Decarbonizing Hard-to-Abate Industries in Northwestern Europe:

A socio-technical innovation system and techno-economic analysis on the most promising hydrogen sources

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Owen Thomson - 4608100

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A socio-technical innovation system and techno-economic analysis on the most promising hydrogen sources

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Owen Thomson

Student number: 4608100

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Graduation committee

Chair	Prof.dr. C.P. van Beers	Economics of Technology & Innovation
	Dr. G. van de Kaa	Economics of Technology & Innovation
First Supervisor	Dr.ir. G. Korevaar	Energy & Industry
Second Supervisor	Prof.dr. C.P. van Beers	Economics of Technology & Innovation
	Dr. G. van de Kaa	Economics of Technology & Innovation
External Supervisor	Dr. J. Dickmeis	Vattenfall

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TU Delft

Executive Summary

Within the energy transition, green hydrogen stands as a key solution for decarbonizing sectors where direct electrification is not viable. This thesis focuses on the competitive landscape of hydrogen production in North-Western Europe, addressing the technological and geographical competition of locally produced green hydrogen. This research introduces a comprehensive analytical tool to assess the viability of various hydrogen production methods, which are competing value chains of European green hydrogen. By synthesizing institutional, economic, societal, and technical considerations, the model facilitates a direct comparison between different green hydrogen alternatives.

The research contributes to the discourse on the energy sources and production methods used in hydrogen value chains. It presents a newly formed systemic approach for organizing the abundant information stream on the subject. This methodology uniquely merges quantitative and qualitative research, laying the foundation for informed discussions. Thus, it enriches the scientific knowledge base. The research not only enhances the academic discourse but also offers tangible benefits to society. It equips stakeholders with comprehensive insights into the system, including institutional, economic, social, and technical aspects of the different value chains and their status. Incorporating stakeholders' perspectives on the system's drivers and barriers enhances the foundation for informed decision-making in complex systems.

The research commenced by applying Hekkert’s (2011) TIS analysis as a tool for structural analysis to systematically map the system. The goal was to delineate its structure and identify potential key competing value chains within the scope of Europe. This initial phase involved a literature review and interviews to select value chains. The subsequent phase, which also used the TIS as a tool, focused on identifying key drivers and barriers within the system through a functional analysis, utilizing a structured approach to examine system functions. Expert interviews played a pivotal role in this stage, providing an understanding of the system's dynamics. In the last phase, the techno-economic analysis was performed by introducing barrier-driven scenarios. Allowing for insights into the cost components and the overall comparison in the levelized cost of hydrogen for every scenario.

The structural analysis showed that the European Commission set the scope with institutions, allowing for technologically mature low-carbon alternatives in this comparison. The functional analysis revealed the intricate interconnectivity of the system functions, illustrating how drivers and barriers can swiftly transform, reflecting the system's complex status. The primary barrier to green hydrogen adoption is its high cost, creating a deadlock with no demand or supply. Technological advancement and governmental intervention emerged as key solutions to this challenge. The techno-economic results show that the least cost-effective value chain is local green hydrogen, and the most cost-effective value chain is local blue hydrogen. Local green hydrogen faces challenges in competitiveness due to high energy prices and low capacity factors compared to other electrolyzer-based methods. Additionally, compared to other types, like blue hydrogen, it has higher overall investment and energy costs.

To achieve green hydrogen's competitiveness in Europe, addressing the cost gap is essential. Recommendations focus on strategic actions and governmental interventions to address this challenge. Aimed at users of the model, these guidelines offer insight into navigating the complexities of the European hydrogen system.

The model, designed as a strategic decision-making tool, provides critical insights into the main cost drivers of hydrogen production: CapEx and electricity prices. To enhance green hydrogen's competitiveness, stakeholders should prioritize identifying and implementing solutions to reduce these significant costs. Effective governmental interventions are pivotal in addressing the prevalent chicken-and-egg problem within the hydrogen economy. Such measures could pave the way for green hydrogen to emerge as a viable and competitive energy source across Europe.

Stakeholders across the green hydrogen value chain should unite in lobbying efforts. The aim would be to elucidate for government bodies the exact forms of governmental intervention mechanisms that could address current barriers. Notably by reducing capital, energy, or operational and maintenance costs, thereby making green hydrogen more competitive. The research found that the value chain is willing to cooperate with lobbies, meaning that if they share costs, they can learn together and overcome the monetary challenges. This approach underscores the necessity of collaborative action and targeted policy support to overcome the systemic barriers facing green hydrogen's widespread adoption. This breakthrough would accelerate technological improvements, enhance hands-on learning, and leverage economies of scale. Consequently, green hydrogen technology could evolve to become self-sustaining, driving competitive market dynamics and fostering widespread adoption.

The ultimate aim is to navigate through the complexities of the hydrogen system, clarifying how various variables interconnect and influence each other. Tools like the one developed in this research provide a foundation for understanding this complexity. By understanding the impact of governmental interventions and other factors on final prices, stakeholders can engage in more strategic decision-making. To deepen the understanding of the system, it is recommended to conduct further interviews and research, exploring the alternatives within and outside the European system more comprehensively. Investigating what drives prices beyond mere economic factors will offer a clearer picture of their current status and potential future developments. This broader analysis will equip users with the insights needed to make informed decisions, considering both the economic and socio-technical dimensions that shape the hydrogen market's evolution.

It is important to delineate which government actions can directly tackle the systemic chicken-and-egg problem hampering green hydrogen's growth. The study suggests that well-designed government interventions could be the key to unlocking funding, spurring technological advancements, and encouraging the adoption of green hydrogen.

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List of Abbreviations

Abbreviation	**Definition**
CapEx	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and storage
CCUS	Carbon Capture, Usage, and Storage system
CO_2	Carbon dioxide
CoSEM	Complex Systems Engineering and management
EC	Expert Consultation
ETS	Emission Trade System
EU	European Union
FLH	Full Load Hours
GHG	Greenhouse Gas Emissions
H_2	Hydrogen
kW	*Kilowatt*
LCA	Life Cycle Assessment
LCOH	Levelized Cost of Hydrogen
MQ	Main research question
MWh	Megawatt hour
NPV	Net Present Value
OpEx	Operational Expenditure
PEM	Proton Exchange Membrane
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBO	Renewable Fuel of Non-Biological Origin
RQ	Research Question
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyzer Cell
SQ	Sub-Question
TEA	Techno-economic analysis
TIS	Technological Innovation System
TRL	Technology Readiness Level
WACC	Weighted Average Cost of Capital

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1
Introduction

1.1 Context

As Roman emperor and philosopher Marcus Aurelius discerned two millennia ago, “What we do now echoes in eternity.” These prophetic words may now be more applicable than Marcus Aurelius ever imagined. In today’s escalating climate crisis, anthropogenic actions have set in motion a series of environmental repercussions, the scope of which spans the centuries to come (National Research Council, 2020). The challenge of climate change, characterized by increasing temperatures on a global scale, extreme weather, and irreversible biodiversity loss, constitutes evidence (IPCC, 2023). Evidence indicates that human actions continue to have a detrimental effect on the fragile ecological equilibrium of our planet (IPCC, 2023). Yet, in these words, there lies a source of hope. They serve as a compelling reminder that the decisions we make today have the potential to not only have long-lasting effects but also to ensure that there will be an "eternity" for these effects to continue to resonate. This critical juncture in human history demands an immediate and radical change in how we produce energy, manage resources, and organize the world.

Central to this radical change is the decarbonization of industries and economies, as the urgency stems from the role of fossil fuel combustion as a primary source of greenhouse gas emissions (GHG) (National Research Council, 2020), which contribute to global warming and have detrimental impacts on the environment, society, and the economy (IPCC, 2023). Fossil fuels have historically underpinned modern industrialization and economic development, whose inherent qualities of energy density, transportability, and, until recent decades, relative abundance have positioned them as an excellent energy source to satisfy expanding demands (Fouquet & Pearson, 2012; Holechek et al., 2022). In response, societies have developed complex systems around the extraction, delivery, and consumption of fossil fuels for centuries, profoundly integrating these resources into global economic and infrastructure networks (Holechek et al., 2022). As a result, the very system that fueled global expansion now threatens the stability of the globe's climate, ecosystems, and future prosperity. The current energy infrastructure’s reliance on fossil fuels presents significant technological challenges, necessitating substantial modifications to integrate renewable energy sources and transform the entire energy system (Holechek et al., 2022; IRENA, 2019). This reliance has been highlighted in recent years through geopolitical events, leading to initiatives such as the REPowerEU plan. This plan aims to create a Europe that is independent of Russian fossil fuels, where affordability, security, and sustainability have become the main pillars of the future energy system (European Commission, 2022).

