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A hydrogen-driven sustainable technology mapping for future energy hubs

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Summary:

This thesis explores hydrogen-driven sustainable technologies for future energy hubs, addressing the urgent need for cleaner energy solutions amidst growing environmental concerns and the decline of fossil fuel resources. The primary objectives are to map technologies related to hydrogen energy, analyse their macro-environmental impacts, and examine the interactions within the hydrogen sector to identify gaps and develop viable business models.

Utilising a hybrid research design, the study employs qualitative analyses including PESTEL and SWOT, complemented by interrelationship and gap analyses. Methods such as comparative analysis and business modelling are also integral to understanding the economic viability and strategic integration of hydrogen technologies within global energy frameworks.

The findings reveal that hydrogen stands as a flexible and sustainable energy source, capable of significantly influencing future energy paradigms. The research highlights the potential for collaborative innovation across various sectors, advocating for strategic stakeholder engagement to harness full capabilities of hydrogen. It concludes that substantial opportunities exist for enhancing energy security and environmental sustainability through hydrogen technology, with future research needed to further explore economic models and refine deployment strategies within energy hubs.

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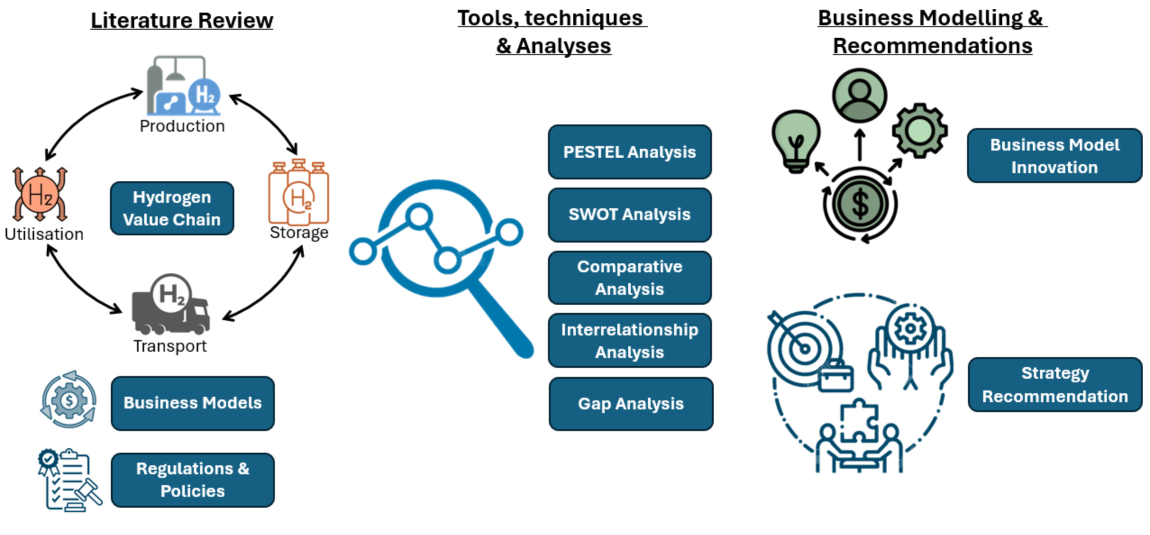
Graphical abstract:



Preface

This thesis report was prepared in the spring of 2024 as a partial fulfilment of the requirements for the master's degree in Process Technology at the University of South-Eastern Norway (USN). I am immensely grateful to my supervisor, Assoc. Prof. Amir Safari, for his invaluable guidance and persistent support throughout this research journey. His expertise and encouragement have been crucial in navigating the challenges of this academic endeavour.

Porsgrunn, 12.05.2024

Saiyam Marahatta

Contents

Nomenclature

List of Symbols	Abbreviations and Units
°C	Degree Celsius
AEM	Anion Exchange Membrane
AWE	Alkaline Water Electrolysis
CATWOE	Customers, Actors, Transformation, Worldview, Owner, and Environmental constrains
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
EU	European Union
EVs	Electric Vehicles
GHG	Greenhouse Gas
GWh	Giga Watt hours
HaaS	Hydrogen-as-a-Service
HER	Hydrogen Evolution Reaction
K	Kelvin
kWh/kg	Kilowatt-hour per kilogram
LOHCs	Liquid Organic Hydrogen Carriers
MMT	Million Metric Tonne
MOFs	Metal Organic Frameworks
MTH	Methanol to Hydrocarbon synthesis
OER	Oxygen Evolution Reaction
PEC	Photoelectrochemical
PEM	Proton Exchange Membrane/Polymer Electrolyte Membrane
PEMFCs	Proton Exchange Membrane Fuel Cells
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal
POM	Partial Oxidation of Methane
QSPM	Quantitative Strategic Planning Matrix
R&D	Research and Development
SIHS	Sustainable Integrated Hydrogen Solutions
SNO	Sulphur, Nitrogen and Oxygen compounds
SOE	Solid Oxide Electrolysis
SOFCs	Solid Oxide Fuel Cells
SRM	Steam Reforming of Methane
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TR	Thermal Reduction
TWS	Thermochemical Water Splitting
UK	United Kingdom
US	United States

WGS	Water Gas Shift
WO	Water Oxidation

1 Introduction

1.1 Background

In recent years, the global landscape of energy production and consumption has witnessed a paradigm shift driven by increasing environmental concerns, the looming scarcity of fossil fuel resources, and unprecedented demand growth. This confluence of challenges has necessitated a profound re-evaluation of existing energy systems, prompting the exploration and implementation of sustainable technologies as a cornerstone for the future of the energy industry.

The critical interplay between environmental sustainability, resource scarcity, and the imperative to curb emissions has propelled a transformative wave across the energy sector. Fossil fuel-dependent models are being reconsidered in favour of innovative and eco-friendly alternatives. Considering the pressing need to combat climate change and overcome the shortcomings of conventional energy sources, there is an increasingly evident call for a comprehensive and sustainable energy framework within the global community.

Sustainable technologies play a pivotal role to provide a strategic route towards robust and environmentally conscious energy solutions. These technologies cover a spectrum of innovations, including renewable energy sources, energy storage devices, and energy-efficient practices. The primary goal is to fulfil current energy demands while simultaneously preserving the delicate natural equilibrium and securing the wellbeing of future generations.

In the context of these significant transformative changes, the idea of energy hubs has surfaced as a promising solution for establishing efficient management systems in sustainable technology. Energy hubs represent a strategic approach to integrated energy systems, bringing together diverse components such as renewable energy generation, storage, and distribution networks. Through the coordinated synergy of these components, energy hubs aim to improve the efficiency, reliability, and sustainability of energy supply chains.

This study investigates the evolving terrain of sustainable technology powered by hydrogen, specifically focusing on mapping the technology for future energy hubs. The research explores how hydrogen holds the immense potential to transform energy generation, storage, distribution, and utilisation. Recognising hydrogen as a catalyst for change in the traditional energy sector, the study emphasises on its role in guiding us toward a future where environmental stewardship and energy security seamlessly converge.

1.2 Objectives

1.2.1 General objectives

1. To understand and categorise the technologies linked to hydrogen for sustainable energy, i.e. "**Mapping technologies**".
2. To assess how these technologies affect the macro-environment, i.e. "**PESTEL analysis**".

3. To explore how different components within hydrogen domain interact, i.e. "**Interrelationship analysis**".

1.2.2 Specific objectives

1. To find gaps in current hydrogen – driven technologies and suggest practical solutions, i.e. "**Gap identification**".
2. To develop model/strategies to make hydrogen technologies commercially viable and suggest strategies for collaboration, i.e. "**Business modelling**".
3. To offer suggestions for stakeholders based on the research, i.e. "**Strategy recommendations**".

1.3 Scope

This research focuses on hydrogen-driven sustainable technologies for the future energy hubs. The scope of the study includes:

1. **Technological scope:** Comprehensive coverage of hydrogen-related technologies.
2. **Macro-environmental scope:** Evaluation of macro-environmental impact assessments.
3. **Strategic integration scope:** Exploration of integration opportunities for efficient and sustainable energy systems.
4. **Research specific scope:** Analysis of gaps in current technologies, development of business model/strategies for commercial viability, and formulation of policy recommendations.
5. **Temporal and geographic scope:** Emphasis on contemporary global developments in hydrogen technology.
6. **Stakeholder scope:** Intended to benefit policymakers, industry professionals, researchers, and the broader global community.

The study is bound by available resources, timeframe, and the prevailing state of hydrogen technologies, aiming to contribute practical insights within these limitations.

1.4 Limitations of the study

Despite meticulous planning and execution, every research endeavour inevitably encounters constraints that shape its outcomes and interpretations. One significant limitation of this study pertains to the dynamic nature of the hydrogen technology landscape. While considerable effort was devoted to ensuring that the research remained current and comprehensive, it is essential to recognise that new developments, including patents, policies, and technological advancements, emerge continuously in the rapidly evolving hydrogen domain. Despite the best efforts to capture the most up-to-date information, the evolving nature of the field posed a challenge in incorporating every new development into this analysis.

Moreover, the expansive breadth of the hydrogen domain presents another limitation. While various facets of hydrogen production, storage, transportation, and utilisation was diligently explored, it is crucial to acknowledge that the examination may not have covered every nuance or niche within this expansive field. As such, there may be areas that warrant further investigation or analysis beyond the scope of this study.

Additionally, practical constraints related to time and resources have inevitably impacted the depth and breadth of this research. Despite striving to conduct a thorough and rigorous analysis within the available means, the finite nature of these resources influenced the extent to which certain topics could be delved into or additional analyses could be conducted.

However, despite these limitations, it is important to emphasise that this study represents a meaningful contribution to the understanding of hydrogen-driven sustainable technologies and their implications for future energy hubs. By transparently acknowledging these limitations, this research aims to provide a nuanced and contextually informed interpretation of the findings while also identifying avenues for future research and exploration.

1.5 Research structure

This thesis is organised into five chapters. The first chapter serves as the introductory chapter, providing essential background information on the objectives of the study, scope of the study, limitations of the study and the overall research structure.

Chapter second introduces to a comprehensive theoretical review within the hydrogen domain. This chapter serves as a foundational exploration of the key technologies involved in hydrogen production, storage, transportation, and utilisation. It systematically examines existing knowledge and emerging trends within the field, providing insights into the current state of hydrogen technologies, as well as the underlying business models, regulations, and policies influencing their development.

The third chapter focuses on the methodology employed in conducting the research. It delineates the research design, methodology, tools, and techniques utilised to analyse the complex landscape of hydrogen-driven sustainable technologies. This includes a detailed discussion of analytical frameworks such as PESTEL analysis, SWOT analysis, comparative analysis, interrelationship analysis, gap analysis, and business modelling.

Chapter four presents the results and discussions derived from the research. It encompasses the findings of the PESTEL analysis, SWOT analysis, comparative analysis, interrelationship analysis, and gap analysis, shedding light on key challenges, opportunities, and integration possibilities within the domain of hydrogen technologies. Moreover, this chapter introduces business modelling as a means of further understanding and implementing strategies within the hydrogen domain for filling up the identified gaps. Additionally, it offers strategic recommendations tailored to various stakeholders, including policymakers, industry players, researchers, and the global community.

Finally, the fifth chapter encapsulates the conclusion and recommendations drawn from the study. It synthesises the key insights garnered throughout the research process and discusses their implications for future energy hubs.

2 Literature review

This chapter provides a comprehensive exploration of key technologies in the production, storage, transportation, and utilisation of hydrogen, shedding light on the current state and emerging trends within the rapidly evolving landscape of hydrogen technologies. Furthermore, it explores the existing business models, strategies, regulations, and policies surrounding hydrogen, providing a holistic understanding essential for the development of sustainable energy hubs in the future.

2.1 Key technologies in production, storage, transportation, and utilisation of hydrogen

2.1.1 Hydrogen production

Hydrogen production is increasingly recognised as a crucial and promising solution for fulfilling global sustainable energy needs due to its status as a carbon-free and environmentally friendly energy source [1]. Several technologies, utilising both renewable and non-renewable sources, have been discovered over the time. Figure 2.1 shows these different technologies for hydrogen production, encompassing both renewable and non-renewable methods.

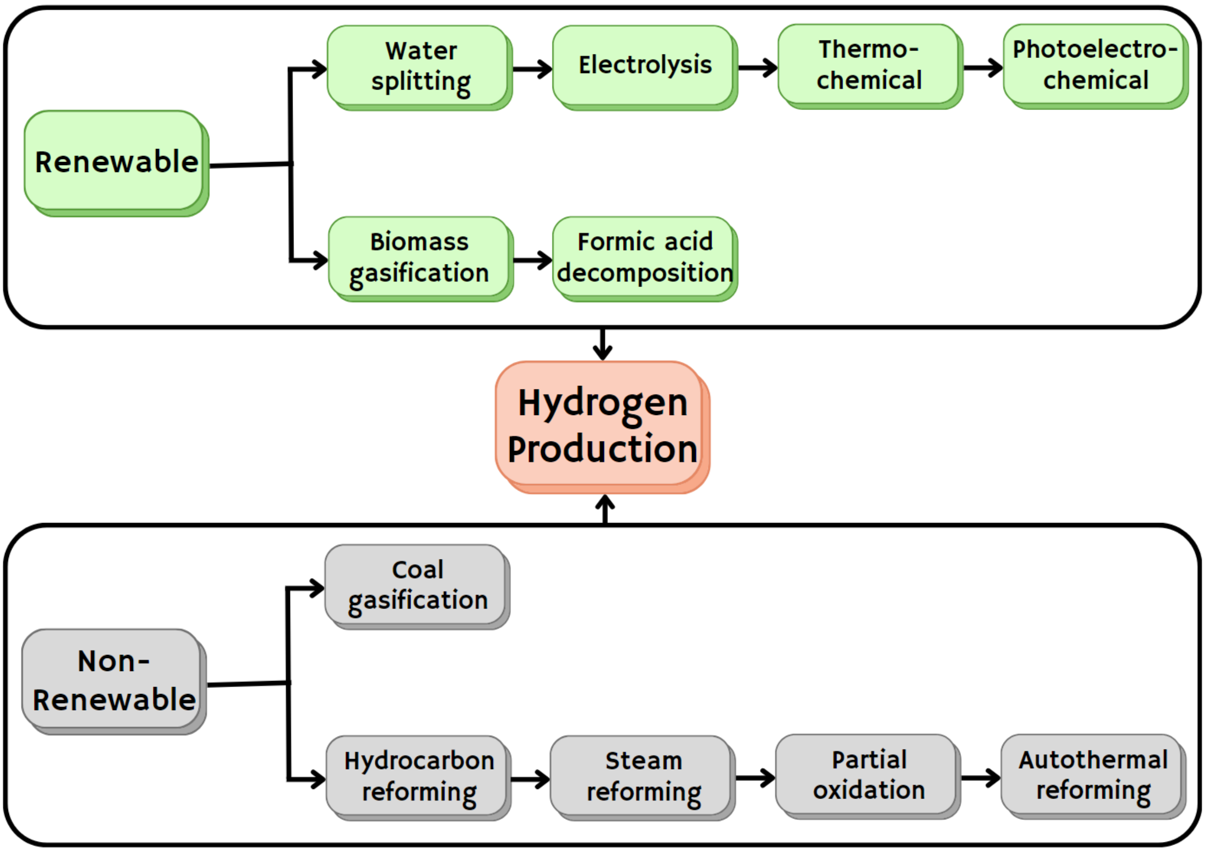


Figure 2.1: Schematics depicting diverse pathways and technologies for hydrogen production.

2.1.1.1 Renewable

2.1.1.1.1 Water splitting

Producing hydrogen utilising water together with various driving forces (electric current, temperature, light, or a combination of these) is regarded as one of the most sustainable technologies [2, 3]. However, the process is energy-intensive, requiring a minimum of 45 kWh/kg of hydrogen [4]. Water splitting methods include electrolytic, thermochemical, photoelectrochemical, or hybrid processes [5, 6].

2.1.1.1.1.1 Electrolytic

This process involves splitting water into hydrogen and oxygen using electricity as represented in reaction (2.1).

$$2H_2O(l) + electricity \rightarrow 2H_2(g) + O_2(g) \tag{2.1}$$

Despite its potential, electrolysis is considered costly due to the use of expensive electricity often derived from non-renewable sources. But it is often referred to as a highly suitable method to produce hydrogen due to its cleanliness, utilising sustainable water and producing oxygen as a by-product [7]. It can be categorised into four forms based on electrolyte and ion-based agents [8]:

(a) Alkaline water electrolysis (AWE)
(b) Solid oxide electrolysis (SOE)
(c) Proton exchange membrane/Polymer electrolyte membrane (PEM) water electrolysis
(d) Anion exchange membrane (AEM) electrolysis

2.1.1.1.1.2 Thermochemical

This process involves two-step thermochemical reactions using metal oxides to thermally dissociate water into hydrogen and oxygen. The standard two-step procedure utilising iron oxide involves the following reaction [9]:

$$Fe_3O_4 \rightarrow 3FeO + 1/2\ O_2 \tag{2.2}$$

$$3FeO + H_2O \rightarrow Fe_3O_4 + H_2 \tag{2.3}$$

Reaction (2.2) is a highly endothermic thermal reduction (TR) step, requiring temperatures above 1600 K [9]. Reaction (2.3) is a slightly exothermic water oxidation (WO) or hydrolysis step, occurring spontaneously at ambient temperatures up to about 1200 K. Thermochemical water splitting (TWS) is suitable for large-scale hydrogen production due to economies of scale [10, 11] . This technology can be driven solely by thermal energy or in hybrid forms using light or electricity [12]. Moreover, this technology is minimally dependent on catalysts, utilising only water for hydrogen production and recycling other substances.

