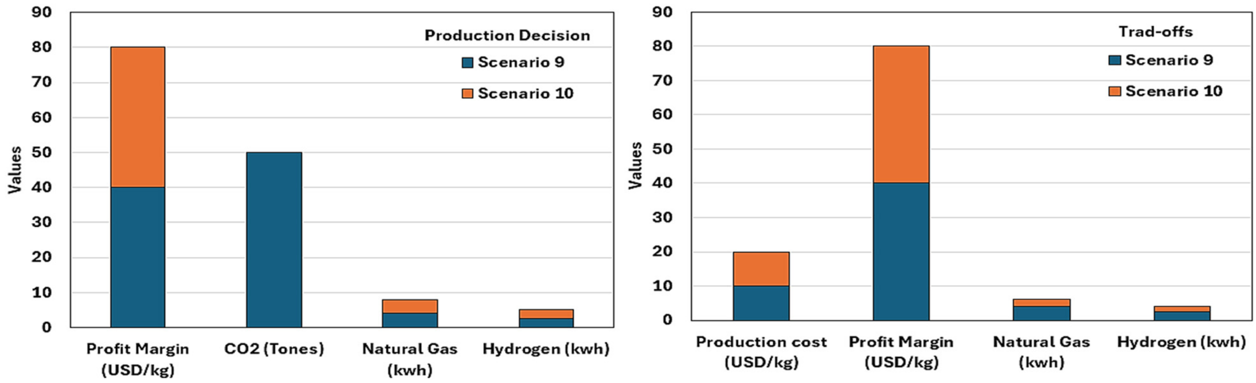


Fig. 8. Metrices analysis of test scenarios 9 and 10 environment impact sensitivity.

emissions and global warming (Osman et al., 2022).

Choosing between these hydrogen production methods involves balancing immediate economic benefits against long-term environmental sustainability. Green hydrogen offers the most sustainable solution with minimal environmental impact, while blue hydrogen presents a compromise with some emissions at a lower cost. Grey hydrogen, although the cheapest, faces significant environmental challenges that could undermine its economic benefits over time due to stricter environmental regulations (Reuß et al., 2019). Market regulations are crucial in overcoming barriers to entry, stimulating investment, and accelerating the adoption of hydrogen technologies. Governments use direct subsidies, tax incentives, grants, and public procurement policies to offset the higher costs associated with hydrogen technologies and ensure market demand or price stability for hydrogen products (Scheibe & Poudineh, 2023; Wang et al., 2021; Q. Zhang, Chen, et al., 2022). Table 5 provides a comprehensive summary of the trade-offs between environmental and economic impacts for different hydrogen production methods.

Table 6 explores the trade-offs between financial profitability and environmental sustainability in hydrogen production through a decision tree analysis. Factors such as production methods, scale of production, energy sources, technology investment, market expansion, transportation, and distribution, short-term vs. long-term considerations, and public perception and brand value are considered. The analysis reveals nuanced trade-offs across different factors, such as traditional production methods such as steam methane reforming (SMR) offering lower

Table 5
Trade-offs between environmental and economic impact for different methods of hydrogen production.

Criteria	Green Hydrogen	Blue Hydrogen	Grey Hydrogen
Projected Costs	High ($500 million)	Moderate ($300 million)	Low ($200 million)
Environmental Impact	Near-zero emissions	Reduced CO_2 emissions with concerns about methane leakage	High CO_2 emissions, misaligned with environmental goals
Market Demand	Increasing, with willingness to pay a premium	Seen as transitional, with specific industry interest	Stable from industries not prioritizing clean energy
Trade-Offs	High upfront cost vs. environmental sustainability and market premium	Balance cost with improved environmental performance vs. CCS uncertainties	Lower upfront costs vs. future regulatory risks and reputational concerns
Decision Factors	High initial investment. Alignment with environmental standards. Potential for premium pricing	Moderate investment. Uncertainties around CCS. Potential future methane regulations	Competitive pricing. Regulatory penalties. Reputational risks due to high emissions
Decision	Chosen due to long-term viability, meeting environmental standards, and premium pricing potential.	Considered for its balance but ultimately not chosen due to CCS concerns and methane emissions.	Not chosen due to misalignment with sustainability goals and potential future regulatory challenges.

Table 6
Trade-offs with in-depth look of the decision-making on financial and environmental output.