Various Renewable Energy Sources (RES), like solar, wind, and hydroelectric power, are emerging as viable alternatives as the globe moves away from fossil fuels (IPCC, 2023); however, they continue to struggle to match the security of supply, energy density, and transportability that occur simply with fossil fuels (IEA, 2022). While hydroelectric facilities are limited by environmental and geographical considerations (IRENA, 2023a), the fluctuating nature of solar and wind energy highlights the necessity for advanced electric storage solutions and smart grid infrastructures for the decarbonization of the current economies and industries (Ellabban et al., 2014). With electricity supply periodically surpassing demand due to such intermittencies and geographical constraints, the grid becomes congested, which causes energy curtailment and stability problems during peak hours. These difficulties underscore the grid's limitations in utilizing RES to its full potential, needing greater energy storage, better grid management, and demand-response techniques (Ellabban et al., 2014; IEA, 2023c). This results in the future renewable energy system facing a stark reality: current technologies and status do not allow for the sole electrification of all sectors, causing unfavorable sustainable energy losses in times of desperate need for these valuable resources.

Hence, during the last few years, ambitious claims have been made about the significance of hydrogen in the future energy system. Hydrogen can be created through many methods. One low-emission method is through electrolysis, a method that uses electricity to split water into hydrogen and oxygen, creating green hydrogen (Shiva Kumar & Lim, 2022). This technology provides the option for flexibility and energy security in the energy system, as hydrogen can be electrolyzed whenever electricity is abundant and the sole other resource, water, is present (IEA, 2019). It is an excellent vector for renewable energy since it can easily be stored, transported, and has a high energy density, which addresses the intermittent nature of solar and wind power by being able to be stored (Abdin et al., 2020; IEA, 2019).

Low-carbon hydrogen, often described as the Swiss army knife of the energy transition, is not universally applicable or ideal in all scenarios or industries. In 2021, Michael Liebreich introduced the concept of the hydrogen ladder, a framework that provides a merit order in the application of hydrogen across various industries based on its efficiency and necessity for decarbonization. Liebreich stresses that even though low-carbon hydrogen can be used in all applications, that does not mean that it should be, laying the focus on harder-to-abate industries. Van der Spek et al. (2022) build forward on the idea of the hydrogen ladder, as they mention the need for a clear perspective as production of green hydrogen is limited for the coming years, meaning the allocation of this low-carbon resource and production methods should be optimized to industries where the most impact can be made. This discretion is particularly relevant in the top sections A and B of the ladder, where the use of hydrogen is unavoidable. Therefore, this form of hydrogen and its derivatives are seen as vital in enhancing the scope of RES in hard-to-abate sectors, as these sectors, with the current technologies, may not be directly electrifiable (IRENA, 2023b).

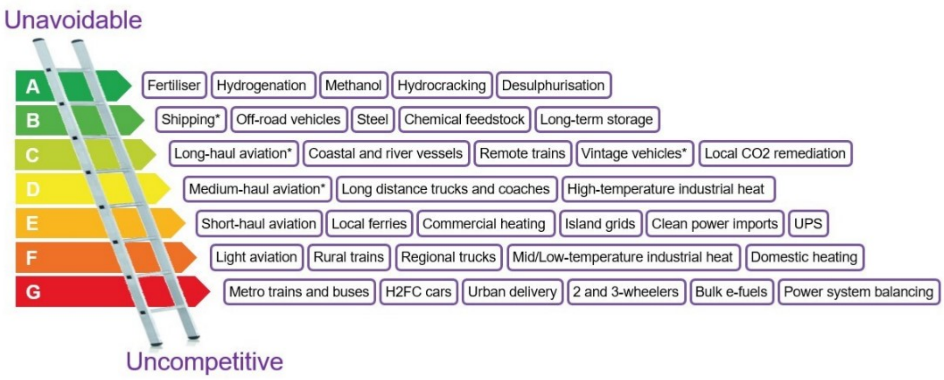

Figure 1.1: The Hydrogen Ladder by Liebreich (2021)

The hard-to-abate industries like aviation, steel, petrochemicals, and fertilizer, where the decarbonization is led by the introduction of clean hydrogen, do stress the necessary advancements to reach net zero. The industries stress hydrogen's importance because of its adaptability to less adaptable sectors. This adaptability aids decarbonization efforts by integrating significant amounts of renewable energy, thus enhancing the system's sustainability and resilience and contributing to meeting the Paris Agreement goals (DNV, 2022).

The role of hydrogen in the energy transition is widely known, yet the amount of low-carbon and renewable hydrogen in the international hydrogen system is negligible, underscoring the imperative for increased advocacy and strategic lobbying for green hydrogen production and utilization. This substantial transformation presents both a technical and socio-economic challenge, requiring strategic investment redirection, policy reformation, and a change in overall mindset.

1.2 Problem Statement

The actualization of low-carbon and green hydrogen's potential inside the energy system is a critical position in the current energy transition narrative. Green hydrogen generation and integration are still in the early stages, despite being hailed as the foundation for future sustainable energy infrastructures (DNV, 2022). This current position underlines the critical need for energy companies to innovate and strategically pivot inside this emerging industry, as well as the current technological and economic challenges that must be identified and overcome.

In hard-to-abate industries like chemical, fertilizer, steel, and aviation, where electrification faces technological limitations and direct use of renewable electricity is not possible, hydrogen is the only option to decarbonize. Therefore, green hydrogen promises a workable route to significant decarbonization by incorporating this renewable energy into the value chain (Deloitte, 2023; Liebreich, 2021). Hydrogen can be produced in various ways, varying in their costs, emissions, and more. All are dependent on their geographical and technological aspects (Ajanovic et al., 2022).

Both Europe and the United States are actively advancing the development of green hydrogen production infrastructure to meet the growing demand for sustainable energy carriers in those hard-to-abate sectors (IEA, 2023b). Consequently, it is important to acknowledge that other countries and industries are also strategically positioning themselves to fulfill this growing demand (DNV, 2022). This growing demand brings along one critical risk factor that necessitates a thorough examination of the investment made in local green hydrogen production. This risk factor originates from the competition of cheaper per-unit generation technologies or cheaper production in other countries (European Commission & Directorate-General for Energy, 2023).

For a company to reach a strategically dominant position, it needs a thorough analysis of both local and international competitors to effectively navigate the hydrogen market. This involves anticipating future scenarios and the complex variables that could impact decision-making in an unpredictable regulatory landscape. To gain a comprehensive understanding of the competitive landscape and assess the potential risks of the competition of production methods, a multifaceted study is required to be undertaken. A complex study that includes all institutional, economic, societal, and technical factors within a systematic comparison of alternative hydrogen production methods in a European context.

The main difficulty facing stakeholders is sifting through the distributed collection of knowledge about the different hydrogen production methods, their status, and the overall market dynamics. Relevant information is readily accessible; however, it is dispersed over several sources, each using a distinct set of metrics and units, making comparing them challenging and often unsatisfactory. Because it limits the clear, unified vision required to comprehend the competitive environment of low-carbon hydrogen production technologies, this fragmentation of critical information poses a barrier to strategic decision-making. The lack of consistent structure makes it more difficult to evaluate the available information, which could result in the exclusion or incorrect assessment of crucial elements influencing investment decisions and market strategies.

Therefore, research is necessary for the case of the North-Western European hydrogen system. An overview of relevant factors could enhance the decision-making process for companies on what steps to undertake now and in the future by gaining an overall insight into the status and outlook of the system. The final deliverable of this master thesis will be a model created for the user to assess the feasibility of hydrogen types based on techno-economic factors. This model would be able to answer the main research question with options to influence its outcome, where necessary, to discuss minimizing risk in the future. This is all to see a meaningful apples-to-apples comparison between the most promising alternatives of green hydrogen for decarbonization of hard-to-abate industries based on their techno-economic properties influenced by socio-technical and political characteristics.