2.1.1.1.1.3 Photoelectrochemical

This process utilises sunlight and specialised semiconductors to dissociate water molecules into hydrogen and oxygen. A typical photoelectrochemical (PEC) cell comprises of an anode and a cathode submerged in an electrolyte, linked to an external circuit, and exposed to sunlight [13]. When a photon with sufficient energy hits a semiconducting material, it excites an electron from the valence band to the conduction band, creating a hole [14]. These energetic holes and electrons (h^+/e^-) participate in oxidation/reduction reactions in the aqueous electrolyte, producing oxygen and hydrogen at the respective sides of the photoanode and counter electrode [14] as represented by reactions (2.4) and (2.5):

$$2H_2O + 2h^+ \rightarrow 1/2\ O_2 + 2H^+ \tag{2.4}$$

$$2H^+ + 2e^- \rightarrow H_2 \tag{2.5}$$

2.1.1.1.2 Biomass gasification

Biomass gasification is a thermochemical process conducted at high temperatures, involving the partial oxidation of biomass [15, 16]. The process transforms biomass into producer gas which can be further cleaned and conditioned to produce hydrogen or syngas in a controlled environment with heat, oxygen, and steam [17-19]. Biomass gasification for hydrogen production has two routes: steam gasification, converting biomass into H_2, CO, CO_2, and CH_4 at high temperatures; and supercritical water gasification, involving hydrothermal gasification of biomass in supercritical water, serving as both a reactant and reaction medium [17, 20]. Catalytic gasification aims to reduce temperature and improve H_2 yield and selectivity of biomass conversion [17].

2.1.1.1.2.1 Formic acid decomposition

Formic acid (HCOOH), a hydrogen carrier, is produced from cellulosic biomass hydrolysis and methyl formate hydrolysis, offering potential for large-scale hydrogen production [21, 22]. Hydrogen yield from formic acid decomposition occurs through dehydration and dehydrogenation pathways [23] which is represented by reactions (2.6) and (2.7):

$$HCOOH \leftrightarrow CO + H_2O \tag{2.6}$$

$$HCOOH \leftrightarrow NCO_2 + H_2 \tag{2.7}$$

Dehydrogenation is more spontaneous, but boosting its selectivity over dehydration is crucial to inhibit poisonous CO formation [24].

2.1.1.2 Non – renewable

2.1.1.2.1 Coal gasification

Coal gasification is a thermal process that transforms natural coal into syngas, primarily composed of H_2 and CO, along with small quantities of CO_2, CH_4, and water vapor, through its reaction with oxygen, air, or steam [25]. The high-temperature process occurs at 800–1300 °C and 30–70 bar pressures, partially oxidising coal into syngas, as shown in Eq. (2.8) [26]:

$$C + H_2O \leftrightarrow CO + H_2 \tag{2.8}$$

The water-gas shift (WGS) reaction further converts the CO to CO_2 and H_2 as:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2.9}$$

Thus, the overall reaction is:

$$C + 2H_2O \leftrightarrow CO_2 + 2H_2 \tag{2.10}$$

Various gasification processes, such as fixed bed, fluidised bed, or entrained flow, can be used for hydrogen production from coal, with entrained flow processes preferred to maximise carbon conversion and minimise char, tars, and phenols [27]. Coal-based hydrogen production is mature but costlier and complex than natural gas methods; nevertheless, due to coal's global abundance, exploring clean technologies for its use remains worthwhile [27].

2.1.1.2.2 Hydrocarbon reforming

Hydrocarbon reforming is a thermal process to produce hydrogen that primarily utilises methane or natural gas, alongside other light hydrocarbons like ethane, ethanol, propane, and butane [28]. Methane is the preferred hydrocarbon due to its high hydrogen content, making up about 25% by weight [17]. Hydrocarbon reforming is an energy-intensive process utilising components like carbon dioxide, steam, and oxygen as oxidising agents, with the following respective processes [17]:

2.1.1.2.2.1 Steam reforming

Steam reforming of methane (SRM) is an endothermic catalytic process that occurs at high temperatures (750–950°C) and pressures (14–20 bar), converting methane and steam into hydrogen-rich syngas [29-31]. The process involves two main steps: initial reformation, where methane reacts with steam to form CO and H_2, and subsequent WGS reaction, converting CO to CO_2 and additional H_2.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{2.11}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2.12}$$

2.1.1.2.2.2 Partial oxidation

Partial oxidation of methane (POM) is an exothermic process that occurs at elevated temperatures (700–900°C) and standard atmospheric pressure, ensuring complete conversion of reactants and yielding optimal products [32].

$$CH_4 + 1/2\ O_2 \leftrightarrow CO + 2H_2 \tag{2.13}$$

The CO thus produced undergoes subsequent conversion to CO_2 and H_2 via WGS reaction.

2.1.1.2.2.3 Autothermal reforming

This process combines steam reforming (Eq. 2.11) and partial oxidation (Eq. 2.13), resulting in an exothermic reaction with an outlet temperature ranging from 950–1100 °C and gas pressures up to 100 bar to produce hydrogen [27]. The produced CO form either of the process (Eq. 2.11 and Eq. 2.13) is converted to CO_2 and additional H_2 via WGS reaction.

2.1.1.3 Blue hydrogen

Renewable hydrogen production methods are often colour-coded "*green*", symbolising their environmentally friendly nature, while non-renewable hydrogen production methods are often colour-coded "*grey*". However, non-renewable hydrogen production methods that employ processes wherein the released CO_2 is captured and stored underground (carbon sequestration) are colour-coded "*blue*". Figure 2.2 illustrates the grey, blue, and green hydrogen production process.

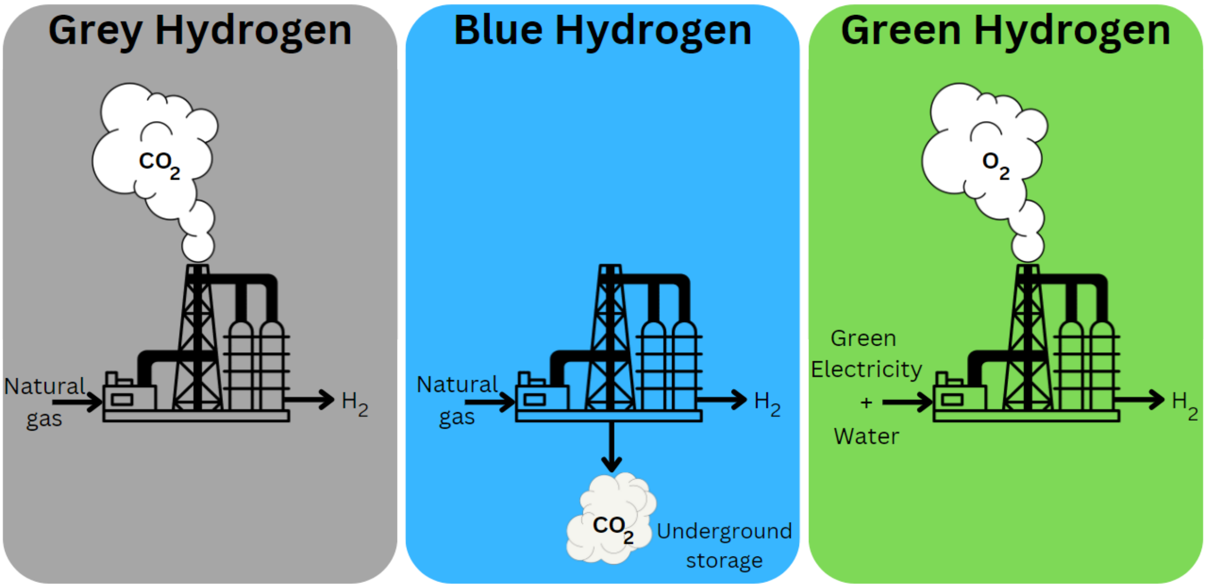


Figure 2.2: Grey vs. blue vs. green hydrogen production process.

Blue hydrogen production can be seen as a crucial stepping stone in the transition to climate neutrality, offering an alternative to using natural gas by integrating carbon capture and storage (CCS) to reduce greenhouse gas (GHG) emissions. Although technical challenges may arise with CCS in future, blue hydrogen is considered less costly than green hydrogen production methods [33]. Leveraging existing infrastructure from grey hydrogen production is a benefit, but safe CO_2 storage is essential [33]. Moreover, there is no standardised definition for blue hydrogen in terms of the required amount of CO_2 to be captured from grey hydrogen production methods, but studies suggest capturing 70-95% of CO_2 [33]. Concerns exist about fugitive methane emissions, but countries with low emissions like Norway, the UK, and the Netherlands can mitigate these issues [33].

Appendix provides the insights to different colour codes of hydrogen based on the production method.

2.1.2 Hydrogen storage and transport

Hydrogen storage and transportation pose significant challenges due to its low volumetric energy density at room temperature, high volatility, compressive nature, and the ability to permeate metal-based materials [17, 30]. Figure 2.3 presents one of the diverse approaches for hydrogen storage and transport, depicting storage options in grey boxes and transport options in yellow boxes.

2.1.2.1 Physical storage and transport

2.1.2.1.1 Gaseous

Hydrogen can be effectively stored and transported in its gaseous state through compression. Gaseous hydrogen storage and transport employ high-pressure vessels, including metallic or composite types, with characteristics like high tensile strength and low density [34]. The transportation of gaseous hydrogen is typically achieved using high-pressure gas cylinders, tube trailers on lorries or by exploring the possibility of repurposing existing natural gas pipelines [30, 35].

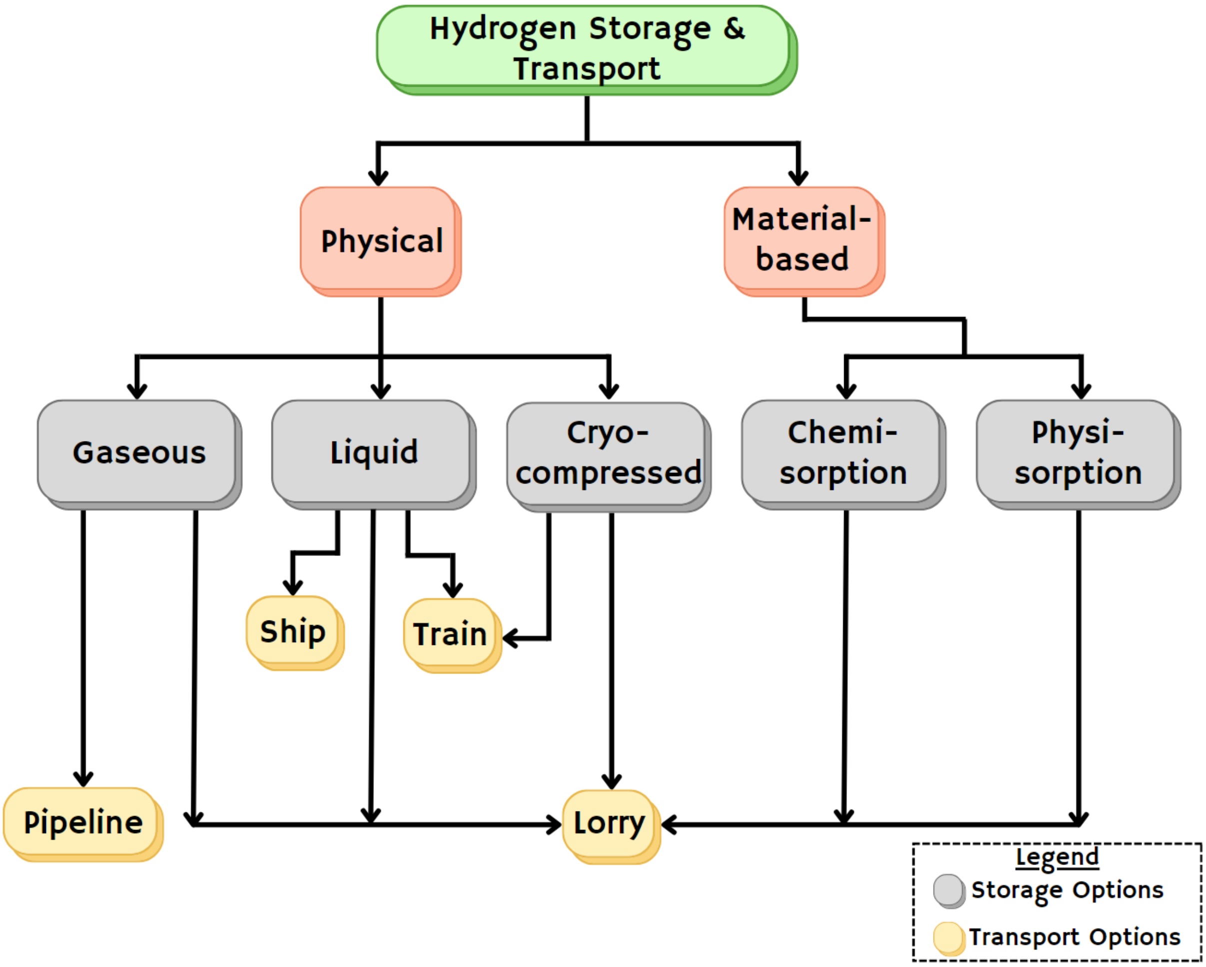


Figure 2.3: Schematics depicting diverse hydrogen storage (grey) and transport (yellow) options.

2.1.2.1.2 Liquid

Hydrogen can be stored and transported in its liquid state by liquefaction at – 253°C, offering high density and storage efficiency [30, 36]. Although energy-intensive and time-consuming, with approximately 40% energy loss compared to 10% for compressed hydrogen, it is suitable for medium to large-scale storage and transport, including road, rail, and intercontinental shipping, albeit still in developmental stages [30, 37]. Efficient insulation and protective measures are crucial due to the extremely low temperatures involved [30].

2.1.2.1.3 Cryo-compressed

Hydrogen can be stored and transported in the form of supercritical cryogenic gas, which combines features of compressed gaseous and cryogenic systems [38]. This storage process involves compressing hydrogen to 300 bars at – 233°C without liquefaction, minimising boil-off and offering potential advantages like high storage density, quick refuelling, and safety with a vacuum enclosure [30, 39]. However, challenges include limited research, infrastructure availability and cost, and lower energy density by volume, leading to larger pressure vessels

[35]. Transportation of cryo-compressed hydrogen could be possibly achieved through trains and lorries [30].

2.1.2.2 Material-based storage and transport

2.1.2.2.1 Chemisorption

Chemisorption storage of hydrogen involves integrating hydrogen atoms into the chemical structure of materials like metal hydrides or liquid organic hydrogen carriers (LOHCs) such as N-ethyl carbazole, methanol, dibenzyltoluene, or toluene [30, 40, 41]. Metal hydrides, like $LiAlH_4$, can absorb and release hydrogen at room temperature or through heating [30, 40]. Challenges include cost, weight, and operating temperature control, as well as managing charge-discharge rates and controlling unwanted gas formation during desorption [30]. LOHCs offer easy manageability under ambient conditions, emit no CO_2 during storage/release, and allow for reusable carrier liquids, but have limited storage capacity [30]. Moreover, ammonia produced via the Haber-Bosch method, can also serve as a hydrogen storage medium by bonding itself with a lean hydrogen molecule and releasing the hydrogen through dehydrogenation [30]. Hydrogen stored through general chemisorption is typically transported by lorries, while ammonia-based chemisorption even permits transportation via pipelines, both offering potential safety benefits [30].

2.1.2.2.2 Physisorption

Physisorption storage of hydrogen utilises porous materials like metal-organic frameworks (MOFs) or carbon nanotubes to physically adsorb hydrogen molecules [42, 43]. While offering high surface area, low hydrogen binding energy, quick charge-discharge kinetics, and low material cost, physisorption methods require low temperatures and high pressures, limiting their suitability for high-demand scenarios [44]. Hydrogen stored via physisorption is usually transported by lorries offering potential safety benefits [30].

2.1.3 Hydrogen utilisation

Hydrogen, the most prevalent element in the universe, despite being predominantly found in combined forms on Earth, offers a plethora of potential uses [17, 45]. These uses can be broadly categorised into material applications and energy applications [45]. Material applications involve refining substances with hydrogen, often requiring special processes with pressure, temperature, and catalysts [45]. Energy applications utilise hydrogen’s energy to generate electricity, heat, and mechanical energy through different pathways depending on the technology employed [45]. Figure 2.4 outlines this diverse utilisation pathways of hydrogen.