Factor	Financial outputs	Environmental outputs
Production Method	Lower costs with traditional methods like SMR. Established, reliable technology.	Higher emissions with SMR. Cleaner but costlier green hydrogen production.
Scale of Production	Economies of scale reduce per-unit cost. Increased efficiency in large-scale operations.	Potential for higher total emissions. Need for emission control technology.
Energy Source	Cheaper using fossil fuels. More accessible and established infrastructure.	Higher emissions with fossil fuels. Renewable sources lead to cleaner production.
Investment in Technology	High upfront capital investment. Long-term return on investment uncertain.	More efficient and less polluting. Future-proofs against stricter regulations.
Market Expansion	New revenue streams in different markets. Adaptation costs to meet varying regulations.	Compliance with diverse environmental standards. Opportunity in green-focused markets.
Transportation & Distribution	Cheaper methods may limit scale or efficiency. Cost considerations for distribution network.	Sustainable methods reduce transport emissions. Higher infrastructure investment.
Short-term vs. Long-term	Immediate profitability with less eco-friendly practices. Delayed investment in green tech.	Higher initial costs for sustainability. Long-term benefits in compliance and reputation.
Public Perception & Brand	Potential short-term financial gain. Long-term risk to brand value and customer trust.	Enhances brand value and customer loyalty. Aligns with global environmental trends.

costs but higher emissions, and green hydrogen production methods being cleaner but costlier. Larger-scale production operations may reduce per-unit costs. However, it can lead to higher total emissions, necessitating emission control technology. The findings highlight the complexity of decision-making in hydrogen production, where financial considerations often conflict with environmental objectives. Balancing these trade-offs requires careful evaluation of each factor and consideration of long-term sustainability goals. Market dynamics and public perception also play significant roles in shaping decision outcomes.

Impact of DSS on Saudi Arabia's hydrogen energy strategy

The DSS is aimed to transform the impact on Saudi Arabia's hydrogen energy strategy to achieve both immediate and long-term strategic objectives. The DSS will improve decision-making processes and optimize resource allocation. In the short-term, the DSS will enhance efficiency and accuracy of decision-making across the hydrogen energy sector by providing real-time, data-driven insights that enable swift and informed decisions. This capability is particularly vital in a rapidly evolving market like hydrogen energy, where prompt response to market changes can secure a significant competitive edge. Long-term, the DSS is expected to drive sustained economic growth within Saudi Arabia's energy sector, attract substantial domestic and foreign investments, stimulate technological innovation, and contribute significantly to the diversification of the Saudi economy. Its capacity to optimize hydrogen production with minimal environmental impact will play a pivotal role in Saudi Arabia's transition to a low-carbon economy, positioning the Kingdom as a leader in the global energy transition. Table 7 present a summary of the DSS impact on Saudi Arabia's.

Sensitivity analysis

The sensitivity analysis depicted in the above figures demonstrates the relationship between various factors, such as supply, demand, environmental benefits, hydrogen production, and production cost, with their respective decisions. Specifically, Figs. 9(a) and 9(b) focus on the demand and supply relationship and its influence on production decisions, highlighting the application of the law of demand and supply. Fig. 9(a) illustrates the behavior of production decisions with varying supply while keeping demand constant at 100 Mtpa, whereas Fig. 9(b) shows the influence of fluctuating demand on decisions with supply held constant at 100 Mtpa. In both cases, the decision to “Commit to supply at 8 Mtpa” occurs when there is excess supply or when demand is less than supply, which is consistent with the principles of economic equilibrium.

According to the law of demand and supply, producers are incentivized to supply more when the price is higher and reduce supply when the price drops, provided the quantity demanded remains unchanged. In Fig. 9(a), as the supply exceeds 100 Mtpa, the respond value becomes positive, signaling a surplus, which leads to the decision to commit to production at 8 Mtpa. On the other hand, when the supply falls short of demand, as shown by negative respond values, production ceases. Conversely, Fig. 9(b) illustrates that when demand is lower, and the supply remains high, the decision is to “Commit to supply.” As demand increases, the respond value turns negative, resulting in the decision to “Don't Produce.” This aligns with the economic principle that production decisions depend on the interaction between demand and supply, aiming to maintain equilibrium without overproduction or shortages.

Figs. 9(c), 9(d), 9(e), and 9(f) extend the analysis to other variables, such as environmental benefits, hydrogen production, and production costs, and their effect on production strategy. Specifically, Fig. 9(c) indicates that an environmental benefit of 6 or more results in a commitment to production, whereas lower values necessitate reevaluation. Figs. 9(d), 9(e), and 9(f) present similar analyses for hydrogen production and production cost, with the decision to produce contingent on achieving a favorable balance. Together, these figures provide a comprehensive sensitivity analysis that reflects how changes in demand, supply, and other influencing factors can significantly impact the production strategy to optimize resource allocation and economic viability.

