

CRANFIELD UNIVERSITY

Sultan Bin Thiyab Kaheel

**Developing a Strategic Roadmap Toward Hydrogen energy
Economy for energy mix integration In Saudi Arabia**

School of School of Water, Energy and Environment
PhD in Energy and power

PhD
Academic Year: 2021 - 2024

Supervisor: Dr Jerry Luo
Associate Supervisor: Prof Patrick Luk
2024

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**This thesis is submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy**

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ABSTRACT

Hydrogen has come to the forefront as a hopeful solution in the transition toward cleaner, more sustainable sources of energy that will meet global decarbonization goals. However, while it is a great potential, a few challenges are found within the hydrogen sector, including fluctuating renewable energy costs, policy uncertainties, and complex issues related to storage, transportation, and market integration. These make efficient production and distribution of hydrogen hard, hence acting as a barrier to large-scale adoption.

This research addresses these challenges through developing a strategic DSS intended to optimize the production and distribution of hydrogen. The presented DSS integrates multi-criteria decision-making and decision tree methodologies to obtain a flexible tool based on data that will balance economic feasibility, technological adaptability, environmental sustainability, and compliance with regulations. By putting all these elements together, the DSS provides an integrated approach to making decisions for addressing issues with hydrogen energy systems.

This work is motivated by the fact that literature lacks integrated frameworks that might guide decision analyses in hydrogen production. Most works have focused on isolated issues related to the analysis of technology costs or even policy impacts, excluding the important needs for a strategic approach that captures all these significant factors in one fell swoop. This study fills this gap by presenting one unified system able to support relevant, strategic decisions by any stakeholder.

A case study undertaken in Saudi Arabia validates the DSS against practical, real-world scenarios for completeness in aligning with the Vision 2030 energy transition pathways of the country. It should not only promote efficiency and costeffectiveness of hydrogen production but also meet green practices by remaining in step with environmental targets and market demand. Besides, the integration of machine learning techniques enhances the predictive capabilities of DSS and hence increases its adaptability toward dynamically changing energy markets.

These research findings pinpoint the DSS as a very important tool for furthering hydrogen production and distribution while offering valuable insights for policymakers, industry leaders, and investors in the same instance. Given that this study provides a structured approach to decision-making, it will contribute valuably to the global effort of developing a sustainable hydrogen economy and support broader goals for energy security and environmental stewardship.

Keywords:

Hydrogen economy; Market Penetration Feasibility; Production Capacity, Cost and Efficiency, Strategic Planning, Hydrogen Energy Influencing Factors

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TABLE OF CONTENTS

ABSTRACT
i
ACKNOWLEDGEMENTS
iii
LIST OF PUBLICATIONS
iv
TABLE OF CONTENTS
v
LIST OF FIGURES vii
LIST OF TABLES
ix
LIST OF EQUATIONS
x
LIST OF ABBREVIATIONS xi
1 INTRODUCTION
1

1.1 Background	1
1.2 General Introduction	1
1.3 Research Gap	2
1.4 Aim and Objectives	3
1.5 Motivation	3
1.6 Outline of the Thesis	4
2 Advancing Hydrogen: A Closer Look at Implementation Factors, Current Status and Future Potential (Literature Review)	6
2.1 Introduction	6
2.2 Influencing Factors on Hydrogen Energy Transition.	8
2.2.1 Technical Factors	9
2.2.2 Logistical Factors	19
2.2.3 Capital Availability	36
2.3 Hydrogen Alignment with Fossil Fuels	37
2.3.1 Hydrogen Energy Utilisation and Implementation	39
2.3.2 Role of Hydrogen.	42
2.4 Hydrogen Alignment with Hydropower.	45
2.5 Discussion	46
2.6 Conclusions	51
2.7 References	52
3 Development of Decision Support System for Sustainable Hydrogen Production	91
3.1 Introduction.	91
3.2 Methods.	95
3.2.1 Employing the influencing factors into the proposed H ₂ DSS.	98
3.2.2 H ₂ DSS Framework Description	101
3.3 Case Study	104
3.3.1 Saudi Arabia Hydrogen Energy Landscape	107
3.3.2 Decision Tree Construction	110
3.4 Conclusion	134
3.5 References.	135
4 Empirical Analysis and validation of a Decision Support System for Economic Hydrogen production with an insight from Surveys: Case Study of Saudi Arabia	146

4.1 Introduction	146
4.1.1 Study Objectives	148
4.2 Methods	150
4.2.1 Data Collection	152
4.2.2 Statistical Analysis	154
4.3 Result and discussion	156
4.3.1 Survey Design and Representation	169
4.3.2 DSS Effectiveness	172
4.4 Discussion and Future Research Directions	173
4.5 Conclusions	174
4.6 References	177
5 General Discussion, Recommendation, and future Research Direction.	186
5.1 All-Encompassing Decision-Making Strategy	186
5.2 Ability to Adapt to Ever-Changing Conditions	187
5.3 Strategic Focus on Hydrogen Market of Saudi Arabia	187
5.4 Integrating Financial, Environmental, and Logistical Factors	188
5.5 Decision Tree Dynamic	189
5.6 Improved Decision-Making and Future Research Potential	191
5.7 Differentiation from Other Studies	191
5.8 Future Research Directions.	194
5.9 Conclusion	198
6 Conclusion	200
6.1 Summary	200
6.2 Contribution to Knowledge	201
7	204
8 APPENDICES	238
8.1 A detailed summary of the survey result	238
8.2 The Code Outline for MATLAB Web App Designer: -	245

LIST OF FIGURES

Figure 2-1 Hydrogen energy implementation factors.	8
Figure 2-2 Hydrogen energy production methods and challenges	10
Figure 2-3 Global hydrogen production based on BAU, 1_5D, SoS1, and SoS2 scenarios [59].	11
Figure 2-4 The three pillars of hydrogen advancement.	12
Figure 2-5 Advancements and challenges in hydrogen technology development.	13
Figure 2-6 Hydrogen energy production efficiencies adapted from [83]].	15
Figure 2-7 Hydrogen energy production efficiencies adapted from [70]].	19
Figure 2-8 Hydrogen demand: (a) global demand according to [102]; (b) demand under uncertainty using the United States as a case study [101].	21
Figure 2-9 Hydrogen demand: (a) global demand according to [102]]; (b) demand under uncertainty using the United States as a case study [101]].	22
Figure 2-10 Financing cost of hydrogen: (a) based on some European locations [115]; (b) based on some non-European locations [115].	32
Figure 2-11 The comprehensiveness of Hydrogen-energy-influencing factors.	47
Figure 3-1 The implementation factors of hydrogen energy	94
Figure 3-2 A comprehensive approach to the hydrogen energy influencing factors.	100
Figure 3-3 A Comprehensive hydrogen decision support system including the influencing factors	102
Figure 3-4 Kingdom of Saudi Arabia hydrogen energy transition	106
Figure 3-5 H ₂ DSS user interface for KSA (Input based on scenario 6 of table 4)	110
Figure 3-6 Hydrogen energy production decision tree	113
Figure 3-7 Metrics analysis of test scenarios	126
Figure 3-8 Metrics analysis of test scenarios 9 and 10 environment impact sensitivity	
127 Figure 3-9 Sensitivity Analysis (a), (b), (c), (d), (e), (f)	
133	
Figure 4-1 description of what the graphs represents, (a) The potential trade opportunities in the H ₂ market to a certain extent, (b) Overall impact on increasing the green hydrogen market's trade share., (c) Strategic planning clarity in H ₂ development, (d), The ability to analyse market trends and	

forecast demand for green hydrogen, (e) The system's effectiveness in providing real-time market dynamics in the H2 market,(f) The impact of sustainability and environmental impact , (g) The predictive capabilities to incorporating advanced analytics and modelling techniques 160

Figure 4-2 The survey response concerning involvement in the energy industry
(a, b, c) 172

LIST OF TABLES

Table 2-1 A Description of some examples of EU directives	25
Table 2-2 Proposed convergence of regulations and directives.	26
Table 2-3 Selected results of influencing indicators based on data from [120].32	
Table 2-4 Tax and financial parameters.	34
Table 2-5 Impact analysis of green hydrogen in the ammonia industry and fertiliser production.	40
Table 2-6 Other roles for hydrogen.	43
Table 2-7 Summaries of hydrogen-influencing factors.	48
Table 3-1 Description of the decision sequences steps	103
Table 3-2 Saudi Arabia's hydrogen energy production, CO ₂ emission reduction plans, and future goals.	108
Table 3-3 In-depth look of the decision-making	118
Table 3-4 H ₂ DSS test scenarios	122
Table 3-5 Trade-offs between environmental and economic impact for different methods of hydrogen production.	128
Table 3-6 Trade-offs with in-depth look of the decision-making on financial and environmental output	129
Table 3-7 DSS short-time and long-term impact on Saudi Arabia's zero-emission goals output	131
Table 4-1 The Descriptive Statistics	161
Table 4-2 The Correlations of the dimensions table	163
Table 4-3 The Correlations and dimensions	164
Table 4-4 The Correlation and Spearman's Table	165
Table 4-5 The Descriptive Reliability Statistics	168
Table 8-1 A detailed summary of the survey result	238

LIST OF EQUATIONS

(3-1)	99
(3-2)	113
(3-3)	113
(3-3)	114
(3-4)	114
(3-6)	114
(3-7)	115
(3-8)	115
(3-9)	115
(3-10)	115
(3-11)	116
(3-12)	116
(3-13)	116
(3-14)	117
(3-15)	117
(3-16)	117
117 (3-17)	117

LIST OF ABBREVIATIONS

Full Term	Short Term
Application Base	AppBase
Carbon Dioxide	CO ₂
Decision Support System	DSS
Demand and Break-even Quantity Difference	D _s
Distribution Cost	DCost
Editable Field	EditField
Engagement Level Indicator	ELI
Energy Usage for Process i	E _i
Environmental Benefit Indicator	EBI
Environmental Impact Score	EIS
Emissions after Green Technology Implementation	E _{Green} Emissions
Emissions Saved	E _{Saved}
Emission Factor for Green Process i	E _{fgren_i}
Emission Factor for Process i	E _{fi}

Energy Efficiency	η
Fixed Cost	Fcost

Logistical Factor	LF
Market Growth Evaluation Indicator	MGE
Million tonnes per annum	Mtpa
Multi-Criteria Decision Making	MCDM
Natural Gas Energy	w_tf3
Off-take Agreement	OTA
Policy and Regulation Factor	PR
Profitability Ratio	Profit Margin
Production Cost	Pcost
Regulatory Compliance Penalty	RCP
Selling Price	SP
Supply Chain Efficiency	w_Lf2
Target Quantity to be Sold	Q_t
Technical Factor	TF
Text Area	TextArea
Trade Policy Impact Indicator	TPI
Transportation Cost	w_Lf1

User Interface	UI
User Interface Figure	UIFigure

Weight of Emissions Saved in EIS	w_E1
Weight of Energy Efficiency in EIS	w_E2
Weight of Hydrogen Energy in TF	w_tf2
Weight of Natural Gas Energy in TF	w_tf3
Weight of Storage in LF	w_Lf2

1 INTRODUCTION

1.1 Background

With the development and implementation of more sustainable and cleaner energy sources, hydrogen has appeared as one of the most interesting options, holding great potential. Interest has been driven by climate change mitigation policies, energy security, and the finite nature of fossil fuels. Hydrogen is an energy-dense molecule with the capability to generate power with zero direct emission, representing a transformational shift from a hydrocarbon-based economy [1,2]. It ranges in its use from electricity generation and industrial processes to transportation, therefore being a versatile energy carrier needed in a future energy system. Hydrogen can complement other variable renewable sources, such as solar and wind, providing grid stability with more reliable storage solutions. Hydrogen is used for heavy industry and long-haul transport as a feasible decarbonization option where direct electrification is not easy [3–5]. However, high production costs, challenges in infrastructure development, and a lack of harmonization in regulation frameworks burden the road to wider adoption of hydrogen [6,7]. This calls for an integrated and flexible Decision Support System that can manage such complicated tasks of hydrogen energy integration successfully.

1.2 General Introduction

The hydrogen solution is increasingly being recognized as key to the global energy transition goals, providing clean, sustainable, and flexible energy solutions. Hydrogen is one of the cornerstones for Saudi Vision 2030 in powering economic diversification and sustainability. With its wealthy renewable resources, Saudi Arabia is on the frontline in providing green hydrogen, and to reach either of the objectives of national energy security and global sustainability, this is crucial. Adoption of a robust DSS is thus important on this journey to allow for insightful decisions by policymakers and industry players in terms of hydrogen production, market integration, and distribution. DSS provides a structured framework for the processing of complicated data sets, analysing the market

trends, and assessment of environmental impacts that enables transitioning toward a hydrogen-driven economy. References [8,9]. With the DSS, Saudi Arabia will have the capability to develop its hydrogen strategy to meet international standards by systematically overcoming the impediments that come with economic, environmental, and logistical challenges. The present research aims at the betterment of the role DSS will play in enhancing the field of hydrogen by optimizing resources and providing strategic insights towards sustainability [10,11].

1.3 Research Gap

The most current approaches to hydrogen strategy, despite promising prospects, appear piecewise and without the integrated frameworks necessary for reasoned decision-making. Current literature regarding hydrogen runs from a focus on mainly technical and environmental benefits to a lack of comprehensive models that consider various multi-dimensional factors in terms of economic viability, regulatory compliance, and logistic challenges [10,11]. This means that for countries like Saudi Arabia, where hydrogen production is gaining steam, the need for a centralized DSS that provides real-time insight and adaptive decision making capabilities is highly critical [12,13]. A DSS is therefore proposed in this present research that will aid in synthesizing economic, logistics, and environmental data to optimize hydrogen production and distribution. This will enable the DSS framework to support Saudi policymakers in achieving their ambitious hydrogen targets and set a benchmark for other developing economies. The study details that the well-designed hydrogen DSS will increase adaptability, boost precision, and upscale hydrogen projects by a big margin toward establishing a sustainable hydrogen economy.

The growing importance of hydrogen energy in global decarbonization strategies has led to extensive research on its production, distribution, and integration into existing energy systems. However, a critical research gap exists in the integration of decision-making tools to address the multifaceted challenges associated with hydrogen energy. Existing studies focus on isolated aspects of hydrogen development, such as production technologies, cost analysis, supply chain

logistics, and policy impacts, without a holistic approach that combines these factors into a unified framework for decision-making. Current research rarely incorporates dynamic, real-time decision-making tools that can adapt to rapidly changing conditions in the energy sector. Additionally, there is a lack of dedicated Decision Support Systems (DSS) tailored to the unique complexities of the hydrogen sector, such as storage and transportation constraints, variable energy efficiency, and the integration of green and blue hydrogen pathways.

This research aims to bridge these gaps by developing a strategic Decision Support System that integrates economic, environmental, technological, and regulatory factors. The proposed DSS will incorporate multi-criteria decision making techniques and dynamic decision trees to provide a flexible, adaptable framework for hydrogen production optimization. The study will validate the effectiveness of the DSS in aligning with the Kingdom's Vision 2030 goals and demonstrate its potential as a scalable model for other regions pursuing hydrogen-based energy transitions.

1.4 Aim and Objectives

This study aims to develop decision support system to offer Saudi Arabia an appropriate sustainable strategy that will be able to guide the integration of hydrogen into its energy mix toward resilience and competitiveness within the global hydrogen market. To achieve this aim, the following objective have been outlined to be accomplish:

1.5 Motivation

This research will be informed principally by the imperatives of sustainable energy solutions and the imperatives of urgent climate action. The diversification of the economy and reduction in greenhouse gases are some of the planks on which Saudi Arabia envisions its future in its ambitious program called Vision 2030,

placing hydrogen among the strategic energy resources. With abundant renewable resources and a strategic geographic position, Saudi Arabia is wellpositioned to lead in the emerging global hydrogen economy. However, this will need a powerful and agile DSS that can handle the complexities of the production and distribution of hydrogen. The present work would like to contribute to the ambition of Saudi Arabia by providing an integrated DSS model that will enlighten major decisions from resource allocation to market integration in a bid to make the country one of the leading hydrogen energy-producing nations in the world [6,12,14–17]. Therefore, the proposed DSS will be a precious property for policymakers, industry leaders, and investors in deciding on hydrogen development's technical, economic, and logistical challenges. At the end of the article, this study contributes to the global discussion of hydrogen energy by establishing a base capable of developing sustainable energy systems for the substitution of fossil fuel dependency, which will ultimately meet environmental goals on a long-term basis. This work takes forward the hydrogen economy as being economically viable and environmentally sustainable to set a cleaner energy future for Saudi Arabia and beyond by creating a DSS that couples' data driven insights with strategic foresight [12,17].

1.6 Outline of the Thesis

The structure of this thesis is as follows:

Chapter 1 gives the background information, problem statement, and objectives that frame the ensuing analysis.

Chapter 2 offers a detailed review of the current hydrogen energy landscape, covering technical and economic issues and the regulatory driving forces behind the development and uptake of hydrogen technologies. This chapter goes on to discuss how public-private partnerships and international cooperation help advance hydrogen energy.

Chapter 3 elaborates on the development of the DSS framework. It describes the methods and tools used for the modelling of hydrogen production and distribution

scenarios and includes the integration of methodologies from MCDM with decision tree models within the framework of the DSS.

In addition to applies the DSS framework to the case study of Saudi Arabia, evaluating its effectiveness in guiding strategic decisions related to hydrogen energy production and export. This chapter comprises an in-depth analysis of the results and their consequences for policy makers and industry stakeholders.

Chapter 4 is dedicated to the validation procedure of the DSS. This means that the recommendations of the tool are checked against real world data and scenarios to validate its accuracy and reliability.

Chapter 5 This chapter will present research on hydrogen energy development regarding optimization production and strategic energy planning using DSS. It will provide insight into how such systems can overcome technical, financial, environmental, and logistic barriers. The contribution of this study is particularly relevant to the ever-growing knowledge base on hydrogen energy regarding its adaptability and contextual relevance. Second, it represents the relevance of the study in view of suitability for adaptation.

Chapter 6: This last chapter of the thesis closes with a summary of the main findings of the study, the limitations of the study itself, and recommends some future lines of research. The last chapter of the present work will reinforce the message about the important role this DSS plays in contributing to the global transition to a sustainable hydrogen economy. This research has been done to add a strong tool of decision-making to the fast-growing knowledge body of hydrogen energy systems, thus aiding the world's shift towards cleaner and more sustainable energy solutions.

2 Advancing Hydrogen: A Closer Look at Implementation Factors, Current Status and Future Potential (Literature Review)

Abstract:

This review article provides a comprehensive analysis of the hydrogen landscape, outlining the imperative for enhanced hydrogen production, implementation, and utilisation. It places the question of how to accelerate hydrogen adoption within the broader context of sustainable energy transitions and international commitments to reduce carbon emissions. It discusses influencing factors and policies for best practices in hydrogen energy application. Through an in-depth exploration of key factors affecting hydrogen implementation, this study provides insights into the complex interplay of both technical and logistical factors. It also discusses the challenges of planning, constructing infrastructure, and overcoming geographical constraints in the transition to hydrogen-based energy systems. The drive to achieve net-zero carbon emissions is contingent on accelerating clean hydrogen development, with blue and green hydrogen poised to complement traditional fuels. Public–private partnerships are emerging as catalysts for the commercialisation of hydrogen and fuel-cell technologies, fostering hydrogen demonstration projects worldwide. The anticipated integration of clean hydrogen into various sectors in the coming years signifies its importance as a complementary energy source, although specific applications across industries remain undefined. The paper provides a good reference on the gradual integration of hydrogen into the energy landscape, marking a significant step forward toward a cleaner, greener future

2.1 Introduction

The survey focuses on the identified influencing factors of hydrogen development, including technology, logistics, and policy, which are crucial for setting development strategies and scientifically justified and validation obtained [18]. The future of the energy sector is marked by concerns about the security of supply and climate change, as well as the increasing prices of energy services.

Hydrogen is becoming an increasingly important energy vector and a key component of the global energy revolution. It has the potential to drive transformative changes in energy and transportation and reduce emissions in sectors where electrification may not be a feasible solution [19,20]. However, despite the promising potential of hydrogen, the industry is uncommercialised

due to the uncertainty of demand and the lack of reliable distribution systems and storage networks for hydrogen [21]. There is a need to consolidate an automated approach to hydrogen development that can be adapted to various constraining factors, levels of interest, and potential incentives [22–24]. To expedite hydrogen development, it is imperative to adopt a comprehensive policy approach and conduct a rigorous analysis of regulatory measures while drawing insights from existing projects. Advancing hydrogen energy has the potential to combat global warming and enhance energy security, particularly in nations with limited energy resources.

The major concerns for the energy sector's future are the security of the energy supply and addressing climate change. Hydrogen (H_2) is emerging as a viable and environmentally friendly energy carrier with the potential to have a significant impact on our global energy system thanks to renewable energy technologies. It has established itself as a candidate for a key place in our future energy environment since it can be used for both energy transportation and storage. In addition to concerns about energy supply security, climate change and local air pollution and the increasing prices of energy services impact policymaking around the world [25,26]. For these reasons, Ref. [27] employed Spearman's technique to analyse the national development of a hydrogen economy. Their study also aimed to assess environmental performance parameters to establish correlations between renewable energy's environmental, economic, and energy use factors. The significance of links between ecological factors and energy use has also been emphasised using Spearman's correlation to identify indicators of energy sustainability measurement [28–32]. Ref [33] reported that a remote generator will save almost 90% of its total costs due to the decrease in the cost of hydrogen fuel by 2030. Further research is needed to enhance the efficiency and dependability of fuel cells and other hydrogen-based technologies according to several studies [34–40]. Research by [41–44] discusses the main findings related to energy conversion efficiency and environmental impact, as well as the challenges in identifying the relative challenging factors in the hydrogen energy transition process.

This article provides an insightful review of hydrogen energy development systems, challenges in optimizing their deployment, and their implementations. It categorises the influential factors into technical and logistical, as depicted in Figure 2-1. Technical factors encompass 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. It also addresses challenges in identifying prominent obstacles during the hydrogen energy transition.

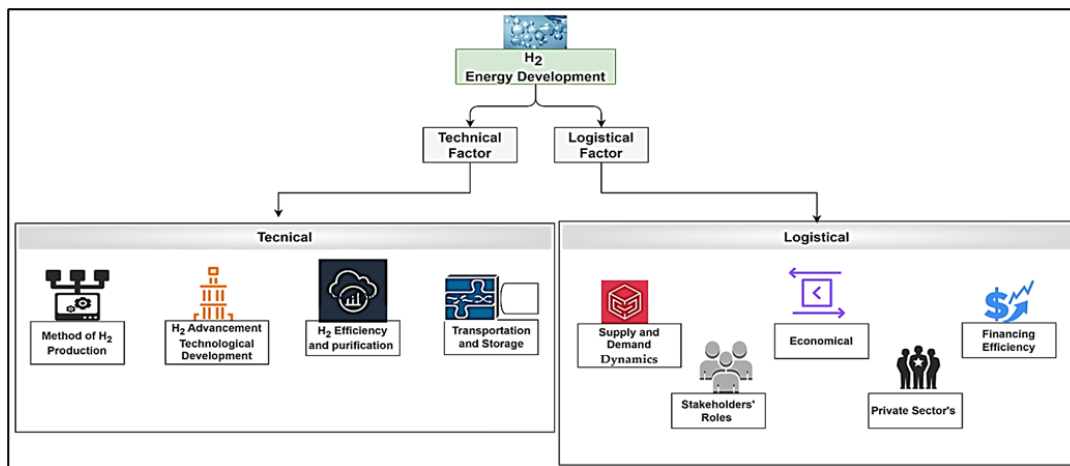


Figure 2-1 Hydrogen energy implementation factors.

2.2 Influencing Factors on Hydrogen Energy Transition.

Technical considerations play a role in determining the feasibility and long-term sustainability of hydrogen. Ongoing research and development are focused on optimizing each of these factors with the goal of promoting the use of clean hydrogen as an ecofriendly energy source. Specifically, when it comes to producing zero-carbon hydrogen, various technical aspects come into play. These include selecting the method for hydrogen generation, continually advancing hydrogen technology, enhancing efficiency implementing purification techniques, and developing efficient transportation and storage solutions. These factors collectively determine the feasibility and sustainability of hydrogen generation and play a pivotal role in achieving low-to-zero-carbon clean hydrogen

as a sustainable energy source. The following section discusses each of the technical factors.

2.2.1 Technical Factors

Ongoing research and development are focused on optimizing each of these factors with the goal of promoting the use of clean hydrogen as an ecofriendly energy source. Specifically, when it comes to producing zero-carbon hydrogen, various technical aspects come into play. These include selecting the method for hydrogen generation, continually advancing hydrogen technology, enhancing efficiency implementing purification techniques, and developing efficient transportation and storage solutions. These factors collectively determine the feasibility and sustainability of hydrogen generation and play a pivotal role in achieving low-to-zero-carbon clean hydrogen as a sustainable energy source. The however, the following section discusses each of the technical factors.

2.2.1.1 Hydrogen Generation Method.

Hydrogen is the simplest chemical element on Earth and has an atom composed of a single proton and a single electron. It can accumulate and provide energy, acting as an energy carrier [45]. It can be produced using several resources, such as fossil fuels (natural gas and coal), water, nuclear energy, and other renewable energy sources like biomass, wind, solar, and geothermal. Hydrogen can be produced at or near the point of use. Hydrogen can be produced using several different processes, which include thermal–chemical processes [46–48], photoelectric processes [49–51], and electrolytic processes [52–54]. Microorganisms such as bacteria and algae can also produce hydrogen through biological processes [55–57]. Figure 2-2 shows hydrogen energy production methods.

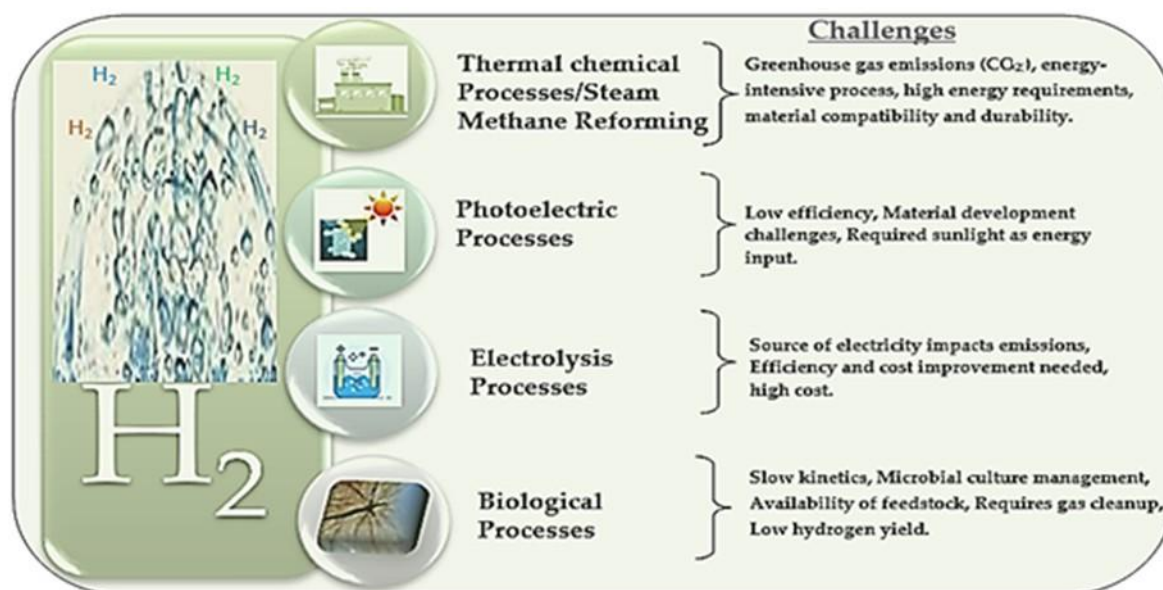


Figure 2-2 Hydrogen energy production methods and challenges

Thermal–chemical processes use heat and chemical reactions to extract hydrogen from natural gas, coal, biomass, and even water. Natural gas contains methane that can be used to produce hydrogen by thermal–chemical processes like steam reforming and partial oxidation [46]. In steam reforming, methane and other hydrocarbons react with high-temperature steam under pressure, and, in the presence of a catalyst, the reaction is accelerated. The reaction products are hydrogen and carbon monoxide. Electrolytic processes used electricity to make chemical reactions. The most common process is the electrolysis of water, where water is split into hydrogen and oxygen using electricity [58]. This is a sustainable method for producing hydrogen because there would be no greenhouse emissions during production when integrated with renewables. Photoelectric chemical processes use sunlight energy to split water into hydrogen and oxygen. In a photoelectric chemical cell, the semiconductors are like those used in photovoltaic solar electricity generation. They are immersed in a water-based electrolyte where sunlight energises the water splitting process into hydrogen and oxygen, like in the electrolysis of water [49]. Biological processes include the microbial conversion of biomass, where microorganisms consume and digest biomass to release hydrogen [55–57]. This happens in fermentation-based systems where microorganisms such as bacteria break down organic matter to

produce hydrogen. A global hydrogen production projection has been reported by [59] based on four scenarios as shown in Figure 2-3.