2.1.3.1 Material applications

2.1.3.1.1 Refining and upgrading hydrocarbon fuel

Hydrogen plays a crucial role in hydrocarbon fuel refining and upgrading processes to address challenges associated with heteroatoms and metals in crude oil, such as SNO (i.e. sulphur, nitrogen, oxygen), nickel, vanadium, chromium, and others [46, 47]. These elements pose challenges such as corrosion, catalyst deactivation, and environmental pollution [48-50]. Hydrogen is added for chemical de-metallisation (via a process referred to as “hydro-processing”), primarily through hydrotreating and hydrocracking processes [17]. Hydrotreating uses high-pressure hydrogen to remove contaminants (SNO and metals) and saturates olefins and aromatics to produce cleaner fuel, while hydrocracking converts low-value gas oils into valuable products by improving hydrogen-carbon ratios [51-53]. Additionally, hydrogen aids in upgrading heavy oils by lowering viscosity, and mitigating transportation and processing challenges [54, 55].

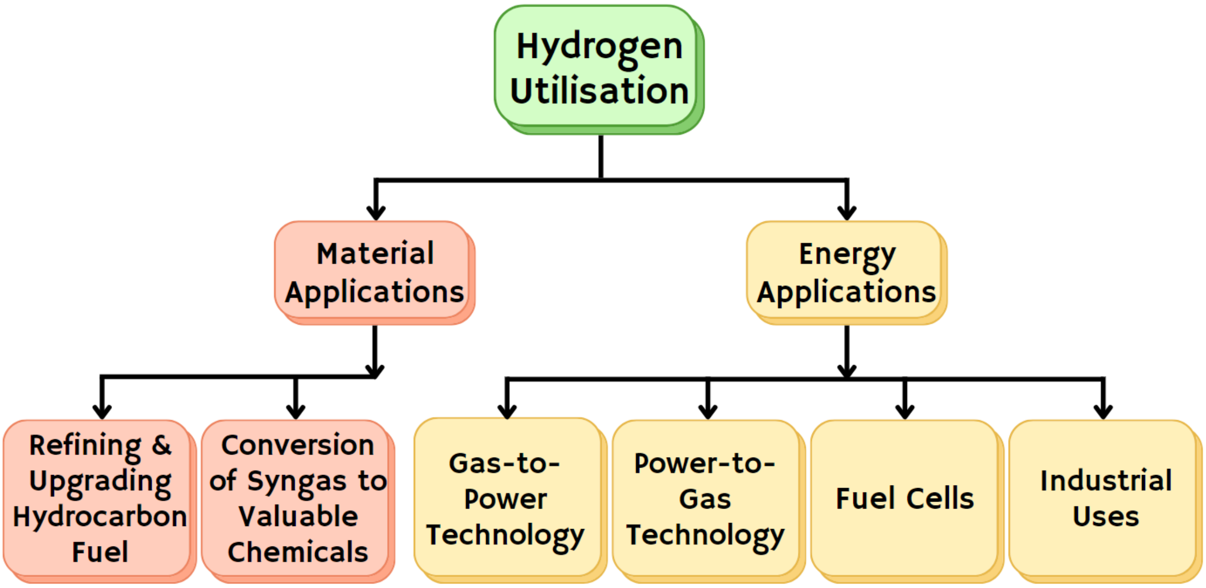


Figure 2.4: Schematics depicting diverse hydrogen utilisation pathways.

2.1.3.1.2 Conversion of syngas to valuable chemicals

Syngas, comprising *CO* and H_2, can be produced using recycling and renewable methods, with *CO* derived from carbon capture, and H_2 sourced from renewable options [17, 56, 57]. The produced syngas can be then further converted into value-added chemicals through Fischer-Tropsch synthesis (Eq. 2.14), methanol synthesis (Eq. 2.15), and methanol to hydrocarbon synthesis (MTH) (Eq. 2.16) reactions respectively via controlled bond activation [58-60].

$$nCO + (2n+1)H_2 \rightarrow C_nH_{(2n+2)} + nH_2O \tag{2.14}$$

$$CO + 2H_2 \rightarrow CH_3OH \tag{2.15}$$

$$CH_3OH \rightarrow CH_2 + H_2O \tag{2.16}$$

Catalysts facilitate these reactions under suitable temperature and pressure conditions [60-62]. The resulting hydrocarbons, free of heteroatoms and impurities, are processed into fuels and petrochemical products with superior combustion properties [63, 64].

2.1.3.2 Energy applications

2.1.3.2.1 Gas-to-power technology

Hydrogen emerges as a sustainable alternative to traditional fuels, offering minimal emissions for heating and power generation [65]. Its use in boilers and heating systems produces minimal emissions compared to natural gas, and it proves effective in combustion units for power generation and household cooking [66-68]. Notably, hydrogen can easily integrate into existing natural gas infrastructure due to its compatibility with the Wobbe Index [26]. Specialised burners may be needed to optimise combustion, ensuring safety and efficient flame control [69].

2.1.3.2.2 Power-to-gas technology

Power-to-gas technology offers a solution to intermittent renewable energy challenges [70]. Traditional short-term storage methods have limitations [71], prompting the use of hydrogen for long-term storage [72, 73]. This method involves converting surplus electricity into hydrogen gas via water electrolysis [74], with the hydrogen evolution reaction (HER) occurring at the cathode and the oxygen evolution reaction (OER) at the anode [75]. The resulting hydrogen can be stored for later use in various applications, including natural gas networks, methanation processes, hydrogen combustion engines, or fuel cells [76-78].

2.1.3.2.3 Fuel cells

Hydrogen has emerged as a direct energy carrier in fuel cells, producing eco-friendly energy with water and heat as byproducts [79]. Hydrogen fuel cells offer lower maintenance costs and longer lifespans due to fewer moving parts [80], finding applications in electric power generation and transportation [81-83]. Hydrogen's properties, including its high energy release compared to hydrocarbons, low viscosity, and high specific impulse, make it appealing for aerospace and maritime industries [84-86]. However, challenges such as storage volume, low-temperature storage requirements, and liquid hydrogen's combustion issues in aviation, including low ignition energy and high flame velocity, must be addressed for efficient utilisation in transportation [86, 87].

2.1.3.2.4 Industrial uses

Hydrogen is revolutionising the metallurgical industry by replacing oxy-acetylene flames, known for CO and CO_2 emissions, with clean and efficient oxy-hydrogen flames [88, 89]. Oxy-hydrogen flames offer precise cutting and welding, with eco-friendly water as the byproduct, making them suitable for non-ferrous metals and thick materials [90]. Moreover, hydrogen's role extends to metal reduction processes, where it significantly reduces energy consumption and GHG emissions compared to conventional methods [91-93]. The reduction process involves hydrogen diffusion and chemical reactions at the ore surface, influenced by temperature, pressure, hydrogen flow rate, and mineralogy [94, 95].

The utilisation of renewable hydrogen presents a promising avenue for the aluminium industry to align with global decarbonisation goals. By replacing fossil fuels in high-temperature smelting processes, hydrogen emerges as a sustainable alternative, epitomising the industry's commitment to reducing carbon emissions [96].

Hydrogen also offers its crucial use in silicon epitaxial growth for semiconductor manufacturing, acting as a reducing agent to create clean silicon surfaces [97]. This process ensures the removal of contaminants and supports the growth of advanced materials, such as strained silicon and silicon-germanium, vital for semiconductor innovation [97].

2.2 Comprehensive summary of hydrogen technologies: from production to utilisation

Hydrogen technologies encompass diverse methods across production, storage, transportation, and utilisation as shown in Figure 2.5.

In production, renewable methods like water splitting via electrolysis, thermochemical, and photoelectrochemical processes, as well as biomass gasification, stand alongside non-renewable approaches including coal gasification and hydrocarbon reforming such as steam reforming, partial oxidation, and autothermal reforming. Between these two categories, non-renewable production methods employing CCS, i.e. blue hydrogen, offer a transitional solution, mitigating environmental impacts while leveraging existing infrastructure.

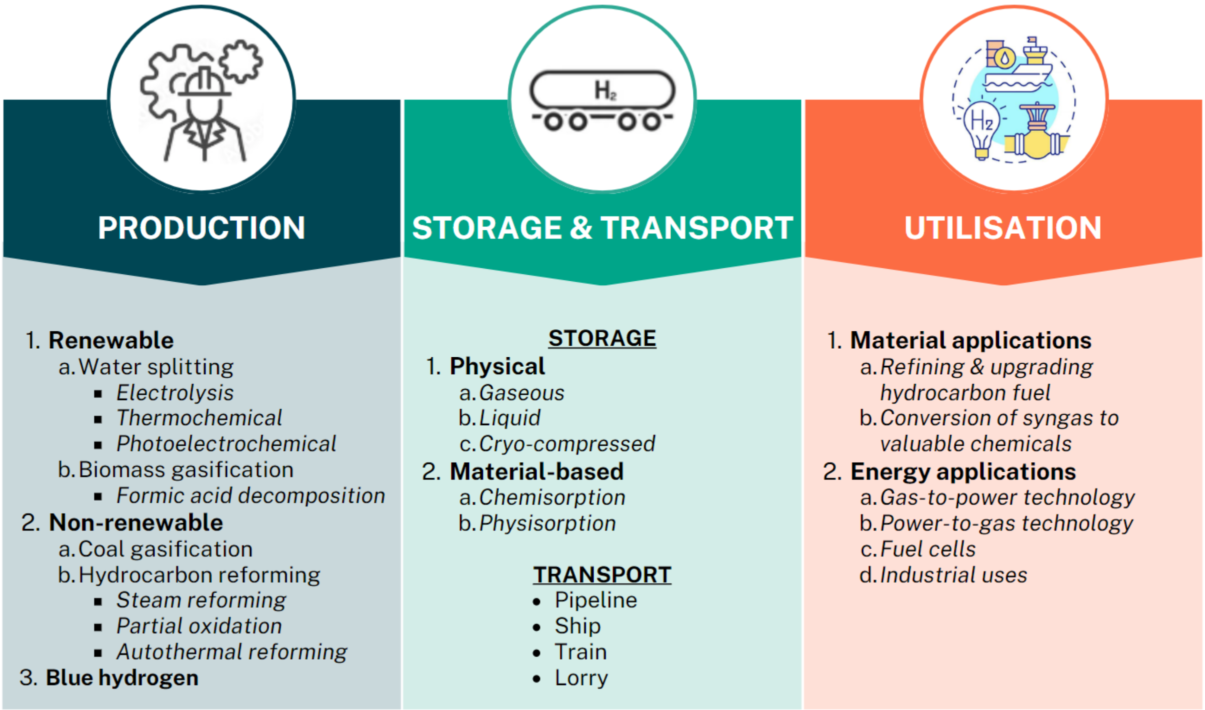


Figure 2.5: Hydrogen value chain.

Storage options range from physical methods like gaseous and liquid storage to material-based approaches including chemisorption and physisorption. Transportation modalities include pipelines, ships, trains, and lorries.

Utilisation pathways involve material applications like refining hydrocarbon fuels and converting syngas to valuable chemicals, as well as energy applications like gas-to-power technology, power-to-gas technology, fuel cells, and industrial uses such as metallurgical processes and semiconductor manufacturing. This comprehensive overview elucidates the breadth and depth of hydrogen technologies across the entire value chain.

2.3 Emerging trends in hydrogen technologies

Recent developments in hydrogen technologies are reshaping the landscape of energy production, storage, and utilisation. Countries worldwide are spearheading initiatives to reimagine their energy portfolios, with programs such as the United States’ “Hydrogen Hubs” and the European Union’s “Hydrogen Accelerators” leading the charge [98]. Patenting and innovation trends underscore the global momentum in hydrogen-driven technologies, with significant contributions from regions like the EU, Japan, and the USA [99]. Advancements in electrolysis and fuel cell technologies are driving innovations in both chemical and automotive sectors, with projections indicating a substantial rise in market size by 2030 [99]. Additionally, emerging technologies in hydrogen production are leveraging Carbon Capture, Utilisation, and Storage (CCUS) to reduce GHG emissions, highlighting a promising pathway towards sustainable energy solutions [100].

2.3.1 Emerging trends in production

The landscape of hydrogen production is undergoing significant transformation, with a growing emphasis on green hydrogen initiatives. While currently over 95% of hydrogen production is derived from fossil fuels, consuming 6% of the world's natural gas and 2% of its coal, there is a resurgence of interest in expanding green hydrogen projects worldwide [101]. Ambitious ventures like the "HyDeal Ambition" project and collaborations between Western Green Energy Hub and Korea Electric Power Corporation are poised to make substantial contributions to green hydrogen production, with capacities exceeding 3 million tons annually [102, 103]. Additionally, initiatives led by companies like ExxonMobil to establish world-scale blue hydrogen plants, signal a commitment to low-carbon hydrogen production [104].

Innovations in electrolyser technology, such as the Siemens Silyzer 300 and Cummins Hylyzer, are driving advancements in green hydrogen production [105, 106]. These electrolysers, leveraging PEM technology, demonstrate the capability to produce ultra-pure hydrogen with minimal oxygen concentrations [105, 106]. Recent inventions by Siemens further enhance electrolyser efficiency, including technologies to optimise module operation under varying electrical power availability and mitigate maintenance requirements through innovative heat exchange systems [107, 108]. Moreover, novel designs for connecting electrolytic cell stacks offer mechanical robustness and scalability, overcoming limitations in series connection configurations [109].

Patent analyses reveal a plethora of innovative approaches to hydrogen production. Patents like EP3348672 focus on utilising anion exchange membranes and active oxygen reduction materials to enhance electrolyser longevity [110]. Another patent, EP3615713, optimises PEM electrolyser performance by reversing water flow post-shutdown [111]. Innovations also address safety concerns, with patents like CN108603297A introducing gas-liquid separators to prevent hydrogen and oxygen buildup in alkaline water electrolysers [112]. Furthermore, US10883182B2 introduces a microfluidic electrolyser powered by solar cells for cost-effective hydrogen production from seawater [113].

2.3.2 Emerging trends in storage

Efficient hydrogen storage is crucial for enabling widespread utilisation. Salt caverns, long used for gaseous hydrogen storage, are being scaled up globally, with ambitious projects by SSE Thermal and Equinor in the UK and Mitsubishi Power Americas and Magnum Development in Utah expected to provide significant capacity to store up to 320 GWh and 300 GWh of hydrogen energy, respectively [114-116]. E-methanol production presents an innovative method for storing hydrogen, with projects underway to utilise green hydrogen and captured CO_2 for maritime fuel [117].

Metal hydrides offer promising potential for hydrogen storage, with ongoing research focusing on enhancing storage capacity and operating parameters [98, 118, 119]. Carbon-based materials, including MOFs, are also under investigation, leveraging advancements such as AI to predict materials with improved storage capabilities [120].

Recent patents highlight the multifaceted approach to hydrogen storage. US20220017364A1 focuses on formulating metal hydrides, emphasising manganese hydride, while EP3807211B1 addresses the physical geometry of the storage vessel to increase capacity [121, 122]. US10435296B2 introduces an organic liquid hydrogen storage material with enhanced gravimetric and volumetric capacities [123]. Safety measures, such as impervious boundaries in salt caverns and explosion-proof valves, are also addressed in patents like US10221689B1 and CN114562587A [124, 125].

2.3.3 Emerging trends in utilisation

In the realm of hydrogen utilisation, innovations are reshaping the landscape to make hydrogen fuel cells more competitive with electric vehicles (EVs). Advantages such as quick refuelling, showcased by Hyundai N Vision 74's hybrid fuel cell-lithium-ion battery system [126], and NamX HUV's removable capsule setup [127], aim to overcome challenges in hydrogen vehicle adoption. Toyota's hydrogen engine in GR Yaris H2 and Garrett's electric compressor promise enhanced performance and familiar driving experiences [128, 129].

The aviation industry is poised for significant hydrogen integration, with studies indicating feasibility by 2035 [130, 131]. Hydrogen's potential extends to short-range aircraft propulsion and emissions reduction, with emphasis on novel designs and system innovations [132]. The recent industrial-scale test in Navarra by Norsk Hydro represents the first successful implementation of hydrogen as an energy source in aluminium production [96].

Patent filings in fuel cells for transportation, particularly PEM fuel cells (PEMFCs), indicate continued innovation. Toyota's patent optimises vehicle design by placing the motor at the rear, creating space for hydrogen tanks [133]. The autonomous refuelling patent, US10288222B2, outlines a method connecting, monitoring, and disconnecting a hydrogen fuel cell vehicle from a refuelling station based on tank pressure [134]. Danish and Japanese patents focus on control systems for hydrogen refuelling stations, emphasising safety and operational efficiency [135, 136]. Chinese patent, CN110800146B, highlights transferring hydrogen effectively from a long-term to a short-term storage medium [137]. Additionally, US patents explore fuel cell systems for electric aircraft propulsion [138].

Table 2.1 summaries the emerging trends in hydrogen production, storage, and utilisation.

Table 2.1: The emerging trends in production, storage, and utilisation.

Aspects	Emerging Trends
Production	• Growing emphasis on green hydrogen initiatives, aiming to increase production capacity. • Establishment of world-scale blue hydrogen plants, signalling commitment to low-carbon production. • Innovations in electrolyser technology (e.g., Siemens Silyzer 300, Cummins Hylyzer). • Patent analyses revealing approaches to enhancing electrolyser longevity, performance, and safety.
Storage	• Scaling up storage capacity using methods like salt caverns and metal hydrides.

	• Exploration of e-methanol production and R&D on carbon-based materials like MOFs. • Patents addressing formulation of storage materials and safety measures.
Utilisation	• Innovations to enhance competitiveness of hydrogen fuel cells with EVs (e.g., vehicle design, refuelling methods). • Integration of hydrogen in the aviation industry for propulsion and emissions reduction. • Patent filings focusing on fuel cell optimisation and control systems for refuelling stations. • Implementation of hydrogen as an energy source in aluminium production.