Table 7

DSS short-time and long-term impact on Saudi Arabia's zero-emission goals.

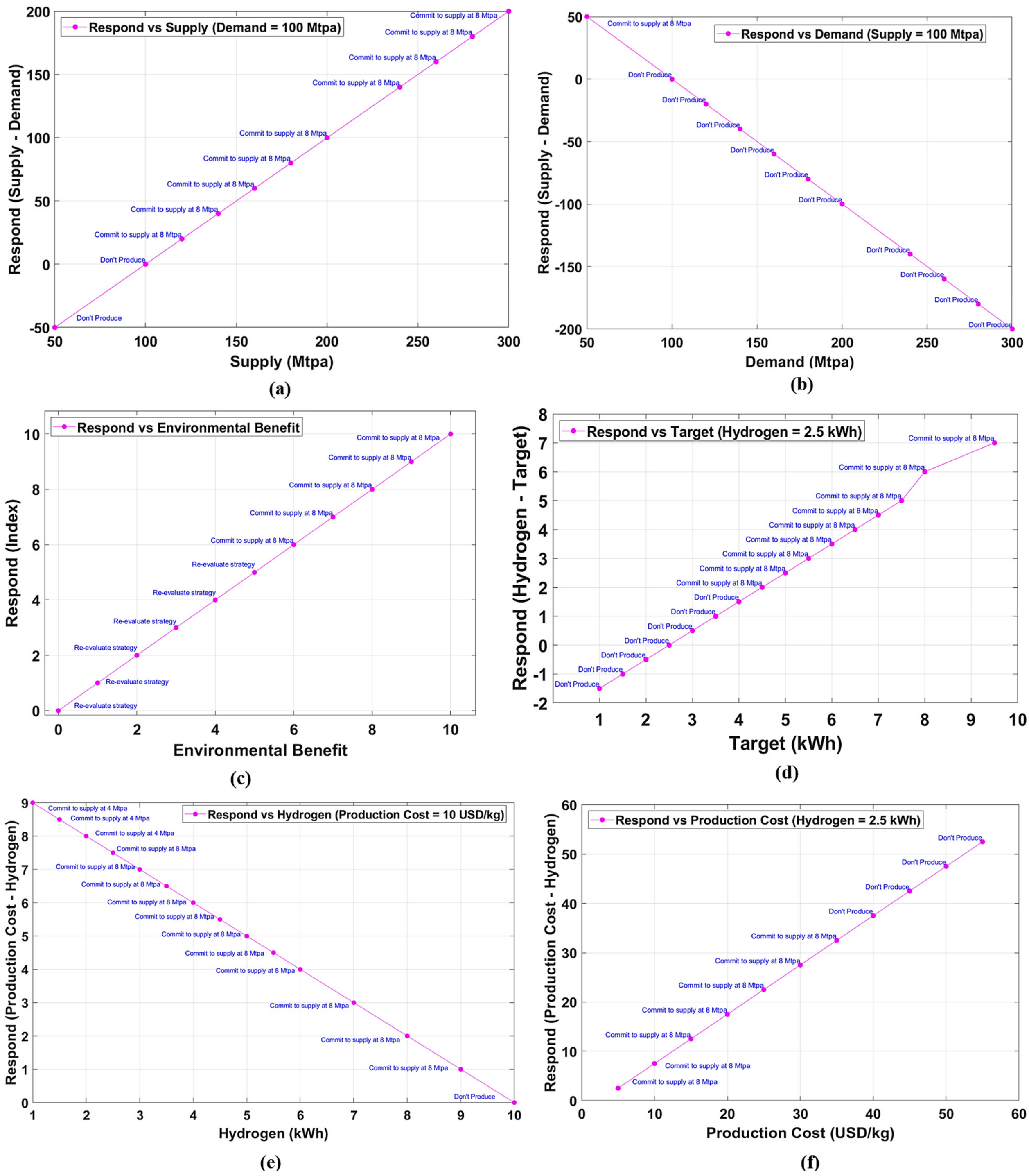
Impact area	Short-term effects	Long-term effects	Expected outcomes	Measurable goals
Economic Impact	Considering profit margins fluctuation due to change in costs and demand in decision making.	Profit margins stabilize as production costs are optimised.	Improved profitability of hydrogen production in Saudi Arabia's zero emission target.	Achieve stability of profit margins.
Policy Adaptation	Quick responses may be required to changes in subsidies or regulations to meet emissions targets.	Sustainable compliance with regulations with DSS that adapts to long-term policy changes.	Greater resilience to policy shifts in meeting Saudi Arabia's emissions goals	Integrate scenario planning into DSS to optimised decision making
Supply Chain Efficiency	Temporary supply disruptions may occur due to logistic challenges.	A more efficient and resilient supply chain.	Fewer disruptions and improved logistics.	Reduce supply chain costs.
Technological Development	Initial focus will be expanding and updating the DSS with more information driven by more reliable data from different sectors.	Continuous improvement and integration of new technologies, tools, policies and stakeholders.	Better decision-making system for hydrogen production.	Add dynamic demand forecasting to DSS by implementing artificial intelligent in decision making
Stakeholder Engagement	There may be initial challenges in getting all stakeholders on board.	Stronger relationships and a shared vision among stakeholders.	Increased support from stakeholders leading to better decision making.	Increase stakeholder engagement and satisfaction
Risk Management	Critical risks related to decisions making in market demand and policies need to be identified.	Better strategy to manage risks for Saudi Arabia's 2030 zero-emission goals.	Better decision-making under uncertain conditions.	Implement risk mitigation strategies for hydrogen production considering Saudi Arabia's zero emission goals.
Environmental Impact	There will be an immediate focus on meeting emissions targets.	Cut CO_2 emissions and long-term sustainability with ongoing environmental monitoring.	Alignment with Saudi Arabia's vision 2030 environmental goals.	Ensure all hydrogen production is zero-emission by 2030.