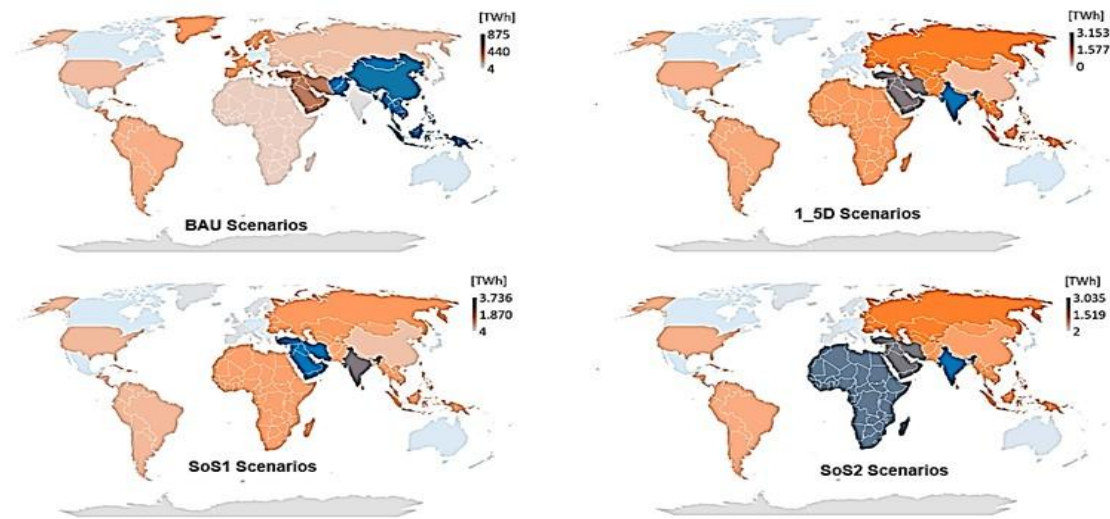


Figure 2-3 Global hydrogen production based on BAU, 1_5D, SoS1, and SoS2 scenarios [59]. (1_5D refers to the 1.5-degree decarbonization scenario, SoS2 stands for the State of Sustainability Scenario, and BAU represents the Business-As-Usual approach to energy projections).

Green hydrogen is produced from electrolysis integrated with renewable energy resources [60]. One key challenge in producing green hydrogen is the amount of electricity required from renewable energy resources. Improving production efficiency, lowering production costs, creating and scaling up hydrogen storage and transportation technologies, and current system integration are important technological considerations for expanding hydrogen energy.

2.2.1.2 Advancements in Hydrogen Technology Development

The development of hydrogen energy has the potential to reduce global warming and provide energy security for nations that do not currently have sufficient energy resources. Extensive research has shown that hydrogen, if successfully developed, might power vehicles and generate electricity [27,44,45,61–64]. The three pillars of the development of hydrogen energy are fuel-cell installation, hydrogen power plants/mass supply chains, and CO₂-free hydrogen, as shown in Figure 2-4. Technological influencing factors pertain to these three pillars of hydrogen development and assure economic efficiency [65]. The status of

research and design projects' development has been outlined, projecting a global energy model to the year 2050 as reported in the following research [27,42,66].

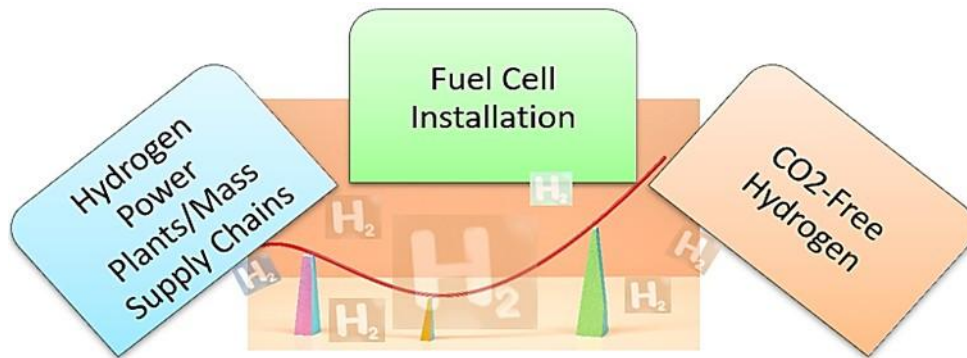


Figure 2-4 The three pillars of hydrogen advancement.

The goals of the technology development projects are to drastically expand the utilisation of hydrogen in the power generation field, to build the world's first full scale hydrogen supply chain by approximately 2030, to establish flexibility in the energy supply system, and to contribute to ensuring energy security through the development and implementation of technologies [19,67]. The use of hydrogen technologies in renewable energy development and the stabilisation of electricity distribution networks would derive from both a comprehensive approach and strategic planning. Japan and Romania are setting up a global supply network as a top priority, as reported in [68,69]. For example, Japan's policy is to import fossil fuels from abroad and use them to make blue hydrogen by capturing carbon dioxide using carbon capture, utilisation, and storage (CCUS) technologies as well as establishing international hydrogen supply networks. Hence, the results from the associated hydrogen import verification tests are expected soon [21].

Fuel cells turn hydrogen-rich fuels into energy [70]. Fuel cell applications and integrated renewable power with hydrogen production systems are studied in technology validation projects to bring hydrogen and fuel cells to market [36,61,71–74]. Solutions to problems with weight and hydrogen compression and storage are required as reported by [24,35,75].

The use of fuel cells to power electric motors has many advantages. They are quiet and create no exhaust greenhouse gases [64]. Hydrogen fuel cells could replace

lithium batteries in long-distance and heavy-duty vehicles, but hydrogen prices must be lowered [42]. Long distances and insufficient network use may not necessitate track electrification, making hydrogen-powered trains more viable for freight and rural/regional lines [76,77].

The adoption and utilisation of hydrogen-energy-powered automobiles can be achieved. The current position of fuel cells and fuel-cell vehicles has been widely accepted in Japan, as was reported in [68]. However, there is need for proposed regulations to improve top-level design, pilot demonstration, and hydrogen supply chain expansion for the transportation sector. The cost of hydrogen relative to fossil fuels, the difficulties of a loss of cargo space due to fuel storage, and the implementation of worldwide refuelling networks are also influencing factors. Nonetheless, to achieve financial success, it is necessary to fulfil the standards of cost, durability, and reliability. Figure 2-5 gives a summary of current advancements and challenges in hydrogen technology development in three stages: production, transportation, and storage.

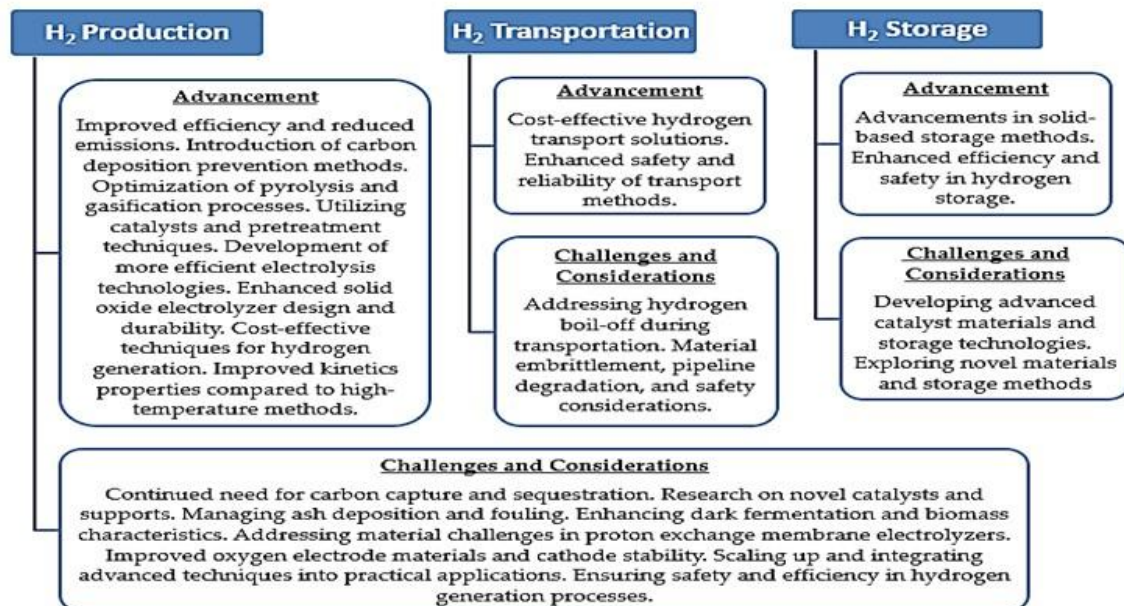


Figure 2-5 Advancements and challenges in hydrogen technology development.

2.2.1.3 Hydrogen Efficiency

Technical considerations play a role in determining the feasibility and long-term sustainability of hydrogen. The economic viability of hydrogen depends on the production process. Hydrogen is not a readily available energy source. It is usually stored in water, hydrocarbons such as methane, and other organic matter. The challenges of using hydrogen as an energy storage mechanism come from being able to efficiently extract it from these compounds.

Hydrogen is often considered for its potential in energy storage, particularly in power-to-gas systems where excess electricity is used to produce hydrogen through electrolysis [78]. This hydrogen can then be stored and later converted back to electricity when needed. However, this process is fraught with efficiency losses as reported in [79–82]. The efficiencies of hydrogen production have been reported in [83] as shown in Figure 2-6. Each conversion step from electricity to hydrogen and then back to electricity involves energy loss. These losses make the entire process less attractive compared with direct electrical energy storage methods like lithium-ion batteries. Furthermore, the efficiency loss becomes particularly significant when grid-scale energy storage is considered. The most employed method of hydrogen production is steam methane reforming (SMR), which involves high operating temperatures and pressures necessitating a large energy input. Though relatively efficient, the method also produces a significant amount of CO₂ as a byproduct, undermining the clean energy credentials of hydrogen.

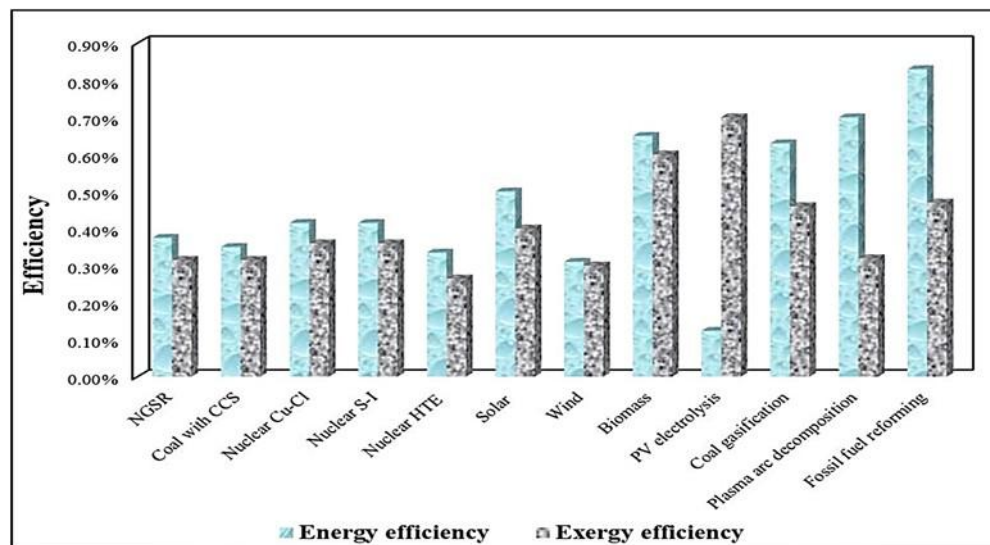


Figure 2-6 Hydrogen energy production efficiencies adapted from [83]].

Hydrogen energy production efficiency has been reported in several studies. Water electrolysis, and more especially alkaline electrolysis, exhibits a wide range of energy efficiencies, ranging from 61% to 82% [84]. Electro photolysis, which uses photo-electrochemical processes, has energy efficiencies ranging from 0.5% to 12% [85]. Energy efficiencies for photolysis and photosynthetic processes range from 1% to 3% and are less than 5% [86]. Ref. [87] reported that water thermolysis procedures have energy efficiencies of 20% to 55%, whereas Ref. [86] reported that chemical processes involving redox reactions had energy efficiencies of 3% to 5%. Additionally, steam methane reforming, which produces hydrogen from hydrocarbons like natural gas, often achieves energy efficiencies ranging from 74% to 85% [88]. Fossil-fuel partial oxidation technologies exhibit energy efficiencies between 60% and 75 [88]. The energy efficiencies of proton exchange membrane (PEM) technology, which is essential to water electrolysis, typically range from 67% to 84% [89]. These results demonstrate the variety of efficiencies in hydrogen generation techniques and the significance of choosing the most appropriate strategy based on energy effectiveness and purity. According to research by [90], microorganisms can attain energy efficiencies in “biolysis”, or dark fermentation, that range from 60% to 80%. Ref. [87] reported that microalgae often display lower energy efficiencies, often less than 1%, with a range of 1% to 3%, with the “biophotolysis”, or photo fermentation, technique. According to a review [87], energy efficiencies of between 70% and 80% have been attained with “bioelectrolysis”, or microbial electrolysis. Additionally, Ref. [91] reported that co-fermentation hydrolysis produced energy efficiencies of between 35% and 45%.

The concept of green hydrogen, which produces hydrogen through electrolysis using renewable energy, offers a more environmentally friendly alternative to SMR. However, challenges include the total energy requirement and availability of renewable sources of energy. While hydrogen holds promise as a medium for energy storage, challenges in terms of efficiency need to be addressed.

Infrastructural development must be overcome for it to play a significant role in future energy systems.

Hydrogen is a sustainable energy source that presents unique challenges due to its low volumetric energy density, high diffusivity, and technical complexities. To ensure hydrogen production, storage, and delivery at scale, efficient transportation and storage methods are essential. Compressed hydrogen gas is a common storage method, suitable for fuel cell vehicles and small-scale industrial applications. However, high-pressure storage requires robust tanks, increasing costs and posing safety risks. Liquid hydrogen storage, which involves cooling hydrogen to cryogenic temperatures, is preferred for long-distance transportation and bulk storage. However, this process is energy-intensive and requires specialized tanks.

Chemical carriers like ammonia and liquid organic hydrogen carriers (LOHCs) offer alternative storage solutions by chemically binding hydrogen to other substances. Ammonia can be transported using existing infrastructure and converted back to hydrogen at the point of use, but it is toxic and requires additional energy for reconversion. LOHCs allow hydrogen to be stored and transported under ambient conditions, utilizing existing fuel transport systems.

Transportation of hydrogen presents logistical challenges, with pipelines being the most cost-effective method for large volumes over long distances. However, hydrogen can cause embrittlement in metals, weakening pipeline structural integrity and increasing leak risk. Dedicated hydrogen pipeline projects are being developed in regions like Europe to address these challenges. Shorter distance transportation via road or rail offers flexibility but higher costs and limited capacity.

2.2.1.4 Transportation and Storage

Storage and transportation have significantly impacted the cost effectiveness and practicality of using hydrogen in various industries. A viable hydrogen infrastructure requires that hydrogen be able to be delivered from where it is produced to the point of end use, such as a refuelling station. Delivering hydrogen

from the point of production has an impact on the overall cost [92]. As shown in Figure 2-7, transportation can be categorised as semi-centralised, centralised, or intercontinental depending on distance, while storage can be liquefaction, compression, or physical or chemical bonding such as in NH_3 , metals, and hydrides [92,93]. The major challenges faced while transporting hydrogen in liquefied form include maintaining a very low temperature, of about $-250\text{ }^\circ\text{C}$, requiring high energy for storage [94]. Additionally, liquification consumes about 20 to 40% of the energy brought by hydrogen [95]. Other challenges include the risk of leakage, long-term storage and boil-off control. Until effective solutions for these challenges are found, hydrogen's adoption in the industrial sector will remain limited.

Hydrogen, a sustainable energy source, requires efficient, cost-effective, and safe storage and transportation systems due to its unique properties. Compressed hydrogen gas is commonly used in fuel cell vehicles and small industrial applications but involves high material costs and safety concerns.

Liquid hydrogen storage, which involves cooling hydrogen to cryogenic temperatures, increases energy density but consumes around 30% of the hydrogen's energy content. Infrastructure like cryogenic tanks and insulated pipelines adds further cost and complexity.

An emerging alternative is the use of chemical carriers like ammonia or liquid organic hydrogen carriers (LOHCs), which can be produced using existing industrial processes and transported through established infrastructure but requires energy-intensive conversion back to hydrogen and poses toxicity risks. LOHCs allow hydrogen to be stored under ambient conditions, reducing storage challenges but involve costly hydrogenation and dehydrogenation processes.

Transporting hydrogen introduces additional logistical complexities. Pipeline transport is the most efficient for large volumes over long distances, but hydrogen can weaken metal pipelines through embrittlement, increasing leak risks. Retrofitting existing natural gas pipelines offers a partial solution, but material

compatibility limits hydrogen blending ratios. Shorter distances require road and rail transportation using tube trailers or cryogenic tankers, but is more expensive due to fuel, labour, and specialized equipment costs.

Real-world projects demonstrate the viability and challenges of these methods, such as the Japan-Australia Hydrogen Supply Chain successfully transporting liquefied hydrogen over long distances, Saudi Arabia using ammonia as a hydrogen carrier, and the Hydrogen Backbone initiative in Europe aiming to create a transcontinental hydrogen pipeline network.

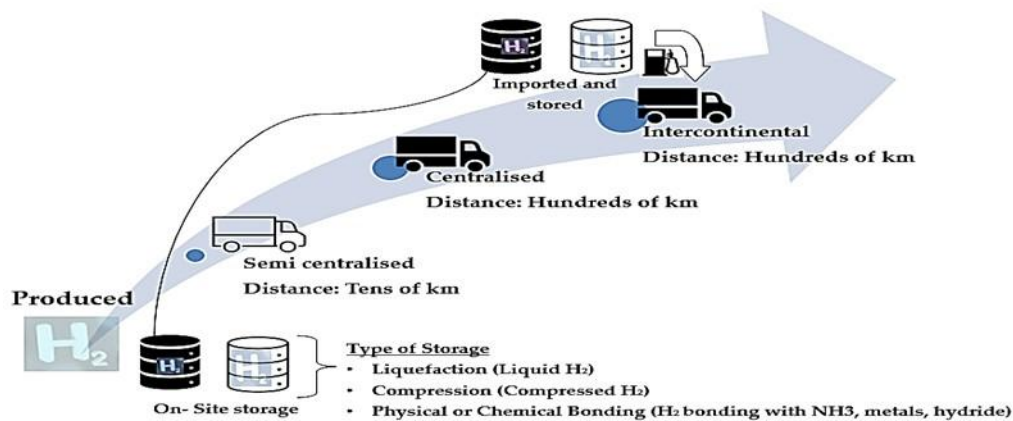


Figure 2-7 Hydrogen energy production efficiencies adapted from [70]].

2.2.2 Logistical Factors

The economic feasibility and long-term sustainability of hydrogen implementation is dependent on logistical factors. The objective of ongoing research and development is to maximise and encourage the use of clean hydrogen as an environmentally beneficial energy source. Specifically, several logistical considerations apply when producing hydrogen. Regulations, stakeholder responsibilities, economic considerations, financial effectiveness, and private sector participation are all examples of logistical factors. The production and implementation of hydrogen presents several logistical challenges. This section discusses the logistical barriers in the shift to hydrogen energy.

2.2.2.1 Hydrogen Energy Supply and Demand Dynamics.

The supply and demand of hydrogen energy is another influencing factor. Hydrogen's value as an energy carrier is determined by manufacturing costs and consumption. For example, in the Netherlands, hydrogen is generated by SMR without carbon capture for €1.50/kg [96]. If carbon emissions were taxed higher, grey hydrogen costs would be expected to grow [97]. However, currently, green hydrogen costs €5/kg, with power accounting for two-thirds and electrolysis for one-third of the costs, but this could drop to €2/kg by 2030. Hence, hydrogen production is feasible by 2030 if current plans are carried out, but supply and distribution may rise up even further as reported by [98].

However, demand for energy around the globe is forecast to increase steadily over the next few decades. Concerns about the reliability of the energy supply, global warming, and climate change all impact governments' decision-making, while concerns about the potential economic and geopolitical effects of oil supply disruptions have prompted the development of alternate fuels [99,100]. In an examination of research in [68], the projections for 2050 for both the supply and consumption of hydrogen vary widely. Figure 2- 8a shows hydrogen global demand; it has been reported that, even with uncertainties, hydrogen demand increases according to [101] as shown Figure 8b.

The Decision Support System (DSS) is a significant advancement in optimizing hydrogen production and distribution, but it has limitations such as data reliability, stakeholder survey biases, and real-world implementation challenges. Data reliability is crucial for the system's accuracy, as it relies on quality, completeness, and timeliness of inputs. To mitigate this limitation, future iterations should incorporate automated data validation processes and leverage real-time data streams from IoT sensors, energy markets, and policy databases. Additionally, establishing data-sharing partnerships with government agencies, industry stakeholders, and research institutions can improve data accuracy and completeness. Stakeholder survey biases are another limitation of the DSS, as they can influence results by providing responses that align with socially desirable or politically correct perspectives. To address these biases, future research

should adopt a mixed-methods approach, combining quantitative surveys with qualitative interviews and focus groups.

Real-world implementation presents technical challenges, such as complex integration with existing infrastructure, software systems, and data platforms. Regulatory and policy challenges, organizational resistance, and financial constraints can also pose challenges. To overcome these challenges, the DSS should be designed with modular architecture for customization and scalability. Pilot projects can demonstrate the system's value in real-world settings, building confidence among stakeholders and highlighting ROI. User-friendly interfaces and explainable AI techniques can improve transparency and foster greater acceptance.

In conclusion, while the DSS represents a significant advancement in optimizing hydrogen production and distribution, it faces limitations such as data reliability, stakeholder survey biases, and real-world implementation challenges.

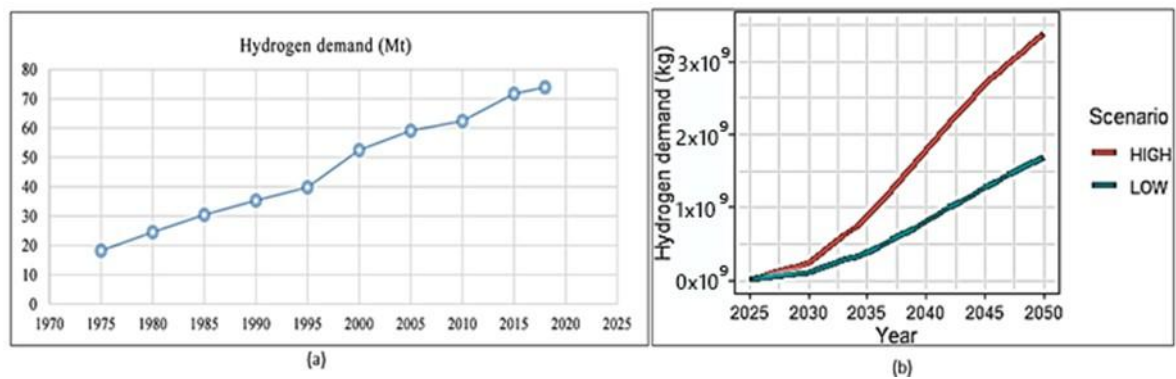


Figure 2-8 Hydrogen demand: (a) global demand according to [102]; (b) demand under uncertainty using the United States as a case study [101].

Research by [59] reported hydrogen energy demand using four scenarios. Their results show that the worldwide demand for hydrogen is high in the 1_5D scenario, standing at 2776 TWh, whereas the demand in SoS1 scenario is slightly lower, at 2055 TWh. Contrarily, the SoS2 scenario projects 2688 TWh of hydrogen demand. The findings indicate that hydrogen is utilised in the final

energy consumption under the BAU scenario. Their research concludes that the scenario that places a priority on addressing climate change lacks a security of supply strategy, and that not all regions can produce hydrogen domestically by 2100. In Ref. [102], global supply based on trade by country is reported based on export and import as shown in Figure 2-9. This shows that about 40% of all hydrogen exports are made by the Netherlands, with Canada coming in second. About 15% of all hydrogen is sold in Belgium, the US, and Germany, which together account for 90% of all exports. Moreover, half of all hydrogen imports come from the top two importers, which are Belgium and the United States.

France imports 8%, the Netherlands 5%, and Germany 5% of pure hydrogen, respectively. These nations contribute more than 80% of world imports.

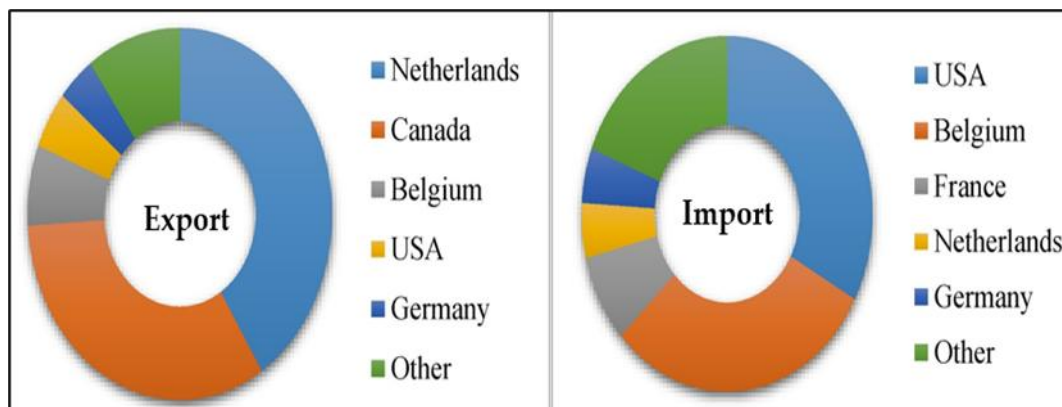


Figure 2-9 Hydrogen demand: (a) global demand according to [102]; (b) demand under uncertainty using the United States as a case study [101].

Studies on the hydrogen supply chain are at an early stage. Current research on hydrogen supply chains focusses on how hydrogen relates to influencing factors regarding management of electricity and distribution networks that fuel renewable energy sources (RES). The concept of designing a hydrogen supply chain that differentiates the phases of supply, production, storage, and distribution of electricity is needed [31].

The use of hydrogen technologies in RES stabilisation may reduce the operational safety of electricity distribution networks. However, a comprehensive approach and strategic planning is needed. This strategic design should assist in

approaching future global energy needs. It is important to have a good understanding of the types of environments and the existing literature to make rising RES share a future policy goal [103]. For instance, Japan may need to import hydrogen; thus, setting up strategic plans for a global supply network is a top priority [104]. To attain the economies of scale required to rapidly reduce affordable hydrogen, a significant expansion of upstream production, midstream transportation, and storage facilities for liquefied hydrogen, methylcyclohexane (MCH), and ammonia will be required [31]. Examples of some active initiatives are described [31,68,77]. Various pilot projects are being conducted in Japan to build a worldwide hydrogen supply chain. In Japan, current projects include hydrogen being transported in the form of (I) liquid hydrogen, MCH, and ammonia. As a result, Japan's domestic policy objective is to use surplus fossil fuels from abroad to make blue hydrogen by capturing carbon dioxide using CCUS technologies and establishing international supply networks. MCH is now employed as a fuel for thermal power plants and hydrogen is undergoing verification testing as an import [105]. Another project in Japan is ongoing as an attempt to extract hydrogen from brown coal, of which Australia has large reserves, and liquefy it for shipping to Japan by sea [35].