2.4 Previous attempts at technology mapping in the energy sector

Hydrogen is often featured as a key component of a feasible transition to a low-carbon economy. Recognised as pivotal in the long-term decarbonisation goals, hydrogen has been subject to comprehensive analyses aimed at understanding its role and potential within various contexts.

The Strategic Research and Innovation Agenda 2021-2027, outlined by the clean hydrogen joint undertaking, underscores the imperative of advancing hydrogen technologies to meet the objectives of the Horizon Europe program [139]. This agenda aligns seamlessly with overarching sustainability frameworks like the European Green Deal and the Fit-for-55 package, all aimed at fostering a sustainable, climate-neutral economy by 2050 through concerted efforts in research, innovation, and infrastructure development [139].

In a comparative scenario analysis titled “Mapping the Future of Green Hydrogen: An Integrated Analysis of Poland and the EU’s Development Pathways to 2050,” the focus is on mapping out green hydrogen development pathways [140]. By integrating sectoral models with a computable general equilibrium model, the study highlights the critical importance of ambitious GHG reduction targets and the expansion of renewable energy sources [140]. These factors are deemed essential for enabling large-scale utilisation of hydrogen, particularly in addressing challenges like balancing intermittent renewable energy supply, estimating production potential, and enhancing energy storage capabilities while stabilising electric power systems.

In parallel, a perspective on hydrogen energy R&D and innovation activities in Turkey sheds light on global efforts towards hydrogen adoption as a green fuel, with specific attention to the roles played by the European Union and the United States [141]. Turkey’s involvement, facilitated through governmental organisations and foundations, aims to provide comprehensive numerical analyses spanning from 1970 to 2020 [141]. Such analyses serve as invaluable references for strategic planning and activities in the sphere of hydrogen energy.

In the context of Sub-Saharan Africa, a technological review paper delves into the potential of hydrogen technology to address the region’s energy crisis [142]. Despite acknowledging challenges and complexities, the paper explores avenues to leverage hydrogen’s benefits in expanding electrification coverage and mitigating electricity shortages [142]. Discussions revolve around hybridisation systems incorporating hydrogen fuel cells tailored to the unique challenges of the sub-Saharan context, accompanied by ongoing research efforts and risk mitigation strategies [142].

However, challenges persist, as evidenced by the paper exploring contested hydrogen pathways in Germany [143]. Here, multiple disagreements among stakeholders regarding production methods and applications have been discussed, contributing to uncertainties, and impeding the progress of hydrogen technologies [143]. This study underscores the intricate politics surrounding hydrogen adoption and suggests that targeted political prioritisation could alleviate tensions and foster a cohesive vision for hydrogen's role in the energy transition [143].

Hydrogen stands out as a crucial element with various initiatives highlighting its potential and significance. From strategic agendas to comparative analyses and regional perspectives, efforts have shed light on hydrogen's role as a cornerstone of a sustainable energy economy. Despite challenges and disagreements, ongoing collaboration and informed decision-making are imperative for unlocking hydrogen's transformative power. Moving forward, stakeholders must collaborate to advance both hydrogen technologies and policies, ensuring a cleaner and greener energy future.

2.5 Hydrogen business models

The advancement of hydrogen technologies presents a transformative opportunity in the global energy landscape, offering a pathway towards decarbonisation (via green hydrogen and blue hydrogen) and sustainable development. However, the realisation of this potential hinges not only on technological innovation but also on the development of effective business models that address the inherent uncertainties and challenges within the hydrogen market. Various business models have emerged to navigate these complexities, ranging from risk-sharing agreements to innovative approaches like hydrogen-as-a-service (HaaS) [144]. Understanding and implementing these models is crucial for stakeholders across the hydrogen value chain to foster collaboration, mitigate risks, and accelerate the transition to a hydrogen-based economy.

Table 2.2 presents an overview of business models pertaining to hydrogen technologies [144].

Table 2.2: An overview of hydrogen business model.

S. No.	Business Model	Key Features	Focus	Addressed Uncertainty
1	Take or Pay	Consistent payment schedule; flexibility for buyer; predictable cashflows; attracts investment.	Risk Sharing	Demand uncertainty
2	Take & Pay	Contractual guarantee; predictable revenue stream; risk mitigation; attracts financing for projects.	Risk Transfer	Demand uncertainty
3	Insurance	Mitigates investment risk; protects against failures; enhances investor confidence; supports project viability.	Risk Transfer	Demand uncertainty

4	Accessing Financing & Lowering Costs	Leverages development banks; bi-lateral agreements; lowers borrowing costs; facilitates global participation.	Risk Transfer	Demand uncertainty
5	Expression of Interest	Non-binding declaration; transparency in the market; facilitates information sharing; ensures flexibility.	Risk Alignment	Production & Infrastructure Uncertainty
6	Book & Claim	Allows receiving carbon credits for hydrogen use, even when not directly used; access to global buyers; reduces production risk; expands market reach.	Risk Alignment	Production & Infrastructure Uncertainty
7	Redeploy Existing Assets	Utilises existing networks; lowers entry costs; creates sustainable pathway; allows smooth transition for stakeholders.	Risk Alignment	Production & Infrastructure Uncertainty
8	Contract for Difference	Agreed minimum price; protection against price fluctuations; incentivises investment; defends against price volatility.	Risk Sharing	Regulatory Uncertainty
9	Auctions	Auction approach; policy intervention; subsidy provision; aligns suppliers and buyers, stimulates market competition.	Risk Alignment	Regulatory & Collaboration Uncertainty
10	Demand Aggregation	Alliance for centralised demand, lobby for regulations; accelerates product development, creates a strong market.	Risk Alignment & Risk Transfer	Collaboration Uncertainty
11	Co-opetition	Partnership between competitors; creates regional Hydrogen Hubs; connects competitors, explores new contracting strategies.	Risk Alignment	Collaboration uncertainty
12	HaaS	Infrastructure provision, long-term off-take agreement; addresses "chicken or egg" problem; guarantees profitability.	Risk Transfer	Collaboration uncertainty
13	Value Chain Collaboration	Full value chain involvement; margin sharing; accelerates adoption; reduces the need for subsidies.	Risk Sharing & Risk Alignment	Collaboration Uncertainty

2.6 Existing hydrogen regulations and policies

Existing hydrogen regulations and policies have gained significant traction in recent years as global societies, governments, and businesses are prioritising the deployment of hydrogen as a key energy resource [145, 146]. This surge in interest stems from the declining costs of electrolysers, the availability of renewable electricity, and global commitments to reducing

GHG emissions [147]. Consequently, leading economies are formulating and adopting specific hydrogen strategies and roadmaps to guide their goals and necessary support measures [145, 148]. These strategies encompass various policy and regulatory measures, including incentives, grants, tax benefits, and frameworks to stimulate investment, ensure safety, and foster a level playing field for hydrogen technologies. Moreover, these roadmaps outline the infrastructure needs for hydrogen production, transportation, and storage, alongside strategies like market incentives, procurement plans, and public-private partnerships [145]. They also emphasise knowledge exchange, joint research initiatives, and harmonisation of standards to promote cross-border trade and best practices sharing.

The proliferation of national hydrogen policies and roadmaps underscores the global momentum towards hydrogen adoption [146]. Notably, Asian and European economies are leading the charge, with countries like Japan, South Korea, China, and Australia making significant strides in their hydrogen agendas, policies, roadmaps, or initial guidelines, reflecting a growing global emphasis on hydrogen [149-152]. Japan, for instance, relies heavily on hydrogen imports, while South Korea focuses on fuel cells for automotive and stationary power applications [149, 150]. Australia aims to become a significant hydrogen hub, leveraging renewables and natural gas [151]. In Europe, countries like Germany, France, the Netherlands, Norway, Portugal, Spain, and the UK have developed and implemented national hydrogen strategies to align with the EU's goal of carbon neutrality by 2050 [146, 153]. Figure 2.6 depicts the timeline of existing and emerging hydrogen strategies, regulations, and policies [154].

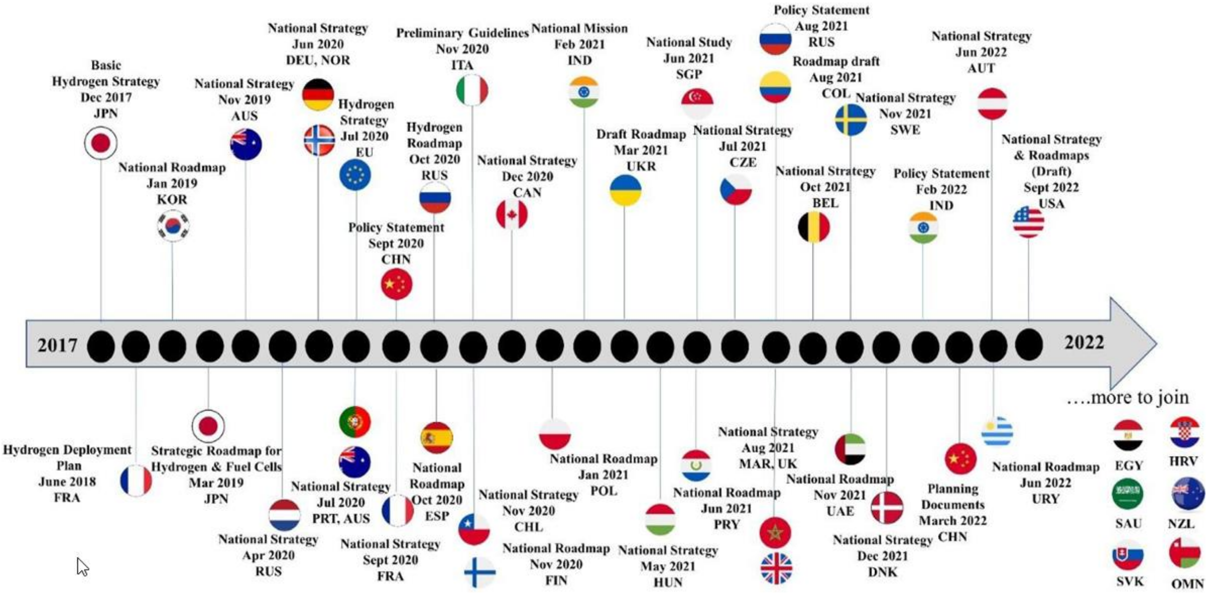


Figure 2.6: Existing and emerging hydrogen strategies, regulations, and policies [154].

In the Americas, Chile and Canada were the pioneers in developing comprehensive national hydrogen plans [146]. Chile, in particular, has become a global leader in promoting hydrogen adoption and exports green hydrogen to various regions [155, 156]. Furthermore, the US has recently outlined a comprehensive plan for leveraging clean hydrogen to meet national decarbonisation goals, emphasising collaboration across sectors and government agencies to drive progress and achieve tangible targets [157].

The increasing number of countries with hydrogen policies and regulations reflects a growing recognition of hydrogen's role in fostering sustainable energy transitions [146]. This trend underscores the collective effort among advanced and emerging economies to embrace hydrogen as a crucial component of their future energy landscapes [156].

3 Methodology

This chapter discusses the research methodology employed in this study and outlines the structured approach used to investigate hydrogen-driven sustainable technologies for future energy hubs. Through a hybrid research design and qualitative analysis techniques, this study aims to comprehensively understand the factors shaping the hydrogen domain. Ethical considerations are properly addressed to ensure integrity and transparency throughout the research process, fostering credibility and responsible exploration of sustainable technologies.

Figure 3.1 depicts the conceptual flowchart of the methodology.

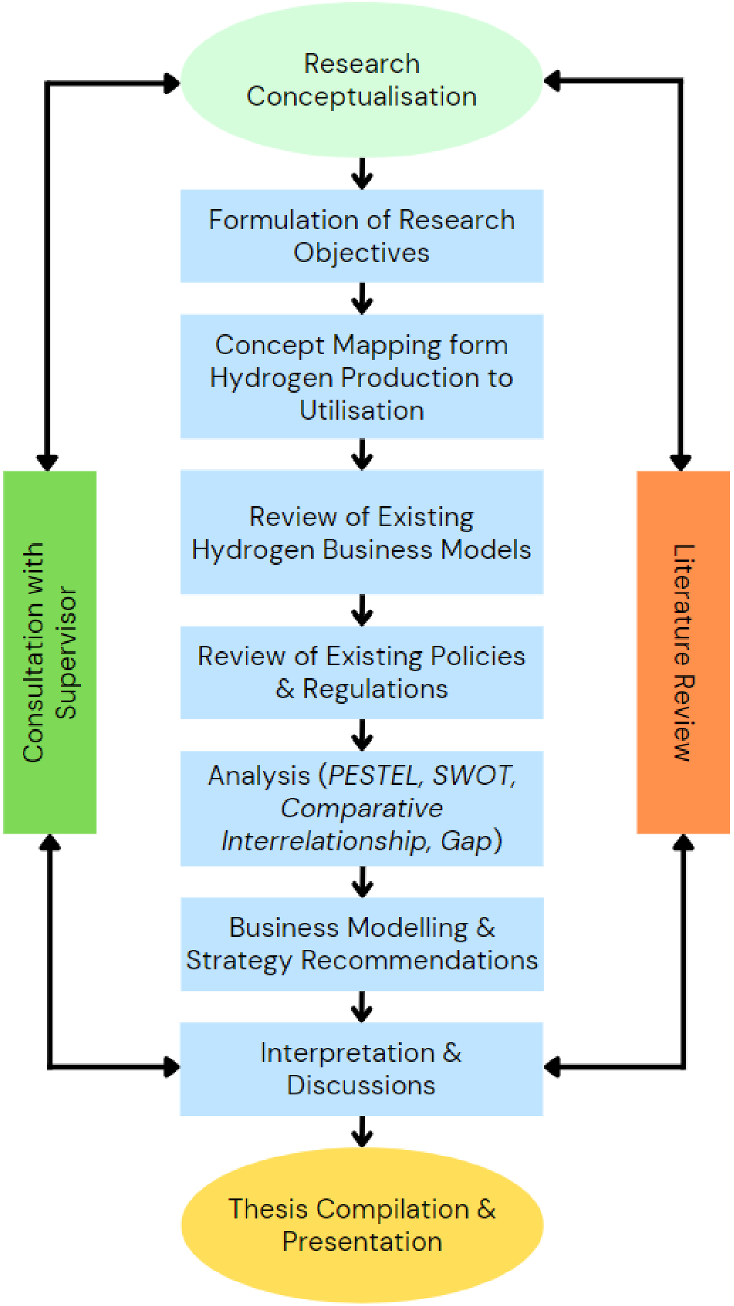


Figure 3.1: Flowchart of Research Methodology.

3.1 Research design

Research design serves as a framework or a plan for a study, guiding the collection, measurement, and analysis of data [158]. It functions as a blueprint, essentially a map developed to direct the research process, ensuring a systematic and organised approach to the study [158].

The research design employed in this thesis is structured to comprehensively explore and analyse the landscape of hydrogen-driven sustainable technologies for future energy hubs. Given the multifaceted nature of the research objectives, a hybrid research design incorporating a mix of an explanatory study and descriptive study was chosen to systematically investigate various aspects of hydrogen technologies.

The chosen research design allows for a meticulous examination and synthesis of existing literature pertaining to hydrogen technologies. By undertaking a systematic review of journals articles, conference papers, reports, patents, emerging trends, previous attempts at technology mapping, and the examination of existing business models, regulations, and policies, this research design enables a comprehensive understanding of hydrogen value chain.

3.2 Research methodology, tools, and techniques

The research methodology, tools, and techniques employed in this thesis are instrumental in uncovering insights, evaluating trends, and proposing actionable recommendations for future energy hubs. Qualitative analysis techniques such as PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) and SWOT (Strengths, Weaknesses, Opportunities, and Threats) analyses are employed to assess the external and internal factors influencing hydrogen technologies. These analyses provide a structured framework for evaluating the macro-environmental factors shaping the hydrogen domain and identifying strategic considerations for future development.

Furthermore, the research also integrates comparative analysis of hydrogen policies and strategies, interrelationship analysis, gap analysis, and business modelling to provide a comprehensive understanding of the hydrogen landscape. Comparative analysis of hydrogen policies and strategies helps identify patterns in the regulatory framework within the value chain of different nations. Interrelationship analysis allows for the examination of the intricate connections between various factors and stakeholders within the hydrogen ecosystem, shedding light on potential synergies and dependencies that influence its development. Gap analysis identifies disparities between the current state of hydrogen technologies and desired future outcomes, and by pinpointing areas where advancements are needed, informs strategic decision-making and resource allocation to bridge these disparities effectively. Business modelling provides valuable insights into the economic viability and sustainability of hydrogen initiatives by developing models that simulate various business scenarios and outcomes, enabling stakeholders to make informed decisions.

In addition to traditional qualitative analysis techniques, online tools such as Canva and Visual Paradigm Online were utilised to create various schematics and diagrams. These tools offered versatile platforms for visually representing complex concepts and relationships, enhancing the clarity and accessibility of information presented within the thesis. By leveraging these online tools, visually engaging illustrations were created that complemented the textual content, aiding in the communication and understanding of key research insights.