Future research directions

The decision tree's flexibility allows for adaptations based on changing parameters, external factors, and market dynamics, ensuring that financial and environmental outcomes remain aligned with evolving conditions. This adaptability is crucial for responding to unforeseen circumstances, technological advancements, or regulatory changes, enabling continuous optimization of both financial and environmental performance. In summary, the decision tree acts as a strategic guide, aligning financial decisions with environmental goals. It promotes a holistic approach that recognizes the interconnectedness of financial and environmental sustainability in hydrogen production. Through its structured decision-making process, the system aims to maximize profitability while minimizing environmental impact, contributing to a more sustainable and economically viable hydrogen energy sector (Herrando et al., 2022; Troncia et al., 2023). The decision tree serves as a strategic tool that balances financial and environmental considerations in hydrogen production. It evaluates cost-effectiveness, emissions compliance, market price versus total cost, and profit margins, while also allowing for adjustments based on changing conditions (Mansoury et al., 2023). The flexibility of the decision tree in adapting to changing parameters, external factors, and market dynamics is crucial for maintaining alignment between financial and environmental outcomes. This adaptability is essential for responding to unforeseen circumstances, technological advancements, and regulatory changes, allowing for continuous optimization of both financial and environmental performance. In this context, several future research directions are proposed:

- **Integration of Machine Learning-Based Decision Support Systems (ML-DSS):** Future research should explore the use of ML-DSS to analyse historical data, predict trends, and enhance decision-making processes. This approach could provide greater adaptability to market trends and handle complex relationships, though it may introduce increased complexity and potential subjectivity.
- **Development of Dynamic Updating Methods:** Research should focus on creating decision tree models that can continuously update and adjust their parameters in response to real-time market data, technological advances, and regulatory changes. This would improve the system's responsiveness and ensure that it remains relevant in a rapidly evolving hydrogen energy sector.
- **Advanced Integrations and Scenario Planning:** Further studies could examine the integration of advanced tools, such as scenario planning and dynamic forecasting, to better handle policy changes and market fluctuations. This would help in refining the decision-making process, making it more robust and flexible.
- **Enhancement of Predictive Capabilities:** Enhancing the predictive capabilities of the decision tree through advanced algorithms and data analytics will allow for more accurate forecasting of outcomes, contributing to more informed decision-making in hydrogen production.
- **International Collaboration:** Promoting international collaboration in research could lead to the development of more universally applicable decision-making models, aligning with global best practices and enhancing the system's relevance across different geopolitical and economic contexts.
- **Optimization of Environmental and Financial Balance:** Research should continue to explore ways to optimize the balance between environmental sustainability and financial performance, ensuring that hydrogen production remains both economically viable and ecologically responsible.
- **Simplification and Transparency in Complex Scenarios:** While comprehensive, the current decision tree model could benefit from simplification to avoid oversimplification of complex scenarios. Future research should aim to balance the need for clear, straightforward decision-making with the requirement for detailed, accurate analysis.