It has been reported that global oil demand is expected to rise by more than 30% by 2030, necessitating a doubling of present production levels. In addition, it has been highlighted that there may be a shortage of oil, necessitating the search for alternate sources of transportation fuel to meet expanding demand and restricted resource availability [106]. In the future, the cost of hydrogen will depend on its usage and production costs. Currently, hydrogen is mostly produced using SMR. There is a growing need for hydrogen that does not release carbon dioxide, and, if present plans are executed, the production of hydrogen energy might be deployed by 2030. Researchers typically utilise hypothetical settings to test ideas, and scenario-based studies often to look forward to the years 2030 and 2050. Based on the findings of hydrogen cross-sectoral research, supply and demand in the various markets operating will vary widely.

The supply and demand of hydrogen energy play a crucial role in the hydrogen energy transition, affecting the feasibility, cost-effectiveness, and scalability of hydrogen production and distribution. This balance is influenced by market equilibrium, which determines price stability and economic viability. When supply exceeds demand, there may be a surplus of hydrogen, leading to decreased prices and potential financial losses for producers. Conversely, when demand outpaces supply, hydrogen prices may rise, creating opportunities for profit but also posing risks of market volatility and supply chain constraints.

The supply-demand balance also affects production decisions, as producers may invest in expanding production capacities if demand forecasts predict a surge in consumption, while if demand is stagnant or declining, they may scale back operations or shift focus to alternative markets. The development of hydrogen infrastructure, including production facilities, storage systems, and distribution networks, also plays a significant role in this balance.

Government policies, such as subsidies, carbon pricing, and renewable energy mandates, can significantly influence supply and demand dynamics. Incentives for green hydrogen production can stimulate supply, while regulatory frameworks promoting hydrogen adoption in industries like transportation and power generation can drive demand. The interplay of these policies shapes how supply and demand influence the broader hydrogen economy.

Global competition and trade dynamics further complicate the supply-demand balance, as countries with abundant renewable resources may become export hubs for green hydrogen, influencing global supply chains and domestic markets.

Hydrogen Storage and Transportation Challenges In certain countries, low-carbon hydrogen generation is already in use, although this is not widespread due to a lack of specific regulatory and legislative structures. As a result, certain parts of the hydrogen supply chain (including production, transport, storage, and

distribution) are governed by separate sets of laws and regulations. However, if green hydrogen is to make the move from a niche player to a widespread power source, initial resistance to hydrogen development and the reaching of a minimum threshold for market penetration will require an integrated policy. National hydrogen plans, priority setting in policies, guarantees of origin, and enabling policies should form the backbone of this policy strategy. Nations can share risks, lessons learned, and best practices in the implementation of hydrogen-related solutions. By working together on safety and standards, nations can develop a common policy. Most agreements and regulations governing renewable energy systems in Europe could be adopted, depending on the possibilities and objectives set. A description of some directives of European (EU) committees is listed in Table 2-1 according to information collected from [38,98,107,108].

Table 2-1 A Description of some examples of EU directives

Directive	Description	Year	Area
(EU) 2018/2001	Renewable energy (RE) liquid and gaseous transport fuels of non-biological origin	2018	Renewable energy
2014/94/EU.	Alternative fuel infrastructure directive	2014	Hydrogen energy
98/70/EC	Fuel quality directive		Fuel directive
(EU) 2015/652	Greenhouse gas (GHG) council directive that sets the production of clean hydrogen, hydrogen from fossil fuels, and methane from hydrogen.	2015	Blue hydrogen energy
Horizon Europe EU research framework initiatives	Initiatives that fund hydrogen research and innovation projects (2021–2027)	Ongoing	Hydrogen energy

Fuel Cells and Hydrogen Joint (FCH JU)	The European Commission backing of a public private collaboration	Ongoing	Hydrogen energy
EU	Important Project of Common European Interest (IPCEI)	Ongoing	Renewable energy
IPCEIs	Focus on microelectronics and batteries	2020	Energy
22 EU member states and Norway	Manifesto	Ongoing	Energy

Ref. [107] described the Chinese government as an example of an initiative to advance regulatory and legislative policies for hydrogen energy. Policies governing the hydrogen energy industry should be improved upon first-hand. Throughout the last few years, China's support for the hydrogen energy industry has increased [109], and local governments have issued hydrogen energy development plans and incentive policies [100]. However, each area's policy standards are fragmented and do not cohesively align. Hence, most hydrogen energy subsidy policies should be revised and improved considering ongoing advancements in this field.

An integrated policy strategy is required to overcome the initial resistance to hydrogen development and to satisfy a minimal threshold for market penetration. National hydrogen plans, priority setting in policies, origin assurances, and enabling policies should form the backbone of this approach. Global agreements and regulations for renewable energy systems should be implemented with reasonable targets in mind. Most importantly, more effective rules are required to regulate the hydrogen energy industry. Most industrialised countries have created incentive programmes and strategies to produce hydrogen energy to support the industry's rapid expansion. These policies might be utilised to shape ideas for policies that would bring about low-carbon status by 2030 and carbon neutrality by 2060, as reported in [39,107]. Table 2-2 suggests a convergence of directives and regulations based on some current regulations.

Table 2-2 Proposed convergence of regulations and directives.

Regulation	Actions Required
The government	<ul style="list-style-type: none"> • Secure land. • Regulate the use of land. • Assess environmental impact.
Ministry of energy	<ul style="list-style-type: none"> • Deliver permits to build and operate pipelines for the transport of gaseous products.
Fluxes	<ul style="list-style-type: none"> • Transport natural gas from gas terminals to distribution system operators and large industrial consumers
Federal regulator	<ul style="list-style-type: none"> • Supervise transparency in the electricity and natural gas market in the following ways: • Approve the transmission tariffs of fluxes. • Watch over consumer interests. • Monitor whether the market situation is in the general interest and line with general energy policy. • Advise the authorities.
The Flemish Regulator of Electricity and Gas Market (VREG). Regional regulations: the Commission Wallonne Pour Energy (CWaPE) and the Brussels Energy Regulator (BRUGEL)	<ul style="list-style-type: none"> • Be responsible for the organisation and functioning of regional electricity and natural gas markets. • Advise the regional authorities and monitor the application of the law.

2.2.2.2 Intricacy of the Hydrogen Economical Factor

Hydrogen production relies on high-quality electrical energy, compression, liquefaction, transportation, transfer, and storage. It is in direct competition with utility-supplied power for stationary use, and liquid synthetic hydrocarbons have the potential to become the future's primary form of energy transport [35,66]. Hence, hydrogen prices need to be reduced to the lowest level feasible. In addition, the viability of the hydrogen economy hinges on its ability to make thermodynamic sense; otherwise, superior alternatives will quickly capture consumer demand. Furthermore, distribution networks already exist for most manufactured liquid hydrocarbons, but, as hydrogen needs a whole new network for energy production and distribution, systems will be drastically altered if the economy moves to be hydrogen-only. As a result, all factors involved in a hydrogen economy must be considered before making any financial investments. The following publications have discussed economic factors based on different case studies and scenarios [30,42,53,64,66,99,110–113].

A comprehensive look into the energy requirements of a hydrogen economy can help answer some fundamental questions. Hydrogen economies must take into consideration the energy needed for the manufacturing, packaging, transportation, storage, and transfer of pure hydrogen. Refs. [114] have reported the need for comparing how energy output compares with the energy content of the delivered hydrogen. Fuel cell and hydrogen tank systems are expected to drop by as much as 70% by 2030, resulting in half of a backup generator's improved efficiency [28]. Generator systems are only slightly more efficient, but the cost of supplied hydrogen will decrease by 20–40%. Production cost reductions have less of an impact on total cost decreases, but remote generators will save almost 90% of their total costs due to a decrease in the price of hydrogen fuel [24,34].

To compete with conventional power sources, the cost-effectiveness of hydrogen generation must increase. It must abide by basic thermodynamic rules to succeed. Liquid hydrocarbons can be transported via existing networks, but transporting hydrogen calls for new infrastructure, which would significantly alter current energy systems. Numerous research must look at economic factors in this situation. It is critical to assess the energy requirements for a hydrogen-based economy. According to predictions, technologies like fuel cells and hydrogen tanks might be significantly more cost-effective by 2030, especially when it comes to enhancing backup generators. These emphasise the significance of cost reduction and energy efficiency for the viability of hydrogen-based energy systems.

The hydrogen sector faces numerous economic uncertainties that could significantly impact its adoption and long-term viability. These uncertainties are driven by fluctuating renewable energy costs, evolving policy frameworks, and global competition in the hydrogen market. The cost of hydrogen production, particularly green hydrogen produced via electrolysis, is heavily dependent on the price of renewable energy inputs such as solar and wind power. However, these costs are not static and can be affected by seasonal variability, geopolitical influences, and market dynamics.

In emerging economies or regions with less mature renewable markets, these fluctuations are even more pronounced. The reliance on government subsidies or incentives to support renewable energy development creates an additional layer of uncertainty. Any changes in subsidy policies or financial support mechanisms can directly impact the cost structure of hydrogen production, making it more challenging for projects to achieve consistent profitability.

Policy frameworks play a crucial role in shaping the hydrogen economy. Governments influence the sector through regulations, subsidies, tax incentives, and carbon pricing mechanisms. However, the inconsistency and volatility of

policy decisions can create significant economic instability for hydrogen producers and investors. One primary concern is the lack of long-term policy commitments, as many hydrogen initiatives rely on favorable policies that could be reversed or modified with political shifts.

Regulatory inconsistencies across regions further complicate the hydrogen landscape. Countries may adopt different standards for hydrogen purity, storage requirements, and safety protocols, making it difficult to establish uniform production and distribution processes. In the absence of harmonized international regulations, hydrogen producers face added costs in adjusting their operations to meet varying regulatory demands in different markets.

Another policy-related challenge is the evolving landscape of carbon pricing. The introduction of carbon taxes or emissions trading systems can make hydrogen more competitive relative to fossil fuels, but fluctuating carbon prices and inconsistent enforcement across jurisdictions can lead to unpredictable market dynamics, affecting hydrogen's economic appeal. If carbon pricing mechanisms are not robust or universally applied, hydrogen may struggle to compete against cheaper, carbon-intensive energy sources.

Global competition in the hydrogen sector introduces another layer of economic uncertainty. Countries such as Japan, Germany, South Korea, and Saudi Arabia are investing heavily in hydrogen technologies and infrastructure, each aiming to become a hub for hydrogen production and export. This competitive landscape can lead to price volatility and market saturation, particularly if supply outpaces demand in the short term. Technological advancements in hydrogen production, storage, and transportation will influence global competition, with nations developing more efficient electrolysis technologies, cost-effective storage solutions, or innovative transportation methods potentially disrupting established market players.

To mitigate these risks, stakeholders must adopt flexible, data-driven decision-making tools like the Decision Support System (DSS). By integrating economic indicators, policy scenarios, and market trends into the decision-making process, the DSS provides a robust framework for navigating the complex and dynamic hydrogen landscape.

2.2.2.3 Financing Efficiency

The internal and external financing environments are rarely considered simultaneously by scholars, and empirical studies do not consider the efficiency of financing costs and capital. For example, the hydrogen energy industry in China is still in its infancy and needs to improve its financing efficiency to develop to its full potential. This will help China achieve its long-term objective of transforming its economy into one based on high-quality sustainable development [38,107]. Seventy Chinese hydrogen energy firms were analysed in one study, with their funding efficiency between 2014 and 2020 evaluated using a Data Envelopment Analysis (DEA) model [39]. The following research explored the financing of hydrogen energy and the factors that affect it based on different case studies and scenarios [26,38–40,42–44]. The collective findings could be used as the basis for policy recommendations to aid the government in achieving its dual carbon target of peaking its carbon emissions by 2030 and being carbon neutral by 2060. The levelized cost of hydrogen (LCOH) with solar PV and electrolyser prices is shown in Figure 2-10a, b according to [115]. Currently, the cost of LCOH varies from 31€/MWh_{H₂}, LHV (1.0€/kg H₂) in Atacama to 81€/MWh_{H₂}, LHV (2.7€/kg H₂) in Helsinki. This is anticipated to decline by 33% by 2030 and by 67% by 2050. Notably, PV power prices already account for around 63% of LCOH and might reach 74% by 2050. This shows that electrolyser expenses will not have a significant impact on LCOH in the future. Additionally, it refutes the idea that inexpensive electrolysers are constrained by poor PV yield. Most high-priced electrolysers require high full load hours (FLHs).

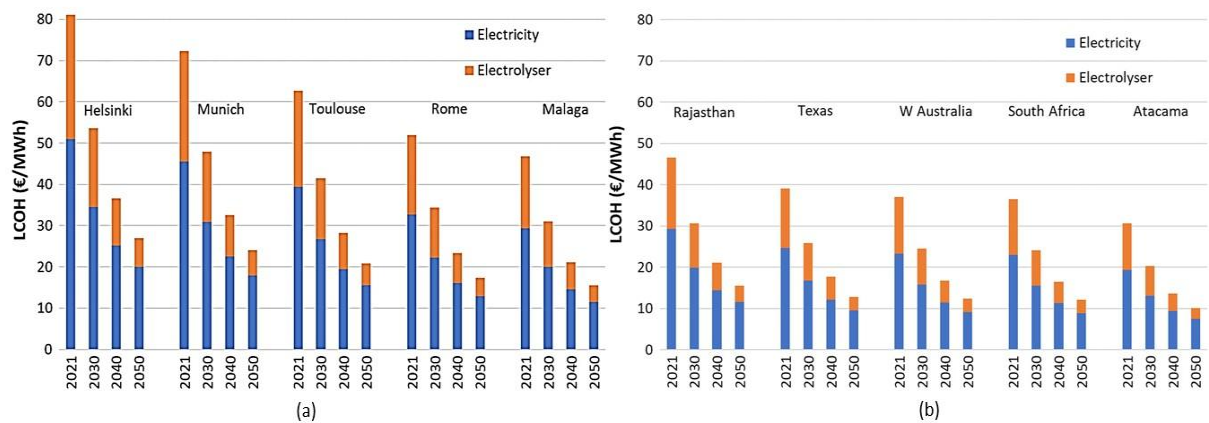


Figure 2-10 Financing cost of hydrogen: (a) based on some European locations [115]; (b) based on some non-European locations [115].

Since the lack of financial resources is a major obstacle to a company's capacity and decision to obtain greater standards of environmental performance, a green hydrogen producer on a modest scale can be profitable. Hence, efforts to promote the extensive use of hydrogen technologies have some flexibility under the current policy framework. For instance, the 'Reward Instead of Subsidy' policy for fuel-cell vehicles has accelerated the planning and layout of China's hydrogen energy industry [28,116]. The Modigliani–Miller (MM) theorem can be applied to H₂ finances, and states that in a frictionless capital market, the value of a company is independent of its capital structure [117,118]. In 1963, the MM theorem was developed, and it states that an increase in liabilities could increase the value of a capital structure and enterprise value, but the Chinese domestic capital market is expanding due to market-oriented reforms and improved regulation [119]. According to [120], scaling up hydrogen usage not only reduces equipment costs but also enhances capital utilisation. For instance, when considering the total cost of ownership (TCO) for passenger cars, achieving cost reductions in fuel-cell vehicles necessitates scaling up component manufacturing and the hydrogen supply chain. Their report highlights that, by 2030, TCO for large passenger vehicles may decrease by around 45%, driven by lower vehicle capital expenditure, reduced hydrogen distribution and retail costs, and more cost-effective hydrogen production. These reductions are crucial for achieving

cost parity with battery electric vehicles (BEVs). Table 2-3 gives a summary of the influencing indicators.

Table 2-3 Selected results of influencing indicators based on data from [120].

Influencing Indicators	Cost USD cents/km	Percentage	Comment
As at year 2020	47.2	-	-
Scale-up of manufacturing Step 1	8.6	18%	Annual production of 200,000 vehicles
Scale-up of manufacturing Step 2	4.5	10%	Annual production of 700,000 vehicles
Green hydrogen production	5.3	11%	transition to 2.5 larger HRS and 40 trucking capacity
Electrolysis deployment and transition to production systems	2.4	5%	50 GW electrolysis deployment and transition to ~100 MW production systems
Parity with BEV	26.4	-	-

A techno-economic financial analysis of a system to sell green hydrogen and create feedstock and laboratories showed that a PV-based hydrogen generation facility on a modest scale can be profitable, demonstrating the benefits of hydrogen energy financing [121]. It has been reported that small-scale electrolysis units can generate greater economic and environmental benefits than larger facilities, as they can meet up to 14% of the potential demand for medical oxygen [121,122]. Ref. [121] reported the cash flow required to compute the levelised cost of hydrogen (LCH) and the net present value (NPV). Their outcome calculated the return on investment using NPV and considering all expenses and

income. The NPV was negative for the first scenario (selling of hydrogen). The second scenario's NPV was positive at +228.7 kV (selling of coproduced oxygen and hydrogen). Both the internal rate of return (IRR) and the modified internal rate of return (MIRR) are higher than the weighted average cost of capital (WACC), 5.7%, at 9.8% and 7.3%, respectively. Table 2-4 shows the tax and financial parameters according to [121].

Table 2-4 Tax and financial parameters.

Parameter	Value
Equity rate of return	7.0%
Inflation rate	1.2%
Tax rate on earnings	30%
System degradation rate	0.5%/year

2.2.2.4 Stakeholders' Roles in Hydrogen Energy Development

Numerous sectors have already embraced hydrogen development, indicating a promising expansion of the hydrogen economy. This convergence engages companies across various sectors in collaborative efforts to develop and implement hydrogen-based solutions. These sectors encompass the automotive, chemical, energy, design, and financial industries. The wide array of sectors and regions participating in hydrogen development initiatives serves as evidence of hydrogen's significance in the shift toward a decarbonised economy. The diversity in both sectoral and geographical engagement underscores the pivotal role of hydrogen in the transition to a decarbonised economy [66]. These groups intend to collaborate to develop effective solutions and hasten the transition to sustainable energy [121,122]. This shows that the push to decarbonise the global economy is progressing, and hydrogen is a key component of that progress, as reported in [70]. The development and implementation of hydrogen solutions considering stakeholders' roles will play a fundamental role in building a clean

and diversified energy system. As a result, hydrogen may make headway in the drive toward decarbonising the world's energy system.

A guaranteed alignment with key stakeholders' interests, such as industry, end users, academia, the investment community, and other government agencies has an impact. Countries like China, the United Kingdom, Japan, the United States, Germany, and South Korea are among the nations that have differentiated themselves in this field through their implementation strategies as reported in [123]. One of the key channels for this input is through requests for information and workshops to seek and incorporate input from a wide range of stakeholders into activity planning. These workshops would provide an open venue for discussing the status of technologies and the obstacles to their development and implementation.

Influencing factors in coordinating the priorities of various stakeholders go beyond national borders [124]. These include the need to develop a framework for seasonal and long-term hydrogen utilisation and use, set the role and pledging commitment in an exact time frame, and adhere to the regulation and policies of the strategy [125]. Large-scale implementation of hydrogen projects by the corporate sector requires commercial joint ventures, but the future of the hydrogen business hinges on technological advancements, so the importance of stakeholders and international cooperation are the backbone of hydrogen development. Stakeholders can benefit from events like workshops, roundtable discussions, delegations, and research trips, even when working on a global scale.

2.2.2.5 The Private Sector's Role in Hydrogen Energy Development

The influencing factors of the private sector have an impact on realising a hydrogen economy. It is expected that the private sector will lead the way in developing green hydrogen for applications in transportation and industry as well as hydrogen investment. Adding green hydrogen to the European Commission's hydrogen strategy is now under consideration [25,76].

A best-practices approach to hydrogen interactions is beginning to be applied to this in the private sector, with commission officials including hydrogen. Europe's 10 recommendations from June 2020 in the agency's overall hydrogen plan reported the role of low-carbon hydrogen in facilitating a seamless transition and emphasising the importance of technological neutrality. However, the World Water Forum (WWF) has spoken out against the Commission's strategy, claiming that it is incompatible with the EU's objective of being climate-neutral by 2030 because the Commission intends to continue generating low-carbon hydrogen using gas and carbon capture and storage (CCS) until 2030 [126]. The European Academies of Science and Arts Council (EASAC) has recommended new regulations to speed up the switch from fossil fuels to clean hydrogen in the chemical industries and steel production; as well as reconsidering carbon pricing and the elimination of fossil fuel subsidies, this would require scaling up hydrogen [126,127].

The Hydrogen Backbone Initiative was launched in July 2020 to build 6800 km of dedicated hydrogen transport infrastructure between hydrogen valleys by 2030. In February 2021, European energy regulators proposed a phased approach to hydrogen network regulation considering energy system integration [25]. The European committee has called for new regulations to expedite the transition from fossil fuels to clean hydrogen in the chemical industries and steel production, including a legal framework for market development and infrastructure and EUwide sustainability classification [77].

2.2.3 Capital Availability

From 2001 to 2021, central banks across the world undertook unprecedented monetary easing. This dramatically improved capital availability and liquidity[128,129]. Such policies have a positive impact on the finances of green innovation firms, such as those in the low-emission hydrogen sector, by reducing borrowing costs and appreciating asset values. However, national governance factors and policy decisions on environmental regulation also have a significant

effect in improving capital flows by reducing risk premiums [130]. However, the loose monetary policy produced inflationary pressures prompting central banks to increase interest rates and a reversal of the policy, reducing the overall availability of funds in all sectors including the hydrogen economy [128,131]. Major geopolitical events such as Brexit and US–China tensions have caused economic and regulatory policy uncertainties, negatively impacting capital flows. Refs. [132–134] focused on the impact on environmental sustainability in the presence of economic policy uncertainty and found a negative effect and recommended stable government policies to foster investment.

Due to an increase in awareness of the need for investment in green and sustainable technologies and projects, over the past three decades, ESG assets have increased ten times. ESG assets/investing involves including the environmental, social, and corporate governance benefits, performance, and behaviour of companies/firms in investment decisions [135]. The sustainability factor of green/low-emission hydrogen attracts capital in the ESG-conscious financial environment. Many investment institutions, including European investment banks, the International Finance Corporation, BlackRock, and Goldman Sachs have pledged billions of dollars of investment into hydrogen projects [136]. However, there are ongoing political and academic debates on the effectiveness of ESG-based investing and even hostile political action towards ESG-based investment: for example, the anti-ESG laws in Texas, USA, mandating disinvestment from ESG asset management companies [137]. Despite the authors of [137] not finding any significant economic effects, this remains a risk factor for the free flow of capital into the hydrogen economy [138].

2.3 Hydrogen Alignment with Fossil Fuels

There will always be considerable uncertainty concerning how much oil still exists in the world and how much can be recovered. Oil peak predictions have a lengthy history of being misleading, and previous experience has shown that reserves are often limited. However, there are convincing arguments for accepting modern

forecasts as more reliable than previous predictions [25]. For example, since the 1980s, global production has exceeded the number of discoveries, while the magnitude of new discoveries has shrunk. However, the most recent world energy scenarios indicate that global oil demand will climb by more than a third through 2030. This forecast suggests that total oil production will need to double to keep up with increased demand [43]. However, analysis shows that if we continue to do business as usual, we will face shortages in the supply of oil in the next few decades due to a mismatch between growth forecasts and the remaining potential of conventional oil. Estimates indicate that the production of conventional oil will reach its peak between 2030 and 2050, leading to increased reliance on oil imports and the Organisation of the Petroleum-Exporting Countries. The time has come to diversify the transportation fuel market away from oil, as resource potential versus rising oil demand shows [74]. The hydrogen supply infrastructure can expand and have an impact on the energy transition from fossil fuels [92]. However, this depends on country-specific criteria like feedstock (such as renewable energies), population density, geographic factors, and legislative support; therefore, it must be analysed country-by-country.

Hydrogen infrastructure can deliver significant solutions and cross-national composite reliability for energy security including in the transportation sector. Nonetheless, this requires fuel-cell vehicles to be cost-competitive with conventional automobiles and problems regarding fuel cells and hydrogen storage to be solved [69]. However, hydrogen introduction is comprised of two phases, infrastructure build-up (2015–2030) and hydrogen technology diffusion (2030–2050). Early implementation (2015–2020) and transition (2025–present) make up the initial phase (2020–2030). Scenario results reported tend to converge after the transition phase when the initial infrastructure is created [30]. Hydrogen utilisation will start in heavily populated regions with beneficial support policies and will expand into rural areas during the transition phase. Buses and fleet vehicles like delivery vans operate locally, run on short, regular routes, and return to a central depot for refuelling and maintenance, making them perfect candidates for the early adoption of hydrogen [77]. Zero-emissions requirements

and financial incentives are needed to accelerate hydrogen car adoption. Hydrogen internal combustion engine (ICE) vehicles with bi-fuel conversions may eliminate the need for a nationwide network of refuelling facilities in the early stages.

To go deeper, feedstock price assumptions, which impact production costs, are more vulnerable in longer-term hydrogen supply cost estimates. Overcapacity in supply and refuelling infrastructure is a major factor in the high initial prices for hydrogen. While energy and CO₂ certificates are predicted to increase in price, the cost of the hydrogen supply is expected to remain stable for decades[139]. As the price of fossil fuels reaches a certain threshold, the cost of producing renewable hydrogen will decrease, allowing the two sources to compete on price [20]. Between 60% and 80% of overall supply costs are related to hydrogen production, which is a sizeable component. With 10% going to transportation and liquefaction, the remaining 1% is given to petrol outlets. Once crude oil prices pass the range of \$80 to \$100 per barrel over the long run, hydrogen is positioned to become cost-competitive, excluding taxes and vehicle-related expenditures. Notably, using hydrogen to produce electricity from fossil fuels in centrally located facilities and combining it with carbon capture and storage might result in considerable reductions in carbon dioxide emissions.

2.3.1 Hydrogen Energy Utilisation and Implementation

Setting long-term greenhouse gas (GHG) emission reduction targets cannot be achieved by energy efficiency alone; supporting green hydrogen could help governments combine CO₂ emission goals with carbon trading programmes. These would allow corporations to sell excess emissions to higher-emitting companies [140]. However, green hydrogen policies should work with carbon capture policies to address fair international competition, implementation ease, and windfall profits [108]. In addition, grey hydrogen produces methanol and ammonia and can be created without updating equipment or technology [113,141]. Governments and companies should boost global competitiveness. If some countries control industrial emissions, production could be relocated to

countries with fewer rules and higher GHG emissions. Alternative methods could use renewable energy and green hydrogen.

The rising demand for hydrogen will have a significant impact on the cost of distribution and final consumption. By 2030, improvements in vehicle capital investment, hydrogen delivery and retail, and hydrogen generation could reduce the total cost of ownership (TCO) by as much as 45%. To make fuel-cell cars more affordable, production needs to be ramped up, and high-capacity logistics need to be implemented. High infrastructure utilisation and quick cost reduction are two outcomes that can be expedited in hydrogen energy transition based on demand-driven design. Boosting fuel cell and hydrogen storage tank output can save expenses by 70%, but achieving net-zero emissions is more important than making small improvements [142]. Cost, investor confidence, competition, lack of legislative attention, lack of large-scale proof, and lack of knowledge are key factors in green hydrogen's industrial usage. However, R&D and legislative assistance can help overcome these obstacles [26].

The incorporation of green hydrogen into the ammonia industry and fertiliser production brings about substantial economic benefits and positive environmental impacts [143]. Reduction of harmful emissions from traditional methods of ammonia production contributes to biodiversity protection, safeguarding ecosystems near production facilities [144,145]. Several studies have reported that the economic viability of green hydrogen positively influences the overall cost structure of ammonia production [146–148]. This minimises the environmental impact associated with industrial activities, promoting a more harmonious coexistence between industry and nature. Overcoming challenges and investing in technological advancements are essential for realizing the full potential of green hydrogen in these critical sectors [143,144,148]. The use of green hydrogen in ammonia production should be emphasised due to its considerable financial advantages, favourable effects on the environment, and ability to establish green ammonia as a more sustainable and cleaner substitute in the ammonia sector. Realising these advantages in the creation of green

ammonia will depend on overcoming obstacles and developing technologies. The impact of green hydrogen on ammonia is summarised in Table 2-5.