Through the synergistic utilisation of both traditional qualitative analysis techniques and modern visualisation tools, this study aims to generate robust insights and strategic recommendations that contribute to the advancement of the hydrogen domain.

3.2.1 PESTEL analysis

PESTEL analysis is a strategic tool used to assess the external macro-environmental factors impacting an organisation or industry. It involves examining each segment of the general environment (i.e. political, economic, social, technological, environmental, and legal) to identify opportunities and threats and adjust strategies accordingly [159].

PESTEL analysis provides a holistic framework for assessing the external factors influencing hydrogen-driven sustainable technologies, enabling stakeholders to anticipate challenges, identify opportunities, and formulate strategic responses to navigate the complex and dynamic operating environment. Figure 3.2 illustrates the elements of PESTEL analysis.

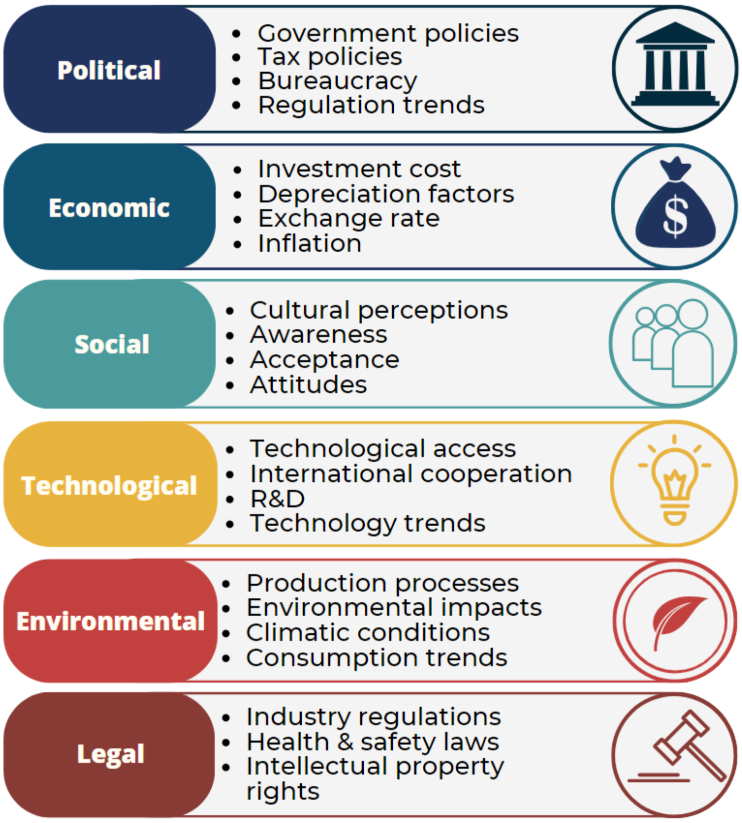


Figure 3.2: PESTEL framework.

3.2.2 SWOT analysis

SWOT analysis is a strategic planning tool used to evaluate the strengths, weaknesses, opportunities, and threats associated with a specific organisation, or technology. The SWOT framework consolidates key information for strategic management, identifying primary issues and guiding strategy development based on internal strengths and weaknesses, and external opportunities and threats [160]. It is a popular tool for understanding both internal and external factors influencing the performance and prospects of a particular entity or initiative.

SWOT analysis provides a structured framework for evaluating the internal strengths and weaknesses, as well as the external opportunities and threats, associated with hydrogen-driven sustainable technologies. By identifying and assessing these factors, stakeholders can develop informed strategies to capitalise on strengths, address weaknesses, exploit opportunities, and mitigate threats. This analysis helps to inform decision-making, resource allocation, and risk management efforts, ultimately supporting the development and deployment of effective and sustainable hydrogen technologies. Figure 3.3 illustrates a typical SWOT framework.

Figure 3.3: SWOT framework [161].

3.2.3 Comparative analysis

A comparative analysis involves systematically comparing two or more subjects to identify both their similarities and differences. This method can be applied to various contexts, whether it’s comparing abstract concepts or tangible data sets. The applications of comparative analysis in everyday business are extensive, including examining emerging trends and opportunities, competitor strategies, financial health, budgeting, and assessing the effects of trends on target audiences [164].

3.2.4 Interrelationship analysis

An interrelationship diagram is a management planning tool that visually depicts cause-and-effect relationships among factors in a complex situation [162]. Its main purpose is to identify logical relationships that might not be easily recognisable, aiding in understanding complex problems by visualising natural links between different aspects [162].

Interrelationship analysis techniques is utilised to explore synergies among different components within the hydrogen value chain. This involves examining how various technologies and processes interact and complement each other to achieve efficient and sustainable energy solutions. By identifying potential integration opportunities, this analysis informs strategies for optimising the performance and effectiveness of hydrogen technologies.

3.2.5 Gap analysis

Gap analysis compares actual performance with desired performance, aiming to identify areas for improvement in resource allocation and integration [163]. It involves assessing the difference between business requirements and current capabilities, facilitating strategic or operational improvements for future goals [163]. This study informs strategic and operational decision-making to bridge the identified gaps between current and desired states.

A gap analysis is conducted to identify shortcomings in current hydrogen technologies and propose practical solutions to address these gaps. By systematically assessing the discrepancies between existing capabilities and desired outcomes, this analysis informs strategies for innovation, research, and development in the hydrogen domain.

3.2.6 Business modelling

A business model is a strategic framework that outlines how an entity (organisation or a cluster of organisations) creates, delivers, and captures value, detailing product/service flows, revenue sources, and stakeholder roles for sustainable profitability. Ostenwalder et al. [165] propose that "a business model is a conceptual tool that contains a set of elements and their relationships and allows expressing the business logic of a specific firm. It is a description of the value a company offers to one or several segments of customers and of the architecture of the firm and its network of partners for creating, marketing, and delivering this value and relationship capital, to generate profitable and sustainable revenue streams".

Business modelling techniques can be employed to develop strategies for enhancing the commercial viability of hydrogen technologies. This involves analysing and revisiting the existing hydrogen business models and developing strategies tailored to fill identified gaps to capitalise on emerging opportunities in the hydrogen sector. By aligning technological advancements with market needs and regulatory requirements, these strategies aim to foster innovation and drive the adoption of hydrogen-driven sustainable solutions.

3.3 Ethical considerations

Research ethics establishes guidelines for the responsible conduct of research, ensuring a consistent and high ethical standard while actively monitoring research conduct. In the context of this study, ethical considerations are centred around the principles of integrity and transparency. Even though there is no direct involvement of human participants, maintaining honesty and transparency in reporting remains paramount, aligning with ethical standards of integrity and accountability.

Respect for knowledge and intellectual property rights is central to maintaining ethical standards. By diligently citing sources from journal articles, scientific papers, books, publications, policies, regulations, patents, or past studies, the contributions of other researchers are acknowledged and respected, and plagiarism is avoided. This practice not only upholds academic integrity but also fosters a collaborative spirit within the scholarly community.

Through the conscientious adherence of these ethical principles, encompassing integrity, transparency, respect for intellectual property, and consideration of societal implications, this study maintains credibility and contributes ethically to the exploration of sustainable technologies for future energy hubs.

4 Results and discussions

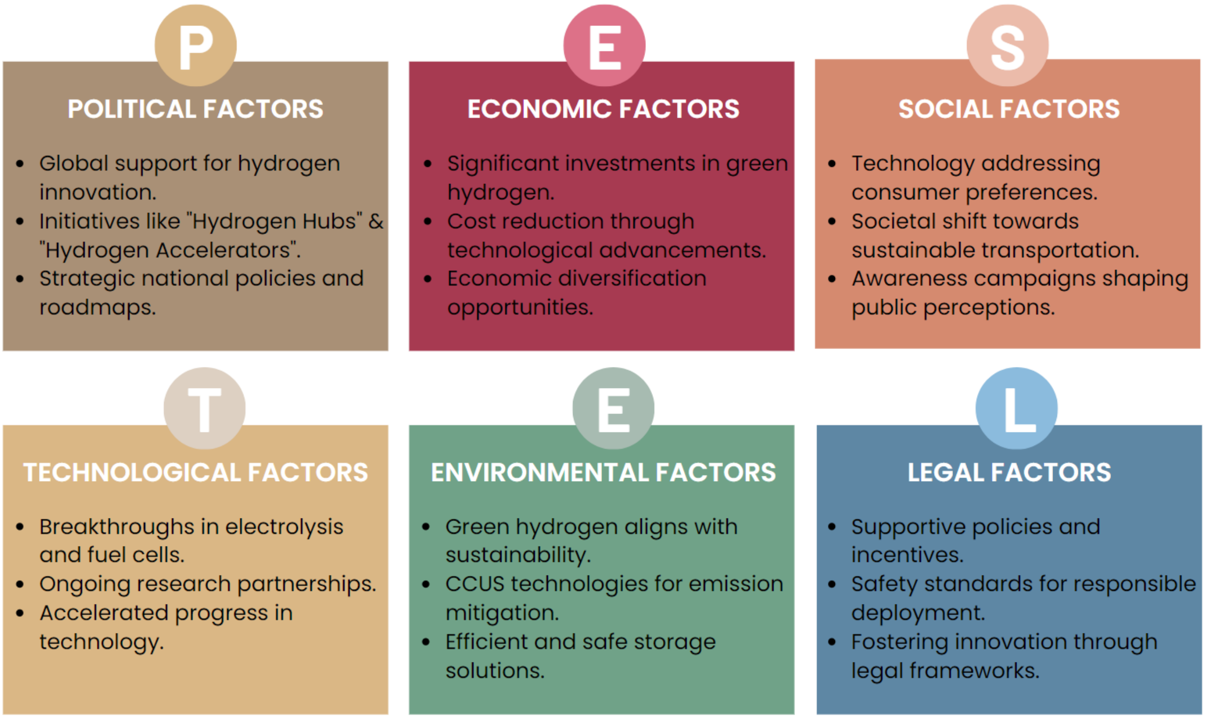
This chapter presents a comprehensive analysis of hydrogen technologies through the lenses of various strategic frameworks and analytical tools. Beginning with a comprehensive PESTEL analysis, the shaping of the trajectory of hydrogen technologies by political, economic, social, technological, environmental, and legal factors is comprehensively explored. This analysis is used as the foundation for a nuanced understanding of the external influences at play. Subsequently, a comparative SWOT analysis is employed, intricately dissecting strengths, weaknesses, opportunities, and threats within distinct domains, including production, storage, transportation, and utilisation of hydrogen technologies. Then follows a comparative analysis of hydrogen policies and strategies to gain insights into the recognisable patterns in the regulatory frameworks employed by different countries. The narrative further unfolds with an insightful interrelationship analysis, presenting hydrogen technology mapping across the entire value chain as its imperative. A critical examination is then conducted through a gap analysis, meticulously scrutinising advancements in technology, infrastructure development, regulatory frameworks, and societal acceptance, thereby unravelling critical areas necessitating attention. The discourse then seamlessly transitions into a robust exploration of business modelling, offering a forward-looking perspective on filling the identified gaps and fostering sustainable growth in the domain of hydrogen technologies. As a conclusive thread, the chapter culminates in strategic recommendations, delineating actionable insights for diverse stakeholders, encompassing policymakers, industry players, researchers, and the global community.

4.1 PESTEL analysis of hydrogen technologies

In the pursuit of a sustainable energy future, conducting a thorough evaluation of the macro-environmental analysis of hydrogen technologies is paramount. While hydrogen emerges as a promising clean alternative to conventional fossil fuels, it is essential to assess the potential macro-environmental consequences across its entire value chain. The PESTEL analysis of hydrogen technologies delves into the external factors that influence the development, adoption, and integration of hydrogen-driven sustainable solutions. By examining the political, economic, social, technological, environmental, and legal dimensions, stakeholders can gain insights into the opportunities and challenges within the hydrogen domain. Figure 4.1 summarises the PESTEL analysis of hydrogen technologies.

4.1.1 Political factors

Political factors play a significant role in shaping the trajectory of hydrogen technologies. Governments worldwide are increasingly recognising hydrogen as a crucial component of their sustainable energy agendas. Initiatives such as the United States' "Hydrogen Hubs" and the EU's "Hydrogen Accelerators" signify a commitment to fostering hydrogen innovation and deployment. National hydrogen policies and roadmaps, developed by countries like Japan, South Korea, China, Australia, and several EU nations, provide strategic frameworks for supporting hydrogen initiatives. These political efforts set the stage for regulatory frameworks, funding mechanisms, and international collaborations to drive the growth of hydrogen industries.



POLITICAL FACTORS

- Global support for hydrogen innovation.
- Initiatives like "Hydrogen Hubs" & "Hydrogen Accelerators".
- Strategic national policies and roadmaps.

ECONOMIC FACTORS

- Significant investments in green hydrogen.
- Cost reduction through technological advancements.
- Economic diversification opportunities.

SOCIAL FACTORS

- Technology addressing consumer preferences.
- Societal shift towards sustainable transportation.
- Awareness campaigns shaping public perceptions.

TECHNOLOGICAL FACTORS

- Breakthroughs in electrolysis and fuel cells.
- Ongoing research partnerships.
- Accelerated progress in technology.

ENVIRONMENTAL FACTORS

- Green hydrogen aligns with sustainability.
- CCUS technologies for emission mitigation.
- Efficient and safe storage solutions.

LEGAL FACTORS

- Supportive policies and incentives.
- Safety standards for responsible deployment.
- Fostering innovation through legal frameworks.

Figure 4.1: PESTEL analysis in relation to hydrogen technologies.

4.1.2 Economic factors

The economic landscape profoundly influences the viability and scalability of hydrogen technologies. Ambitious projects, such as the “HyDeal Ambition” and partnerships between Western Green Energy Hub and Korea Electric Power Corporation, highlight significant investments in green hydrogen production. Technological advancements, exemplified by Siemens Silyzer 300 and Cummins Hylyzer, contribute to cost reductions and efficiency improvements in hydrogen production. The integration of hydrogen into existing industries, including metallurgical processes and semiconductor manufacturing, presents opportunities for economic diversification and job creation. Financing options, access to capital, and market demand are critical economic factors that determine the commercial success of hydrogen technologies.

4.1.3 Social factors

Social acceptance and adoption are key determinants of hydrogen technology uptake. Advancements in fuel cell and hydrogen engine technologies, exemplified by Hyundai N Vision 74 and NamX HUV, aim to address consumer preferences for quick refuelling and familiar driving experiences. The aviation industry’s exploration of hydrogen for propulsion reflects a broader societal shift toward sustainable transportation solutions. Awareness campaigns, education initiatives, and public demonstrations play a crucial role in shaping public perceptions and driving acceptance of hydrogen technologies. Community engagement and stakeholder outreach are essential strategies for fostering societal support and participation in hydrogen initiatives.

4.1.4 Technological factors

Technological advancements drive innovation and progress in hydrogen technologies. Breakthroughs in electrolysis and fuel cell technologies have led to significant improvements in efficiency, reliability, and performance. The Siemens Silyzer 300 and Cummins Hylyzer represent cutting-edge electrolyser systems capable of producing ultra-pure hydrogen with minimal energy consumption. Ongoing research and development efforts focus on enhancing electrolyser efficiency, reducing costs, and expanding application areas. Patent analyses reveal a wealth of innovations, including advancements in membrane materials, system integration, and safety features. Collaborative research partnerships and technology transfer initiatives facilitate knowledge exchange and accelerate technological progress across the hydrogen value chain.

4.1.5 Environmental factors

Environmental considerations are central to the development and deployment of hydrogen technologies. The resurgence of interest in green hydrogen production underscores a commitment to reducing carbon emissions and mitigating environmental impact. Projects like the “HyDeal Ambition” leverage renewable energy sources to produce clean hydrogen at scale, aligning with sustainability objectives. CCUS technologies play a vital role in mitigating GHG emissions associated with hydrogen production from fossil fuels. Storage solutions, such as salt caverns and metal hydrides, offer efficient and safe means of storing hydrogen, minimising environmental risks. Lifecycle assessments and environmental impact studies are essential tools for evaluating the sustainability of hydrogen technologies and guiding decision-making processes.

4.1.6 Legal factors

Legal frameworks and regulations shape the regulatory environment for hydrogen technologies. The proliferation of national hydrogen policies and roadmaps reflects a global commitment to creating supportive policy environments for hydrogen adoption. Incentives, grants, and tax benefits incentivise investment in hydrogen research, development, and deployment. Safety standards, permitting processes, and licensing requirements ensure the safe and responsible operation of hydrogen facilities. Intellectual property rights and patent protection mechanisms foster innovation and technology transfer in the hydrogen sector. Harmonisation of regulations and standards promotes interoperability and facilitates international trade and collaboration in hydrogen-related activities.

4.2 Comparative SWOT analysis of hydrogen technologies

Hydrogen technologies encompass a diverse landscape spanning production, storage, transportation, and utilisation, each facet contributing uniquely to the pursuit of a sustainable energy future. SWOT analysis can be employed to evaluate the strengths, weaknesses, opportunities, and threats associated with hydrogen technologies across these critical domains.

4.2.1 Analysis in production technologies

Comparing hydrogen production methods involves weighing the zero-emission advantage of renewable methods like electrolysis against the established cost-effectiveness of non-renewable methods like steam reforming, enabling stakeholders to prioritise investments in green initiatives and enhance existing processes' efficiency and sustainability. Figure 4.2 provides the SWOT analysis in relation to hydrogen production technologies.