1.3 State of the art

The evolving state of the art and the increasing strategic importance of green hydrogen can be underscored by understanding the growing body of literature and reports from leading consultancies and international agencies. These sources offer a comprehensive overview of the current and future energy system landscape, emphasizing developments specific to Europe. Europe is often regarded as a testing ground for both the technologies and the policies surrounding this energy source, potentially setting a precedent for global deployment (van Renssen, 2020). These entities provide knowledge on the exact role green hydrogen is expected to fulfill in the system throughout the coming years, each contributing to a unique perspective. These perspectives include technological advancements, policy frameworks, market trends, and the obstacles confronting the hydrogen industry.

However, one of the key challenges in synthesizing these different perspectives is the difficulty of drawing a direct comparison, especially between various hydrogen production methods and the dynamics of hydrogen imports in different systems. Therefore, the literature review focuses on the state-of-the-art methods used for directly comparing low-carbon hydrogen varieties. Previous studies compared low-carbon hydrogen varieties, notably green and blue hydrogen. These studies focused on specific fields of interest, encompassing socio-technical and techno-economic domains as well as a range of other critical metrics.

To start, Ajanovic et al. (2024) give insightful information on the role of green hydrogen in the decarbonization of Europe. They do agree that to understand the future prospects of green hydrogen, a comprehensive analysis is necessary. An analysis that answers multiple institutional, technical, social, and economic questions and is specified for green hydrogen. Zainal et al. (2024) provide valuable perspectives on technological maturity, costs, and environmental impact, focusing on green hydrogen and comparing it to other major hydrogen types, or so-called colors, to create an overview of the current hydrogen landscape. An overview that shows each factor and explores multiple important domains to discover the status and outlook. The outlook for green hydrogen, which is positive, has several options for eventually becoming the industry standard, as multiple electrolyzer technologies and policy incentives are on the horizon.

Focusing more on the economic viability and finance of green and blue hydrogen, Webb et al. (2023) explore the cost dynamics of hydrogen. This study debates the comparative economics of green renewable, and blue gas-derived hydrogen with multiple standard metrics such as the Levelized Cost of Hydrogen (LCOH) and CO_2 prices. When considering the latest increase in EU carbon pricing and fugitive emissions, green hydrogen could approach cost parity with blue hydrogen, especially in favorable locations with low-cost renewable energy. Both articles mention blue hydrogen as an important transitional pathway because this hydrogen variety allows a more economically viable transition. Ajanovic et al. (2022) discuss the color spectrum of hydrogen as well and analyze the economic and environmental performance per color. Emphasis is put on the full environmental benefits of green hydrogen. It is very dependent on energy sources and production methods. They stress the necessity of an international hydrogen market to fulfill the potential of green hydrogen but also raise questions about the economic competitiveness of green hydrogen compared to other varieties.

Further contributing to this discourse, Durakovic et al. (2023) explore the economic aspects of green and blue hydrogen and analyze to what extent blue and green hydrogen are complementary or competitive in the future hydrogen mix. Once again, this indicates that exclusively adopting green hydrogen could result in higher transition costs. This study provides a detailed understanding of the dynamics between green and blue hydrogen, shedding light on the short-term economic advantages of blue hydrogen from a long-term viewpoint. AlHumaidan et al. (2023) also examine the hydrogen landscape from the blue hydrogen perspective, including aspects such as economic viability, life cycle analysis, and even policy evaluation of the technologies. The study presents the value chain, encompassing aspects of storage and transport, and provides an in-depth examination of crucial carbon capture technologies required for blue hydrogen production. It highlights the significance of large-scale blue hydrogen production and the vital role of fossil fuels in the transition, reinforcing the findings from previous research.

Adding to this multifaceted analysis, Shirizadeh & Quirion (2023) focus on a model of the hydrogen and electricity production mixes in France, further understanding the landscape and the associated economic status and outlook of blue and green hydrogen. Their study highlights the importance of integrating different hydrogen varieties in the energy system, considering several factors like system costs, production costs, and final electricity and hydrogen costs. A key addition is also the inclusion of nuclear power besides renewable power in the analysis, further enriching the understanding of hydrogen in the energy transition. Adding to these perspectives is the study of Mio et al. (2024), which use process simulation to analyze hydrogen produced from different feedstocks. They utilize various sustainability indicators, including Levelized Cost of Hydrogen (LCOH) and Life Cycle Assessment (LCA), which are recognized as standardized metrics. They provide insight into the practical application of hydrogen in transportation as well as a method of exploring the economic and environmental sustainability of the different hydrogen varieties.

Cheng & Lee (2022) question the commitment of national hydrogen strategies to the decarbonization objectives. This analysis provides an essential policy perspective, complementing the techno-economic aspects in the other studies. In further literature, Noussan et al. (2020) focus more on the geological and technological perspectives and highlight the broad challenges and opportunities of climate strategies. The paper emphasizes the importance of transport and storage for blue and green hydrogen, recognizing the importance of both national and international climate strategies. They advocate for transparent standards and targets in the hydrogen economy. Seck et al. (2022) also perform a comparison between hydrogen varieties and discuss the technical challenges and economic implications, with a focus on technical and geopolitical aspects and the new momentum hydrogen has in national and international climate strategies. They highlight the importance of including the whole supply chain, including storage and transport, in the analysis. Lagioia et al. (2023) further this body of research by examining the production and management of blue and green hydrogen within the EU's decarbonization goals. The study emphasizes the necessity of developing realistic strategies and brings to light the technical and infrastructural challenges involved in the deployment of these technologies. The realistic strategies should comprehensively address plans for the storage and transport of hydrogen, especially for sectors less amenable to electrification.

Griffiths et al. (2021) provide a systemic socio-technical perspective on the role of hydrogen in industrial decarbonization. They clarify the relationship between different actors and variables within the system, developing metrics to evaluate each aspect's performance. This results in a comprehensive overview of the whole hydrogen system, including the functions and roles of the low-carbon hydrogen varieties. An overview that enriches the understanding of the status and outlook of different hydrogen varieties in a simple, non-technical manner. Genge et al. (2023) specifically examine the supply costs of green hydrogen in Europe. They elucidate the implications of importing green hydrogen and the costs associated with oceanic transport. This examination is crucial for understanding the cost dynamics and economic landscape of transportation within the value chain. Their findings highlight the importance of transparency in utilizing green hydrogen as a central energy carrier in the future European energy mix.

Shin's (2022) study provides an insight into the Korean hydrogen value chain, analyzing the technological developments in each step of that chain. It highlights different technologies, such as underground storage of hydrogen or improved international transport, that could help create the hydrogen economy. The study underscores the importance of aligning policy with technological advancements to create a competitive cost per unit for hydrogen, advocating for clear and efficient policies for a global shift from carbo-based to hydrogen-based economies. Furthermore, Lee et al. (2022) focus directly on the economic and environmental aspects of overseas transport, which is part of the intercontinental supply chain. Their insight is that the full supply chain should be considered for the final price of hydrogen, and a techno-economic analysis, including transport and storage, should be conducted for comprehensive calculations of the ultimate import price of hydrogen.

1.4 Knowledge gap

To summarize, the existing literature offers extensive information on various aspects of hydrogen status and outlook. However, a significant knowledge gap exists between the synthesis and integration of all this information. The challenge, therefore, lies not in the scarcity of information, as this is abundant, but rather in the absence of a systemic approach that successfully accumulates, processes, and interprets the different perspectives and information streams. Such an approach is vital to achieving a comprehensive understanding of green hydrogen's risks, commercial status, and involvement in the energy transition.

The field currently employs diverse methodologies and metrics, ranging from socio-technical analyses to economic and environmental value chain assessments. Yet, these are currently not able to be synchronized into a unified framework for the comparison of multiple hydrogen production methods with their unique specifications. The variation in methodologies and metrics, including system costs, LCOH, and policy measures, underscores the significant knowledge gap. The inability to achieve generalized results underscores the need for a unified framework for comparing the different hydrogen varieties and their value chains. Such a framework, incorporating a method or metric that captures most perspectives, would enable more consistent and clear conclusions. Standardization is crucial to accurately assess the viability of various hydrogen types and their potential integration into the European hydrogen system.