Saudi Arabia's commitment to hydrogen energy also plays a strategic role in securing its position as a key energy provider in a world that is increasingly moving towards sustainability. By utilizing its natural resources—such as its extensive natural gas reserves for blue hydrogen and its plentiful solar energy for green hydrogen—the Kingdom aims to remain an influential global energy exporter. This approach ensures that Saudi Arabia stays relevant in the international energy scene, even as the world reduces its reliance on fossil fuels. Major hydrogen initiatives, like the NEOM project, provide Saudi Arabia with an opportunity to establish new international partnerships, particularly with countries in Europe and Asia that are increasing their demand for clean hydrogen. This also boosts Saudi Arabia's geopolitical influence by positioning the Kingdom as an essential player in the renewable energy transition. The integration of a Decision Support System (DSS) into Saudi Arabia's hydrogen policies could have a transformative impact on the nation's energy policy, investment strategies, and international collaboration. By providing a structured, data-driven framework for decision-making, the DSS supports the efficient allocation of resources and the optimization of



(a) (b)

(c) (d)

(e) (f)

Fig. 9. Sensitivity analysis based on (a) Supply with constant demand (b) Demand with constant supply (c) Environmental benefits, (d) Target production with constant hydrogen production, (e) Hydrogen production with constant production cost, (f) Production cost with constant hydrogen production.

hydrogen production and distribution. This aligns directly with Saudi Arabia's Vision 2030, which emphasizes the diversification of the economy and the transition to renewable energy. The DSS could help identify the most viable hydrogen production technologies and locations, considering both economic and environmental criteria, thus informing policies that ensure a sustainable and profitable hydrogen sector.

From an investment strategy perspective, the DSS can facilitate informed decision-making on where and how to allocate substantial financial resources in hydrogen projects. By analysing various factors, such as production costs, technological readiness, and environmental benefits, the DSS can highlight the most economically feasible options for maximizing return on investment. This is particularly important in the context of large-scale projects like NEOM, where significant investments are required. The system's ability to incorporate real-time market conditions and regulatory shifts can also enable more dynamic and adaptive investment decisions, minimizing risks and optimizing the financial performance of hydrogen initiatives. Moreover, the DSS can play a crucial role in enhancing international collaboration. As Saudi Arabia positions itself as a global hydrogen hub, the DSS can provide transparency and strategic insight into the country's hydrogen capabilities, attracting potential international partners. By offering detailed analyses and projections, the DSS can support negotiations, strengthen partnerships, and contribute to international agreements for hydrogen export. This transparency and data-driven approach will not only foster trust among global stakeholders but also position Saudi Arabia as a leader in the international hydrogen economy, reinforcing its role in the global transition to sustainable energy.

Conclusions

The hydrogen decision support system (H_2DSS) proposed in this study is a critical tool for emerging economies like Saudi Arabia, offering a robust framework that integrates multi-criteria decision-making and decision tree methodologies through MATLAB Web App Designer. By balancing economic gains with ecological integrity, the H_2DSS optimizes resource utilization and minimizes financial risks by evaluating factors such as demand and supply, cost analysis, emissions compliance, and production capacity. Tested across eleven strategic scenarios, the system provides stakeholders and investors with tailored, well-informed decisions that align with global sustainability goals. Moreover, the H_2DSS facilitates decision-making for governments by enabling the input of relevant parameters, visualization of outcomes, and the assessment of various scenarios. Its adaptability makes it a promising model for implementation in other countries aiming to transition to hydrogen-based energy systems. By customizing the system to address the specific socio-economic and energy needs of different nations, the H_2DSS can help balance local economic growth with sustainability objectives.

Continuous improvements will be essential in maintaining the balance between economic growth and environmental sustainability, ensuring that hydrogen energy production remains a viable and adaptable component of a cleaner, more sustainable energy future. Future research should focus on enhancing the H_2DSS by integrating machine learning to improve its responsiveness and predictive capabilities. The incorporation of machine learning algorithms would enable the system to process real-time data and continuously adjust decision-making parameters, thereby improving its adaptability and efficiency. Additionally, linking the H_2DSS with real-time data systems would further enable dynamic, data driven decision making. These advancements will ensure that hydrogen energy production remains a viable, efficient, and adaptable component of a cleaner and more sustainable energy future.

CRediT authorship contribution statement

Sultan Kaheel: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Gasem Fallatah:** Writing – review & editing, Supervision, Resources. **Patrick Luk:** Writing – review & editing, Supervision, Methodology. **Khalifa Aliyu Ibrahim:** Writing – review & editing, Visualization, Validation, Software. **Zhenhua Luo:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, 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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