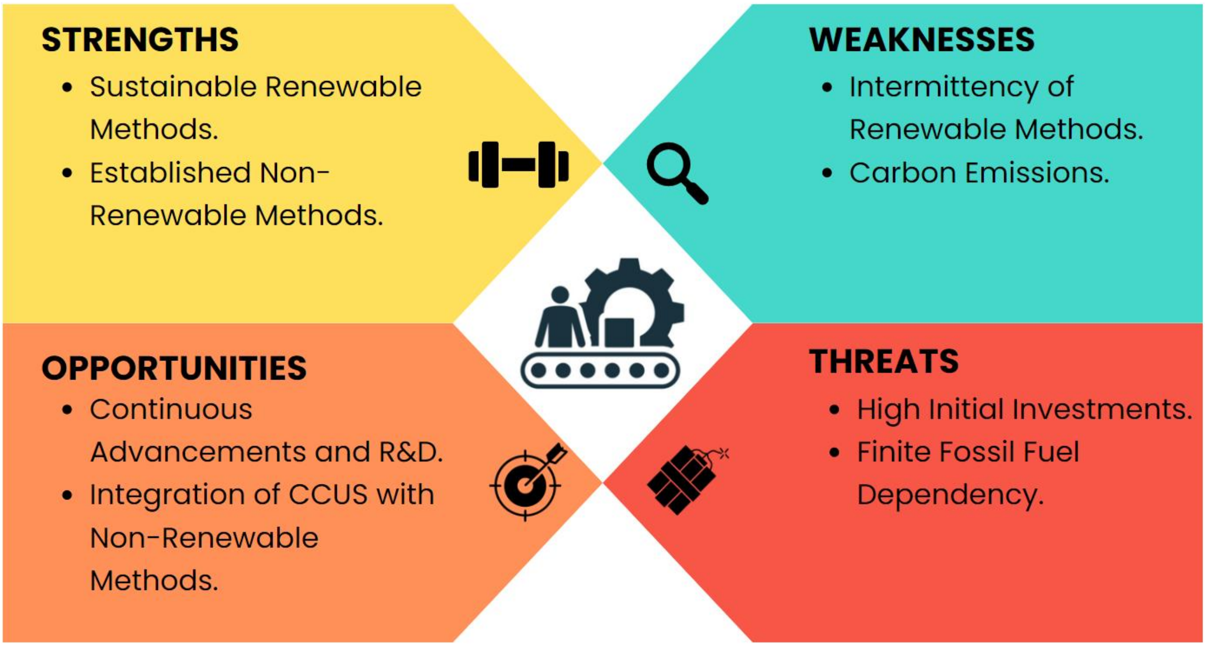


Figure 4.2: SWOT analysis in relation to hydrogen production.

4.2.1.1 Strengths

- *Sustainable renewable methods:* Electrolysis, a renewable method, stands out for its potential to produce zero-emission green hydrogen, aligning with sustainability goals.
- *Established non-renewable methods:* Non-renewable methods, such as steam reforming, boast well-established processes and cost-effectiveness.

4.2.1.2 Weakness

- *Intermittency of renewable methods*: Renewable methods may face challenges related to intermittency and grid integration, impacting consistent hydrogen production.
- *Carbon emissions:* Non-renewable methods contribute to carbon emissions and rely on finite fossil fuel resources, posing environmental concerns.

4.2.1.3 Opportunities

- *Continuous advancements and R&D:* Advances in electrolysis technology, materials science, and process optimisation can enhance the scalability and sustainability of green hydrogen production.
- *Integration of CCUS with non-renewable methods:* Leveraging CCUS with existing methods of production of hydrogen from non-renewable methods can reduce GHG emissions, highlighting a promising pathway towards sustainable energy solutions.

4.2.1.4 Threats

- *High initial investments:* High initial investments for renewable methods may hinder widespread adoption, requiring strategic financial planning.
- *Finite fossil fuel dependency:* The reliance on finite fossil fuels for non-renewable methods poses long-term environmental and resource challenges.

4.2.2 Analysis in storage technologies

Comparing storage technologies involves weighing factors like capacity, density, safety, and cost, enabling stakeholders to find suitable solutions balancing performance, safety, and cost. Figure 4.3 provides the SWOT analysis in relation to hydrogen storage.

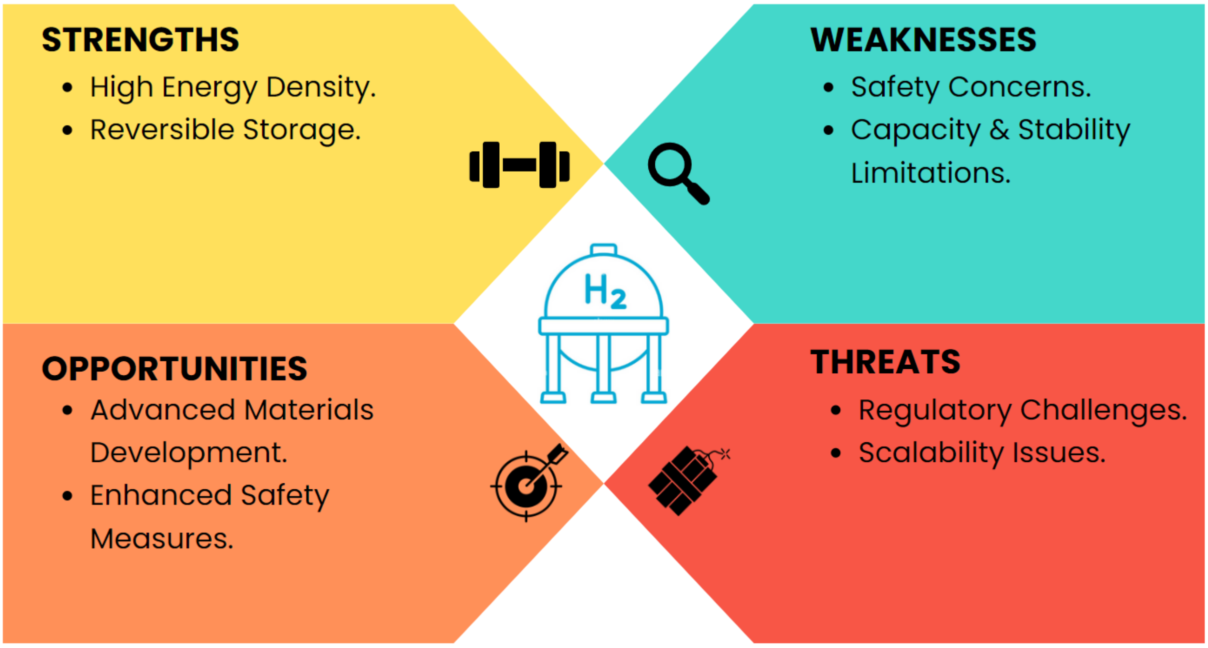


Figure 4.3: SWOT analysis in relation to hydrogen storage.

4.2.2.1 Strengths

- *High energy density:* Physical methods like gaseous storage provide high energy density, ensuring efficient storage solutions.
- *Reversible storage:* Material-based approaches, such as metal hydrides, offer reversible hydrogen storage, contributing to enhanced flexibility.

4.2.2.2 Weakness

- *Safety concerns:* Physical methods may require specialised infrastructure and pose safety risks, necessitating rigorous safety measures.
- *Capacity and stability limitations:* Material-based approaches may have limitations in terms of storage capacity and cycling stability, impacting long-term reliability.

4.2.2.3 Opportunities

- *Advanced materials development:* Ongoing research in advanced materials can lead to improved storage capacity and cycling stability.
- *Enhanced safety measures:* Developing robust safety measures and infrastructure can pave the way for wider adoption.

4.2.2.4 Threats

- *Regulatory challenges:* Safety concerns, including the risk of embrittlement, fire, and explosion, may pose regulatory and public acceptance challenges, requiring clear regulatory frameworks.
- *Scalability issues:* The scalability of storage technologies may be limited by factors such as land availability, cost, and infrastructure requirements.

4.2.3 Analysis in transport technologies

Hydrogen transportation options, including pipelines for cost-effective long-distance transport and mobile solutions like lorries for flexibility, require comparison by stakeholders to design integrated networks that optimise efficiency, minimise costs, and ensure reliability. Figure 4.4 provides the SWOT analysis in relation to hydrogen transportation.

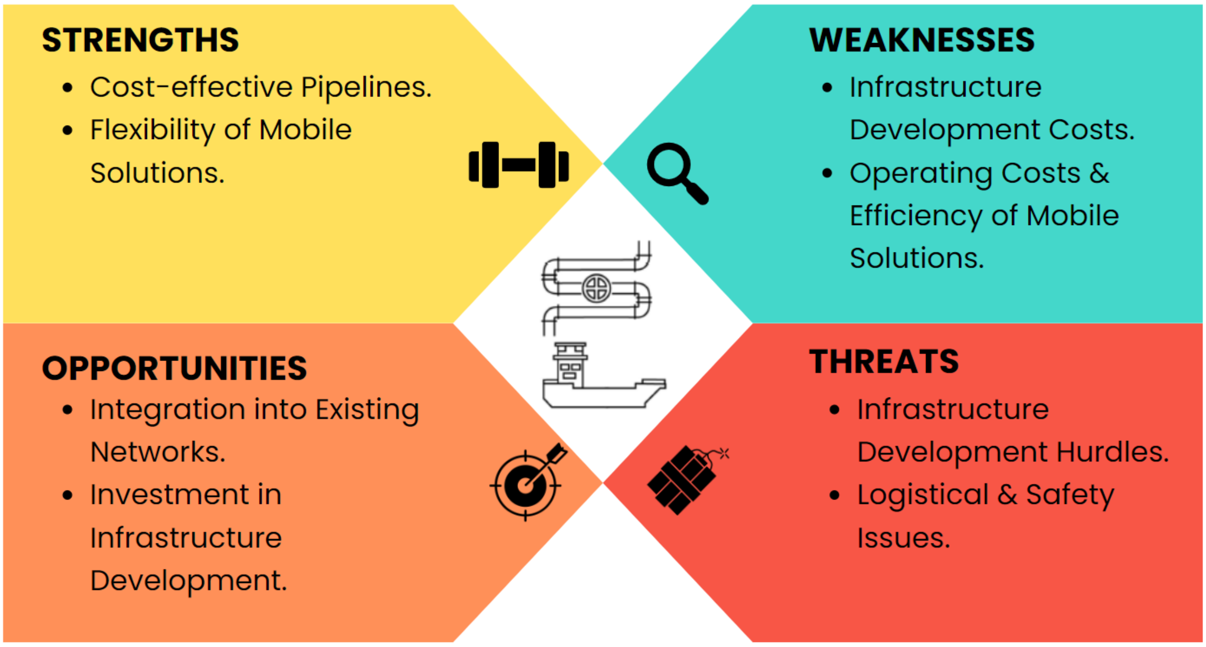


Figure 4.4: SWOT analysis in relation to hydrogen transport.

4.2.3.1 Strengths

- *Cost-effective pipelines:* Pipelines offer cost-effective and efficient long-distance transportation of hydrogen, presenting a reliable infrastructure.
- *Flexibility of mobile solutions:* Mobile transportation solutions, including lorries, tankers, and ships provide flexibility and accessibility, particularly in areas without pipeline infrastructure, facilitating diverse transportation needs.

4.2.3.2 Weakness

- *Infrastructure development costs:* Pipelines require extensive infrastructure development and significant upfront investments, including rights-of-way, permitting, and construction.
- *Operating costs and efficiency of mobile solutions:* Mobile solutions may have higher operating costs and logistical challenges, impacting their overall efficiency. Moreover, the energy efficiency of transportation methods can vary depending on distance, mode, and infrastructure.

4.2.3.3 Opportunities

- *Integration into existing networks:* Expanding and upgrading existing pipeline networks to integrating hydrogen into these networks can enhance overall efficiency and reduce costs.
- *Investment in infrastructure development:* Investing in infrastructure development, such as hydrogen refuelling stations and distribution hubs, can improve accessibility and promote the widespread adoption of hydrogen vehicles.

4.2.3.4 Threats

- *Infrastructure development hurdles:* Challenges related to infrastructure development, including permitting delays, land acquisition, and regulatory hurdles, can impede the expansion of pipeline networks, requiring careful planning and collaboration.
- *Logistical and safety issues:* Logistical challenges may impact the reliability of mobile solutions, necessitating robust operational frameworks. Additionally, concerns about hydrogen transportation safety, including the risk of leaks, spills, and accidents, may impact public perception and regulatory approval.

4.2.4 Analysis in utilisation technologies

Comparing hydrogen utilisation technologies entails assessing factors like efficiency, reliability, and compatibility, enabling stakeholders to integrate hydrogen into energy systems while addressing technical, economic, and regulatory barriers. Figure 4.5 provides the SWOT analysis in relation to hydrogen utilisation.

4.2.4.1 Strengths

- *Efficient fuel cells:* Fuel cells offer high efficiency and zero-emission energy production, making them a clean energy solution with wide range of applications, including transportation, stationary power generation, and portable electronics.
- *Flexibility of gas-to-power systems:* Gas-to-power systems provide flexible and scalable electricity generation, enabling grid stabilisation and integration of renewable energy sources that contribute to emissions reduction, energy independence, and grid resilience.

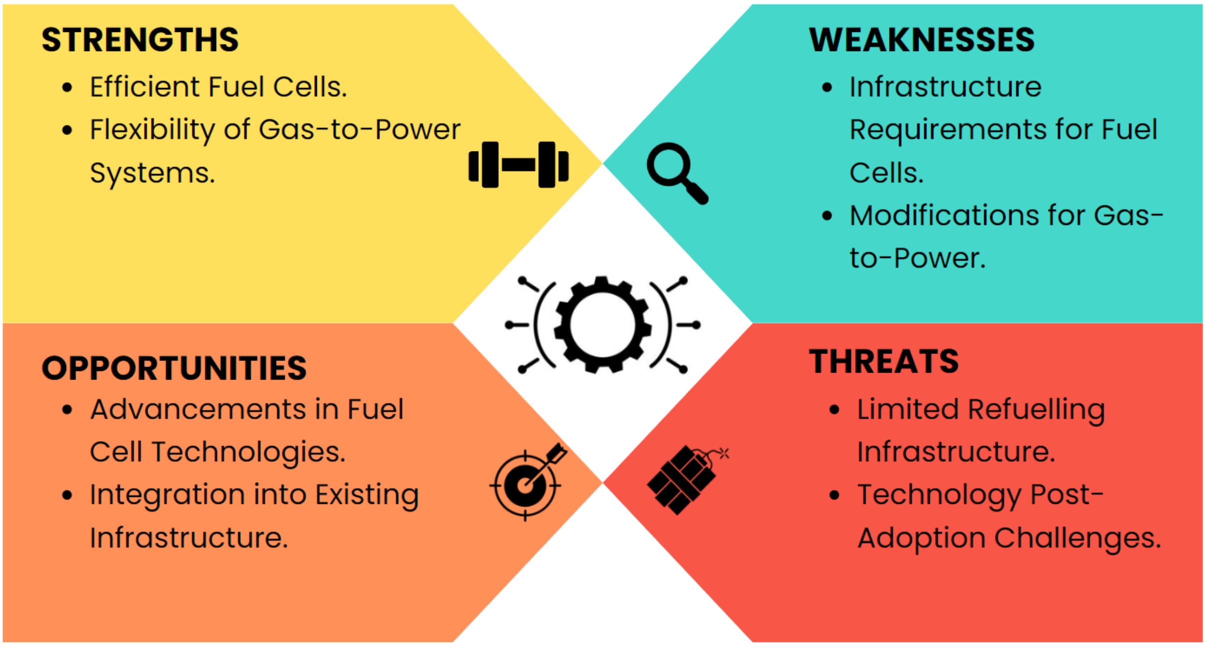


Figure 4.5: SWOT analysis in relation to hydrogen utilisation.

4.2.4.2 Weakness

- *Infrastructure requirements for fuel cells:* Fuel cells require highly developed hydrogen refuelling infrastructure, particularly in rural and remote areas, posing challenges to widespread adoption.
- *Modifications for gas-to-power:* Gas-to-power systems may require modifications to existing infrastructure to address the challenges related to grid integration, dispatchability, and energy storage, impacting their seamless integration.

4.2.4.3 Opportunities

- *Advancements in fuel cell technologies:* Ongoing advancements in fuel cell technologies, including PEMFCs and SOFCs, can lead to improved efficiency and durability, addressing current limitations.
- *Integration into existing infrastructure:* Integrating gas-to-power systems with renewable energy sources, such as solar and wind, can enhance grid stability and reliability, expediting their adoption.

4.2.4.4 Threats

- *Limited refuelling infrastructure:* Limited availability and accessibility of hydrogen refuelling infrastructure may hinder the widespread adoption of fuel cell vehicles and stationary power systems, necessitating strategic infrastructure development.
- *Technology post-adoption challenges:* Concerns about fuel cell durability, reliability, and performance degradation over time can impact consumer confidence and market acceptance, requiring coordinated efforts among industry stakeholders, policymakers, and investors to develop scalable and sustainable utilisation pathways for hydrogen technologies.