1.5 Research Questions

The literature on green hydrogen in hard-to-abate industries is abundant. But a lack of in-depth analysis of the current status and outlook based on their techno-economic characteristics and the socio-technical influences of stakeholders seems like a knowledge gap that must be filled. Especially within literature focusing on technical aspects. There is a demand for an advanced comparison methodology that allows for a straightforward metric to compare key competing, most promising value chains of European green hydrogen, providing a complete overview of the system's current status and prospects. Bringing forward the following main research question (RQ):

RQ ***How do the key competing value chains of green hydrogen, destined for decarbonizing hard-to-abate industries in Northwestern Europe, perform in a techno-economic analysis under the conditions of the drivers and barriers of the innovation system?***

In the European hard-to-abate sectors, hydrogen is seen as the way forward, but a selection of their commercial viability will show what exact alternatives to compare in this current system.

SQ 1. *How are the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe configured?*

For the research to get the proper perspective and determine the precise status of the system at this time, it is necessary to explore the socio-technical innovation system in detail. The system analysis will thoroughly examine the key elements of the innovation system. By doing so, it will pinpoint how these elements operate, providing insights into the drivers and obstacles within the system. This part broadens the focus as the outcomes align for the whole of Europe.

SQ 2. *How do the stakeholders in the European hydrogen system perceive the main system functions of that system, as drivers or barriers?*

Finally, the identified drivers and barriers are incorporated into a techno-economic analysis, enabling calculations for various green hydrogen alternatives. This approach offers a comprehensive view of these alternatives and their respective techno-economic performances.

SQ 3. *How do the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe compare in techno-economic performance?*

Once all the sub-questions are answered, the main research question can be resolved. This is achieved through a multi-dimensional approach that assists users in understanding its competitive position in the current market. Techno-economic assessments that include socio-technical factors will offer insights into the competitive hydrogen landscape in Northwestern Europe and shed light on its present condition and possible future outlook. To the best of the authors' knowledge, there is no mixed-method socio-technical and techno-economic analysis that aims to compare hydrogen systems using one uniform method. Therefore, a simplified tool that enhances decision-making, combining both socio-technical and techno-economic aspects, is the goal of this design.

1.6 Link to the CoSEM Program

The analysis of green hydrogen alternatives within hard-to-abate sectors presents a challenging and multifaceted problem. It is such a problem because it is situated in a multidisciplinary energy and electricity system characterized by inertia and stringent governance. This complexity is displayed through the intricate interplay of diverse stakeholders, complex technological interdependencies, and the unpredictability of environmental, institutional, and socio-economic factors. These elements collectively render the problem a quintessential CoSEM issue. The dynamic nature of this system, coupled with the evolving social context, requires companies to adopt a structured approach to predict trends. A scientifically grounded methodology is required not only to bridge academic knowledge gaps but also to facilitate a thorough commercial and technological evaluation tool for companies.

1.7 Structure of the Thesis

Chapter 1 sets the stage by providing an overview of the current situation, detailing the knowledge gaps, the research questions, and the set scope. identifying existing knowledge gaps, framing the research questions, and defining the scope of this study. Following this, Chapter 2 lays out the theoretical foundation of the research, elaborating on the theories and core concepts used in the thesis. The adopted methodology to answer the research questions is described in Chapter 3. The outcomes of the socio-technical system analysis are presented in Chapter 4, offering insights into the interplay between society and technology within the hydrogen system as well as delivering in-depth analysis on the drives and barriers of the system. Subsequently, Chapter 5 shifts the focus to the techno-economic analysis, presenting a detailed examination of the economic and technical aspects. Discussion and reflection on the findings and the methodologies employed throughout the research are the focus of Chapter 6, as well as providing possible future research. This includes a critical evaluation of the approaches taken and the results obtained. Finally, Chapter 7 wraps up the thesis by reciting the research questions and summarizing the key findings, thereby closing the loop on the study's objectives and contributions.

2
Theoretical Framework

To establish a robust theoretical foundation for this thesis, a detailed framework will be developed, outlining key concepts and theories essential for addressing the research questions. Understanding this theoretical basis is imperative to contextualize the contribution of this thesis to the existing body of knowledge. Section 2.1 involves a detailed exploration of the hydrogen color spectrum. Section 2.2 discusses the chosen method per sub-question.

2.1 Defining the Hydrogen Color Spectrum

Even though hydrogen is an invisible element, a commonly used description of the different varieties is color code oriented. This color system is an easy-to-comprehend system for distinguishing between different varieties without delving into too many complex details. Some discussion is brought up on this system, as it fails in the recognition of certain environmental attributes of the produced hydrogen, meaning that there is uncertainty about its cleanliness (Clifford, 2022; Dawood et al., 2020). For this research, this system will suffice. An explanation of the main hydrogen colors gives insight (Ajanovic et al., 2022; Sen et al., 2022).

Black or brown hydrogen is produced through coal gasification, a process where coal is converted from its solid state into gaseous form. This way, hydrogen, via a chain of processes, can be extracted (Sen et al., 2022). Since it produces the same amount of carbon dioxide as burning the source fuel initially, it is seen as the most carbon intensive approach for producing hydrogen (Arcos & Santos, 2023).

Grey hydrogen is produced through the steam methane reforming (SMR) process (Ajanovic et al., 2022). Methane is combined with steam at high temperatures and pressure to create both carbon dioxide and hydrogen. Together with black hydrogen, grey hydrogen is mostly used in petrochemicals and ammonia production (Ajanovic et al., 2022). Unfortunately, grey hydrogen also has the disadvantage, just like black hydrogen, that it is associated with a significant amount of carbon dioxide pollution. They are currently, the most cost-effective option (Ajanovic et al., 2022).

Blue hydrogen is created through the same process as grey hydrogen, SMR; however, the addition of a Carbon Capture, (Usage), and Storage System (CCS or CCUS) reduces the majority of carbon dioxide (CO_2) emissions before they are emitted into the atmosphere (Arcos & Santos, 2023; Sen et al., 2022). While grey hydrogen production releases greenhouse gases into the air, blue hydrogen production carbon captures them for up to 95% (Hermesmann & Müller, 2022; IRENA, 2020a). At the moment, this less-emitting alternative to black or grey hydrogen also has a price advantage over green hydrogen (Sen et al., 2022), making it an interesting option for many countries in the energy transition (Deloitte, 2023).

Green hydrogen, is generated using water electrolysis with power derived from renewable energy sources. Hydrogen is synthesized by electrolyzing water (H_2O), a procedure that requires an electrical input to start the chemical reaction breaking down water molecules into their component elements, hydrogen (H_2) and oxygen (O_2) (Sadiq et al., 2023). This electrolysis reaction is described in Equation (1) below (Sadiq et al., 2023; Vidas & Castro, 2021):

$$H_2O \xrightarrow{Electricity+Heat} H_2 + \frac{1}{2}O_2 \tag{1}$$

This electrolyzed reaction is powered solely by electricity obtained from renewable resources, ensuring the carbon neutrality of the procedure. Therefore, it is often also referred to as "clean hydrogen," "renewable hydrogen," or "carbon-free hydrogen" (Arcos & Santos, 2023). Alkaline, PEM (Proton Exchange Membrane), and solid oxide electrolyzers (SOEC) are the most common electrolysers discussed in the literature and available for production (IRENA, 2018).

Pink hydrogen is created through the electrolysis of water, similar to green hydrogen (see Equation (1). However, the key difference lies in the electricity source: pink hydrogen uses nuclear power (Arcos & Santos, 2023; Sen et al., 2022). This process involves an electrolyzer, utilizing the low-carbon electricity generated from nuclear energy and water as feedstock (Sen et al., 2022). Alternative names for pink hydrogen include red hydrogen or purple hydrogen. All these variants often employ nuclear heat in so-called hybrid systems, which generate steam to facilitate a more efficient electrolysis process (Arcos & Santos, 2023; Marchant, 2021).

Turquoise hydrogen is made through methane pyrolysis. The natural gas is split by a pyrolyzer, resulting in solid carbon and hydrogen. The solid carbon can more easily be processed and/or stored (Ajanovic et al., 2022). The turquoise color corresponds to the green and blue colors because, despite using natural gas as the raw material, the method has a low carbon intensity, making it a desirable choice (Arcos & Santos, 2023; Sen et al., 2022). At the moment, this technology has not been commercialized as it only raised interest in the production of hydrogen in the last few years; therefore, maturity has not yet been reached for this technology (Ajanovic et al., 2022; Arcos & Santos, 2023).