Table 2-5 Impact analysis of green hydrogen in the ammonia industry and fertiliser production.

Factors	Impact	Details
Economic	Cost Reduction, Market Growth and Efficiency	<ul style="list-style-type: none"> Green hydrogen (G-H₂) can reduce the costs of ammonia production, making the process more economically viable. Energy efficiency improvements in electrolysis can contribute to economic viability and enhance the competitiveness of G-H₂ compared with conventional steam methane reforming (SMR). G-H₂ can encourage market expansion and employment opportunities, especially in the areas of renewable energy technology. Opportunities for employment exist in R&D, infrastructure, and manufacturing, which supports the development of a skilled labour force.
	Diversification of Energy Sources	<ul style="list-style-type: none"> Improves energy security and resilience in the manufacture of fertiliser and ammonia by reducing reliance on fossil resources. Helps to promote sustainable production methods by lowering exposure to the price volatility of conventional energy sources.

			•
International Trade			
Environmental	Opportunities		<ul style="list-style-type: none"> G-H₂ adoption in ammonia production positions countries with surplus renewable resources to emerge as major key players in the global green ammonia trade. <p>International cooperation and the advancement of global sustainability goals can be facilitated by the export of green hydrogen and its byproducts, such as green ammonia.</p>
	Emission	• Carbon	In contrast to conventional processes for ammonia, G-H ₂ , in powering the synthesis of ammonia, significantly reduces carbon emissions, positioning green ammonia as a cleaner alternative.
Reduction			<ul style="list-style-type: none"> The shift towards green hydrogen aligns with global efforts to mitigate climate change and achieve sustainability goals.
Air and Water Quality			<ul style="list-style-type: none"> Pollution from conventional methods is reduced, improving the quality of the air and water, which benefits nearby ecosystems and populations.
	Improvement		<ul style="list-style-type: none"> Since the emissions of dangerous compounds like carbon dioxide and nitrogen oxides are reduced, positive effects on public health are projected.
Challenges with G-H ₂ in green ammonia production	Initial Investment Costs	•	Development of financial incentives and policies between governments and industries to reduce the initial investment costs of establishing green hydrogen and green ammonia infrastructure.
	Intermittency of Renewable Energy	•	Development of regulations and financial incentives between governments and businesses to reduce the initial costs associated with setting up green hydrogen infrastructure.

Technology
Development

•
To make electrolysis technologies more effective and affordable for the large-scale generation of green hydrogen, continue to invest in research and development.

2.3.2 Role of Hydrogen.

The production of hydrogen from waste refineries is a viable path towards developing a clean and renewable energy source. Techniques like gasification and steam reformation may convert organic waste components into useful hydrogen gas, offering a clean fuel choice for a variety of uses. Combining hydrogen production with waste refineries maximises the use of waste materials while lowering greenhouse gas emissions. The significance of H₂ availability is emphasised in relation to refineries' capacity to adjust to new biomass feedstocks. The development of biorefineries, and more especially the hydrotreatment of bio-oil, is a crucial step towards the integration of oils obtained from biomass into the petrochemical industry. The economic viability of noble metal catalysts in the bio-oil processes is hampered, nonetheless. Furthermore, the availability of green H₂ is necessary for catalytic processes that transform CO₂ into methanol, dimethyl ether, and other fuels. The direct synthesis of clean fuels from CO₂ and hydrogen, in which catalysts play a critical role, is one promising breakthrough. Additionally, systems that combine steam-dry reforming with bio-oil and sorption-enhanced steam reforming have promise for producing sustainable syngas from biomass and CO₂. All things considered, these developments highlight how crucial sustainable hydrogen generation is for a variety of uses, including the creation of biofuel and waste processing. Table 2-6 below summaries the future roles of H₂.

Table 2-6 Other roles for hydrogen.

Role of H ₂	Details	Reference
Hydrogen Production	<ul style="list-style-type: none"> Waste refineries can potentially produce valuable hydrogen through conversion operations. 	
	<ul style="list-style-type: none"> Synthesis of hydrogen from waste materials, using methods like steam reforming or gasification, can transform organic elements in waste into hydrogen gas. 	
	<ul style="list-style-type: none"> Hydrogen generated by waste refineries can serve as a clean fuel option for power production, transportation, and industrial uses. 	from Waste [149,150]
	<ul style="list-style-type: none"> Combining waste refineries with hydrogen generation contributes to reducing greenhouse gas emissions and maximizing the use of waste resources. 	
Biorefinery	<ul style="list-style-type: none"> The availability of H₂ is essential for refineries transitioning to new feeds made of biomass. 	[151,152] Development
	<ul style="list-style-type: none"> An important step in biorefinery development is the hydrotreatment of bio-oil, enabling the incorporation of oils obtained from biomass into the petrochemical sector. 	
	<ul style="list-style-type: none"> Sulphide transition metal catalysts, such as CoMoS and MoP, have shown effectiveness in the hydrodeoxygenation of bio-oil, demonstrating high selectivity for hydrogenated molecules. 	

	<ul style="list-style-type: none"> Noble metal catalysts like PtPd bimetallic catalysts, while effective, may pose economic feasibility challenges due to their high cost and increased H₂ consumption.
	<ul style="list-style-type: none"> The viability of catalytic processes for converting CO₂ into methanol, dimethyl ether, automobile fuels, and chemicals depends on the availability of green H₂.
CO ₂	<ul style="list-style-type: none"> Studies show that H₂ costs and CO₂ taxation impact the profitability of green methanol synthesis, requiring renewable energy for economical manufacturing.
Conversion Catalytic	<ul style="list-style-type: none"> Direct synthesis of dimethyl ether (DME) from CO₂ [153–156] and syngas involves bifunctional catalysts, facilitating the conversion of hydrogen into DME.
	<ul style="list-style-type: none"> Direct synthesis of gasoline from CO₂ and hydrogen is a promising approach for producing clean fuel, with various catalysts including nano-metal oxides and zeolites, playing a crucial role in the conversion process.
Bio-oil Combined	<ul style="list-style-type: none"> CSDR is explored as a viable method for producing [157] syngas from biomass and CO₂.
Steam-Dry Reforming oil	<ul style="list-style-type: none"> Research indicates promising developments for bio-CSDR technology, combining decarbonisation (CSDR) with sustainable syngas generation.

- The H₂/CO ratio in syngas from CSDR may vary based on specific operating conditions and feed composition.

Sorption	
Enhanced	• SESR is examined in terms of raw bio-oil, with the combination of dolomite and Ni/Al ₂ O ₃ catalyst
Steam	[158]
Reforming	reported to lead to a gas stream with a high percentage of H ₂ during hydrogen production.
(SESR)	

2.4 Hydrogen Alignment with Hydropower.

Hydroelectricity is the largest source of renewable power, and its total share is bigger than all other sources combined worldwide. Apart from hydrogen energy systems' alignment with RES for stabilisation, there is potential for green hydrogen production using cheap hydropower in hydropower-rich nations such as Brazil, China, Norway, etc. A case study noted that Nepal, which has surplus hydropower which may be curtailed due to low demand, can use green hydrogen production to add value [159,160]. Another study looked at the potential for hydropower in Brazil and concluded that the cheap availability of renewable power, especially excess hydropower, makes it economically viable to produce hydrogen at a lower LCOH [160]. Various historic and new projects are deployed or planned in various nations that are aligned with hydropower [161]. Both studies highlight the potential for generating cheaper green hydrogen with excess hydropower, especially when the water inflow is high, or the power demand is low.

The limited availability of viable sites and other environmental concerns, large capital investment requirements, and the lengthy planning and development process for large-scale hydro projects have slowed their expansion. Also, existing hydro power plants in many developed economies are ageing rapidly. This poses a risk to their long-term viability. Their dependence on seasonal water availability and occurrence of droughts also poses risks [162].

2.5 Discussion

Despite its contributions, this study poses limitations that present challenging questions for future research in hydrogen development. Understanding of all the factors and parties involved in the hydrogen industry will lead towards more effective management and will pave the way for the development of comprehensive strategic plans and suitable computational industrial systems. Therefore, the consideration of all factors of influence will reflect positively on what we aim to achieve in this preliminary study. This paper may help to make decisions for hydrogen energy markets to be penetrated by 2030 and 2050. Furthermore, it will provide a more comprehensive view of the purpose and strategic plan for hydrogen utilisation, including decisions surrounding the location of hydrogen plants, considering infrastructure costs and distance to the end user, supply chain constraints, and the availability of alternative energy sources.

A comprehensive understanding of the factors affecting the development of hydrogen energy projects, including all the challenges facing the developers, is shown in Figure 2-11. The influencing factors are related and can sometimes include sub-factors related to each factor and their interdependence based on the project capabilities. Without rules and legislation to assure the rights of developers and investors, the success of an international hydrogen energy plan may not be realised.

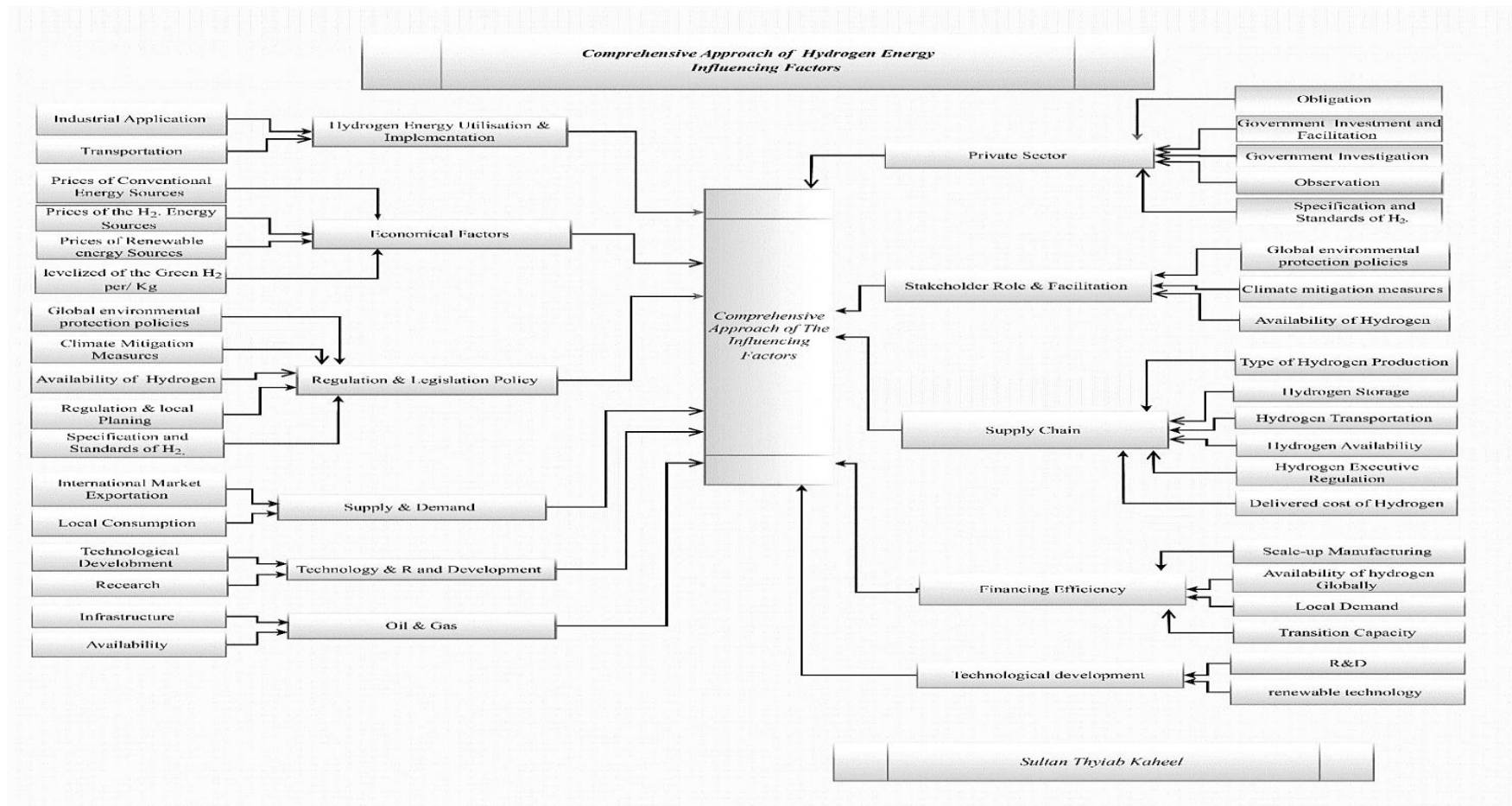


Figure 2-11 The comprehensiveness of Hydrogen-energy-influencing factors.

A summary of the influencing factors in hydrogen energy development is compiled below in Table 2-7. Difficulties in existing hydrogen energy transition strategies related to the key factors are indicated.

Table 2-7 Summarise of hydrogen-influencing factors.

	Factor	Summary
Logistical	Policies	Inclusive policy strategies, enacted through regulation and legislation, are vital to overcoming scepticism and fostering market entry. Collaborative efforts among nations to share risks, lessons, and best practices are crucial.
	Supply and demand of Hydrogen Energy	Achieving hydrogen production by 2030 hinges on executing current plans. Future hydrogen pricing is influenced by production expenses and expected demand. Increases in the price of grey hydrogen are expected with heavier carbon emission taxation under systems like the ETS.
	Energy Supply Chain	Infrastructure and technology availability supporting sustainable demand, storage, and distribution is crucial for long-term supply success. Establishing a global supply network and expanding upstream production are high priorities.
	Role of Stakeholders	The involvement of diverse sectors in hydrogen development underscores its importance in the transition to a decarbonised global economy. The expansion of the hydrogen economy signifies progress in decarbonisation efforts.

Technical	Private Sectors	Private sector involvement is expected to accelerate green hydrogen adoption. The desire for quick financial gains drives the private sector to seek rapid improvements in hydrogen energy technologies, including production, transportation, and storage. Collaborative roles between industry sectors are vital in facilitating the sector's development and progress.
	Production	
	Transportation and Storage	Hydrogen transportation presents logistical challenges. Hydrogen fuel cells could potentially replace lithium batteries in long-distance and heavy-duty vehicles, but this depends on reducing hydrogen prices. Hydrogen-powered trains are considered for freight and rural/regional lines, particularly in maritime and aviation, but solutions for weight and storage issues are needed.
	Hydrogen Technology use,	Technology development indicates that hydrogen fuel costs are expected to decline due to falling hydrogen prices, impacting energy production and distribution. Hydrogen directly competes with utility-supplied power for stationary use, necessitating a well-planned strategy for using hydrogen technologies in renewable energy sources. The integration of the Internet of Things (IoT) devices aids effective data collection.
	Utilisation and demonstrating the decarbonisation of basic chemicals and thermal demand. By 2030, large passenger vehicle Implementation ownership costs may decrease by as much as 45%.	
	Hydrogen Alignment with Fossil Fuels	Hydrogen supply infrastructure has the potential to diversify the transportation fuel market away from oil, dependent on feedstock, population density, geographic factors, and legislative support. Significant investments are required (estimated at \$150–190 million per gigajoule) with potential reductions in carbon dioxide emissions.

2.6 Conclusions

This paper conducts a thorough analysis of hydrogen energy focusing on influencing factors for expanding hydrogen production. It has discussed both technical and logistical factors, including policies, and highlighted the need to incorporate key elements affecting hydrogen production. Currently, hydrogen applications are not fully realised on a large scale due to the absence of comprehensive strategic and economic plans, in both developed and developing countries. Recognising hydrogen as a clean energy alternative entails substantial planning, construction, operation, and overcoming of challenges, particularly depending on region. Efforts to achieve zero net carbon emissions involve speeding up the development of clean hydrogen, which is expected to gain prominence in the near-to-medium term, alongside traditional fuels. This transition is supported by public–private partnerships that facilitate the commercialisation of hydrogen and fuel-cell technologies. Clean hydrogen is poised to be integrated into various sectors in the coming years, complementing existing fuels, although specific applications in different industries remain undefined. The progress of hydrogen development needs to align with global commitments to achieve domestic and international net-zero carbon targets. Nonetheless, hydrogen’s adoption is anticipated to increase gradually in the short-to-medium term, alongside conventional fuels and other decarbonisation technologies, though it will encounter various challenges despite its potential to overcome many fundamental obstacles.

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3 Development of Decision Support System for Sustainable Hydrogen Production

The global energy sector is transitioning towards sustainable sources, with hydrogen being a promising alternative due to its high energy content and clean burning properties. The integration of hydrogen into the energy landscape is a significant step towards a cleaner, greener future. This paper presents an innovative Decision Support System (DSS) that integrates multi-criteria decision-making (MCDM) and decision tree methodologies to optimize hydrogen production decisions in emerging economies, with a focus on Saudi Arabia as a case study. The proposed DSS used MATLAB Web App Designer tools to evaluate demand and supply scenarios, cost and profit margins, policy implications, and environmental impacts, aiming to balance economic viability with ecological responsibility. The study's findings underline the potential of this DSS in guiding policymakers and industry stakeholders towards making informed, scalable, and flexible hydrogen production decisions that align with sustainable development goals. The novel DSS framework integrates the two influencing factors which include technical and logistical considering the components such as data management, modelling, analysis, and decision-making. The analysis component applies statistical and economic analyses to model and assess the costs and benefits of nine different strategic scenarios, while the decision-making component uses the results to decide the most effective strategies for implementing the hydrogen to minimize risks and uncertainties.

3.1 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 [1]. 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 [2,3]. Various hydrogen production methods, such as steam methane reforming, solar-integrated reforming with carbon capture, and electrolysis using renewables and ammonia, have been reported [4]. However, the adoption of hydrogen technology remains in its early stages [5,6]. 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 [7], while green hydrogen is expected to catch up and become competitive [8]. The lack of a combine strategic decision framework for the implementation of hydrogen technology has been extensively reviewed and reported in [3]. The carbon footprint of several approaches to the generation of hydrogen has been analysed in [9,10], and ways to cut down emissions has been reviewed in [11]. More study is required to determine the strategies that will result in the most rapid economical construction and implementation of a hydrogen infrastructure [11,12].

Several research reported uncertainty in demand, storage networks and lack of reliable distribution systems as a key challenge in hydrogen implementation [13–15]. To accelerate hydrogen development, a comprehensive policy approach and rigorous regulatory analysis are necessary [16]. The infrastructure investments required for large-scale hydrogen production and distribution networks further underscore the need for robust automated decision-making system [17]. 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 [18]. Similarly, [3] provides an insightful review of hydrogen energy development systems, challenges in optimizing their deployment, and their implementations as shown in Figure 3-1. 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.

Hydrogen technologies, such as electrolyser, fuel cells, and hydrogen storage systems, play a crucial role in stabilizing renewable energy systems and supporting decarbonization goals. However, their integration into electricity distribution networks can introduce potential challenges that could impact the safety and stability of these networks. The key reasons for this include grid frequency and voltage instability, bidirectional power flows and reverse power issues, delayed response times in grid stabilization, lack of coordinated control systems, and hydrogen infrastructure and safety risks.

Grid frequency and voltage instability can occur due to the intermittent operation of electrolysers, driven by fluctuating renewable energy generation. This can cause sudden shifts in the operation of electrolysers, leading to frequency deviations and voltage fluctuations. Bidirectional power flows can also result in overvoltage conditions in parts of the network not designed for bidirectional flows, increasing the risk of equipment damage and protection system failures due to unintended power flow directions. Delayed response times in grid stabilization can result from the process of converting electricity to hydrogen (electrolysis) and back to electricity (fuel cells), reducing their effectiveness in responding to short-term fluctuations. This can lead to less effective stabilization of short-term frequency deviations or handling sudden surges in electricity demand.

Inadequate coordination between renewable generation, hydrogen production, and grid operations can lead to operational conflicts, such as overloading the grid or inefficient power dispatch. Mismanagement of hydrogen production schedules can result in grid congestion or unexpected power surges, while lack of real-time

monitoring and control may lead to unsynchronized responses to grid demands, increasing the risk of blackouts or system faults.

Hydrogen infrastructure, including storage tanks, pipelines, and fueling stations, introduces additional safety risks to the grid environment, including leakage, explosions, or mechanical failures in hydrogen-related equipment. Addressing these challenges will ensure that hydrogen technologies contribute to both the efficiency and safety of future energy systems.

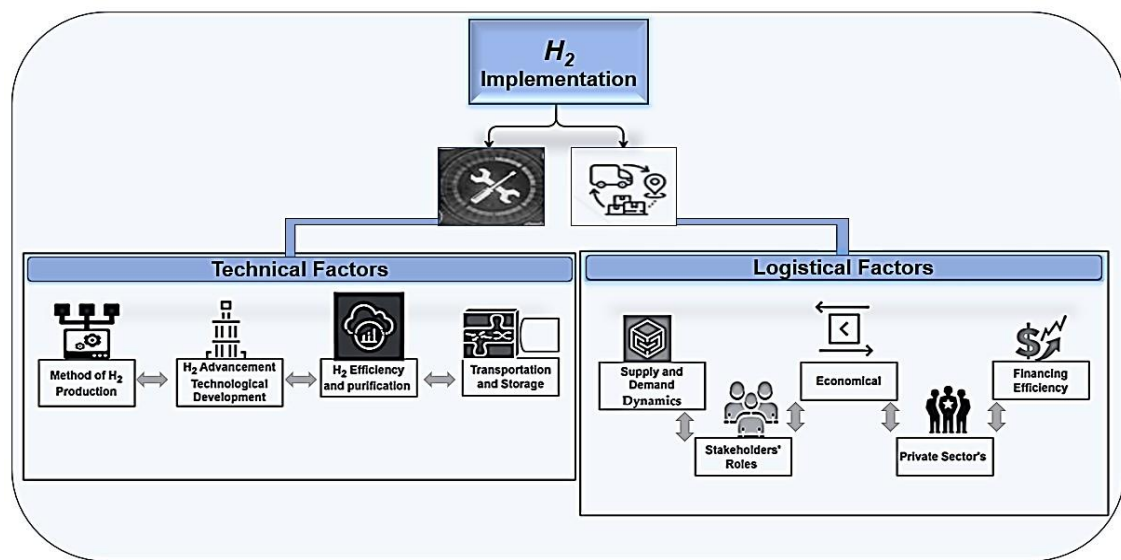


Figure 3-1 The implementation factors of hydrogen energy

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 [13,14]. Effective decision-making is crucial, but without a centralized decision support system (DSS), the process risks inefficiency, higher costs, and missed opportunities [19,20]. The global shift towards clean energy underscores the importance of hydrogen in the energy transition [21–25]. MATLAB-based decision tree models, widely used for optimizing hydrogen production, have proven effective by

integrating machine learning and predictive analytics [26–30]. However, traditional approaches often lack adaptability to dynamic market conditions [31,32]. (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 [33,34]. A centralised decision support systems can assist in tracing projects that did not have the potential for long-term success. Using different factors parameters ranging from demand-supply imbalances to environmental regulations, cost implications and research intends is possible to develop a centralised decision support system (DSS).

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.

3.2 Methods.

A Hydrogen Decision Support System (H2DSS) 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 [35,36]. The integration of dynamic decision trees and machine learning enhances accuracy in complex scenarios, as demonstrated by [37]. The H2DSS 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 significant energy resources and global market influence. Built with MATLAB Web App Designer, the H2DSS 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 provide a comprehensive framework that integrates environmental and financial considerations, ensuring the sustainability and economic viability of hydrogen projects. The H2DSS 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 H2DSS. 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. The H2DSS supports decision-makers by providing a pathway for optimized decisions, offering clarity by breaking down influencing factors across different scenarios.

Dynamic decision trees are an advanced extension of traditional decision tree models, offering greater flexibility, adaptability, and real-time responsiveness in complex decision-making environments like the hydrogen energy sector. They are designed to evolve in response to real-time data and external factors, allowing for more accurate, responsive, and context-aware decision-making. Key characteristics of dynamic decision trees include real-time data integration, adaptability to changing conditions, complex scenario handling, feedback loops, and learning. These features make them well-suited for the hydrogen sector, where factors like supply chain logistics, regulatory policies, and market demand interact in intricate ways.

In this study, dynamic decision trees were used to optimize decisions across various stages of hydrogen production, distribution, and market integration. The Decision Support System (DSS) leverages dynamic trees to assess real-time

variables and provide adaptive recommendations for stakeholders. The DSS evaluates factors like renewable energy availability, production costs, and market demand, adjusting its recommendations to optimize production levels and minimize costs. In addition, The decision tree continuously monitors logistical constraints, transportation costs, and storage capacities, updating pathways to recommend alternative strategies if a disruption occurs in the supply chain. As government regulations and carbon pricing mechanisms evolve, the DSS dynamically integrates these changes into its decision-making process.

Equations provide a critical core to DSS in driving logical and outcomes toward dynamic decision trees. Equations insert quantitative knowledge into the system's decision-making process to evaluate scenarios, compare options, and present optimal strategies of how Equations Work in Decision Trees:

1. Input Variables and Thresholds:

- Equations in decisions provide thresholds for quantifying certain factors such as production costs, emissions, and market demand.
- For instance, if the profitability equation illustrates that the selling price minus the production cost is less than an accepted value, then the decision tree dictates the system to "Don't Produce."

2. Example Equation - Profitability Decision:

$$\text{Profit} = (\text{Selling Price} - \text{Production Cost} - \text{Green Premium}) \times \text{Quantity Sold}$$

If Profit > 0 → Decision Tree recommends "Commit to Supply."

- Profit ≤ 0 → Decision Tree suggests "Don't Produce."

3. Environmental Impact Equation:

$$\text{Environmental Impact Score (EIS)} = w_{E1} \times \text{ESaved/Normalized} + w_{E2} \times \eta \text{Normalized}$$

$$\text{\text{Environmental Impact Score (EIS)}} = w_{\{E1\}} \times$$

$$E_{\{\text{Saved/Normalized}\}} + w_{\{E2\}} \times \eta_{\{\text{Normalized}\}}$$

Environmental	Impact	Score
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$$(EIS) = w_{E1} \times E_{\text{Saved/Normalized}} + w_{E2} \times \eta_{\text{Normalized}}$$

- EIS feeds into decisions involving sustainability goals.
- If the EIS is above some threshold, then the decision tree will go for green hydrogen production; otherwise, it might suggest a reduction in production to save the environment.

4. Run-Time Adaptation:

- Equations are refreshed every minute with current market data and realtime operation processes to enable dynamic readjustment of recommendations by the decision tree according to changes in energy prices, fluctuations in demand, or policy.

3.2.1 Employing the influencing factors into the proposed H₂DSS.

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 Figure 3-2, 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 equation 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.

$$H = f(E, P, S, T, O, R, K, C, F, D) = f(\lambda) \quad (3-1)$$

If λ is any of the influencing factor, then $\lambda = f(x_1, x_2, x_3, \dots x_n)$, 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.