4.3 Comparative analysis of hydrogen policies and strategies

This section delves into a comparative analysis of the national hydrogen policies and strategies of three distinct countries, namely, Japan, Norway, and the US. Each country presents a unique perspective and approach towards harnessing hydrogen as a pivotal component in their respective energy transitions.

Japan emerges as a "*first mover*" with its longstanding commitment and advancements in hydrogen technology. Norway, known for its leadership in renewable energy, offers insights into a nation deeply invested in sustainable solutions with a tremendous opportunity for blue and green hydrogen. The US stands as a "*last mover*" with its recently unveiled ambitious roadmap, signalling a significant shift towards leveraging hydrogen to achieve ambitious decarbonisation targets.

Table 4.1 summarises the hydrogen policies and strategies of Japan, Norway, and the US to identify patterns or recurrences of trends and behaviour across them.

Table 4.1: Comparative analysis of hydrogen policies and strategies among Japan, Norway, and the US.

Aspect	Japan	Norway	US
Initiation of National Strategy	Pioneering force with Basic Hydrogen Strategy (2017).	Hydrogen Strategy (2020) and white paper (2021).	National Clean Hydrogen Strategy and Roadmap (2022).
Goals and Targets	Transitioning into a "hydrogen society" by 2050.	Developing a coherent value chain for hydrogen by 2050.	Producing hydrogen domestically (10 MMT by 2030, 20 MMT by 2040, and 50 MMT by 2050).
Technology Development	Clear targets for cost reduction and technology.	R&D support measures for green and blue hydrogen.	Catalysing innovation and scale for cost reduction.
Infrastructure Development	Establishing robust international supply chains.	Plans for hydrogen hubs, clusters, and infrastructure.	Focus on regional networks for infrastructure.
Policy Instruments	Tax breaks and support for R&D efforts.	Support for R&D, tax incentives, regulations.	Incentives, production tax credit for clean hydrogen.
International Collaboration	Active participation in international organisations	Collaboration for standards and research.	Engagement with federal agencies and stakeholders.
Long-term Vision	Vision for widespread use in all sectors by 2030.	Plan for domestic market by 2050.	Contributing to national decarbonisation goals.

The comparative analysis reveals that while Japan, Norway, and the US each exhibit unique approaches to their hydrogen strategies, notable similarities exist among them. All three countries prioritise the development of robust infrastructure and technology for hydrogen production, distribution, and utilisation. Additionally, they also emphasise the importance of international collaboration, recognising the need for standardised practices and research partnerships. Furthermore, these nations share a long-term vision of transitioning towards widespread adoption of hydrogen as a clean energy solution, setting clear goals and targets for achieving sustainability and decarbonisation.

The imperative of the comparative analysis extends beyond the examined countries in Table 4.1, offering valuable insights for countries with enormous renewable energy potential like Qatar and Saudi Arabia, which are yet to formalise comprehensive national policies and strategies in the hydrogen domain despite their interest in hydrogen as a sustainable energy source. Endowed with vast renewable energy resources, particularly solar energy, these nations possess a unique opportunity to become key players in the global hydrogen market. The absence of cohesive frameworks and initiatives at the national level represents a significant barrier to fully harnessing their potential for green hydrogen production. However, by formalising robust strategies, these countries could unlock immense opportunities to leverage their abundant resources and make substantial contributions to the global transition towards clean energy.

4.4 Interrelationship analysis

Hydrogen technologies form a complex ecosystem where advancements in one area can catalyse developments in others, leading to interconnected networks of innovation and progress. Production methods influence storage options, transportation modalities impact utilisation strategies, and regulatory frameworks shape the entire value chain.

For instance, advancements in electrolysis technology, driven by R&D efforts, can enhance the efficiency and reliability of hydrogen production, thereby influencing the availability and quality of hydrogen for storage, transport, and utilisation. Similarly, improvements in storage technologies, such as enhanced materials and system designs, can directly impact the reliability and safety of hydrogen supply chains, influencing adoption rates and market dynamics. This synergy between production and storage not only enhances the environmental sustainability of hydrogen technologies but also strengthens energy security and grid stability.

This interconnectedness extends beyond production and storage to other aspects of the hydrogen ecosystem. Transportation modalities, for instance, play a crucial role in shaping utilisation strategies. The availability of efficient and reliable transportation methods can facilitate the widespread adoption of hydrogen-powered vehicles and stationary power systems. Moreover, regulatory frameworks and policy decisions can significantly influence technological advancements and market trends. Clear and supportive regulations can incentivise R&D efforts, promote investment in infrastructure, and foster innovation across the hydrogen value chain. Figure 4.6 depicts a visual representation of the interrelationship diagram for the hydrogen ecosystem.

Regulatory frameworks and policy decisions serve as a central hub in Figure 4.6 connecting individually with production, storage, transportation, and utilisation, illustrating their pivotal role throughout the hydrogen value chain.

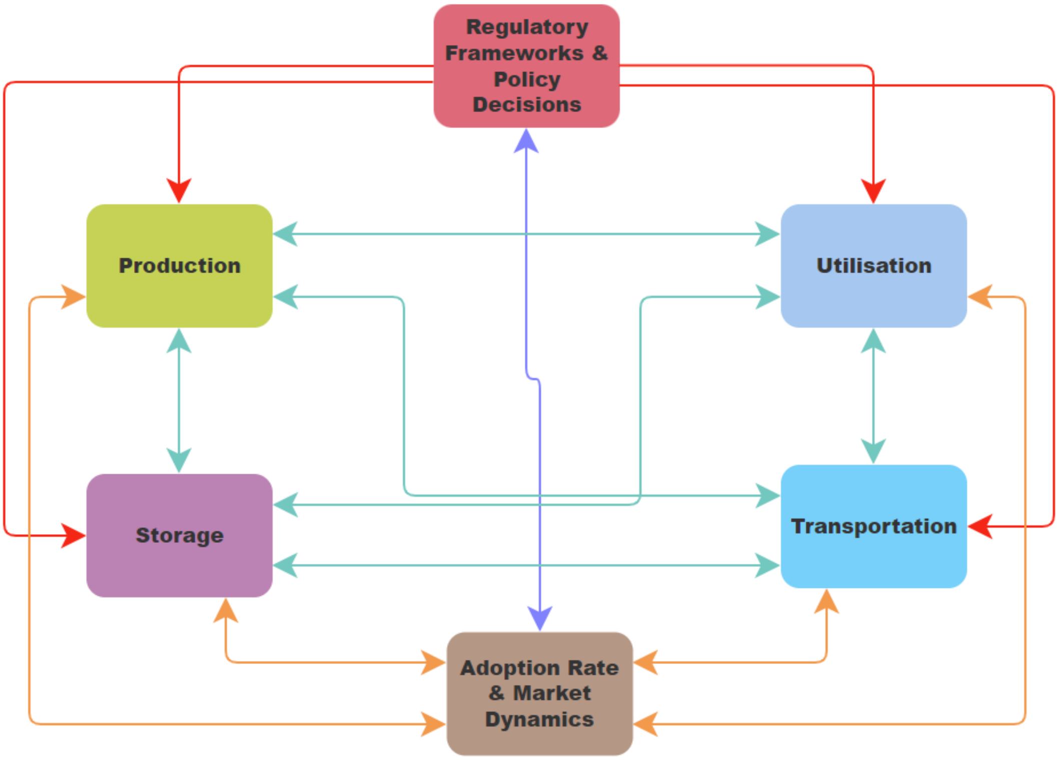


Figure 4.6: Interrelationship diagram of hydrogen ecosystem.

The interconnectedness of production, storage, transportation, and utilisation indicates the interdependencies and synergies between different stages of the hydrogen value chain. Additionally, the bidirectional connection between regulatory frameworks and policy decisions with adoption rate and market dynamics underscores the feedback loop between policy actions and market behaviour. Regulatory frameworks can directly influence hydrogen technology adoption by offering incentives, setting standards, or providing funding. Conversely, market dynamics, including adoption rates and economic factors, can shape policymaking and regulatory frameworks. Furthermore, adoption rate and market dynamics forms a dynamic feedback loop with production, storage, transportation, and utilisation. Changes or challenges in any of these aspects can significantly impact market uptake, technological advancement, and overall system dynamics within the hydrogen ecosystem. By visualising these natural links and dependencies, stakeholders can gain insights into how optimising one aspect of the hydrogen value chain can reverberate throughout the entire spectrum.

Table 4.2 presents the mapping of hydrogen technologies as an imperative of interrelationship analysis across the entire value chain.

Table 4.2: Hydrogen technology mapping across the entire hydrogen value chain.

Aspect	Interconnected Factors	Impacts on Value Chain
Regulatory Frameworks and Policy Decisions	Production, storage, transportation, utilisation, adoption rate and market dynamics.	Incentivises R&D efforts, promotes investment in infrastructure, and fosters innovation.
Production	Regulatory frameworks and policy decisions, storage,	Influences availability and quality of hydrogen for

	transportation, utilisation, adoption rate and market dynamics.	storage, transport, and utilisation.
Storage	Regulatory frameworks and policy decisions, production, transportation, utilisation, adoption rate and market dynamics.	Affects reliability and safety of hydrogen supply chains, influencing adoption rates and market dynamics.
Transportation	Regulatory frameworks and policy decisions, production, storage, utilisation, adoption rate and market dynamics.	Facilitates widespread adoption of hydrogen-powered vehicles and stationary power systems.
Utilisation	Regulatory frameworks and policy decisions, production, storage, transportation, adoption rate and market dynamics.	Influences technological advancements and market trends, shaping adoption rates and investment decisions.
Adoption Rate and Market Dynamics	Regulatory frameworks and policy decisions, production, storage, utilisation, and transportation.	Influences market uptake, technological advancement, and overall system dynamics within the hydrogen ecosystem.

4.5 Gap analysis

In the quest for a sustainable hydrogen ecosystem, a thorough gap analysis is indispensable to pinpoint areas where current progress falls short of envisioned goals, presenting opportunities for targeted interventions and strategic planning. This comprehensive analysis encompasses various facets of hydrogen technology, including technological advancement, infrastructure development, regulatory frameworks, and societal acceptance.

4.5.1 Technological advancement

Technological advancement forms the cornerstone of hydrogen innovation, driving innovation and progress towards sustainable energy solutions. While considerable strides have been made in enhancing electrolysis and fuel cell technologies, critical gaps persist that hinder the seamless integration of hydrogen into our energy infrastructure. Table 4.3 delves into the current state of technological advancement and gaps in hydrogen technologies, identifying key areas where further progress is needed to unlock the full potential of this clean energy source.

Table 4.3: Current state of technological advancement and gaps in hydrogen technologies.

Aspect	Current State	Gap
Integration with renewables	Progress in integrating renewables with hydrogen.	Reliability and efficiency issues with intermittent sources.
Cost-effectiveness	Cost reduction initiatives underway.	Challenges in achieving cost parity with alternatives.
Blue hydrogen	Emerging blue hydrogen production methods.	Storage/utilisation options of the captured CO_2 from the production process in a long run.

4.5.2 Infrastructure development

The development of robust infrastructure is essential to support the widespread adoption of hydrogen technologies and facilitate their seamless integration into existing energy systems. Despite growing momentum in infrastructure development, significant gaps remain in key areas such as pipeline networks and refuelling stations. Table 4.4 examines the current state of hydrogen infrastructure readiness, highlighting areas where targeted interventions are needed to address existing gaps and accelerate the transition towards a hydrogen-based economy.

Table 4.4: Current state of hydrogen infrastructure development and gaps.

Aspect	Current State	Gap
Pipeline networks	Existing networks require expansion.	Challenges in land acquisition and permitting.
Refuelling stations	Limited coverage and accessibility.	Need for extensive network expansion.

4.5.3 Regulatory frameworks

Regulatory frameworks play a pivotal role in shaping the deployment and uptake of hydrogen technologies, providing the necessary governance structure to ensure safety, reliability, and market competitiveness. However, gaps in regulatory frameworks persist, ranging from funding mechanisms and safety regulations to standards and incentives. Table 4.5 assesses the current regulatory landscape surrounding hydrogen technologies, pinpointing areas where regulatory gaps hinder progress and inhibit the realisation of hydrogen’s full potential as a clean energy solution.

Table 4.5: Current regulatory frameworks surrounding hydrogen technologies and gaps.

Aspect	Current State	Gap
Funding mechanisms	Few available.	Gaps in funding accessibility and availability.
Safety regulations	Standards in place but not uniform.	Need for consistent safety protocols.
Standards and incentives	Varied standards and incentives across regions.	Lack of harmonisation hindering global deployment.

4.5.4 Societal acceptance

Societal acceptance and awareness are critical drivers of the successful adoption of hydrogen technologies, influencing public perception, policy support, and market demand. Despite growing interest in hydrogen as a sustainable energy alternative, gaps persist in accessibility, awareness campaigns, and public perception. Table 4.6 explores the current state of societal acceptance of hydrogen technologies, highlighting areas where targeted efforts are needed to bridge the gap between public perception and the realities of the potential of hydrogen as a clean energy solution.

Table 4.6: Current state of societal acceptance of hydrogen technologies and gaps.

Aspect	Current State	Gap
Accessibility	Access to information and resources.	Gaps in accessibility hindering adoption.
Awareness campaigns	Increasing awareness through initiatives.	Gaps in public understanding and perception.
Public perception	Growing interest but lingering scepticism.	Need to build trust and confidence in hydrogen.

4.6 Business modelling for filling up the gap

Drawing from the comprehensive analyses preformed in the preceding sections, it is evident that the hydrogen ecosystem is characterised by a multitude of interrelated factors, including technological advancement, infrastructure development, regulatory frameworks, and societal acceptance. To effectively address these complexities, a business model innovation approach that combines elements of different existing business models seems both logical and practical. Business model innovation involves strategically restructuring the fundamental elements of the existing business models to create unique value propositions, capture novel market opportunities, and secure a competitive edge.

Adhering to the principle of business model innovation, a novel business model, termed "**Sustainable Integrated Hydrogen Solutions (SIHS)**," has been suggested, which encompasses a holistic approach to hydrogen technology development and deployment, leveraging synergies across various domains to maximise impact and efficiency. Following is the mission, vision, and value proposition of the model:

- **Mission:** To be the catalyst for a zero-emissions future where hydrogen is the cornerstone of global energy systems.
- **Vision:** To lead the sustainable energy shift with integrated hydrogen solutions that build economic and environmental harmony.
- **Value Proposition:** To deliver innovative hydrogen solutions that enable seamless adoption, driving progress with community and technological harmony.

Figure 4.7 illustrates the SIHS business model.

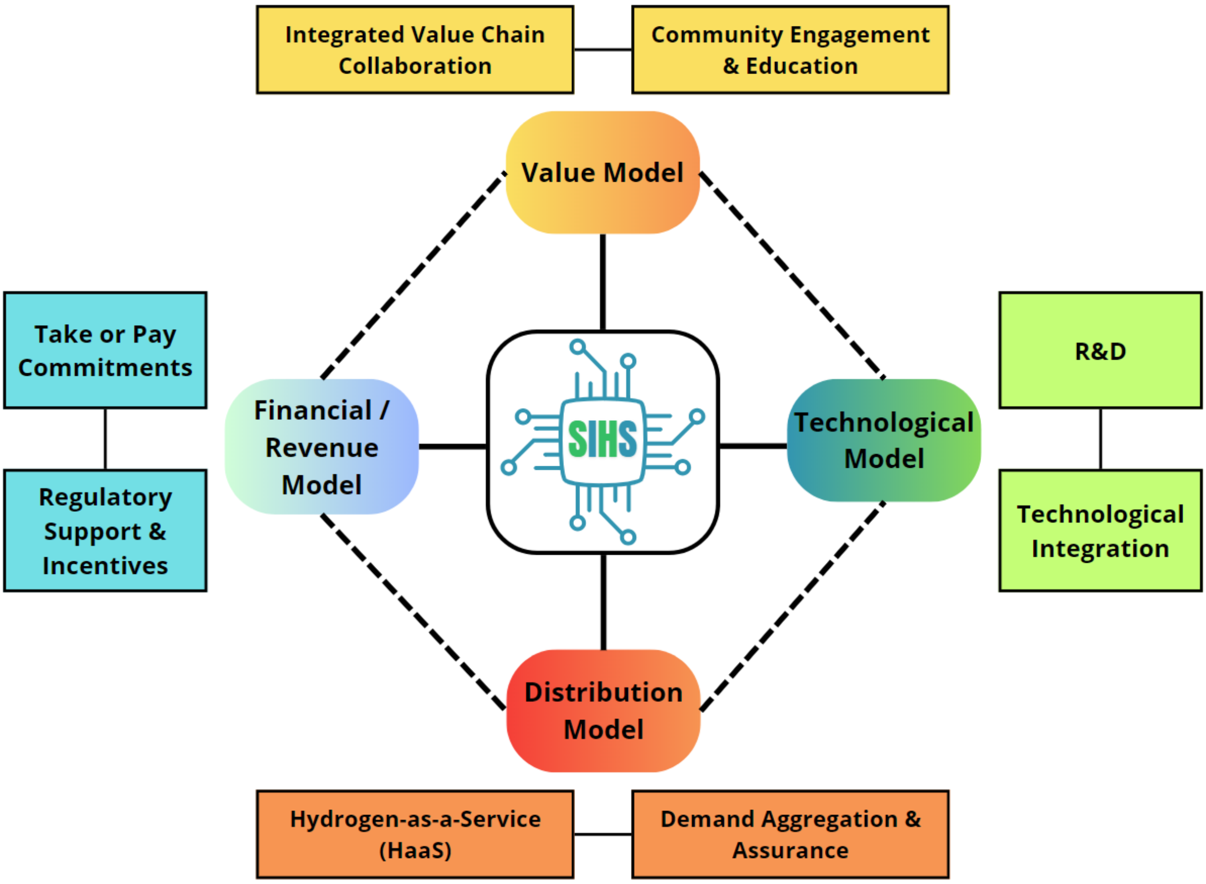


Figure 4.7: SIHS business model.