Yellow hydrogen is produced using grid electricity. Hereby again, a water electrolysis process is used, as with green and pink processes in Equation (1), only the source of electricity differs (Arcos & Santos, 2023). The problem with this type of hydrogen is that the carbon emissions can vary over time; it all depends on the energy sources provided to the grid. When these are renewable or low carbon, there is no problem; however, that is not always the case (Ajanovic et al., 2022; Arcos & Santos, 2023). In one country, for example, the energy mix could be almost renewable, while in another, this is not the case, making the grid energy that is the input for the yellow hydrogen electrolyser carbon energy that has been emitted. It all depends on the total energy mix of the country (Ajanovic et al., 2022; Arcos & Santos, 2023).

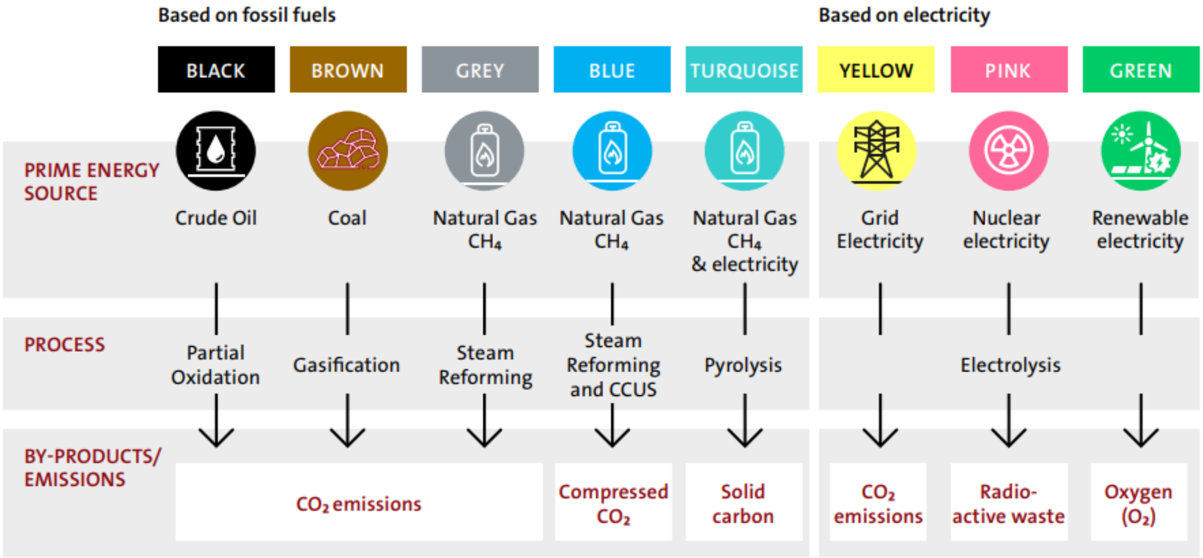

Figure 2.1: Colours of hydrogen from KGAL (2022)

2.2 Theoretical review of methods

In this section, the chosen methods for addressing the subsidiary questions are examined. The suitability of these methods is explained in relation to their effectiveness in answering research questions.

2.2.1 Sub-question 1

Firstly, a research method shall be depicted to be able to answer sub-question 1: *How are the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe configured?*

To be able to answer this research question, the leading competitors' value chains should be defined. Desk research revealed that the European Commission (European Commission, n.d.-a) has a clear long-term strategy where the aim is to transition the economy to net-zero greenhouse gas emissions by 2050. This goal, which is in line with the Paris agreement, allows the system to support strategic investments in "clean" hydrogen (European Commission, n.d.-e). This question is the question of which colors of hydrogen, all having different production methods, energy sources, and therefore different environmental impacts, have a different future in the European hydrogen market, is the question. For this, not only the stakeholders but also the regulations should be defined next to the already-mentioned technology and even the imports that compose the full value chains of hydrogen. Therefore, a structured method is necessary to understand the possible scope of the green hydrogen competitions and discover what the stakeholders actually define as their leading competitors.

The method chosen is the structural analysis that is phase 1 of the Technological innovation system (TIS) analysis proposed by Hekkert et al. (2011), as can be seen in Figure 2.2 below. Because of the complexity of the system of green hydrogen in Europe, a structured approach is necessary to understand the complex dynamics within the system. A key part of analyzing the implementation of a technology, in this case electrolyzers for green hydrogen, is understanding the structure and dynamics of the innovation system around it. Carlsson & Stankiewicz (1991, p.93), one of the first authors to write about this concept, describe a technological innovation system (TIS) as follows: ´*a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional* *infrastructure and involved in the generation, diffusion, and utilization of technology.'* Building upon his foundational work, Hekkert et al. (2007) refined the concept of TIS to create the Technological Innovation System (TIS) framework, as it is a framework specialized in mapping complex innovation systems in a structured manner. It encompasses multiple structural components, including actors, networks, institutions, and networks (Bergek et al., 2008; Hekkert et al., 2007). These structural dimensions form the boundaries of the system (Wieczorek & Hekkert, 2012).

The TIS framework allows for a thorough examination of the systemic interactions between different elements that affect technical innovation, especially in the context of emerging technologies like green hydrogen and, in this case, hard-to-abate industries in the North-West of Europe (Bergek et al., 2008; Hekkert et al., 2007). Comparing TIS to other transition studies like the Multi-Level Perspective (MLP) and Strategic Niche Management, there are considerable differences. The TIS offers methodological benefits by focusing on the innovation dynamics within a specific sector. Whereas the Multi-Level Perspective studies larger socio-technical interactions, Strategic Niche Management concentrates on technological niches (Geels, 2002; Kemp et al., 1998). Technological, economic, social, and institutional factors are all integrated into its comprehensive approach, which is essential for grasping the status and outlook of the entire innovation system. This approach of using the four different components is the main takeaway in this thesis, as it is used as a tool for socio-technical system analysis.

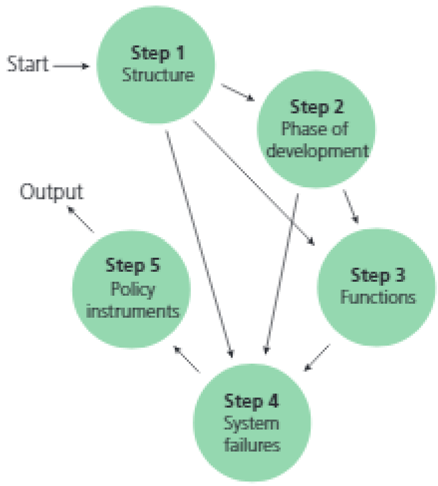

Figure 2.2: The five steps of analyzing a technological innovation system for policy analysis (Hekkert et al., 2011)

2.2.2 Sub-question 2

Secondly, a suitable method shall be depicted for answering the second sub-question of this thesis: *How do the stakeholders in the European hydrogen system perceive the main system functions of that system, as drivers or barriers?*

To answer this sub-question, the search is for a tool that allows the user to discover drivers and barriers to the adoption of a technology. The second method is again based on the TIS analysis proposed by Hekkert et al. (2011). This time, the third phase of the process is used: functional analysis. The combination of structural and functional analysis allows the framework to be used in multiple steps, and here again, the methodological benefits as it focuses on the dynamics within a sector, as stated in subsection 2.2.1.

Focusing on the factors that influence and obstruct technological innovation (TIS) has several benefits, especially when these perceptions are to be incorporated into a techno-economic evaluation (TEA). Drivers are defined as the motivation for development by stakeholders, while barriers are hindering development. This strategy, as described by Hekkert et al. (2007), ensures a precise and pertinent analysis by directly targeting the elements that support or inhibit innovation, making the resulting data more pertinent for technological and economic assessments. Insights gained from comprehending drivers and barriers are also immediately practical, improving TEA procedures. They provide a practical grasp of the 'why' behind a technology's socio-economic, institutional, and technical perspective, improving the strategic depth of the TEA (Bergek et al., 2008). Furthermore, emphasizing TIS drivers and barriers improves stakeholder participation, which is essential for effective TEA.