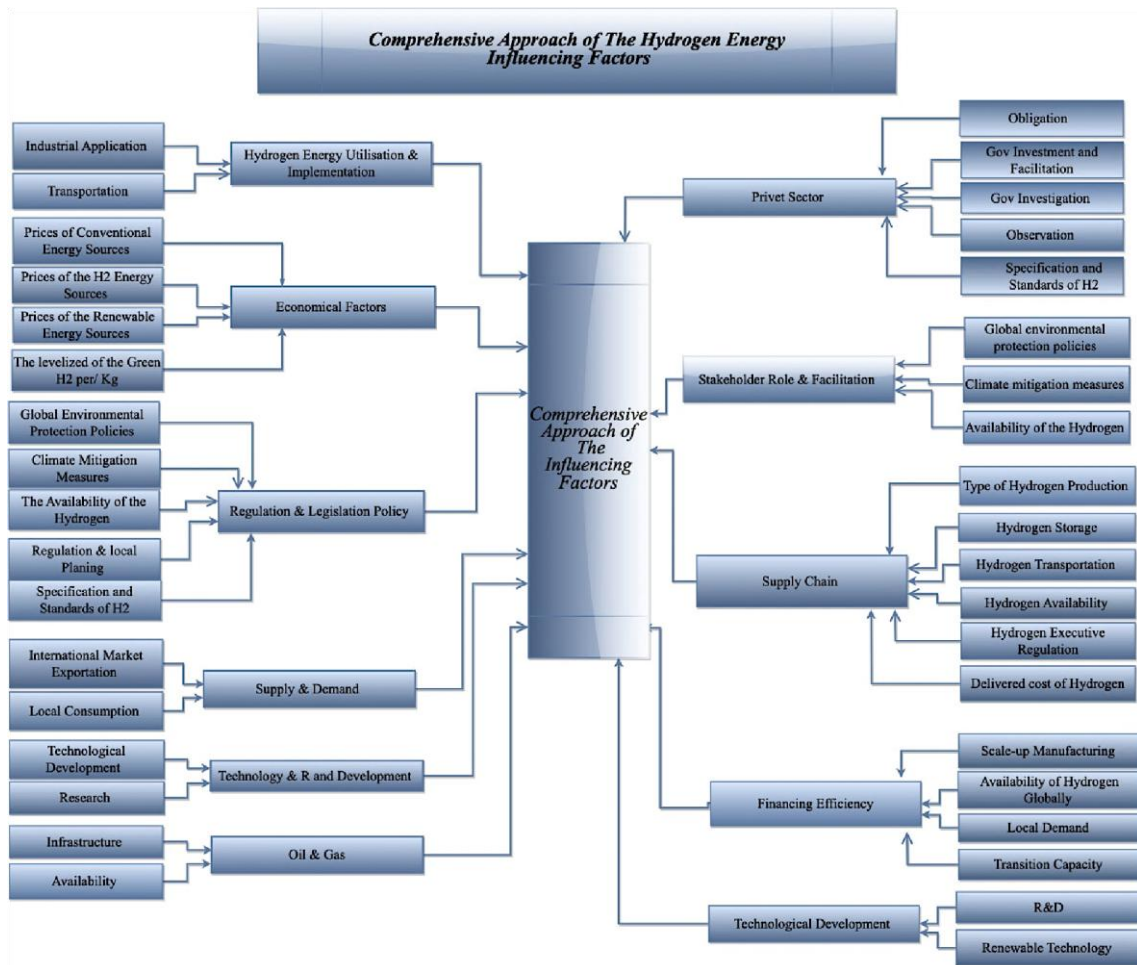


Figure 3-2 A comprehensive approach to the hydrogen energy influencing factors.

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 H2DSS 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 H2DSS 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 [38–40].

3.2.2 H₂DSS Framework Description

A comprehensive localised decision-tree is used to make the best possible decisions in parallel with all factors as shown in Figure 3-3 for the strategic planning and analysis of hydrogen energy projects. The figure is structured as a flowchart, delineating the sequential steps and criteria essential for evaluating and deciding on hydrogen energy initiatives. It starts with the project initiation block, followed by logistic considerations, which are divided into sub-blocks, each corresponding to steps 1 through 5. The flowchart then transitions into technical aspects, covering steps 6 through 11. This includes choosing the energy source, assessing supply chain efficiency, ensuring regulatory compliance, verifying technology reliability, evaluating production capacity, and assessing political stability. The decision tree model provides a clear rationale for decisions made, essential for operational use. This method provides a clear and easy interpretable representation of the decision-making process, enabling stakeholders to understand the rationale behind the final decisions.

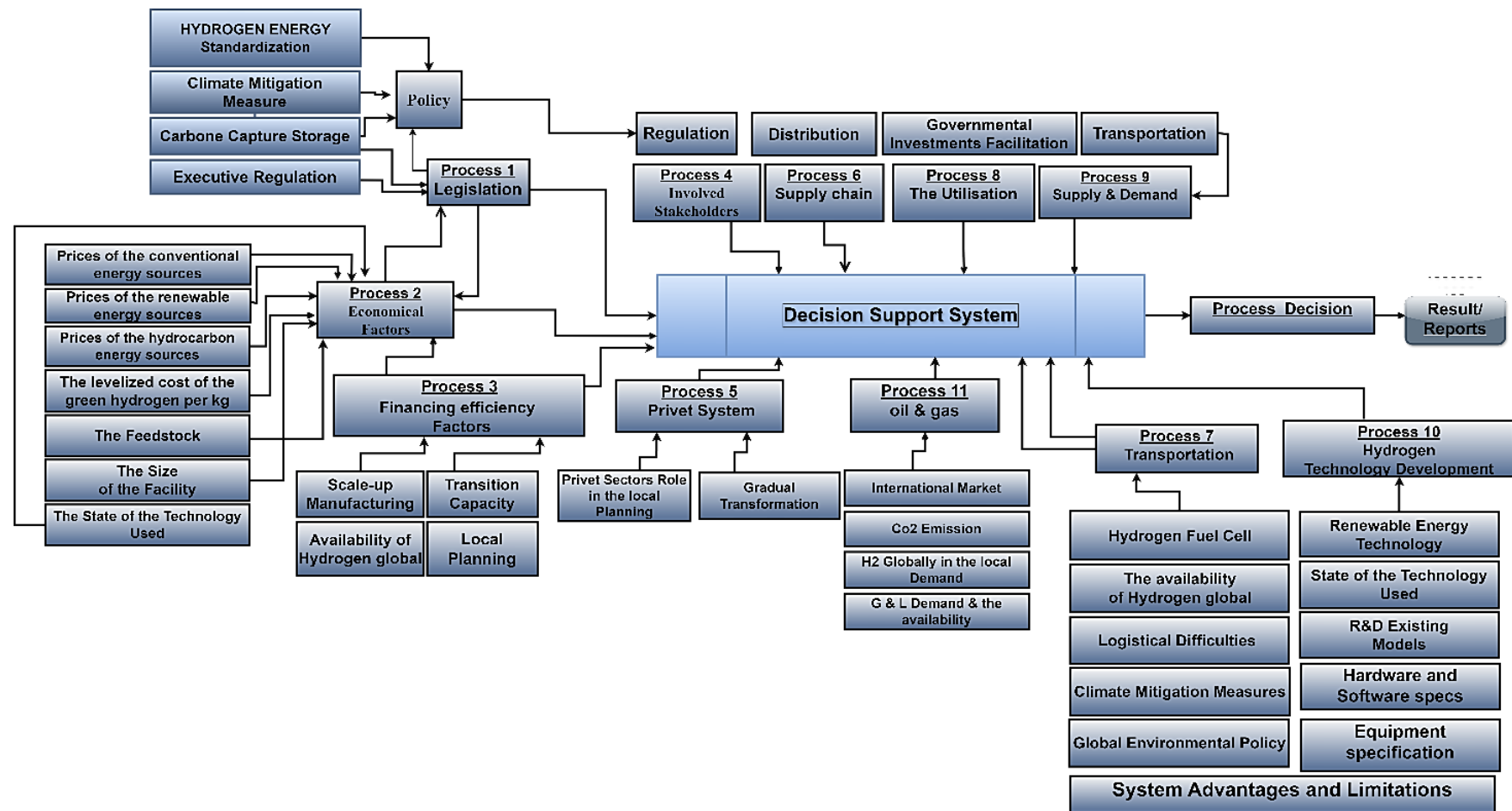


Figure 3-3 A Comprehensive hydrogen decision support system including the influencing factors

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 where conditional paths lead to different outcomes, such as proceeding with the project or reconsidering alternatives. Table 3-1 provides detailed descriptions of each step in the decision sequence.

Table 3-1 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 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.
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3.3 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 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 H2DSS 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 [22,41–44]. The decarbonization strategy plan of Saudi Arabia can be summarized as shown in Figure 3-4 based on the following references [36,44–49].

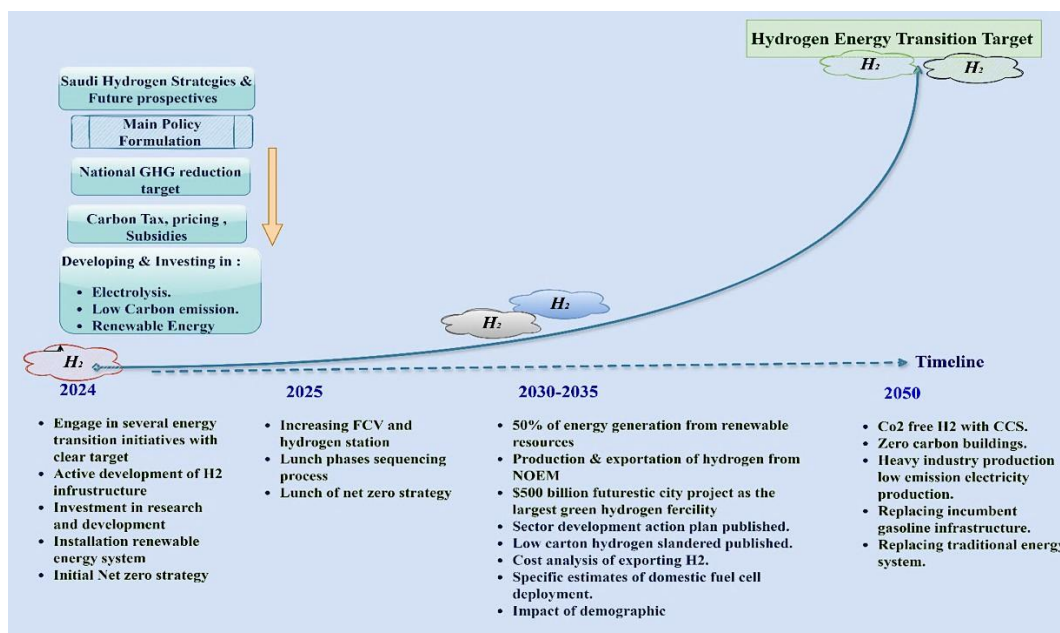


Figure 3-4 Kingdom of Saudi Arabia hydrogen energy transition

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 toward 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 favourable 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 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.

3.3.1 Saudi Arabia Hydrogen Energy Landscape

Research on Saudi Arabia's hydrogen energy production, CO₂ emission reduction plans, and future goals have been reported around natural gas potential [46], future energy forecast [41,44,50], demand and supply dynamics [42,48], economic analysis [9,49], and decarbonisation [7,9]. The systematic 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 3-2 provide a summary of various strategic aspect of Saudi Arabia's hydrogen energy production, CO₂ emission reduction plan based on the following references [22,36,41,42,44–48,51,52]. It has been shared with the experts and decisionmakers 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.

Table 3-2 Saudi Arabia's hydrogen energy production, CO₂ 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 square kilometers
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
CO ₂ Emission Goals	Net zero emissions by 2060 through the Circular Carbon Economy approach
CO ₂ 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	1,200+ 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

Figure 3-5 illustrate an input data for the decision-making process within the H₂DSS user interface (UI). Six scenarios are considered for the H₂DSS test considering the influencing factors and sequence highlighted in Figure 3-3 and Table 3-1 respectively. Each factor, along with its respective unit and example value, contributes to the comprehensive analysis conducted by the H₂DSS 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 (OffTake 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.

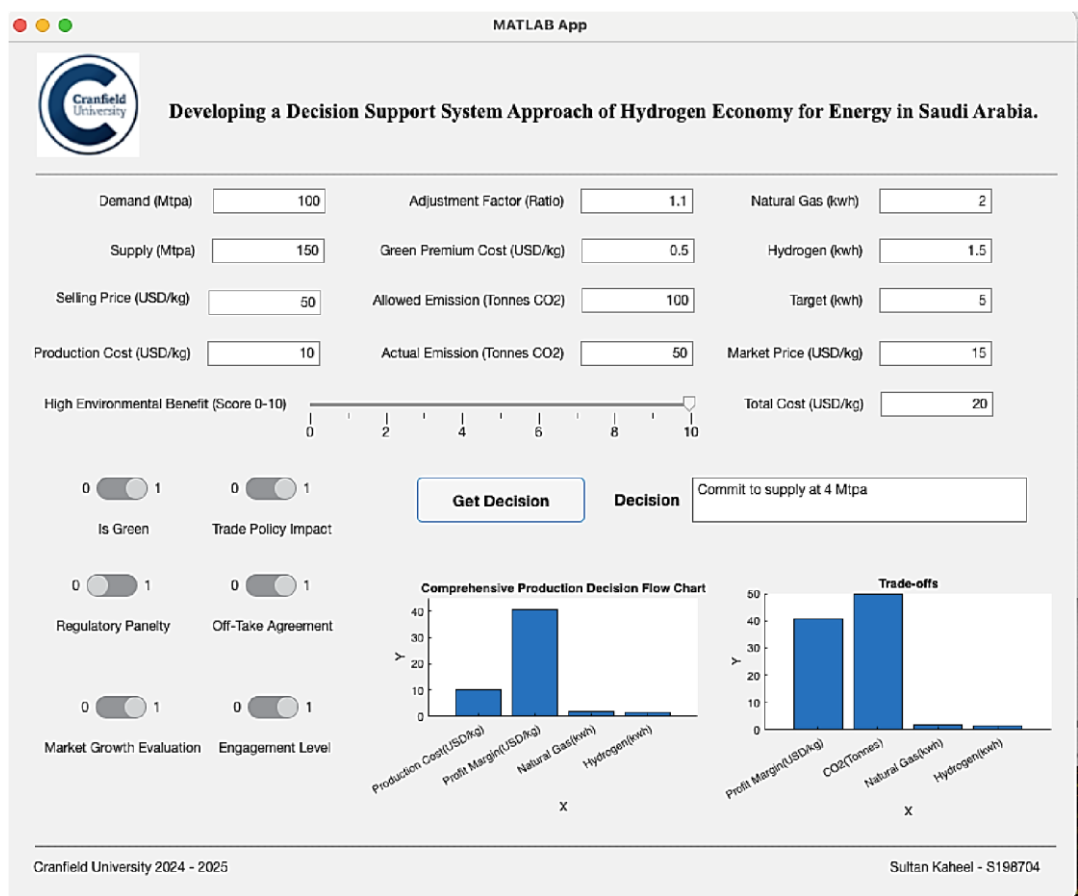


Figure 3-5 H₂DSS user interface for KSA (Input based on scenario 6 of table 4)

3.3.2 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.

Figure 3-6 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 appropriate.

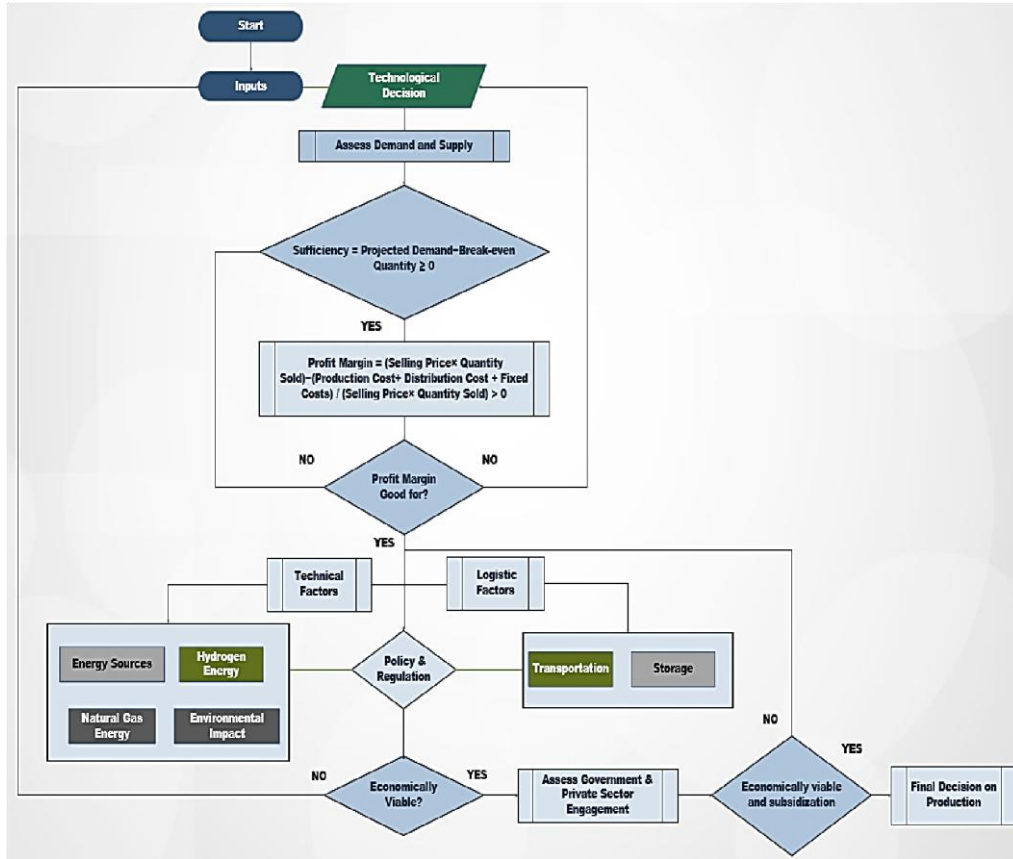


Figure 3-6 Hydrogen energy production decision tree

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 equation 2.

$$\begin{aligned}
 & \text{True,} & \text{if } D_s & \geq 0 \\
 (3-2) \quad & \text{Sufficiency} = 9 & & \\
 & \text{False,} & \text{if } & \\
 & D_s & < 0
 \end{aligned}$$

Where D_s , is the difference between demand and break-even quantity. If $D_s \geq 0$, 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 S_p , production cost

P_{cost} , distribution cost D_{cost} , fix cost F_{cost} and target quantity Q_t to be sold as given in equation 3.

(3-3)

$$PM = \frac{(S_p \times Q_t) - (P_{cost} + D_{cost} + F_{cost})}{(S_p \times Q_t)} \quad (3-4)$$

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

$$PM_{Evaluation} = \begin{cases} \text{True,} & \text{if } PM > 0 \\ \text{False,} & \text{if } PM \leq 0 \end{cases} \quad (3-5)$$

$$TF = (w_{tf1} \times \text{Hydrogen Energy Sources}) + (w_{tf2} \times \text{Gas}) + (w_{tf3} \times \text{Natural Energy}) + U w_{tf4} \times \text{Environmental Impact} \quad (3-6)$$

$$LF = (w_{Lf1} \times \textit{Transportation}) + (w_{Lf1} \times \textit{Storage}). \quad (3-7)$$

Where $w_{tf1}, w_{tf2}, w_{tf3}, w_{tf4}$ represent the weights of technical factors, and w_{Lf1}, w_{Lf2} represent the weights of logistic factors. The policy and regulation (PR) factor depend on TF and LF represented by equation 7. w_{pr1} and 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 equation 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.

$$PR = (w_{pr1} \times TF) + (w_{pr2} \times LF) \quad (3-8)$$

$$\begin{array}{llll} \textit{Economical} & \textit{True,} & & \\ & \textit{target} & \textit{if} & PR \geq \\ & \textit{Viability} = 9 & (3-9) & \\ \textit{Economically} & \textit{if} & PR < \textit{Economical} & \textit{target} \\ \textit{False,} & & & \end{array}$$

The reduction in CO2 emissions due to the use of green or more efficient technologies compared to a baseline conventional emission can be evaluated using equation 9 and 10, respectively. Where i represent a specific define process which leads to the emission, E_i , E_{green_i} , are energy usage, and E_{fi} , E_{fgren_i} are emission

factors, respectively. The emission factor represents the rate at which the process i emit CO2 to the environment. Carbon emissions are quantified by comparing baseline conventional emissions ($E_{Baseline}$) with emissions after implementing green technologies ($E_{GreenEmissions}$), the emissions saved (E_{Saved}) as presented in equation 11.

$$E_{Baseline} \quad Emissions \quad (3-10)$$

$$(tCO_2) = P(E_i \times E_{fi})$$

$$E_{fgren_i}) \quad E_{Green} \quad Emissions \quad (tCO_2) = '(E_{green_i} \times$$

$$(3-11)$$

$$E_{Saved} \quad (tCO_2) =$$

$$E_{Baseline} \quad Emissions \quad (tCO_2)$$

$$- E_{Green} \quad Emissions \quad (tCO_2)$$

$$(3-12)$$

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

$$\eta = \frac{Useful \quad Energy \quad Output}{Total \quad Energy \quad Input} \times 100$$

$$(kWh) \quad (kWh) \quad (3-13)$$

Equation 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. This can be presented as equation 13.

$$EIS = w_{E1} \times E_{Saved} + w_{E2} \times \eta \quad (3-14)$$

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 to 10, $w_{E1} + w_{E2} = 1$, and the normalization of the individual components of E_{Saved} and η need to be considered. For a zero-emission saving, $E_{Saved}(\min) = 0$ and $E_{Green} \text{ Emissions } (tCO_2) = E_{Baseline} \text{ Emissions } (tCO_2)$. Then the normalization of

E_{Saved} is presented in equation 14. Similarly, the normalization of η is presented in equation 15, and become equation 16.

$$\eta_{normalized} = \frac{E_{Saved} - E_{Saved}(\min)}{E_{Saved}(\max) - E_{Saved}(\min)} \quad (3-15) \text{ equation 13}$$

$$= \frac{E_{Saved} - 0}{E_{Saved}(\max) - 0} = \frac{E_{Saved}}{E_{Saved}(\max)}$$

$$\eta_{normalized} = \frac{\eta - \eta_{min}}{\eta_{max} - \eta_{min}} \quad (3-16)$$

$$\eta_{normalized} = \frac{EIS}{E_{Saved}} = \frac{WE1 \times E_{Saved}}{E_{Saved}} + \frac{WE2 \times E_{Saved}}{E_{Saved}} \quad (3-17)$$

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

$$\begin{aligned} & \text{Proceed with production,} & & \text{if} \\ & \text{all conditions are met} & & \\ \text{Final} & \text{Decision} = Q & & \text{Do not produce} \\ & & & \\ & & & \text{if} \\ & & & \text{any condition fails} \\ (3-18) & & & \\ & \text{Re - evaluation,} & & \\ & & & \text{if all met} \\ & \text{but not EIS} & & \end{aligned}$$

Table 3-3 provides a detailed overview of the decision-making framework for planning hydrogen production, organized by objectives, considerations, and expected outcomes. This structured format 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 behaviour 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 toward long-term sustainability and profitability. This approach is crucial for navigating the complexities of green hydrogen production, making the process both competitive and responsible.

Table 3-3 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

3.3.2.1 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 [53]. 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 [53–55]. 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 3-4 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 decisionmaking. 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 CO₂ 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-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.

Table 3-4 H₂DSS 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
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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 supply at 8 Mtpa	Re-evaluate strategy	Re-evaluate strategy	Re-evaluate strategy
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Parameter	Explanation
Demand (Mtpa)	The total market demand for hydrogen in million tonnes per annum.
Supply (Mtpa)	The available supply of hydrogen for production and distribution.
Selling Price (USD/kg)	The market price at which hydrogen is sold per kilogram.
Production Cost (USD/kg)	The cost of producing one kilogram of hydrogen, including operational expenses.
Adjustment Factor	A ratio reflecting market fluctuations, policy changes, or external factors affecting demand.
Green Premium (USD/kg)	Additional cost associated with producing green hydrogen to meet environmental standards.
Allowed Emission (Tonnes CO2)	The maximum permissible carbon emissions during hydrogen production under regulatory frameworks.
Actual Emission (Tonnes CO2)	The actual carbon emissions generated during production.
Total Cost (USD/kg)	Sum of production cost and green premium, representing the overall expense per kilogram.
Is Green	Indicates whether the hydrogen produced meets green certification standards (ON = 1, OFF = 0).
Trade Policy Impact	Reflects the influence of trade policies on hydrogen production and marketability.
Regulatory Penalty	Penalties imposed for non-compliance with environmental or operational regulations.

The bar charts in Figure 3-7 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 50tonnes CO2, well within the 100-tonne 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.

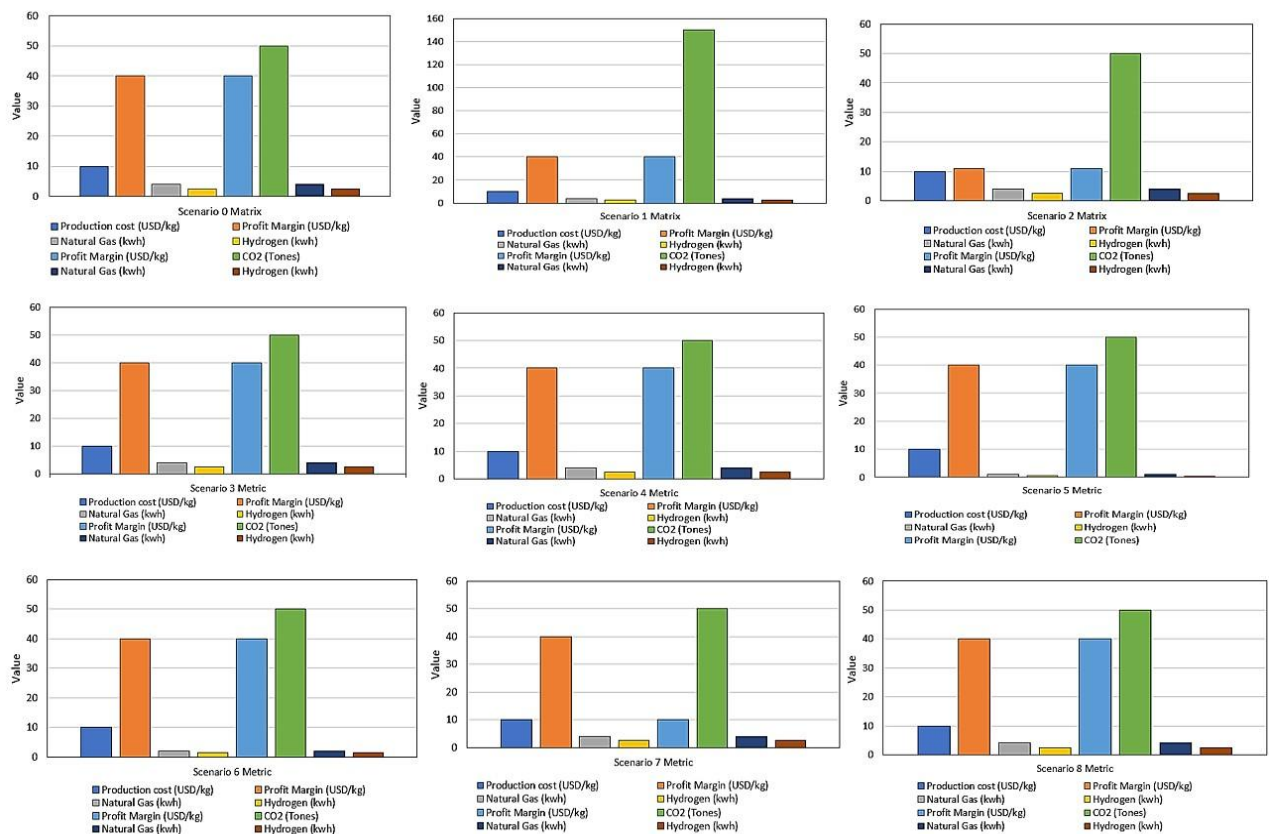


Figure 3-7 Metrics analysis of test scenarios

Figure 3-8 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 equation

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, CO₂ 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 zeroemission strategies align with environmental goals but reduce profitability.

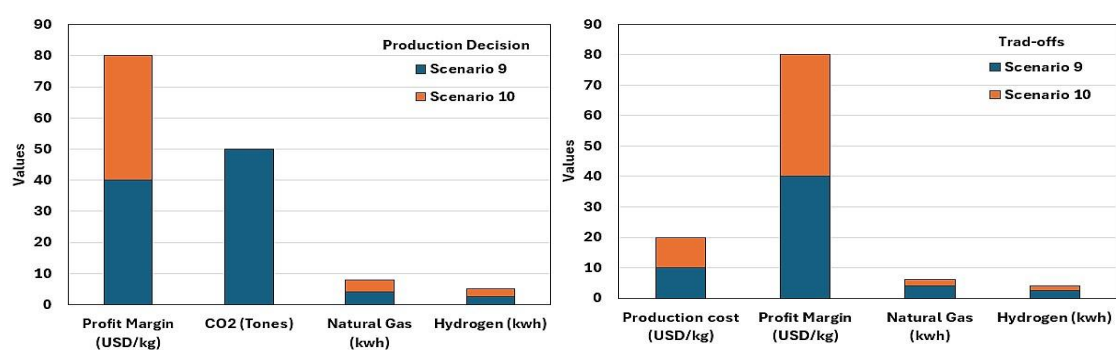


Figure 3-8 Metrices analysis of test scenarios 9 and 10 environment impact sensitivity

3.3.2.2 Trade-off 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 [56,57]. 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 [58,59]. 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 emissions and global warming [58].