4.6.1 Value model

The value model of the SIHS is centred around creating a collaborative platform that integrates stakeholders across the entire hydrogen value chain. By fostering partnerships and synergies, the ecosystem aims to maximise value co-creation and accelerate the transition to a hydrogen-based economy. Key aspects include:

4.6.1.1 Integrated value chain collaboration

Collaboration is the cornerstone of SIHS. By fostering partnerships and alliances across the value chain, the model ensures seamless integration of hydrogen production, storage, distribution, and utilisation. This collaboration allows for shared resources, knowledge exchange, and collective problem-solving across the entire spectrum. By aligning interests and sharing resources, stakeholders can optimise operations, reduce costs, and drive innovation.

4.6.1.2 Community engagement and education

Recognising the importance of societal acceptance, SIHS prioritises community engagement and education initiatives. The model incorporates insights from social sciences and humanities to ensure that the engagement strategies are empathetic and culturally informed, facilitating deeper community connections. Through outreach programs, demonstrations, and partnerships with educational institutions, the model aims to raise awareness, dispel misconceptions, and build trust in hydrogen technology. By involving the community in the transition to hydrogen, the model fosters a supportive environment for its growth and adoption.

4.6.2 Technological model

The technological model of the SIHS focuses on driving innovation and technological advancements in hydrogen production, storage, and utilisation. By investing in R&D and integrating cutting-edge technologies, the model aims to create a robust and scalable infrastructure for hydrogen deployment. Key aspects include:

4.6.2.1 R&D

SIHS invests in R&D to develop cutting-edge technologies for hydrogen production, such as electrolysis, biomass conversion, and renewable energy integration. By pushing the boundaries of scientific knowledge and engineering capabilities, the model aims to unlock new opportunities and overcome existing challenges in the hydrogen industry.

4.6.2.2 Technological integration

By integrating emerging technologies into the ecosystem, such as cost and energy efficient electrolysers to produce green hydrogen from renewable sources and employing CCS to produce blue hydrogen from non-renewable sources, the SIHS model creates a comprehensive and interconnected network. This enables efficient distribution, storage, and utilisation of hydrogen across various applications. By leveraging advancements in automation, data analytics, and materials science, the model optimises efficiency, reliability, and safety across all aspects of hydrogen operations.

4.6.3 Distribution model

The distribution model of the SIHS is designed to ensure seamless and reliable distribution of hydrogen to end-users. By offering hydrogen storage, distribution infrastructure, and fuelling stations as a service, the ecosystem eliminates barriers to entry and accelerates the adoption of hydrogen-based technologies. Key aspects include:

4.6.3.1 Hydrogen-as-a-Service (HaaS)

SIHS offers HaaS solutions, providing end-users with access to hydrogen storage, distribution infrastructure, and fuelling stations as a service. This model eliminates the need for upfront capital investment and provides a seamless transition to hydrogen-based technologies. By providing a turnkey solution, the ecosystem simplifies the adoption process for businesses and consumers, accelerating market growth.

4.6.3.2 Demand aggregation and assurance

Demand aggregation mechanisms are employed to consolidate demand from various sectors and provide assurance to both producers and buyers. Through take or pay commitments, the model guarantees revenue streams for producers and ensures a stable market for hydrogen products. This reduces uncertainty and incentivises investment in hydrogen infrastructure and technologies.

4.6.4 Financial/Revenue model

The financial/revenue model of the SIHS aims to provide financial security and incentivises investment in hydrogen infrastructure and technologies. By offering take or pay commitments to both producers and buyers and advocating for supportive regulatory frameworks and incentives, the ecosystem fosters growth and innovation in the hydrogen industry. Key aspects include:

4.6.4.1 Take or pay commitments

SIHS offers take or pay commitments to both producers and buyers, guaranteeing revenue streams for producers and ensuring a reliable supply for buyers. This model mitigates risk for both parties and encourages long-term investments in hydrogen production and distribution infrastructure. By providing financial security, take or pay commitments stimulate growth and innovation within the industry.

4.6.4.2 Regulatory support and incentives

SIHS advocates for supportive regulatory frameworks and incentives to stimulate investment in hydrogen infrastructures and technologies. This includes subsidies, tax incentives, and other financial mechanisms to lower barriers to entry and stimulate market demand. By working closely with policymakers and industry stakeholders, the model seeks to promote the adoption of hydrogen as a clean energy solution and creates a conducive environment for growth and innovation.

4.7 Strategies recommendation for stakeholders

In navigating the complex landscape of hydrogen technologies, stakeholders play pivotal roles in driving innovation, policy development, and market adoption. As the hydrogen landscape evolves, strategic interventions from various stakeholders become imperative to overcome challenges and unlock the full potential of hydrogen technologies. Tailored strategies are essential for policymakers, industry players, researchers, and the global community to capitalise on the opportunities and address the challenges associated with hydrogen technology deployment. Figures 4.8 summarises these tailored strategies.

Policymakers

- Incentivise R&D
- Harmonise Regulatory Standards
- Implement Supportive Policies
- Foster Public-Private Partnerships
- Promote International Cooperation

Industry players

- Collaborate for Scale
- Diversify Investment
- Focus on Infrastructure
- Diversify Business Models
- Adopt Sustainable Practices
- Engage with Multiple Stakeholders

Researchers

- Address Efficiency Challenges
- Explore Advanced Storage Solutions
- Foster Cross-Disciplinary Collaborations
- Promote Open Innovation

Global community

- Promote Capacity Building Initiatives
- Collaborate for Carbon Mitigation
- Support Knowledge Sharing
- Facilitate Technology Transfer
- Advocate Policy Support

Figure 4.8: Strategy recommendations for stakeholders.

4.7.1 Recommendations for policymakers

Policymakers hold the key to creating an enabling environment for hydrogen technology deployment through regulatory frameworks, funding mechanisms, and strategic initiatives. Key recommendations for policymakers include:

- **Incentivise R&D:** Robust incentive programs should be established to encourage private and public investment in hydrogen-related R&D. Targeted funding can accelerate technological advancements and address gaps in the hydrogen value chain.
- **Harmonise regulatory standards:** International collaboration should be reinforced to harmonise safety, environmental, and technical standards. Standardisation will facilitate global trade, enhance interoperability, and create a cohesive regulatory framework supportive of hydrogen technologies.
- **Implement supportive policies:** Supportive policies such as feed-in tariffs, tax credits, and regulatory frameworks should be developed that promotes the deployment of hydrogen technologies. Clear and consistent policies will provide the necessary market signals to attract investments.

- **Foster public-private partnerships:** Collaboration between government agencies, industry stakeholders, and research institutions needs to be facilitated to accelerate technology development, infrastructure deployment, and market uptake.
- **Promote international cooperation:** Multilateral partnerships and knowledge-sharing initiatives needs to be initiated to harmonise standards, streamline regulations, and facilitate cross-border trade in hydrogen-related activities.

4.7.2 Strategies for industry players

Industry players, including hydrogen producers, equipment manufacturers, and end-users, have a crucial role in driving innovation, scaling up production, and commercialising hydrogen technologies. Key strategies for industry players include:

- **Collaborate for scale:** Industry players should engage in collaborative ventures to scale up hydrogen production, storage, and utilisation technologies. Partnerships across the value chain can drive efficiency, reduce costs, and expedite the commercialisation of hydrogen solutions.
- **Diversify investment:** Diversifying investment portfolios to encompass a range of hydrogen technologies, including both renewable and non-renewable production methods is necessary. Strategic diversification mitigates risks and ensures adaptability to evolving market dynamics.
- **Focus on infrastructure:** Investments should be prioritised in infrastructure development, especially expanding pipeline networks, and enhancing refuelling station accessibility. A well-developed infrastructure is pivotal for ensuring the widespread adoption of hydrogen technologies.
- **Diversify business models:** Diverse business models, including partnerships, joint ventures, and strategic alliances, should be explored to leverage complementary strengths and accelerate market penetration.
- **Adopt sustainable practices:** Sustainable practices should be embraced throughout the value chain, including renewable energy sourcing, CCUS, and lifecycle assessments, to minimise environmental impact and enhance long-term viability.
- **Engage with multiple stakeholders:** Cross-collaboration with policymakers, regulators, investors, and communities is necessary to build trust, address concerns, and foster acceptance of hydrogen technologies.

4.7.3 Suggestions for researchers

Researchers play a critical role in advancing the state-of-the-art in hydrogen technologies, driving innovation, and addressing technical challenges. Key suggestions for researchers include:

- **Address efficiency challenges:** Researchers should focus on enhancing the efficiency and reliability of hydrogen production methods, with particular attention to addressing intermittency issues in renewable technologies. Continuous improvements will contribute to the economic viability of hydrogen.
- **Explore advanced storage solutions:** Advanced materials and innovative approaches for hydrogen storage should be explored, aiming to overcome limitations in capacity,

safety, and cycling stability. Breakthroughs in storage technologies will bolster the reliability of hydrogen supply chains.

- **Foster cross-disciplinary collaboration:** Cross-disciplinary collaboration among researchers from various fields, including materials science, chemistry, and engineering should be encouraged. A holistic approach will expedite breakthroughs and foster innovation across the entire hydrogen ecosystem.
- **Promote open innovation:** Open innovation principles should be embraced, such as open access publication, data sharing, and collaborative research platforms, to accelerate progress and maximise impact.

4.7.4 Initiatives for global community

The global community plays a collective role in addressing shared challenges, leveraging collective expertise, resources, and initiatives. Key initiatives for the global community include:

- **Promote capacity building initiatives:** Technical assistance, training programs, and capacity-building initiatives should be provided to support developing countries in adopting and implementing hydrogen technologies.
- **Collaborate for carbon mitigation:** International collaborations focused on CCUS technologies should be encouraged with hydrogen production. Such collaborations, especially in the form of blue hydrogen, can significantly contribute to global carbon mitigation efforts.
- **Support knowledge sharing:** International platforms, networks, and forums for sharing best practices, lessons learned, and success stories in hydrogen technology deployment should be established.
- **Facilitate technology transfer:** Technology transfer and diffusion mechanisms needs to be fostered to ensure equitable access to hydrogen technologies and promote global collaboration.
- **Advocate policy support:** Supportive policies, regulations, and financial mechanisms at the international level should be advocated to create an enabling environment for hydrogen technology deployment.

5 Conclusion and implications

5.1 Conclusion

The comprehensive analyses conducted in this study highlight the prominent promise of hydrogen technologies in shaping the future of global energy systems. Extensive examination across production, storage, transportation, utilisation, prevailing business models, and policy frameworks reveals that hydrogen stands as a flexible and sustainable solution for critical challenges such as energy security and environmental sustainability. Despite facing obstacles like infrastructure constraints and regulatory complexities, the potential of hydrogen remains substantial. It offers extensive opportunities for collaborative innovation. By harnessing collaborative synergies across different sectors and adopting a comprehensive approach, stakeholders are equipped to unlock the full capabilities of hydrogen, thereby paving the way for a more sustainable, resilient, and inclusive energy future.

5.2 Implications for future energy hubs

The findings of this research have profound implications for the development of future energy hubs, where hydrogen technologies play a central role in driving innovation and sustainability. By unlocking synergies and fostering collaboration, regions can position themselves at the forefront of the global energy transition. Embracing inclusivity in the development of these energy hubs will be crucial for maximising benefits and fostering innovation for communities. Such initiatives have the potential to stimulate economic growth, mitigate climate change, and create lasting socio-economic benefits for stakeholders.

Moreover, strategically positioning hydrogen within energy hubs holds significant promise for shaping future energy landscapes and driving innovation towards sustainability. By incorporating elements such as production, storage, transportation, and utilisation of hydrogen within these hubs, regions can create dynamic ecosystems that capitalise on renewable resources while reducing carbon emissions. This strategic integration not only optimises resource utilisation but also enhances energy security and resilience.

5.3 Future research directions

While this thesis provides valuable insights into the current state and potential of hydrogen technologies, several avenues for future research warrant exploration. Continued research into materials science and engineering is essential to develop cost-effective and efficient solutions for hydrogen production, storage, transportation, and utilisation. Longitudinal studies tracking the evolution of hydrogen markets, policy frameworks, and technological advancements are necessary to provide insights into emerging trends and opportunities. Furthermore, interdisciplinary research that integrates socio-economic, environmental, and technological perspectives is crucial for developing holistic strategies that address the complex challenges associated with hydrogen deployment. Prioritising these research directions will enable academia, industry, and policymakers to collaborate effectively and accelerate the transition towards a sustainable hydrogen economy, unlocking the full potential of this transformative energy source.

Additionally, the application of strategic analysis tools such as CATWOE (Customers, Actors, Transformation, Worldview, Owner, and Environmental constraints) analysis and QSPM (Quantitative Strategic Planning Matrix) analysis could offer a clearer picture of the strategic implications of hydrogen technology deployment. These analytical frameworks can help identify key stakeholders, assess potential transformations, evaluate strategic options, and prioritise actions to achieve desired outcomes. However, due to the limited timeframe for this thesis, the inclusion of CATWOE and QSPM analyses were not feasible. Therefore, future research could explore the application of these tools to further enhance strategic decision-making in the context of hydrogen technology adoption and deployment.

Furthermore, an exploration of the economic models surrounding hydrogen technologies will be instrumental in understanding the financial viability and the potential market penetration of these solutions. Economic studies could explore the cost-benefit analyses, price-setting mechanisms, and economic impact assessments that are vital for strategic investment decisions in the hydrogen sector.

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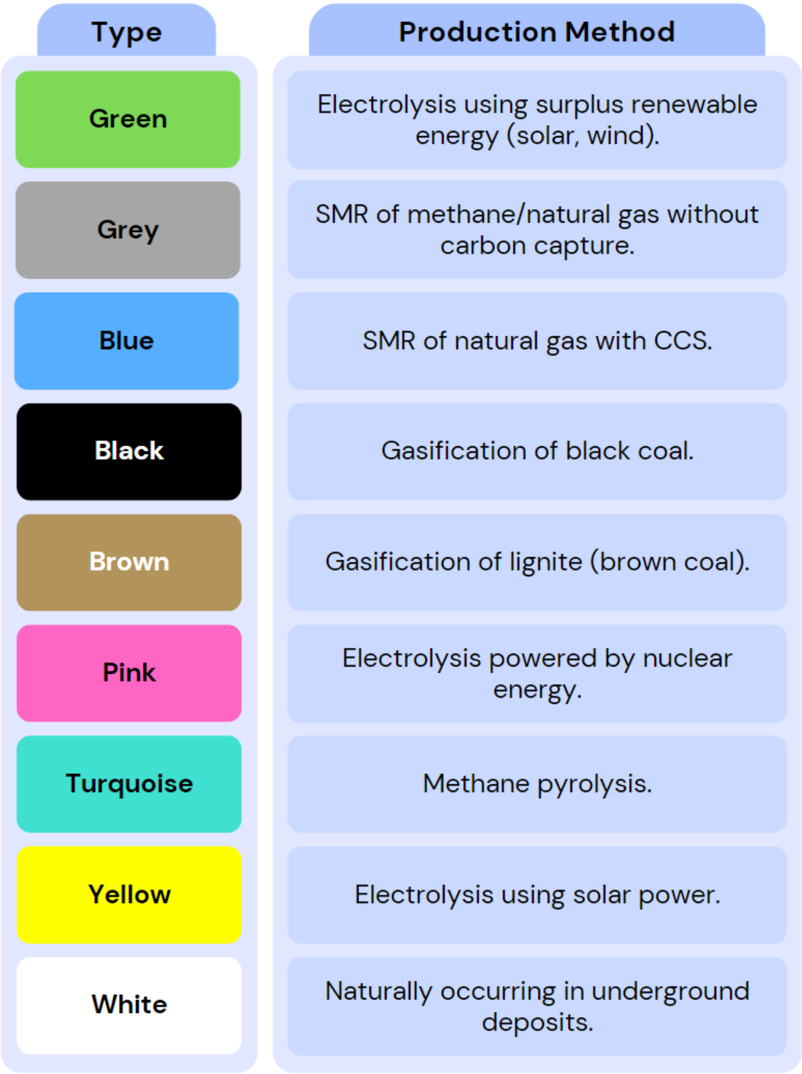
Appendix

Colour codes of hydrogen based on the production method.



Type	Production Method
Green	Electrolysis using surplus renewable energy (solar, wind).
Grey	SMR of methane/natural gas without carbon capture.
Blue	SMR of natural gas with CCS.
Black	Gasification of black coal.
Brown	Gasification of lignite (brown coal).
Pink	Electrolysis powered by nuclear energy.
Turquoise	Methane pyrolysis.
Yellow	Electrolysis using solar power.
White	Naturally occurring in underground deposits.