By focusing on the roles that influence the growth and adoption of technologies within a certain industry, such as green hydrogen, TIS provides methodological benefits (HEKKERT ET AL., 2007). It considers the whole complex, multi-dimensional system of green hydrogen. This approach is crucial for pinpointing drivers and barriers in the green hydrogen industry and guiding the strategic choices and legislation required for game-changing change. The methodological chapter that follows will highlight TIS's exact analytical skills in the context of green hydrogen, a key feature that distinguishes it from other frameworks.

It must be emphasized that only a portion of the TIS analysis, phases 1 and 3, will be utilized, as the actual end goal of a TIS analysis is to provide policy advice on the least-performing functions. In contrast, the objective here is solely to identify where in the system, according to literature and experts, the bottlenecks and drivers are situated and in what form they manifest. This distinction is crucial for understanding the approach and focus of this research. The use of phases 1 and 3 aligns with the research goal of this thesis, so steps 2, 4, and 5 shall not be used.

2.2.3 Sub-question 3

Thirdly, a method shall be depicted to be able to answer the third sub question: *How do the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe compare in techno-economic performance?*

To assess the techno-economic performance, which allows for comparability of the economic viability of the different value chains, a comprehensive method is necessary. The need is for a metric that allows different production methods to be compared. The use of Levelized Cost of Hydrogen (LCOH) as an indicator in comparison studies is commonly adopted in comparing different hydrogen sources (Correa et al., 2022; Mio et al., 2024; Webb et al., 2023). LCOH represents the ratio of the net discounted cost of hydrogen production to the net discounted amount of hydrogen produced over the plant's lifetime, especially for hydrogen as an energy carrier (Mio et al., 2024). This metric provides a clear picture of the cost efficiency of hydrogen production, factoring in all expenditures over the plant's lifespan. It allows for benchmarking the cost-competitiveness of hydrogen production.

The method of reaching the metric of LCOH is techno-economic assessment, a tool that allows for measuring that economic viability. This tool provides structure for developing answers that entail the same scope, boundaries, and units. This method is chosen for its comprehensive scope and ability to provide an apples-to-apples comparison in the form of LCOH values that can be compared by quantifying manufacturing costs and market opportunities. The reason for using this method, adopted by Zimmermann et al. (2020), is its systematic approach, adjusted to fit this study.

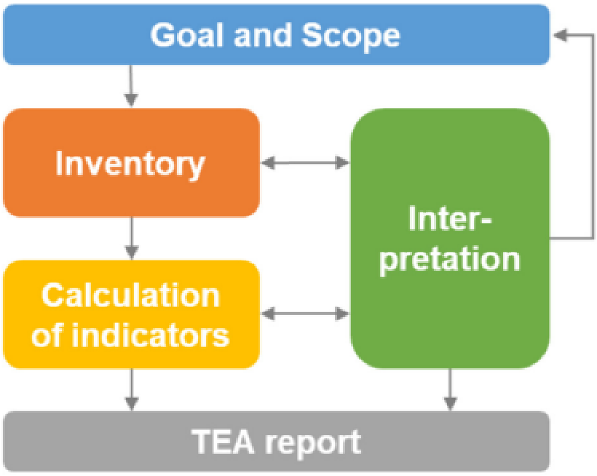

Figure 2.3: Phases of techno-economic assessment by Zimmermann et al. (2020)

Given the diverse 'colors' within the hydrogen spectrum, each representing different production methods and energy sources, a standardized metric for comparison is necessary: the Levelized Cost of Hydrogen (LCOH). LCOH is an essential financial metric that calculates the per-unit cost of hydrogen production over the life cycle of a project, specifically tailored for evaluating hydrogen as an energy carrier (Mio et al., 2024). This metric is instrumental in comparing the economic viability of various hydrogen production methods (Mio et al., 2024; Shirizadeh & Quirion, 2023; Webb et al., 2023). It provides policymakers and investors with a key indicator for making better-informed decisions, ensuring a comprehensive understanding of the cost implications across different hydrogen production technologies.

In order to account for the time value of money in these calculations, the Weighted Average Cost of Capital (WACC) is used as a discount rate to discount the total costs over the years. WACC is used as the discount rate that represents the anticipated rate of return that a business needs to provide to potential investors in order to raise capital and fund its operations (BEIS-UK, 2021). WACC effectively adjusts future costs and production output to their current value through LCOH, providing a thorough and realistic evaluation of the viability of hydrogen generation projects from an economic standpoint. Which is vital for the comparison of projects over their lifetime. The LCOH, in this case, does include inflation as well, to make sure the future costs do not get undervalued, meaning the WACC will be harder to achieve.

The WACC functions as the rate of production and cost discounted over time for levelized costs. A higher WACC makes the LCOH less weighted by the produced hydrogen and more by the other costs. Projects with higher WACC could be interpreted as lower-risk takers with high capital costs, as there is less assurance that the revenue from hydrogen production will eventually yield a sufficiently high rate of return. On the other hand, there are projects with WACC. Here, the LCOH is more weighted by the hydrogen produced and less by the upfront CapEx. Here, there is also a contrasting conclusion with a high WACC. The projects are deemed lower-risk and more confident in a sufficient rate of return through their lifetime (Department for Business Energy & Industrial Strategy, 2021).

2.2.4 Main research question

Lastly, a method shall be depicted to be able to answer the main research question: *How do the key competing value chains of green hydrogen, destined for decarbonizing hard-to-abate industries in*

North-Western Europe, perform in techno-economic analysis under the conditions of the drivers and barriers of the innovation system?

To be able to answer this main question, a combination of qualitative and quantitative analysis is needed. The addition of qualitative socio-technical analysis to a TEA is to create realistic stakeholder-identified scenarios, and a more comprehensive context for the final answer. This allows the user to not only look at the numbers the model is spitting out but also to create specific context for their model, providing more depth to the numbers used. Conclusions can now be drawn on multiple levels, meaning that the inclusion of a structural and functional analysis in a TEA allows for more strategic decision-making by creating a more comprehensive overall picture.

By incorporating the drivers and barriers from the TIS analysis in the TEA, particularly when intended to determine the LCOH, it becomes significantly more insightful. A comprehensive mixed-method. This thorough approach explores not only the immediate economic concerns but also the systemic elements affecting the viability and cost-effectiveness of green hydrogen production. The assessment offers a realistic basis for strategic decisions by addressing the dynamic interaction of these factors, reflecting the complex realities of the energy business.

The goal of the model is to compare the key competitors of green hydrogen in north-western Europe under the conditions of the innovation system to gain an apples-to-apples comparison of the most promising, key competing alternatives of green hydrogen for the decarbonization of these hard-to-abate sectors based on their levelized cost of hydrogen.

The output of the model will be the cost breakdown of the different parts of the value chain compared to other production methods. The levelized cost of hydrogen will be the main metric, as this metric includes economic viability over time and takes inflation into account.

3 Methodology

Chapter 3 outlines the research methodology with distinct sections for clarity. Section 3.1 details the research design, defining the research approach. Section 3.2 elaborates on data collection, highlighting the selection and sources. Section 3.3 describes the application of the Technological Innovation System (TIS) for socio-technical analysis, emphasizing its selective use. Section 3.4 focuses on Techno-Economic Analysis (TEA), evaluating the economic and technical aspects of hydrogen production. A flow diagram visually summarizes the research journey, connecting methodologies to the study's goals. This structure ensures a clear understanding of the methodology's comprehensive and targeted approach.