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 [60]. 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 [61–63]. Table 5 provides a comprehensive summary of the trade-offs between environmental and economic impacts for different hydrogen production methods.

It has been specified that blue hydrogen production typically captures 85-90% of CO₂ emissions, leaving around 10-15% of emissions unaccounted for. This equates to approximately 1-2 kg of CO₂ released per kg of hydrogen produced, depending on the efficiency of the carbon capture technology used.

Table 3-5 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 3-6 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 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.

Table 3-6 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 ecofriendly 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.

3.3.2.3 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 3-7 present a summary of the DSS impact on Saudi Arabia's.

Table 3-7 DSS short-time and long-term impact on Saudi Arabia’s zero-emission goals output

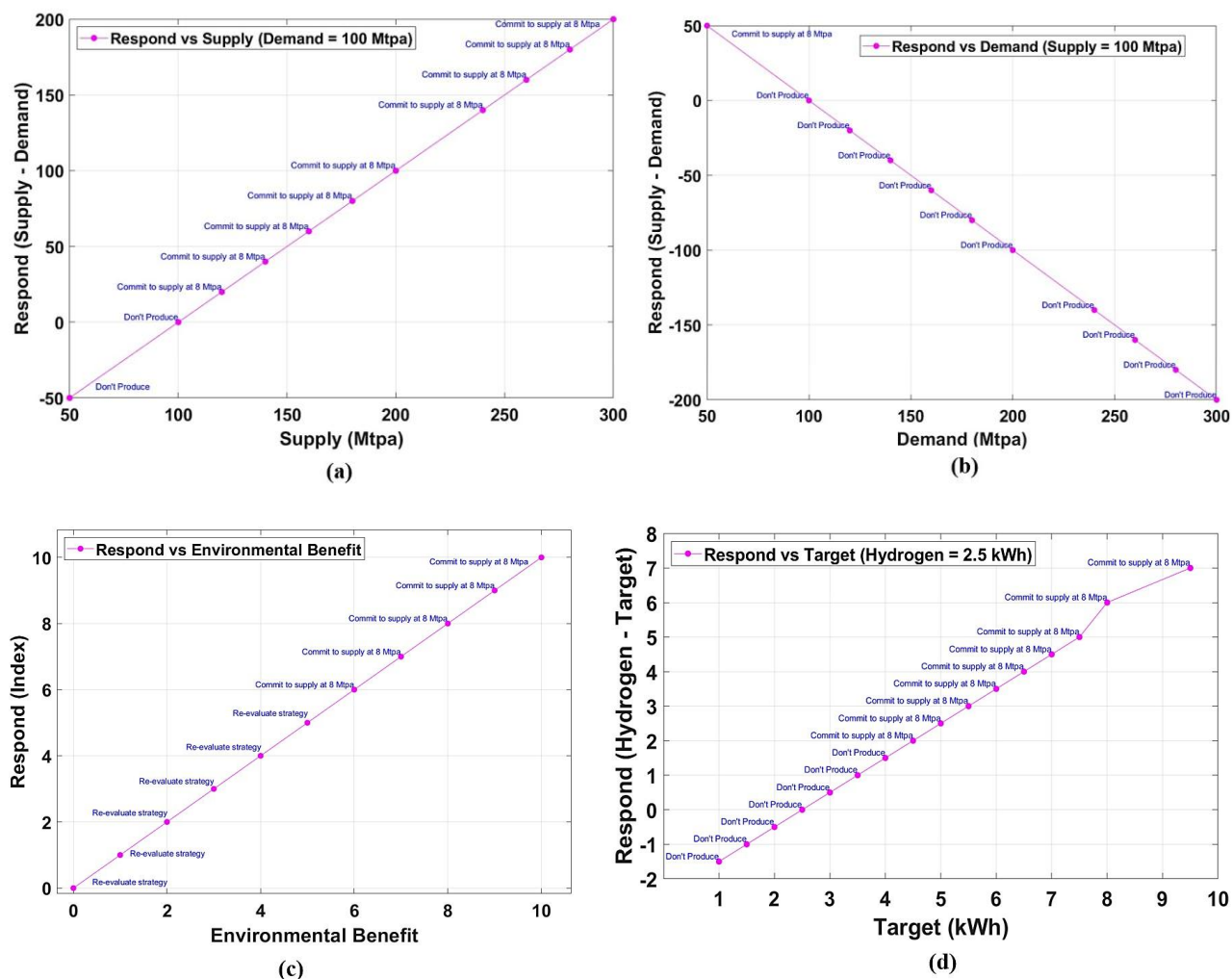
Impact Area	Short-Term Effects	Long-Term Effects	Expected Outcomes	Measurable Goals
Economic Impact	Considering profit margins fluctuation due to change in costs and demand in decision making.	Profit margins stabilize as production costs are optimized.	Improved profitability of hydrogen production in 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.

3.3.2.4 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, Figures 3-8 (a) and (b) focus on the demand and supply relationship and its influence on production decisions, highlighting the application of the law of demand and supply. Figure 3-8 (a) illustrates the behaviour of

production decisions with varying supply while keeping demand constant at 100 Mtpa, whereas Figure (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.



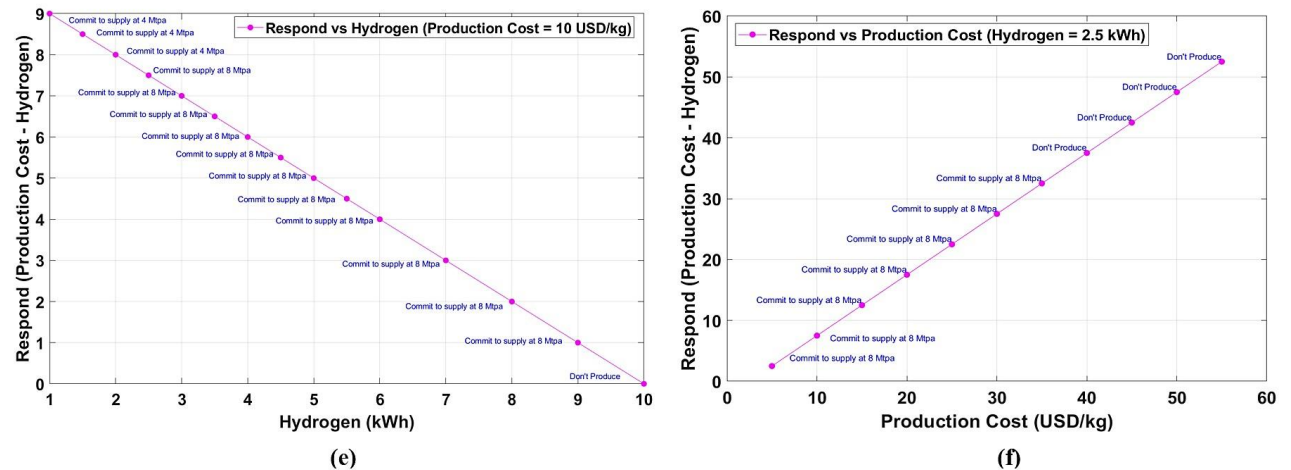


Figure 3-9 Sensitivity Analysis (a), (b), (c), (d), (e), (f)

Figure 3-9. 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.

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 Figure (a), as the supply exceeds 100 Mtpa, the respond value becomes positive, signalling 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, Figure (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.

Figures (c), (d), (e), and (f) extend the analysis to other variables, such as environmental benefits, hydrogen production, and production costs, and their effect on production strategy. Specifically, Figure (c) indicates that an

environmental benefit of 6 or more results in a commitment to production, whereas lower values necessitate re-evaluation. Figures (d), (e), and (f) present similar analyses for hydrogen production and production cost, with the decision to produce contingent on achieving a favourable 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.

3.4 Conclusion

The hydrogen decision support system (H₂DSS) 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 H₂DSS 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, wellinformed decisions that align with global sustainability goals. Moreover, the H₂DSS 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 H₂DSS 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 H₂DSS 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 H₂DSS 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

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4 Empirical Analysis and validation of a Decision Support System for Economic Hydrogen production with an insight from Surveys: Case Study of Saudi Arabia

Abstract

This study investigates the use of Decision Support Systems (DSS) in improving operational efficiency and strategic decision-making in the green hydrogen production sector in Saudi Arabia. The research focuses on optimizing resource allocation and operational efficiencies in a market characterized by rapid technological advancements and evolving regulatory landscapes. The study develops, implements, and validates a DSS tailored for the green hydrogen sector, leveraging real-time data analytics to facilitate strategic planning and optimize trade opportunities. The effectiveness of the DSS is tested through a comprehensive survey, assessing its impact on decision-making processes among stakeholders. The study also addresses barriers to green hydrogen technology adoption, such as insufficient policies and complexities of international standards and regulations. The robustness and reliability of the DSS are validated through statistical analysis, confirming its capacity to support stakeholders in navigating the green hydrogen market effectively and aligning operations with environmental sustainability goals. The findings provide valuable insights into the strategic application of DSS in renewable energy and practical approaches for overcoming regulatory and technological hurdles.

4.1 Introduction

The global energy sector is being driven towards more sustainable and cleaner forms of energy hydrogen appears to be among the more compelling alternatives [220]. This shift has been necessitated by the urgency of climate change mitigation and the finitude of fossil fuel resources. It is reputed that hydrogen is an energetically high molecule, having huge potential to produce power with zero direct emissions, and therefore it is a prospective alternative to the existing

hydrocarbon-based economy [221,222], Important in the adaptability of hydrogen within an emerging energy paradigm are base-load generation and grid storage solutions it can provide. This is relevant especially in the search today for a more stable and dependable complement to existing renewable sources of energy, like solar and wind. Notably, the application of hydrogen extends beyond electricity generation into major areas of heating, industrial processes, and transport [223]. The fact that it can cover the deficiencies of other renewable sources underlines the potential of hydrogen to change energy storage and utilization. For example, H₂ in the transport sector will work in fuel cells that generate electricity in electric vehicles a clean replacement for internal combustion engines[224,225].

Moreover, hydrogen's application in industrial processes and heating opens up a lane for the decarbonization mainly of energy intensive sectors within a more general strategy of GHG reduction [226]. However, efforts for including hydrogen in the mix of energy sources also aim to resolve production, storage, and distribution. For example, part of the challenge in production lies in developing technologies like water electrolysis with renewable energy resources to be able to produce 'green hydrogen', which will become very relevant in terms of building a sustainable hydrogen economy [224,227]. Further, more viable systems of hydrogen storage and distribution are under research and development to make hydrogen as an energy carrier more feasible economically [228]. Overall, hydrogen has a greater role in the future landscape of energy since it has high energy yield, can be put into many uses, and its production can be sustainable. Soon, with enhancing technological efforts to overcome the existing challenges in the production, storage, and distribution of hydrogen, it is prone to take a prime lead in the transition to a decarbonized global economy [229,230].

A hydrogen integration into the global energy matrix brings along an array of complex technical issues, economic and financial issues, and regulatory issues. In that respect, DSS becomes invaluable since it offers a sophisticated analysis backbone that will let stakeholders effectively navigate those complexities. Basically, DSSs are envisioned to process divergent data sets, from real-time

market dynamics to long-term environmental impacts, so that respective decision-making will be able to make an exhaustive scenario analysis [231,232]. However, The DSS facilitates a strategic planning process for real-time decisionmaking by providing better results in appraising the viability of hydrogen projects, optimizing resource use, and seeking future forecasts. Furthermore, DSS plays a very important role in aligning hydrogen initiatives to international standards and local regulatory frameworks. This makes sure that projects are feasible and sustainable, for it is possible that DSS can integrate and analyse the legal requirements with technical and economic data [231,233]. However, this would be particularly important for the hydrogen sector, where the regulatory landscape might be hugely complex and varied across regions. In addition, DSS support is needed for regulatory alignment and economic domains of hydrogen projects; they assist in quantifying the financial risks and benefits involved, since they give an evident picture of the returns on investment or potential cost savings [232,234–237].

This type of economic analysis assumes a huge significance in the sector of hydrogen since high upfront investment costs are weighed against long-term gains and environmental benefits expected from them. Furthermore, DSS contributes to the technical management of hydrogen projects by reviewing technological adaptability. It reviews how the hydrogen generation systems are capable of fitting with the pre-existing and new technologies for better compatibility and performance optimization [238]. Technical assessment is of essence for continuous improvements and scaling up of hydrogen technologies. Finally, stakeholder engagement cannot be downplayed as far as DSS are concerned. These systems aid in better communication and collaboration among various stakeholders, from the industry leaders and policymakers to the technical experts [239]. Instrumental in providing a common platform where data is shared and analysed, DSS would therefore foster an integrated, cohesive approach to hydrogen project development.

4.1.1 Study Objectives

This paper draws from a detailed survey, analysed using Statistical Package for the social Sciences (SPSS) software, to undertake a comprehensive evaluation of a DSS designed for the hydrogen economy. This research was conducted to examine how effectively the DSS could handle the balance of operational demands, technological integrations, and market fluctuations intrinsic to successful hydrogen implementation. Basically, it looks to find out the interdependencies of these factors and system functionality to come up with strengths and pinpoint areas that need improvement. In addition, the study also aims to explain the wider implications of the findings for improving DSS capabilities and, in turn, decision-making based on data-driven decisions in the hydrogen industry at large. It allows for long-term strategic planning and real-time decisions about hydrogen projects by assessing their viability, resources, and trends in the future. The DSS will also play a significant role in aligning hydrogen initiatives at both international standards and local regulatory frameworks, ensuring the feasibility and sustainability of projects. As such, this alignment is very critical to the hydrogen sector, where regulatory landscapes may be complex and immensely different across regions. Another key factor realized in the study concerns the management of economic aspects.

This research provides a comprehensive analysis of the integration of Decision Support Systems (DSS) within the hydrogen industry. It emphasizes the importance of DSS in optimizing hydrogen production and influencing market dynamics. The study outlines the methodology, survey design, data collection process, and statistical tools used to analyze influencing factors. The data analysis reveals how DSS aids strategic planning and market penetration in the hydrogen economy. The practical implications of these findings are discussed, emphasizing how DSS can overcome challenges in policy, technology, and market structures, advancing hydrogen initiatives. The conclusion underscores the utility of DSS in the green hydrogen sector and suggests future research directions, advocating for policy adjustments and technological innovations to improve the scalability and impact of hydrogen energy solutions.

4.2 Methods

This research paper aims to assess the effectiveness of a Decision Support System (DSS) for green hydrogen production optimization within the context of global sustainable energy transitions. The study focuses on Saudi Arabia as a case study, given its strategic importance in the energy sector and its potential for green hydrogen production. The methodology employed in this research is a mixed-methods approach, combining quantitative surveys with qualitative insights to provide a comprehensive understanding of the factors influencing the successful implementation and operation of the DSS. However, the survey focuses on the identified influencing factors of hydrogen development, including technology, logistics, and policy, which are crucial for setting development strategies and scientifically justified and validation obtained [18]. However, the survey is structured into three sections that identifying the critical drivers of hydrogen development, evaluating the relevance of the Development Support System (DSS) to hydrogen energy development, and detailing the integration of energy, trade, and hydrogen energy with the application of DSS. The survey aims to answer all critical questions related to hydrogen energy development and the practical application of DSS, ensuring that the survey answers all critical questions related to hydrogen energy development and the practical application of DSS. The survey is designed to provide a comprehensive understanding of the potential of DSS in supporting hydrogen energy initiatives

However, the survey was carefully designed to ensure that it would bring out all possible dimensions of information about the DSS for hydrogen energy in terms of its use and effectiveness. Structured questions were prepared to tap into different elements of DSS application, mentioned earlier, on areas like technological adaptability, economic impact, stakeholder engagement, and organizational integration. The technological adaptability questions were targeted at establishing how well the DSS could integrate with new and pre-existing

technologies available in the hydrogen sector. In this regard, several questions were raised regarding the system's ability to function with different hydrogen production methods and its compatibility with current technological infrastructures, among others. This focus on technological adaptability is line with similar studies in the renewable energy sector by Puckett [240] and Heidrich et al. [241] ,which underlined the central role that adaptability should play in the design process for DSSs. However, our work focuses on the hydrogen sector and hence brings to the fore some very particular challenges, such as integration with electrolysis and hydrogen storage technologies.

Questions on the economic impact probed its financial implications and benefits of using the DSS, covering issues like cost savings, return on investment, financial risks, and economic efficiency. Whereas broader studies on DSS in general energy management [242], that examined the cost-benefit analysis in wind and solar projects, our research narrows down to the economic dynamics in hydrogen production and distribution. In addition, the survey measured stakeholder engagement through questions on the level of ease of use, level of engagement, user satisfaction, and whether the DSS had improved collaboration and communication among stakeholders [25,26]. However, unlike stakeholder engagements for smart grid DSS applications, our focus on the hydrogen economy reveals unique stakeholder demands and engagement tactics critical to the evolution of this sector. [245].The last section of organizational integration was designed to determine the 'fit' of the DSS within existing processes and systems of an organization. Items enquired about the ease of integration, support of organizational workflows, and consistency of the strategic goals and objectives. While the integration of DSS in conventional energy utilities has been discussed previously [245–248], this study has put an emphasis on the challenges and strategies necessary to integrate DSS in hydrogen energy projects, against the background of a nascent field. The formulation of each question was such that detailed information relating to the perceived challenges and benefits associated with integrating the DSS within the hydrogen sector could be elicited. In other words, this survey was designed to probe the real applicability

of the DSS in supporting strategic decision-making by showing existing gaps or areas for improvement.

A structured questionnaire was designed to obtain data from a wide category of stakeholders in the Saudi Arabian energy sector. However, the questionnaire, administered through a (Statistical Package for the social Sciences) platform, Moreover, the survey was designed for energy professionals, policymakers, academics, and other stakeholders involved in green hydrogen generation and Saudi Arabia's energy transformation strategies, chosen based on their experience and relevance

4.2.1 Data Collection

The process of selecting the participants was meant to give a fair representation of stakeholders in the hydrogen energy sector, a multi-faceted emerging industry. Respondents are selected from all walks of participants, from industry leaders, policy framers, and operational technicians to academic researchers. Such a diversity of participants was purposefully sampled to project the performance of the DSS from different professional perspectives, ensuring that findings would be robust and representative of the complexity within the sector. Most importantly, industry leaders were very instrumental in the delivery of insights from a strategic and high-level operational perspective. The individuals typically manage big hydrogen projects and therefore play an important role in decision-making at critical investment levels. Their input was important in understanding how the DSS can support strategic planning and

resource allocation. Indeed, studies of similar nature have also pointed to the necessity of having the views of top management in assessing DSS implementations within renewable energy projects [249]. Another key stakeholder group would have been the policymakers. Their opinion was important because

they are tasked with developing regulatory frameworks that guide hydrogen production and use; therefore, their input would be imperative in knowing how far the DSS is aligned to existing policies and the changes to be affected in order to promote wider adoption. This methodology is copied from studies on smart grid technologies where the insights of the policymaker were critical in ascertaining the regulatory impacts on the deployment of DSS [250]. Furthermore, the view of operational technicians was valuable in adding a pragmatic dimension to the application of the DSS from a ground-level perspective. These are professionals who use the system daily to ensure the smooth running of the production processes related to hydrogen. Their feedback was vital with respect to assessing the usability and technical robustness of the DSS. This focus on operational staff is consistent with methodologies used in testing DSS tools for energy efficiency, again recognizing the need and value of involving technical users in the evaluation process to obtain specific feedback on system performance [247]. The involvement of academic researchers ensured an independent and analytical view of the DSS. In many cases, these respondents were engaged in cutting-edge hydrogen research and provided very valuable input for assessing the potential of the system for innovation as well as integration with state-of-the-art technological development. Academic views are commonly integrated into studies on DSS within environmental management, where delivery is greatly enhanced by the analytic approach taken by the academic community [251].

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therefore, their input would be imperative in knowing how far the DSS is aligned to existing policies and the changes to be affected in order to promote wider adoption. This methodology is copied from studies on smart grid technologies where the insights of the policymaker were critical in ascertaining the regulatory impacts on the deployment of DSS [250]. Furthermore, the view of operational technicians was valuable in adding a pragmatic dimension to the application of the DSS from a ground-level perspective. These are professionals who use the system daily to ensure the smooth running of the production processes related to hydrogen. Their feedback was vital with respect to assessing the usability and technical robustness of the DSS. This focus on operational staff is consistent with methodologies used in testing DSS tools for energy efficiency, again recognizing the need and value of involving technical users in the evaluation process to obtain specific feedback on system performance [247]. The involvement of academic researchers ensured an independent and analytical view of the DSS. In many cases, these respondents were engaged in cutting edge hydrogen research and provided very valuable input for assessing the potential of the system for innovation as well as integration with state-of-the-art technological development. Academic views are commonly integrated into studies on DSS within environmental management, where delivery is greatly enhanced by the analytic approach taken by the academic community [251].

4.2.2 Statistical Analysis

The study utilized SPSS as the primary statistical tool due to its ability to manage large datasets and compute complex tests. Descriptive statistics were used to provide basic variable information, including means, standard deviations, and ranges, to identify central tendencies and variability in responses however, this is in line with methodologies applied within other studies in the energy sector [252,253] that used descriptive statistics in analysing performance data from DSS. However, the mean represents the average value of a dataset, indicating

the average response of stakeholders to survey questions about the DSS. A high mean value indicates that respondents find the DSS highly useful, which is crucial for understanding general sentiment and identifying areas of well-received information. In addition, Standard Deviation measures the dispersion or variability of responses around the mean. A low standard deviation suggests consensus among respondents, while a high standard deviation indicates a wide range of opinions. In this study, a high standard deviation for items related to supply chain efficiency might suggest differing experiences or challenges among stakeholders. Understanding the variability in responses helps identify areas of disagreement or diverse experiences, which can be critical for tailoring the DSS to meet varied needs.

To identify the variance, it is the square of the standard deviation, provides another measure of dispersion. High variance indicates that responses are spread out over a wide range, suggesting significant differences in stakeholder experiences or perceptions. In this study, high variance in responses related to DSS functionality might highlight areas where the system's performance is inconsistent. The Cronbach's Alpha reliability test was also carried out to see the internal consistency of the survey. It had a high value of Cronbach's Alpha of 0.872, which ensured strong internal consistency and guaranteed that the questions measured the intended construct reliably. This method to test reliability is consistent with methods used in power system DSS evaluations in order to assure the reliability of their survey instruments [254], was followed by exploratory factor analysis to determine underlying variables that could explain patterns in the data. Important dimensions influencing DSS effectiveness were identified, including technological adaptability, economic impact, and engagement of stakeholders. Factor analysis is also a standard technique within the process of DSS evaluation, which has already been evidenced in other studies examining factors that affect DSS adoption in agricultural settings [250]. This analysis provided more in-depth insights into the factors driving the effectiveness and acceptance of the DSS within the hydrogen sector by identifying latent variables. Furthermore, correlation analysis was undertaken to establish the relationship

between variables. This constituted the identification of positive significant correlations among variables like the effectiveness of DSS systems and influencing factors such as technological adaptability, economic impact, and stakeholder engagement. Similar studies in estimating the impact of DSS on supply chain optimization [4], have been utilized to understand the interdependencies of variables. These extensive statistical analyses provided foundational knowledge for further investigating how the DSS impacted the hydrogen sector, along with dependencies. In this regard, one could notice from similar studies the use of rigorous statistical methods, such as being key to getting reliable data with insights that would lead to further refinement of the DSS to help stakeholders make improved decisions.

The survey utilized a full SPSS package for analysis due to its robust capabilities for managing large datasets and performing complex statistical tests, ensuring thorough and reliable data analysis and solid foundation for results interpretation. Descriptive statistics were used first to summarize the data and describe variables. In this respect, computations of the means, standard deviation, and range were performed to describe central tendencies and variability in responses. This approach is in line with methodologies used within similar studies in the energy sector [255,256]. which also applied descriptive statistics in the analysis for DSS performance data. In addition, the reliability tests were conducted using Cronbach's Alpha to find out if the survey has internal consistency. A value of Cronbach's Alpha of 0.872 indicated strong internal consistency, hence the questions in this survey reliably measured the intended constructs. This method for reliability testing is similar to those done where the DSSs for water resource management were checked to make sure the reliability of the survey instruments. Next, an exploratory factor analysis was conducted to establish variables that could explain the patterns in data. The main dimensions found to be influencing DSS effectiveness were technological adaptability, economic impact, and stakeholder engagement. Factor analysis is already a standard in DSS evaluation, evidenced by such works [257–260].

4.3 Result and discussion

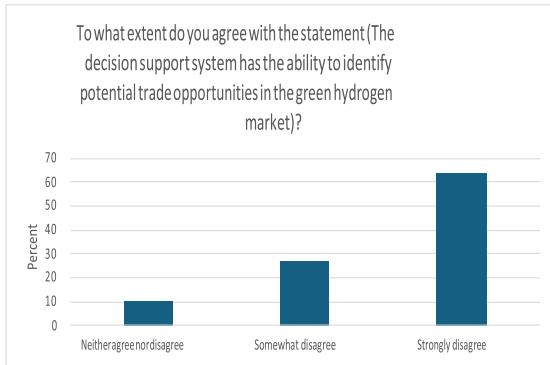
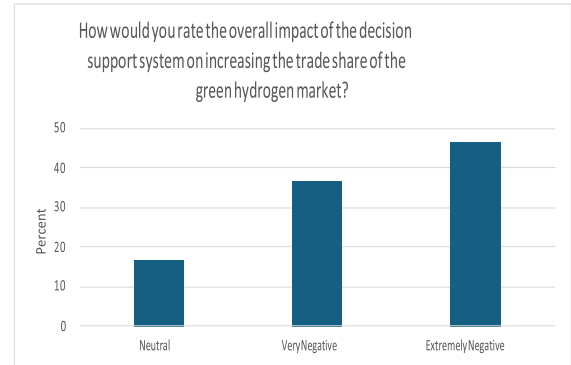
The study highlights the contribution of DSS to the operational and strategic frameworks being developed for the emerging green hydrogen industry. By identifying trade opportunities and enabling complex decision-making through real-time data-driven insight, DSS is one of the key drivers in this fast-moving market of technological change and shifting regulations. It also requires finetuned policy and enhanced regulatory support to accelerate green hydrogen technologies to wide market diffusion, and DSS will become one of the transformative tools in scenario analysis and policy impact assessments that will help make the case for regulatory adjustments and nurture an enabling environment for technological integration.

However,

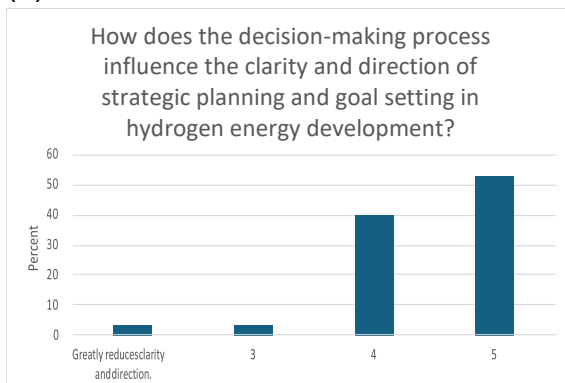
The study emphasizes the role of Decision Support Systems (DSS) in the green hydrogen industry, highlighting its role in identifying trade opportunities and facilitating complex decision-making through real-time data-driven insights. DSS is essential for accelerating green hydrogen technologies and fostering an enabling environment for technological integration. However, the integration of innovative technologies like AI and machine learning could enhance the system's responsiveness to market changes and provide valuable comparative insights.

Statistical measures like the mean, Cronbach's Alpha, and correlation coefficients are crucial in survey-based studies, as they help establish the reliability and significance of the data collected. The study, which targeted the optimization of green hydrogen production in Saudi Arabia, provided valuable data on the system's reliability, efficacy, and areas for improvement. The reliability check was impressively benchmarked at a Cronbach's Alpha of 0.927, confirming the reliability of the data.

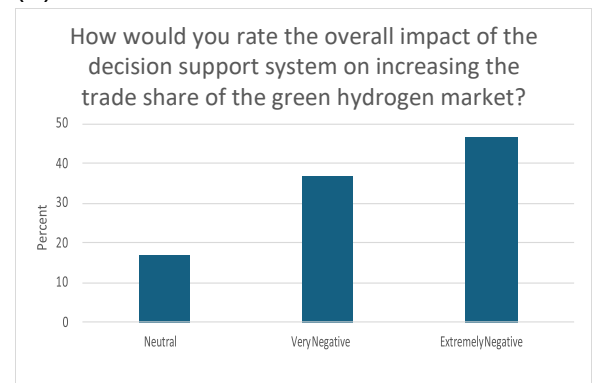
The 80.3% response rate from industry leaders and academia researchers further underscored the study's relevance and significance to stakeholders, highlighting the deep interest in the DSS's role in hydrogen energy initiatives. The survey results underline strong support for DSS capabilities and the need for further refinement and regulatory support in the green hydrogen industry. As Fig. 1 shows, the overwhelming majority of respondents indicate that the DSS has the capability to identify trade opportunities in the hydrogen market and thus will turn into a critical tool in market analysis and expansion. Figure 1.b, on the other hand, is sceptic about the role of the DSS in extending the market share of green hydrogen. It also illuminates those areas where the system itself or some external factors need further revaluation so that its effectiveness could be enhanced. That would actually point to the requirement of continuous improvement and adaptation of the DSS in order to take it totally toward facilitating a workable green hydrogen economy.



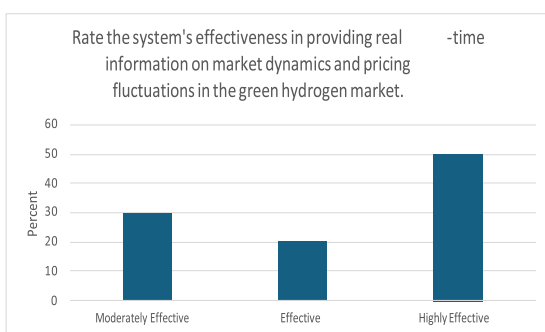
(a)



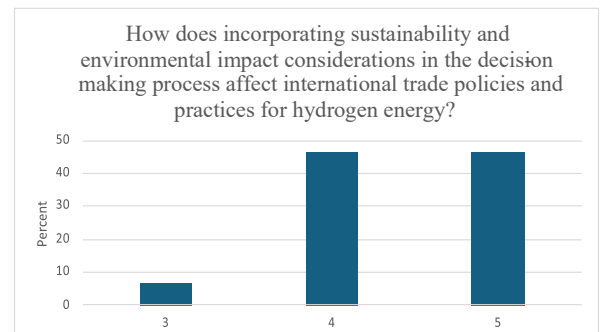
(b)



(c)

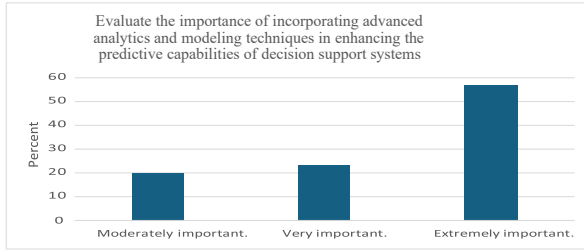


(d)



(e)

(f)



(g)

Figure 4-1 description of what the graphs represents, (a) The potential trade opportunities in the H2 market to a certain extent, (b) Overall impact on increasing the green hydrogen market's trade share., (c) Strategic planning clarity in H2 development, (d), The ability to analyse market trends and forecast demand for green hydrogen, (e) The system's effectiveness in providing real-time market dynamics in the H2 market,(f) The impact of sustainability and environmental impact , (g) The predictive capabilities to incorporating advanced analytics and modelling techniques

The results in Figure 4-1.c indicate that 53.3 % of the respondents agreed to the statement, "The DSS improves clarity and orientation in strategic planning regarding the development of hydrogen energy." This positive response proves that the DSS makes strategic decisions through clear guidance and aligning with the long-term goals, which is the prerequisite for the successful integration and scaling of hydrogen technologies. Figure4-1. d indicates that there are mixed feelings regarding the trend analysis capability of the DSS with respect to market trends and demand forecasting for green hydrogen. With 50% of the surveyed population not able to tell its effectiveness, clearly, there is a need for improvement in the DSS market analytical capabilities and user training to build confidence in its predictive functions. Figure4-1.e further indicates that 50% of the respondents strongly agree that the DSS is effective in giving real-time market dynamics and pricing information. About 20% judge it as effective, while 30%

judged it as moderately effective. This generally means that the DSS can be relied upon to provide timely, correct, and applicable market insights to support operational decision-making. Figure 4-1.f shows that 46.7% of the respondents view the DSS as extremely important to integrate concerns on sustainability and environmental impact into decision-making, while 46.7% find it very important. This encapsulates the role of the DSS in supporting environmentally responsible trade policy and practices toward the global goals of sustainability. Figure 4-1.g shows indicates that 56.7% percent of the respondents indicated that incorporating advanced analytics and modelling techniques into the DSS was extremely important, while 23.3% percent considered it very important. This result therefore underlines how important sophisticated tools of analysis are in augmenting the DSS to be more predictive about market trends and dynamics. Table 4-2 presents the correlation analysis, which supports the validation of the DSS. The key dimensions of D1, D2, and D3 are all significantly positively correlated with overall items. Descriptive statistics are presented in Table 1, where the mean scores are 33.3333, 72.6000, and 41.1000 for D1, D2, and D3, respectively, showing different levels of effectiveness. The standard deviations indicate a medium variation in responses, with D2 leading in terms of variability.

Table 4-1 The Descriptive Statistics

Dimensions	Mean	Std. Deviation	Number of completed response
D1	33.3333	5.22813	30
D2	72.6000	11.40659	30
D3	41.1000	4.95740	30
All Items	143.4667	18.85285	30

As shown in Tables 4-2 and 4-3, key dimensions are very significantly positively correlated with one another. For instance, D1, which identifies trade opportunities, has high positive correlation coefficients with D2 (strategic planning clarity) and D3 (market trend analysis), with a coefficient of 0.587 and 0.578, respectively. The correlations are significant at 0.01 levels, portraying strong relationships. The correlation of D1 to overall effectiveness is 0.750, so identification of trade opportunities is very much aligned with the overall success of the DSS. Similar conclusions can be drawn for D2 and D3, whose overall correlations come in at 0.958 and 0.872, respectively. These results underline that all these factors are interlinked to determine the success of the DSS and therefore require a holistic approach, from market analysis and strategic planning down to real-time information. These descriptive statistics allow for deepening the understanding of the perception of the different components of the DSS and the challenges related to green hydrogen production that exist among the respondents. For example, the average score of the transition challenges to green hydrogen was 3.67 with a standard deviation of 1.124, indicating that the challenges are only moderate with a demand for focused strategies to overcome them. The high concern in policy and regulatory barriers was strongly indicated with a mean value of 4.33 and a standard deviation of 0.844, calling for advocacy and reform in these areas. The mean and standard deviation of the integration constraints of green hydrogen into existing energy systems, both technological compatibility and regulations, were 3.63 and 1.189, respectively, indicating that enhancing technological compatibility and regulatory frameworks is required.

Table 4-2 The Correlations of the dimensions table

Dimensions			D1	D2	D3
Spearman's rho	D1	Correlation Coefficient	1.000	0.587**	0.578**
		Sig. (2-tailed)		0.001	0.001
		Number of completed response	30	30	30
	D2	Correlation Coefficient	0.587**	1.000	0.741**
		Sig. (2-tailed)	0.001		0.000
		Number of completed response	30	30	30
	D3	Correlation Coefficient	0.578**	0.741**	1.000
		Sig. (2-tailed)	0.001	0.000	
		Number of completed response	30	30	30
**. Correlation is significant at the 0.01 level (2-tailed).					

Table 4-3 The Correlations and dimensions

Correlations and dimension's		D1	D2	D3	All Items
D1	Pearson Correlation	1	0.604**	0.553**	0.750**
	Sig. (2-tailed)		0.000	0.002	0.000
	Number of completed response	30	30	30	30
D2	Pearson Correlation	0.604**	1	0.764**	0.958**
	Sig. (2-tailed)	0.000		0.000	0.000
	Number of completed response	30	30	30	30
D3	Pearson Correlation	0.553**	0.764**	1	0.872**

	Sig. (2-tailed)	0.002	0.000		0.000
	Number of completed response	30	30	30	30
All Items	Pearson Correlation	0.750**	0.958**	0.872**	1
	Sig. (2-tailed)	0.000	0.000	0.000	
	Number of completed response	30	30	30	30
** . Correlation is significant at the 0.01 level (2-tailed).					

Table 4-4 The Correlation and Spearman's Table

Correlations Dimensions			D1	D2	D3	All Items
Spearman's rho	D1	Correlation Coefficient	1.000	0.587**	0.578**	0.732**
		Sig. (2-tailed)		0.001	0.001	0.000

		Number completed of response	30	30	30	30
	D2	Correlation Coefficient	0.587**	1.000	0.741**	0.948**
		Sig. (2-tailed)	0.001		0.000	0.000
		Number completed of response	30	30	30	30
	D3	Correlation Coefficient	0.578**	0.741**	1.000	0.849**
		Sig. (2-tailed)	0.001	0.000		0.000
		Number completed of response	30	30	30	30
		Correlation Coefficient	0.732**	0.948**	0.849**	1.000
		Sig. (2-tailed)	0.000	0.000	0.000	
	All Items	Number completed of response	30	30	30	30
**. Correlation is significant at the 0.01 level (2-tailed).						

The final effect rated the lowest was financial incentive for adopting green hydrogen, with a mean score of 2.63 and a standard deviation of 1.159, which indicated that there is a need to increase economic support. Challenges to international cooperation for green hydrogen related to trade barriers and standards were rated at a medium level, with an average of 3.53 and a standard deviation of 1.252, which shows that there are issues that call for attention. Governmental support in research and development in green hydrogen technologies showed some mixed responses, with a mean score of 3.57 and a standard deviation of 1.331, which indicates variability in perception or probably inconsistencies in policy implementation. Attracting private investment in green hydrogen projects without regulatory stability and long-term commitment was rated high with a mean score of 4.20 and standard deviation of 0.925. Another big challenge rated as such with a mean score of 4.20 and a standard deviation of 0.847, is the absence of internationally harmonized green hydrogen standards and certification. The overall impact of the DSS on increasing green hydrogen market trade share received an average score of 4.30 with a standard deviation of 0.750, an indication of its effectiveness in enhancing trade opportunities.

However, the off-take agreements were perceived to have a strong influence on demand projections for green hydrogen with a mean score of 4.27 and a standard deviation of 0.944. The capability of the DSS in spotting possible trade opportunities within the green hydrogen market received very high agreement, with a mean score of 4.53 and a standard deviation of 0.681. The ability of the DSS in analysing trends within the green hydrogen market and in predicting demand for the commodity to a great degree of accuracy received an average score of 4.23, with a standard deviation of 0.858. Logistics in hydrogen energy were taken as a major factor in the development of this source of energy, with a mean of 4.07 and a standard deviation of 0.828. This reflects on the necessity to

have proper supply chain management. The effectiveness of the system in dispensing real-time information about the market dynamics and price fluctuations scored an average of 4.20 and a standard deviation of 0.887, which shows how important this had to be within a dynamic market environment. Current trade policies were perceived to be about average in the level of their impact, rated at a mean of 3.97 with a standard deviation of 0.850, indicating that improvement in policy frameworks could still be realized. The DSS stakeholder engagement in hydrogen projects was scored high, with a mean of 4.07 and a standard deviation of 0.868, underlining collaborative efforts. The influence of the DSS on decision-making in the green hydrogen market was very high, with a mean of 4.30 and a standard deviation of 0.750. Taking into consideration environmental impact together with the cost in choosing energy sources had an average score of 4.20, with a standard deviation of 0.847, thus showing the role of the DSS in striking a balance between these factors. It fell under the category of general satisfaction with the performance and functionality of the DSS for trade decisions in the green hydrogen market, with a mean of 4.23 and a standard deviation of 0.774. The supply chain efficiency for delivering green hydrogen was rated at 4.50 with a standard deviation of 1.280; however, variability seems to suggest that there have been some areas where further improvement is required. The willingness to recommend the DSS to others in the green hydrogen market was rated relatively mid-level, with a mean of 3.57 and a standard deviation of 1.406, thus leaving some space for improvement.

Finally, the compliance of the situation in the hydrogen production emissions rules was perceived to be only average, with a mean of 3.53 and a standard deviation of 1.008, and tighter control of the situation might be required. The positive mean score regarding the reliability of technology used in green hydrogen production was 4.03, with a standard deviation of 0.928; this therefore supports the technological robustness of the DSS. The mean score on market and economic viability of the green hydrogen projects was 3.33, with a standard deviation of 1.373, an indication of areas that require strategic improvement. The question

evaluating the environmental benefits versus operational impacts of hydrogen generation received an average score of 3.47, with a standard deviation of 1.074, indicating the need for integrated assessments.

Table 4-5 The Descriptive Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	Number of uncompleted responses Items
0.927	0.947	36

4.3.1 Survey Design and Representation

The series of pie charts below Figure 4-2 gives a graphical display of the survey responses concerning the current involvement in the energy industry, adoption of automated analytical systems, and knowledge concerning such systems. As shown in the first pie chart, nearly two-thirds of the respondents work in the energy industry at present. This high percentage will ensure that the feedback comes from people with appropriate experience, thus adding credibility to the findings and ensuring that the data reflects real world perspectives. The second pie chart indicates that slightly more than half of the surveyed participants is engaged or will engage in DSS practices. This growing

interest shows the relevance of the study and shifting of this sector toward data driven decision-making processes. It underlines industry recognition of the need for structured appraisal of environmental and financial impacts.

The third pie chart shows that most of the respondents had knowledge or experience related to integrating DSS into business decision-making for sustainability. This high level of expertise thus ensures that the results are based on practical knowledge, critical in establishing the real-world applicability and impact of DSS.

The study aimed to validate the Decision Support System (DSS) for optimal hydrogen production and distribution through a comprehensive survey. The survey was designed to capture quantitative and qualitative data on stakeholder perceptions, challenges, and expectations of DSS implementation in the hydrogen sector. The four most important sections of the questionnaire were related to specific functionalities of the DSS and/or the wider hydrogen energy transition.

The survey design and structure included demographic information, main factors affecting hydrogen production (D1), effectiveness of the DSS in supporting strategic decisions concerning the hydrogen industry (D2), market trends and control (D3), and distribution methods. The online survey was set up on a secure platform, and invitations were sent out via email to relevant stakeholders in industry associations, government bodies, and academic institutions dealing in renewable energy and hydrogen technologies.

The survey was distributed through multi-channel methods to grab a wide and representative sample of the main stakeholders for the hydrogen sector. The sample size was targeted at 50 relevant stakeholders from various industries, with an emphasis on securing a balance in their respective professional backgrounds and regions. Pilot Testing: A pilot survey was conducted on a small group of respondents comprised of hydrogen industry professionals to detect any problems concerning clarity, question framing, and response options. Feedback from the pilot study was integrated to refine the final survey to ensure that questions were clear, unbiased, and represented the research objectives.

Cronbach's Alpha Test for Reliability: The Cronbach's Alpha test was used to determine the internal consistency of the survey. With an overall value of 0.872, this shows the strong reliability that the items of the survey have been consistently measuring the intended constructs. Anonymity and Confidentiality: The assurance of anonymity and confidentiality in their responses provided a platform where respondents gave their honest and unbiased feedback, helping reduce any potential response biases and enhanced the credibility of data collected.

Among the factors influencing decisions related to hydrogen production, regulatory policies, technological advancement, and economic considerations were highlighted as the most relevant. The DSS proved to be very effective in terms of optimization strategies for production, integration of real-time data, and support of strategic decisions with regard to market trends. Market Trends and Control (D3): The stakeholders appreciated the system's ability to predict market trends and adjust to changing supply-demand dynamics; however, some suggested further improvement in the market forecasting algorithms.

In conclusion, the comprehensive survey methodology described above ensures that the empirical analysis conducted in this study is rigorous and credible. By engaging such a wide range of stakeholders, with strong data collection and validation techniques, these results provide a comprehensive overview about the efficiency and applicability of DSSs in the hydrogen sector.

Figure 2 The survey response concerning involvement in the energy industry (a, b, c).

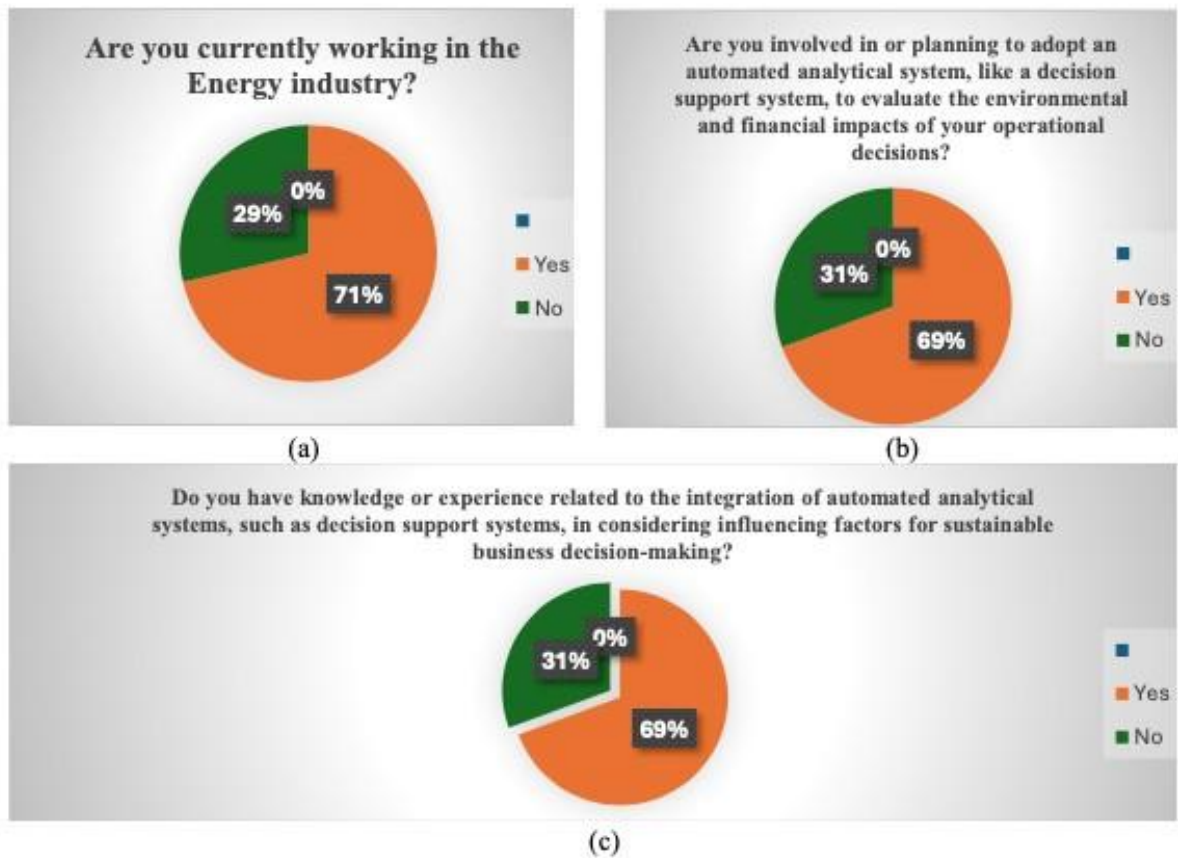


Figure 4-2 The survey response concerning involvement in the energy industry (a, b, c)

4.3.2 DSS Effectiveness

The analysis reveals that stakeholders consider the Decision Support System (DSS) highly effective, particularly in areas requiring real-time data analysis and strategic decision-making. For instance, the mean rating for the DSS's impact on market trend analysis and trade decision efficiency was significantly above average. This underscores its pivotal role in enhancing both operational and strategic outcomes. Survey responses highlighted the DSS's significant contributions to improving stakeholder engagement and regulatory compliance. High agreement levels among participants, reflected in kappa values above 0.3,

indicate that the DSS aligns project operations with regulatory standards effectively and enhances collaboration across various stakeholders.

Responses indicate that the DSS is highly effective in managing the complexities involved in incorporating green hydrogen into current energy systems. The high ratings for the DSS's capability to Analyse and respond to market dynamics demonstrate its value in promoting the wider use of hydrogen technologies. Statistical analyses show strong correlations between the DSS's effectiveness and significant influencing factors, including technological adaptability, economic fluctuations, and stakeholder involvement. These results highlight the DSS's ability to adapt to and positively impact the evolving hydrogen energy sector. By structuring the Results chapter in this manner, the study effectively communicates how the DSS contributes to advancing hydrogen energy initiatives. It highlights the critical linkages between the system's functionality and essential influencing factors, thereby validating the DSS's effectiveness and providing strategic insights for optimizing its use in future energy projects.

4.4 Discussion and Future Research Directions

The survey highlights the importance of Decision Support Systems (DSS) in promoting green hydrogen adoption, as they can synchronize financial and environmental outcomes with evolving scenarios. DSS enhances operational processes and stakeholder participation, which is crucial for sustainable energy transitions. Its adaptability to specific infrastructural and regulatory contexts makes it a valuable tool in strategic energy planning. DSS's real-time data processing capabilities enhance decision-making precision, managing the balance between immediate operational demands and long-term sustainability goals in the hydrogen sector. However, Future research should consider

longitudinal studies to track the evolution and long-term impact of DSS in the green hydrogen sector, incorporating advanced technologies like artificial intelligence and machine learning to improve predictive accuracy and responsiveness to market changes. Comparative analysis across sectors can yield insights for cross-sectoral innovations and integrated energy management strategies. Policy development impact could be explored to create supportive frameworks for green hydrogen technology adoption. In addition, international collaboration and standards could help streamline adoption processes and scale up hydrogen technology deployment globally. By addressing these areas, future research can enhance the strategic application of DSS, ensuring it meets current operational needs and sets a foundation for sustainable growth in the renewable energy sector.

4.5 Conclusions

The survey analysis has revealed critical insights of the Decision Support System's (DSS) crucial role advancing green hydrogen in the integration of energy sectors, operational decision-making, and strategic planning. A clear enhancement of this would be strong tools for stakeholders to deal with the complexities inherent in hydrogen implementation, underpinning the central role of DSS in improving precision and user engagement with the system. Particular noting in the survey was the system's ability to handle market analysis, regulatory compliance, and technological integration. Variability in the responses for the different experiences of stakeholders underlined the adaptability of the DSS to various operational contexts and challenges. Furthermore, the study highlights the importance of the Digital Supply System (DSS) in promoting a sustainable and efficient hydrogen economy. It suggests that policymakers should create regulatory frameworks to facilitate the integration of green hydrogen technologies, industry leaders can use this information to improve operational strategies, and technology providers should continually improve their DSS capabilities to meet the evolving demands of the hydrogen economy. The study also suggests that further research should focus on integrating advanced

predictive analytics to forecast market trends and anticipate regulatory changes, customizing DSS tools to cater to different hydrogen production methods, and developing user-friendly interfaces to make the technology more accessible. The findings underscore the DSS's role in transforming the energy sector's future. energy future.

However, the results from the survey represent full validation of the DSS Decision Support System for green hydrogen production, outlining its effectiveness in a number of critical areas. First and foremost, the DSS has been very good at recognizing trade opportunities within the hydrogen market, which is of fundamental importance to stakeholders seeking to gain an advantage from rising trends and market dynamics. In its entirety, this aids in better and more strategic decision-making that will help stakeholders discover and exploit potential areas of growth. Moreover, the DSS has turned out to be very instrumental in strategic planning. Through clear insights and recommendations, it aligns strategies by an organization that will meet the set long-term objectives. This becomes very important in the hydrogen sector, in which shifting to green requires careful planning and coordination across various dimensions, such as technological integration, regulatory compliance, and market positioning.

It further gains strength from the ability of the system to deliver real-time market insight. Having real-time information about market dynamics and the fluctuation in prices helps stakeholders make timely, effective decisions, hence improving operational efficiency and responsiveness to changing market conditions. This is quite important in staying competitive within the fast-changing energy market. However, areas for improvement were also identified from the survey. One such gap was related to the effect of DSS on increased market share. Whereas the system is very good at picking out opportunities, translating such opportunities into significant market share gain still seems elusive. Improving the functionality of the DSS in this regard will go a long way in

enhancing its overall impact and effectiveness. Besides, there has to be more confidence instilled in the system's market trend analysis. Mixed responses in this area suggest some additional training may be required for the user or even refinements in the system itself. What is most encouraging, however, is the good reception concerning sustainability considerations and advanced analytics capabilities within the DSS. A system so aligned to contemporary market needs and environmental goals depicts it as relevant for sustaining development. Infused with sophisticated analytical tools, the DSS will project and respond better to environmental and economic variables, hence fostering more sustainable business practices. Provided that a system can be developed to show its strengths and address the identified gaps, it shall be able to stabilize its position as one of the pivotal tools in the development of hydrogen energy. This improves the impact on market share and market trend analysis, not just for improved system performance but also in terms of enhanced user confidence and satisfaction. As a consequence, this will enable its wider adoption and integration by DSS.

The refined and improved DSS will be a valuable tool in helping the Kingdom of Saudi Arabia to contribute to its hydrogen economy. This will position the country to assume forefront positions in the global hydrogen market by 2030, as the system will support trustworthy and effective decision-making in reaching the set goals of sustainability. These data show great interest and a need in the hydrogen sector for DSS, thus confirming the objective of this study in the optimization of hydrogen production and distribution processes by using advanced decision support systems. All these strategic uses of DSS will therefore be driving progress toward a more sustainable and economically viable energy future for Saudi Arabia.

The Decision Support System (DSS) for hydrogen production and distribution has been enhanced by incorporating machine learning (ML) techniques. This transforms the DSS from a static tool to a dynamic, data-driven system capable of responding to market conditions, renewable energy variability, and policy changes. The integration strengthens the DSS's ability to support complex

decision-making processes, especially in rapidly evolving markets like Saudi Arabia. ML techniques, such as regression models and decision trees, are valuable for predicting hydrogen demand, optimizing supply chains, and managing production strategies. These models can forecast hydrogen demand based on renewable energy costs, policy incentives, and market dynamics, allowing for proactive adjustments to production levels. Decision trees classify scenarios based on inputs like production costs, environmental impact, and regulatory factors, guiding whether to increase production, maintain current output, or pause operations. A proof-of-concept was developed using historical data from hydrogen projects, focusing on variables like energy availability, production costs, and market demand. The system's adaptability ensures its effectiveness in dynamic environments, supporting short-term operational goals and long-term strategic planning. This approach aligns with Saudi Arabia's Vision 2030, promoting a sustainable and efficient hydrogen economy.

4.6 References

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5 General Discussion, Recommendation, and future Research Direction.

This chapter gives a broad discussion of the contributions this study has offered towards the research in general in hydrogen energy development through DSS applied in optimizing hydrogen production and strategic energy planning. On the other hand, this again provided new insights about ways of overcoming a number of technical, financial, environmental, and logistic barriers to such systems. Added to this is the fact that it is adaptable and contextually relevant; this sets the study apart from the current literature and places it in a position whereby it is a valuable contribution to the ever-growing knowledge base on hydrogen energy.

5.1 All-Encompassing Decision-Making Strategy

Amongst the key contributory elements of this study, there is the development of a decision-making framework including various optimization criteria for multicriteria decision analysis within hydrogen energy production. Most research works on the subject, available in literature, concern very specific or isolated aspects, such as production technologies, environmental impacts, or cost efficiency. Contributing to establishing a more integrated approach by gathering in one decision-making instrument those factors of a technical, financial, environmental, and logistical nature.