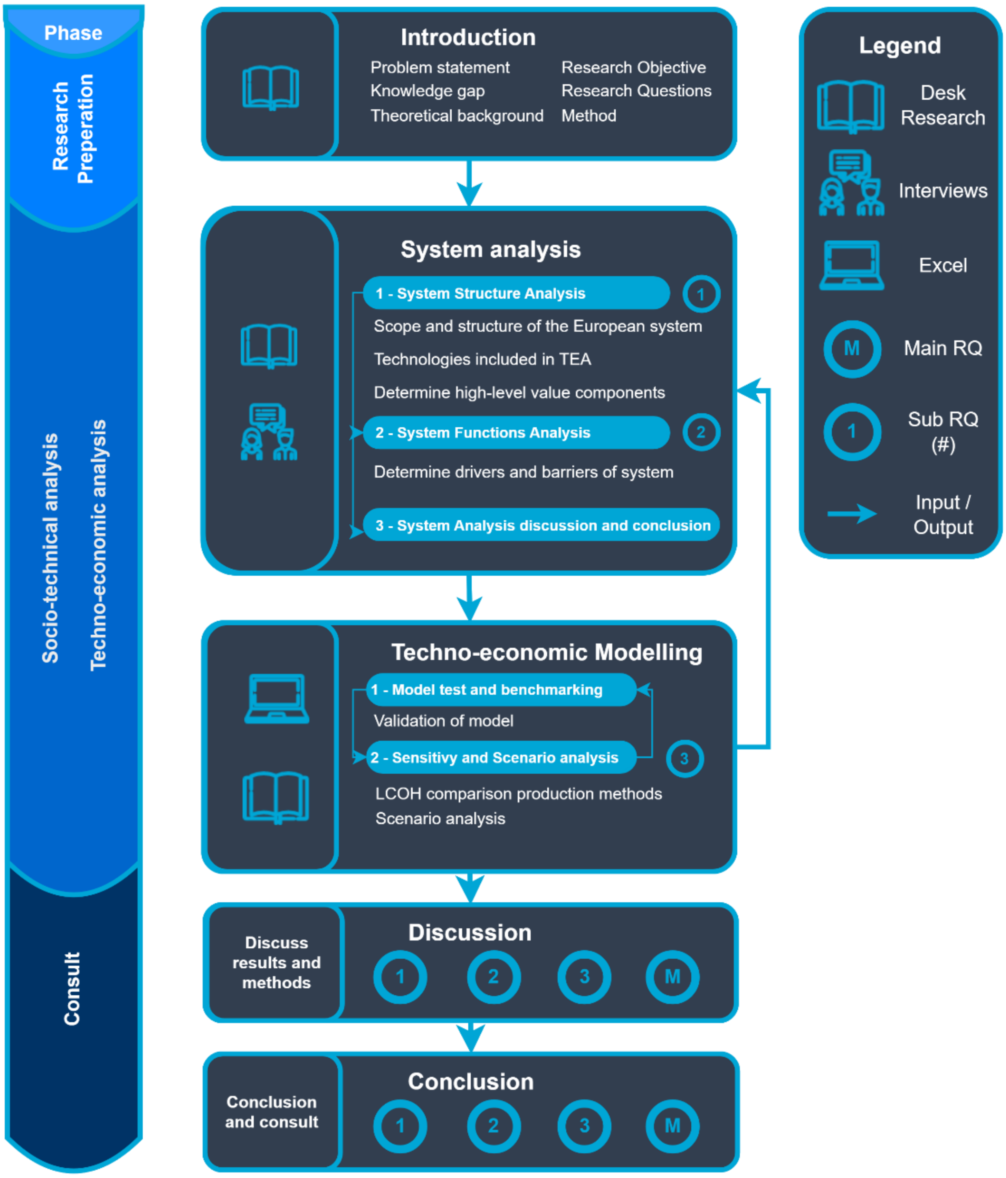

Figure 3.1: Research Flow Diagram

3.1 Research design

The flow of the research can be found in Figure 3.1 above. The different phases of the thesis are presented on the left, emphasizing the integration of qualitative and quantitative methods. This mixed-method approach resulted in an analytical phase where distinct analyses intersected and iteratively refined, highlighting the dynamic interplay between different research dimensions. This integration leads to an iterative analytical phase, significantly strengthened by expert feedback and validation, ensuring the research's depth and accuracy.

3.2 Data Collection

This section elaborates on the data collection for this thesis. Given the dynamic nature of the system's development and the possibility of future data contradicting the previous data, the data collection scope was set to February 10, 2023, and was concluded by that date. Up-to-date literature was used to create a state-of-the-art overview with the input of experts around the value chain. Besides the collection, the management of data is especially important, as this must be in line with overall the Delft University of Technology, general data protection regulation, and human research ethics committee guidelines. The collection and analysis methods are covered in the sections that follow.

3.2.1 Literature Review

The literature for the review originates from the Scopus and ScienceDirect online databases. These sources were assessed and selected with the aid of relevant articles and peer evaluations. A structured literature review was used according to the PRISM Scheme to ensure a comprehensive search for a possible (Page et al., 2021), which can be found in APPENDIX A. Grey literature, alongside scientific literature, was incorporated to achieve a more complete and current comprehension of the situation and structure. International agencies like the IEA and IRENA are regarded with the same esteem as scientific articles, together forming a robust foundation of techno-economic data.

In the search queries, the key concepts and the information needed to relate theory to this topic were sought after. The literature review only includes articles published after 2021 to be as up-to-date as possible; older literature was only contributed via snowballing, but it was carefully vetted to ensure that it would still have a beneficial effect on the paper's conclusion. Because a problem statement is present and not a research objective, a literature review was performed on the theoretical framework and methodology, as new insights could be discovered as the problem statement was already a known academic gap.

3.2.2 Expert Consultations

The interviews or consultations were designed to gather a diverse range of perspectives from the stakeholders, or experts, within the hydrogen value chain. These interactions were particularly focused on understanding the system structure as well as identifying the drivers and barriers of the innovation system in Europe. Contrasting the information from the consultations with the insights drawn from the reviewed literature is one of the primary objectives.

The term 'consultation' is used to describe these interactions because, although they began as semi-structured interviews, they often evolved into more in-depth discussions; however, for the sake of consistency with the used literature, they shall be depicted as interviews in this section. During these conversations, interviewees, who were experts in specific areas of the value chain, shared a wealth of ideas, information, and suggestions, contributing significantly to the research. These exchanges provided a platform for an open exchange of insights, enhancing the depth of understanding of the subject matter. Desk research was employed to create a set-up for the semi-structured interviews used to collect the required data to answer the research question.

Semi-structured interviews were conducted with experts on the issue, resulting in an open conversation that reflects the flexible nature of qualitative data (Bryman, 2016; Myers & Newman, 2007). This form allowed the interviewee the opportunity to explain and go deeper into the questions, leading to more in-depth discoveries, while also being able to iterate the questions for future interviews. In addition to questions about their fields of expertise, all of the respondents were also asked a few interdisciplinary questions to elicit their opinions on various subjects from multiple disciplinary perspectives. The reason for using Bryman's semi-structured interview is the flexibility and depth the interview allows. The interviewer can respond to the interviewee, enabling them to delve deeper into specific subjects. This will provide rich qualitative data while also understanding the context for that exact interviewee (Bryman, 2016; Myers & Newman, 2007).

Their various economic, technical, institutional, and social viewpoints in the systems thinking of Hekkert et al. (2007, 2011) help formulate the different drivers and barriers in the system while also providing knowledge on the system structure. Stakeholders that are connected to the value chain of green hydrogen were interviewed; the interviews would initially be conducted physically and otherwise using an online video platform because this involved the subject more in the interview (Bryman, 2016). The interviewees were found through company, personnel, and TU Delft networks and were asked for contacts in the hydrogen system open for conversation.

The interviews were structured around the seven system functions framework proposed by Hekkert et al. (2007). The design of the questions allowed for flexibility and interchangeability. The absence of certain discussions was not critical since the functions are interlinked. The primary focus was on the interviewees' perspectives regarding the most significant drivers or barriers within the system, facilitating discussions about what they considered crucial for the system's operation or obstacles. Unlike Hekkert's objective of formulating policy recommendations, the aim here was to explore the European hydrogen system to identify existing barriers or drivers, and to understand how different stakeholders involved in the beginning and throughout the value chain perceive them.

The interviewees were provided with the list of questions in advance to ensure they were aware of the conversation's intended scope. It was communicated that they could focus on selected questions, especially in cases of time constraints, to facilitate a productive dialogue within the limited time available. The primary objective remained to understand the system and identify potential drivers or barriers, as perceived by the interviewees. Consequently, the direction of the conversation often concentrated on the interviewees' expertise in specific areas. This approach allowed for more in-depth insights into topics where the interviewees had greater knowledge. Summaries of these interviews are available in Appendix D.