This comprehensive strategy helps stakeholders make more informed decisions, considering the entire value chain of hydrogen energy within an integrated framework. The consideration of these linked factors together contributes to insights beyond those provided by classic models that are oblivious to systemwide implications of hydrogen energy development. Such an integrative

approach will be important for the stakeholder who needs a more nuanced understanding of how the different aspects of hydrogen production interact to influence outcomes.

5.2 Ability to Adapt to Ever-Changing Conditions

This study contributes in several keyways regarding the adaptiveness of DSSs to dynamic external conditions. Most consider static conditions under which hydrogen energy systems work and fail to foreground the question of the operational areas in view of energy markets, continuous technological advancements, and regulatory frameworks. This research identifies the need for decision tools to be flexible in their decisions regarding such changes.

The DSS developed under this research is real-time, scenario-based, and allows recasting of strategies as new information unfolds. That is very instrumental in ensuring the long-term viability of hydrogen energy projects within a rapidly changing global energy landscape. The flexibility of such an approach, the study says, will provide the ability to optimize financial and environmental sustainability to ensure that hydrogen production is profitable while remaining within set sustainability thresholds.

5.3 Strategic Focus on Hydrogen Market of Saudi Arabia

The contribution this work provides is on Saudi Arabia's contribution to the hydrogen economy at a global level. Even though most works of hydrogen energy are usually performed on a wide and general perspective, the analyses of this research were adapted to the particular conditions of Saudi Arabia, who should become one of the main countries involved in such production due to its good renewable resources of energy and its strategic geographic location.

The insights drawn from this research relate to the NEOM Green Hydrogen Project and, therefore, provide actionable insights applicable directly to largescale hydrogen projects in similar emerging markets. Among the challenges that arise within Saudi Arabia are high production costs, insufficient infrastructure, and gaps within regulatory frameworks. This study addresses those challenges and gives detailed recommendations that could be applied within Saudi Arabia's Vision 2030 and for its ambition to become a global leader in hydrogen production. This is a focused approach that makes the study different from other studies which have failed to show such specificity and contextual relevance.

5.4 Integrating Financial, Environmental, and Logistical Factors

In particular, this study contributes to the body of knowledge by encapsulating all these aspects-financial, environmental, and logistical-into one integrated decision model. Much of the previous work on the subject has focused either on a single aspect or on the optimization process of only one dimension of hydrogen production, such as cost minimization or environmental benefits. To that extent, this research appraises these various factors in tandem, thus offering a more holistic review of hydrogen energy development than is found elsewhere.

This study developed a DSS considering not only the production cost of hydrogen, but it also covers the environmental impact brought about by various ways of its production and logistical challenges associated with the storage and transportation of hydrogen. The presence of such multidimensional analysis will provide a more realistic view about the viability of the hydrogen energy projects; hence, the tool becomes very powerful for those stakeholders that seek project balance in technical, financial, and environmental aspects.

5.5 Decision Tree Dynamic

Probably the most innovative point of this research is connected with the development of a decision tree framework, which can be adjusted in real time. Unlike the majority of traditional models of decision making, which are often static and cannot provide a possibility to take into consideration changes in conditions, the proposed decision tree framework is dynamic and able to be continuously optimized. That is very important for the hydrogen energy sector, as external factors may strongly affect project outcomes, including weather patterns, market demand fluctuations, and changes in regulatory requirements.

the decision tree is dynamic because the balance of financial and environmental concerns is part of the project lifecycle continuously. It is also flexible; every change in stakeholders' strategies owing to new conditions ensures sustainability for hydrogen energy projects through time. This innovation positions this study against existing research, as it offers a major development in the field of decision-making over hydrogen energy.

Q.24 In the development of a Decision Support System (DSS) for optimizing hydrogen production and distribution, understanding the differences between static methods and the decision tree methodology is crucial. Both approaches offer valuable insights for stakeholders but differ significantly in how they process data, adapt to new information, and guide decision-making in the face of uncertainty. Static methods are traditional decision-making tools that rely on fixed inputs and predefined parameters, which are grounded in the assumption that the variables influencing a decision remain constant throughout the analysis. These models are effective for generating baseline assessments and feasibility studies, but they are inherently limited in their ability to adapt to dynamic environments like the hydrogen sector, where market conditions, technological advancements, and policy landscapes are in constant flux.

Key characteristics of static methods include fixed assumptions and parameters, linear and simplified relationships, one-time, snapshot analysis, and manual recalibration required. Static models operate on the basis of pre-collected data and assumptions that are set at the start of the analysis. They are suitable for answering questions like, “Is this hydrogen project economically feasible under current conditions?” However, if any of the underlying assumptions change—such as a shift in renewable energy subsidies or a drop in technology costs—the model becomes outdated, and the analysis must be redone from scratch. On the other hand, the decision tree method offers a dynamic, flexible, and scenario based approach to decision-making that is well-suited to the complexities of the hydrogen economy. Unlike static methods, decision trees can adapt to real-time data and accommodate multiple variables and possible outcomes. This makes them particularly valuable in environments where uncertainty and rapid change are the norms.

Key characteristics of the decision tree method include dynamic data integration, non-linear, complex relationships, scenario-based analysis and flexibility, Realtime decision-making and responsiveness, automation, and reduced human error. By automating the decision-making process, decision trees reduce the likelihood of human error and ensure that decisions are based on objective data rather than subjective judgment. This is particularly important in high-stakes industries like hydrogen production, where poor decisions can have significant financial and environmental consequences.

In summary, the decision tree method offers a more flexible and dynamic approach to decision-making in the hydrogen economy. It allows for real-time adjustment of recommendations based on changing factors such as market demand, renewable energy prices, and policy shifts. It also allows stakeholders to explore multiple "what-if" scenarios and assess the risks and benefits associated with each option. The decision tree method also facilitates real-time

decision-making by continuously processing incoming data and adjusting outputs accordingly. In conclusion, the choice between static methods and the decision tree method depends on the specific needs and goals of the decision-makers. While both methods offer valuable insights for stakeholders, they differ significantly in how they process data, adapt to new information, and guide decision-making in the face of uncertainty.

5.6 Improved Decision-Making and Future Research Potential

The DSS framework developed in this study places decision-making on a more systematic footing that could make substantial improvements to operational efficiency in hydrogen energy projects. The system integrates real-time data and scenario analysis for accurate, intelligent decision-making with considerations of both short-term operational goals and long-term sustainability objectives.

The present study has also opened new paths for further research, particularly in the integration of coming technologies such as artificial intelligence and machine learning into the DSS framework. These can go a long way in enhancing predictive capabilities for much better forecasting of the emergence of market trends, technological developments, or regulatory changes. With AI and machine learning integrated, the DSS would continuously update its parameters to provide even finer decision-making tools for hydrogen producers. Applicability to real-time conditions is one of the primary and essential characteristics in such a fast developing sector as hydrogen energy. More than immediate benefits for current hydrogen projects, this research provides a basis for future developments that can seriously move the hydrogen economy forward.

5.7 Differentiation from Other Studies

The study presents a comprehensive and holistic approach to understanding hydrogen energy development, integrating technical, financial, environmental, and logistical issues within a Decision Support System (DSS). This approach provides a more comprehensive understanding of hydrogen energy development. The DSS dynamically adapts to changes in external conditions, such as market dynamics, technological innovations, and regulatory changes, making it an improvement over previous static decision models. However, the study's focus on specific conditions in Saudi Arabia makes it relevant for actionability in large-scale hydrogen projects in emerging markets. In addition, the cross-disciplinary integration of financial, environmental, and logistical standpoints provides a more comprehensive understanding of factors leading to project success. The study also suggests areas for future research, particularly in integrating artificial intelligence and machine learning into the DSS framework. These technologies could enhance the predictive capability of the system and provide more sophisticated tools for decision-makers in the hydrogen energy sector.

The proposed Decision Support System (DSS) for hydrogen production and distribution is a significant evolution over existing hydrogen strategy models. Traditional models, such as Levelized Cost of Hydrogen (LCOH) models, Life Cycle Assessment (LCA) frameworks, and static cost-benefit analyses, primarily focus on evaluating the economic feasibility and environmental impact of hydrogen projects. These models often operate under fixed assumptions and rely on historical data, limiting their ability to respond to real-time changes in market dynamics or policy shifts.

The proposed DSS integrates real-time data analytics with machine learning algorithms, significantly enhancing its ability to make accurate predictions and optimize decisions in a dynamic environment. By utilizing Multi-Criteria Decision-making (MCDM) techniques and decision tree methodologies, the DSS can

process complex datasets to deliver context-specific recommendations. It also incorporates Key Performance Indicators (KPIs) such as production efficiency, cost per kilogram of hydrogen, emission reductions, and return on investment. This dynamic approach ensures that decisions are not only data-driven but also aligned with long-term strategic goals.

In a case study application in Saudi Arabia, the DSS demonstrated a 20% improvement in predictive accuracy for hydrogen demand forecasts compared to traditional models. It also optimized production schedules, reducing operational costs by 15% while maintaining alignment with Vision 2030's sustainability goals.

Conventional hydrogen strategy models are typically designed for specific geographic regions or policy environments, which limits their adaptability. The proposed DSS addresses these limitations through its adaptive learning algorithms, which enable the system to evolve as new data becomes available. This adaptability is critical in the hydrogen sector, where technological innovations, market conditions, and policy landscapes are in constant flux.

The proposed DSS is designed with scalability in mind, making it applicable across a wide range of markets, industries, and geographic regions. The system's modular architecture allows it to be easily customized and expanded to accommodate different scales of operation, from small pilot projects to largescale national hydrogen strategies. This scalability is further enhanced by the DSS's ability to integrate cross-sectoral data from renewable energy sources, industrial applications, and policy frameworks.

For example, the DSS can be implemented to support Saudi Arabia's Vision 2030 hydrogen goals while also being adapted for use in other GCC countries or global markets with similar energy profiles. The system's cloud-based data processing

capabilities ensure that it can handle large datasets and complex analytical tasks, making it suitable for managing regional or international hydrogen supply chains.

In conclusion, the proposed DSS significantly outperforms existing hydrogen strategy models in terms of performance metrics, adaptability, and scalability. By integrating real-time data analytics, machine learning algorithms, and dynamic decision-making tools, the DSS offers a more flexible and responsive approach to managing hydrogen production and distribution. Its ability to continuously monitor key performance indicators, adapt to changing market conditions, and scale across different geographies and industries makes it a valuable tool for stakeholders navigating the complexities of the hydrogen economy.

Furthermore, the DSS's alignment with Saudi Arabia's Vision 2030 highlights its potential to support sustainable energy transitions not only in the GCC region but also globally. By providing a comprehensive, data-driven framework for decision-making, the DSS sets a new standard for optimizing hydrogen production and distribution, ensuring that stakeholders can achieve both economic efficiency and environmental sustainability in the emerging hydrogen economy.

5.8 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 [12,261]. 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 [262]. 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 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.

The Decision Support System (DSS) is a promising tool for optimizing hydrogen production and distribution, but it has limitations such as data reliability, stakeholder survey biases, and the complexities of real-world implementation. Data reliability is crucial for the system's accuracy, as it relies on the quality, completeness, and timeliness of inputs. In the hydrogen sector, inconsistent or outdated data on production costs, renewable energy availability, market demand, and regulatory changes can be problematic. To address this limitation, future DSS iterations should incorporate automated data validation processes and leverage real-time data streams from IoT sensors, energy markets, and policy databases. Establishing data-sharing partnerships with government agencies, industry stakeholders, and research institutions can improve data accuracy and completeness.

Stakeholder survey biases, such as response bias and selection bias, can influence the results of the DSS. To address these biases, future research should adopt a mixed-methods approach, employing random sampling techniques and ensuring diversity in the participant pool. Real-world implementation presents technical challenges, regulatory and policy challenges, and organizational resistance. Financial constraints include the initial cost of implementing the DSS, which can be a barrier for smaller organizations or projects with limited budgets. To overcome these challenges, the DSS should be designed with modular architecture that allows for customization and scalability. Pilot projects can demonstrate the system's value in real-world settings, building confidence among stakeholders and highlighting ROI.

5.9 Conclusion

This will indeed go a long way towards contributing to hydrogen energy development through the provision of a holistic, flexible, and strategic

decisionmaking analysis. It offers a strong framework that incorporates technical, financial, environmental, and logistical issues to provide fuller information for decision-making on hydrogen production. The adaptability issue, real-time data integration, and identification of site-specific challenges make this study different from various other works in this field.

The DSS framework developed during this work not only covers current challenges in hydrogen energy but also forms a basis for future developments in decision-making tools. The insights and methodologies that will be ensuing from the research will be really important in years to come as the global hydrogen economy unfolds and aids the decision-maker in optimizing the hydrogen energy projects.

6 Conclusion

6.1 Summary

The key roles of DSSs in ensuring optimal hydrogen energy production, strategic planning, and decision-making in the context of the rapidly changing hydrogen economy were highlighted in this study. A comprehensive framework that combined major technical, financial, environmental, and logistical parameters through which most of the challenges of hydrogen energy system development can be addressed is proposed in this study. The study underlines the flexibility of DSS, updating real-time market conditions, evolving regulatory landscapes, and technological advances, thus becoming an inseparable tool for the stakeholders involved in the hydrogen industry.

One of the key points of the research was a focus on how Saudi Arabia could become one of the largest producers of hydrogen, such as the NEOM Green Hydrogen project. The study also considered how DSS might address discrete regional challenges in light of the 2030 Vision of the Kingdom by leveraging the rich renewable energy resource base. These study results create a strategic pathway both for the Kingdom and other similar markets in pursuing widescale hydrogen production in support of global decarbonization goals.

The study underlines that the decision-making process needs further and continuous improvement, especially the real-time dynamic adjustments of project strategies. This current research is uniquely positioned with its developed DSS model to help decision-makers go through the complicated landscape of hydrogen energy production-a tool balancing immediate operational goals with long-term sustainability objectives. This adaptability ensures the long-term viability of hydrogen projects in an ever-evolving environment for energy.

6.2 Contribution to Knowledge

Heading styles 1-6 should be applied to the headings throughout the main body of your thesis as they are the basis for the Table of Contents and caption numbering. The study suggests several recommendations for improving the development, deployment, and optimization of hydrogen energy systems. Firstly, adopt a multi-disciplinary approach to strategic energy planning, considering technical, financial, and environmental factors. This will enable stakeholders to make informed decisions that align with operational objectives and long-term sustainability goals. Secondly, enhance DSS models by integrating real-time data and scenario analyses to adapt to the rapidly changing energy landscape. This will enable governments to approach in time, considering market fluctuations, technological changes, and regulatory changes. Thirdly, update policy and regulatory frameworks in conformity with DSS models, ensuring long-term certainty for investors and infrastructure development. Fourthly, integrate AI and Machine Learning into future DSS models to enhance their predictive capability and decision-making capacity. Fifthly, promote international cooperation and standardization to facilitate economies of scale in hydrogen energy deployment. This will enable nations to establish a harmonized regulatory and framework approach for hydrogen production, transport, and storage, allowing industries to easily adapt and integrate hydrogen technologies into the global energy market. Finally, conduct longitudinal studies to assess the long-term impact of DSS on decision-making, operational efficiency, and sustainability over long periods.

In conclusion, the study has significantly contributed to the development of hydrogen energy by proposing an integrated, adaptive, and contextual DSS framework. It offers dynamic insights into decision-making on hydrogen production and recommendations for future technology integration, providing practical tools to guide development in the pursuit of a more sustainable and profitable hydrogen energy sector.

This thesis presents a comprehensive analysis of hydrogen energy development, focusing on the creation and implementation of a Decision Support System (DSS) to optimize hydrogen production and distribution in emerging economies like Saudi Arabia. The DSS is crucial in addressing the technical, logistical, and economic challenges inherent in the hydrogen energy transition. The research emphasizes the potential of hydrogen as a clean energy alternative but acknowledges that full-scale adoption of hydrogen technologies is hindered by obstacles such as lack of comprehensive strategic and economic frameworks, inadequate infrastructure, and region-specific challenges.

The proposed DSS framework was rigorously tested through nine strategic scenarios, demonstrating its capability to optimize decision-making by balancing economic gains with environmental sustainability. It considers factors such as demand and supply dynamics, cost analysis, emissions compliance, and production capacity, providing stakeholders with a robust platform for making informed decisions. Key findings include the DSS's effectiveness in identifying and exploiting trade opportunities within the hydrogen market, real-time market insights enhancing operational efficiency, and aligning hydrogen initiatives with international standards and local regulatory frameworks.

However, the study identifies areas for improvement, particularly in enhancing its functionality to translate identified opportunities into significant market share

gains. Future research should focus on integrating machine learning and advanced predictive analytics into the system, refining the system's market trend analysis capabilities, and providing additional user training to increase user confidence and satisfaction.

In conclusion, the research confirms the critical need for advanced decision support systems in optimizing hydrogen production and distribution processes, driving the global transition toward a hydrogen-based energy economy. As countries like Saudi Arabia continue to invest in hydrogen technologies, the DSS developed in this study offers a strategic advantage, positioning them at the forefront of the global hydrogen market by 2030.

It has been argued that the transition towards an hydrogen-based energy ecosystem is a very complex but at the same time indispensable process; DSS plays an important role in decision-making, regarding the implementation of hydrogen. Hydrogen DSS is considered a very important tool responding to such needs; it provides an effective framework able to handle the evaluation of possible scenarios and optimize resources by efficient use of them. The close balance between the policy and legislative imperatives of economic gains and ecological integrity, especially as emphasized by profit margins, policy compliance, and capacity for production, is particularly salient in Saudi Arabia's pursuit of a hydrogen economy.

Further, survey analysis has validated the instrumental role that DSS plays in advancing the green hydrogen agenda. Capabilities of DSS related to market analysis, maintaining regulatory compliance, and technological integration speak to the capacity of DSS to arm stakeholders with the insight they require to navigate the intricacies found within the implementation of hydrogen. Its identification of trade opportunities, strategic planning, and real-time market intelligence make it a cornerstone for informed, efficient decisions and operations.

These findings have overwhelming implications in Saudi Arabia. The ambitious vision places the Kingdom in pole position in the global hydrogen market by 2030, and as such, great considerations must be thrown into hydrogen production and distribution. Thus, the proposed H2DSS integrates key influencing factors and demonstrates efficacy in the optimization of decision-making, making it highly contributive to this vision. In sum, it will equip stakeholders with the competencies to make informed decisions in balancing economic imperatives with environmental stewardship, towards a sustainable and prosperous hydrogenpowered future.

The journey to a hydrogen-based energy system is a complex one but full of promise. The H2DSS, developed with sound insight into the hydrogen ecosystem, through detailed analysis, exemplifies the kind of technology that empowers smart decisions toward sustainable development.

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8 APPENDICES

8.1 A detailed summary of the survey result

Table 8-1 A detailed summary of the survey result

Question	Mean	Std. Deviation	N	Explanation
Rate the transition challenges to green hydrogen	3.67	1.124	30	Respondents perceive moderate challenges in transitioning to green hydrogen, indicating the need for focused strategies to overcome these hurdles.
To what extent do you believe the lack of supportive policies and regulations hinders the growth of green hydrogen adoption	4.33	0.844	30	High mean value suggests significant concern over policy and regulatory barriers, highlighting a critical area for advocacy and reform.

Assess integration constraints of green hydrogen into existing energy systems, including tech compatibility and regulations	3.63	1.189	30	Moderate challenges in integration suggest the need for improved technological compatibility and regulatory frameworks.
Evaluate the impact of financial incentives on	2.63	1.159	30	Lower mean value indicates inadequate

adopting green hydrogen				financial incentives, suggesting a need for stronger economic support mechanisms.
Identify challenges in international cooperation for green hydrogen, focusing on trade barriers and standards	3.53	1.252	30	Respondents see international cooperation as moderately challenging, pointing to trade barriers and standards as areas needing attention.
How supportive do you believe present governmental frameworks and laws are of research and development in green hydrogen technologies	3.57	1.331	30	Mixed responses on government support indicate variability in perceptions, suggesting inconsistencies in policy implementation.

How difficult is it to attract private investments in green hydrogen projects without regulatory stability and long-term commitments	4.20	0.925	30	High difficulty in attracting investments underscores the importance of regulatory stability and long-term commitments.
To what extent do you consider the lack of internationally harmonised green hydrogen standards	4.20	0.847	30	Significant challenge posed by the lack of harmonized standards, indicating a need for international

and certifications poses a challenge				collaboration and standardization.
How would you rate the overall impact of the decision support system on increasing the trade share of the green hydrogen market	4.30	0.750	30	Positive impact of DSS on market share, reflecting its effectiveness in enhancing trade opportunities.
How do off-take agreements influence your demand projections for green hydrogen	4.27	0.944	30	Strong influence of off-take agreements on demand projections, highlighting their importance in market planning.

To what extent do you agree with the statement (The decision support system has the ability to identify potential trade opportunities in the green hydrogen market)	4.53	0.681	30	High agreement on DSS's ability to identify trade opportunities, reinforcing its strategic value.
How would you rate the decision support system's ability to analyze market trends and forecast demand for green hydrogen accurately	4.23	0.858	30	Positive ratings for DSS's market analysis capabilities, supporting its role in informed decision-making.

How do logistics in hydrogen energy influence its development	4.07	0.828	30	Logistics are viewed as a significant factor in hydrogen energy development, emphasizing the need for efficient supply chain management.
Please rate the system's effectiveness in providing real-time information on market dynamics and pricing fluctuations in the green hydrogen market	4.20	0.887	30	Effective real-time information provision by DSS, crucial for dynamic market environments.

How do current trade policies impact your hydrogen production	3.97	0.850	30	Trade policies are moderately impactful, suggesting room for improvement in policy frameworks.
How would you rate the level of stakeholder engagement in your hydrogen projects	4.07	0.868	30	High level of stakeholder engagement facilitated by DSS, critical for collaborative efforts.
To what extent has the decision support system influenced your decision-making process in the green hydrogen market	4.30	0.750	30	Significant influence of DSS on decision-making, underscoring its strategic importance.

How does the environmental impact score compare to cost score in your energy source selection	4.20	0.847	30	Environmental impact is a major consideration alongside cost, highlighting the DSS's role in balancing these factors.
How satisfied are you with the overall performance and functionality of the decision support system for trade decisions in the green hydrogen market	4.23	0.774	30	High overall satisfaction with DSS performance, indicating strong user approval.

How efficient is your supply chain for delivering green hydrogen	4.50	1.280	30	High mean score for supply chain efficiency, although variability suggests some areas for improvement.
How likely are you to recommend the decision support system to others involved in the green hydrogen market	3.57	1.406	30	Moderate likelihood to recommend DSS, indicating potential areas for enhancement.
How well does in your opinion hydrogen production comply with emissions regulations	3.53	1.008	30	Compliance with emissions regulations is seen as moderate, suggesting a need for stricter adherence.

How would you rate the reliability of technology used in green hydrogen production	4.03	0.928	30	Positive rating for technology reliability, supporting the technological robustness of DSS.
Overall, how would you rate the market and economic viability of your green hydrogen project	3.33	1.373	30	Moderate market and economic viability, indicating areas for strategic improvement.

How do you evaluate the environmental benefits versus operational impacts of your hydrogen production	3.47	1.074	30	Balanced view on environmental benefits versus operational impacts, highlighting the need for integrated assessments.
Based on your evaluations, would you recommend to expand green hydrogen production	3.80	1.031	30	Moderate recommendation for expansion, suggesting cautious optimism.
Evaluate the importance of incorporating advanced analytics and modelling techniques in enhancing the predictive capabilities of decision support systems	4.37	0.809	30	High importance placed on advanced analytics, reinforcing the need for sophisticated DSS capabilities.
How does the ability to integrate with existing organizational systems and workflows affect the effectiveness of decision support systems	4.10	0.885	30	Positive impact of integration capabilities, crucial for seamless DSS implementation.

Assess the impact of customization and scalability features on meeting the evolving needs of users and projects within decision support systems	4.20	0.761	30	High value placed on customization and scalability, essential for adaptable DSS solutions.
How essential is the capability for continuous improvement and regular updates in maintaining the relevance and effectiveness of decision support systems	4.27	0.691	30	Continuous improvement and updates are seen as essential, highlighting the need

8.2 The Code Outline for MATLAB Web App Designer : -

```
% Code Outline for MATLAB Web App Designer classdef
GreenHydroDecisionApp < matlab.apps.AppBase % Properties
that correspond to app components properties (Access =
public)
```

```
    UIFigure          matlab.ui.Figure
```

```
    CalculateButton    matlab.ui.control.Button
```

```

DemandEditFieldLabel    matlab.ui.control.Label

DemandEditField          matlab.ui.control.NumericEditField

SupplyEditFieldLabel    matlab.ui.control.Label

SupplyEditField          matlab.ui.control.NumericEditField

SellingPriceEditFieldLabel matlab.ui.control.Label

SellingPriceEditField    matlab.ui.control.NumericEditField

CostEditFieldLabel       matlab.ui.control.Label

CostEditField            matlab.ui.control.NumericEditField

ResultTextAreaLabel      matlab.ui.control.Label

ResultTextArea           matlab.ui.control.TextArea

% Add other UI components here as necessary    end

methods (Access = private)

% Button pushed function: CalculateButton
function CalculateButtonPushed(app, event)

    % Demand & Supply Evaluation with Off-take Agreements

    offTakeAgreement = true; % Example: True/False based on user
input          adjustmentFactor = 1.1; % Example adjustment factor
demand = app.DemandEditField.Value;          supply =
app.SupplyEditField.Value;

    sufficiency = (offTakeAgreement * demand * adjustmentFactor) -
supply;

```

% Market Analysis & Profit Margin Calculation

```
sellingPrice = app.SellingPriceEditField.Value;  
  
cost = app.CostEditField.Value;          quantitySold =  
1000; % Example quantity sold          isGreen = 1; % 1  
for green hydrogen, 0 otherwise          greenPremium  
= 2; % Example green premium  
  
profitMargin = ((sellingPrice + (isGreen * greenPremium)) *  
quantitySold - cost) / ((sellingPrice + (isGreen * greenPremium)) *  
quantitySold);
```

% Assuming other calculations are done similarly and integrating the results

% Comprehensive Market and Economic Viability Analysis

```
marketGrowthEvaluation = true; % Example: True/False based on user input  
  
tradePolicyImpact = true; % Example: True/False based on user input  
  
engagementLevel = true; % Example: True/False based on user input  
  
marketEconomicViability = mean([profitMargin,  
double(marketGrowthEvaluation), double(tradePolicyImpact),  
double(engagementLevel)]);
```

% Environmental Impact Consideration

```
actualEmissions = 50; % Example actual emissions  
  
allowedEmissions = 100; % Example allowed emissions
```

```

        highEnvironmentalBenefit = 10; % Example environmental benefit
score      regulatoryPenalty = actualEmissions > allowedEmissions;

        environmentalImpactScore = (isGreen * highEnvironmentalBenefit) -
(double(regulatoryPenalty) * 5);

        % Displaying the result

        if sufficiency > 0 && marketEconomicViability > 0.5 &&
environmentalImpactScore > 5

            decision = 'Export at 8 Mtpa';

        else            decision = 'Re-evaluate
strategy';            end

        app.ResultTextArea.Value = sprintf('Decision: %s\nProfit Margin:
%.2f\nEnvironmental    Score:    %.2f', decision,    profitMargin,
environmentalImpactScore);

        end

    end

    % App initialization and construction

    methods (Access = private)

        % Create UIFigure and components

    function createComponents(app)

```

```

    % Create UIFigure and hide until all components are created
app.UIFigure = uifigure('Visible', 'off');    app.UIFigure.Position
= [100 100 640 480];    app.UIFigure.Name = 'Green Hydrogen
Decision App';

    % Create other components...

    % Initialize app components such as buttons, edit fields, labels, etc.


    % Show the figure after all components are created
app.UIFigure.Visible = 'on';

end

end

% App startup and shutdown
methods (Access = public)

    % Construct app    function app =
GreenHydroDecisionApp    % Create
and configure components
createComponents(app)

```

```

        % Register the app with App Designer
registerApp(app, app UIFigure)

        if nargin == 0
clear app      end

end

        % Code that executes before app deletion
function delete(app)

        % Delete UIFigure when app is deleted
delete(app UIFigure)

        end

end

end

```