Table 3.1: Overview of Expert Consultations

#	Stakeholder group	Interview job title	Code in text	Date	Duration (min)
1	Power Company	Business Developer	EC1	Oct-23	**45**
2	Power Company	Policy Communicator	EC2	Nov-23	**45**
3	Knowledge Institute	Professor	EC3	Nov-23	**45**

4	Knowledge Institute	Business Innovation	EC4	Nov-23	**60**
5	Financial Institute	Researcher	EC5	Nov-23	**30**
6	Power Company	Innovation manager	EC6	Nov-23	**45**
7	Hard-to-abate Industry	Analyst	EC7	Nov-23	**45**
8	Hard-to-abate Industry	Analyst	EC8	Jan-24	**30**

3.2.3 Data Management Plan

TU Delft mandates adherence to the General Data Protection Regulation and Human Research Ethics Committee guidelines for all research activities. In alignment with these requirements, during interviews, explicit consent was sought from each interviewee prior to commencing the interview. The interviewees were informed about the use of their input in this thesis, which will eventually be made public, and were advised to refrain from sharing sensitive information. Following the interview, a summarized and anonymized transcript was sent to the interviewee. This allowed the interviewee an opportunity to propose any modifications, ensuring clarity and agreement on the information to be published. Once a consensus on the transcript's contents was reached and a definite agreement by the interviewee was given, the text could be incorporated into the thesis. To maintain compliance with TU Delft's regulations on data handling, a data management plan was established. For qualitative analysis and reasoning, Microsoft Word will be employed, while Microsoft Excel will be used for numerical and performance analysis. All data will be securely stored within TU Delft's OneDrive environment.

3.3 Socio-technical System Analysis

To comprehend the dynamics of the European hydrogen system, a comprehensive system analysis was undertaken. This socio-technical analysis was conducted in two stages, executed concurrently. Firstly, the various hydrogen varieties and their respective value chains were identified and defined for inclusion in the techno-economic model. This is the structural analysis based on the structural components of the TIS analysis. Secondly, an examination of the European hydrogen system was conducted to identify key variables that could be classified as drivers and barriers. This is the functional analysis based on the system functions of the TIS analysis (Hekkert et al., 2011). The conclusion of the structural analysis highlighted the chosen value chains that were eligible in the European landscape. The conclusion of the functional analysis highlighted the drivers and barriers that were most influential on the European hydrogen system. The systemic functions and underlying variables, in combination with the main value chains, formed the basis for scenarios in the techno-economic analysis.

3.3.1 Structural analysis

The structural analysis, part of the TIS analysis by Hekkert et al. (2011), was used as a tool to be able to answer SQ 1: *How are green hydrogen leading competitors' value chains for decarbonizing hard-to-abate industries in Europe configured?*

For this study, the hydrogen value chain focused solely on the energy source and production method. The value chain, typically segmented from research to application, varies across studies (Alsaba et al., 2023; Eicke & De Blasio, 2022), with key segments identified as production, distribution, and end-use (TÜV, n.d.). This research targeted hard-to-abate sectors as the end-use, where the nuances of hydrogen storage and transmission were deemed uniform across types. All hydrogen was assumed to be equally functional at the endpoint. The emphasis was thus on production, exploring technology, and energy sources. This approach assumed that the rest of the supply chain—transportation, storage, and distribution—had minimal impact on the comparative analysis due to similarities across hydrogen types. The focus on production allowed for an in-depth assessment of various hydrogen production techniques and their contribution to decarbonization. Offering a concise comparison of their environmental and economic impacts and identifying competitive alternatives within the hydrogen market. International import costs were out of scope, but the comparison was still made based on the techno-economics of their energy sources and production methods. This is to see how competitive all energy source and production technology combinations can be for international competition.

In this phase, green hydrogen alternatives were chosen based on the political and socio-economic situation. However, this status had to be accumulated through a methodological approach. The structural analysis of the TIS provides this approach and helps identify the most important components of the system. While an in-depth review of the literature offered an extensive industry background, first exploratory interviews with experts offered concrete suggestions. The emphasis was on alternatives that comply with European regulations, are technologically feasible, and have an established market. A balanced understanding was ensured by this dual-method approach, which highlights possibilities that are ready for more in-depth techno-economic examination while eliminating those that are unrealistic.

The structural analysis of the TIS analysis manual by Hekkert (2011) was used for this part of the analysis. By using the four components of the TIS - actors, institutions, networks, and technology - the structure was defined for the European hydrogen system. This structure was useful for exploring the scope of the comprehensive innovation system, whereby decisions on what set the European hydrogen system boundaries could be made based on this analysis. The structural components of separate analyses were used as filters that helped in the selection of the main competitors. Consequently, in between these components, the main takeaways were used to further refine the search and funnel the results into a manageable few for the techno-economic analysis. In Figure 3.2, the flow of the structural analysis is shown, and below, the different parts, or filters, of the analysis are elaborated on.

3.3.1.1 Actor analysis

The different stakeholders in the system were mapped out to understand the scope of the hydrogen system and identify the present stakeholder groups. The focus was also on the value chain within the European hydrogen system, specifically on pinpointing exact stakeholder groups. These groups, primarily concentrating on the implementation of (green) hydrogen, form the backbone of the system. Appendix B provides an example of such a system, which served as inspiration for creating a version tailored to the European hydrogen system. This coherent overview not only facilitated a clearer understanding of the system's structure but was also instrumental in guiding the search for interviewees. The stakeholder groups were discussed in order of the present actor categories provided by Hekkert et al. (2011). The interactions between the actors were analyzed and explained.

3.3.1.2 Institutional analysis

The institutional analysis solely focused on formal 'hard' institutions, as Hekkert et al. (2011) argue, as the informal 'soft' institutions are impossible to map systemically. This analysis incorporated key European legislation, regulations, mandates, and policy instruments that are expected to impact hydrogen projects in the coming years. These institutions are considered crucial in determining the specific hydrogen varieties to be included in the techno-economic analysis.

3.3.1.3 Network analysis

The actor analysis partially fulfilled the network analysis by assessing the relationships between different stakeholders in the system. The network analysis focused on the body of literature discussing hydrogen import, which allowed for identifying potential non-European stakeholders that could become part of the value chain arriving in Europe and thus influence the system. However, these costs for in-land transport were not included in the scope of this thesis. The network analysis focused on the possible international competitors, renewable energy hotspots with great potential. It also examined what variables and parameters were necessary for the TEA that allowed for the same result as including more variables but could be simplified for greater clarity in assessing the key drivers of the ultimate price.

3.3.1.4 Technological analysis

The technological analysis focused on introducing the various production methods applicable within the European system, specifically emphasizing hydrogen production systems suitable for future European contexts. This background enhances the understanding of the hydrogen production methods used in the analysis, creating a better context. This exploration specifically addresses the technological approaches to hydrogen generation. With particular emphasis on the most prevalent methods and their underlying technologies, notably in fossil fuel-based and electricity-based hydrogen production (KGAL, 2022; Zainal et al., 2024). The conclusion of the structural analysis identified the green hydrogen value chains critical for decarbonizing hard-to-abate industries in Europe.

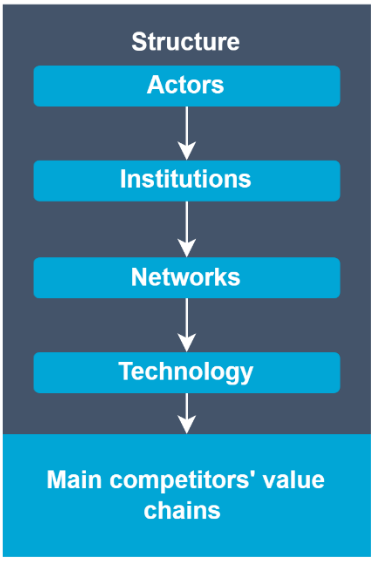

Figure 3.2: Structural analysis flow

3.3.2 Functional analysis

The functional analysis part of the TIS analysis by Hekkert et al. (2011) was used to be able to answer SQ 2: *How do the stakeholders in the European hydrogen system perceive the main system functions of that system, as drivers or barriers?*

The primary objective was to identify drivers and barriers within the system. However, to effectively accomplish this, it was essential to establish a shared understanding of what these terms mean and how they translate within the context of this research. This involved defining the activities that either hinder or facilitate innovation and exploring the specifics of their impact. The core question addressed

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which parts of the system are already on a successful trajectory and which areas require further encouragement or development. Drivers are identified as variables that positively influence system functions or overall system functions that foster the diffusion and implementation of technology. Conversely, barriers are perceived as variables that negatively influence system functions, thereby impeding innovation within the system. This distinction is crucial for understanding the dynamics at play in the development and advancement of technology within the system.

By interviewing stakeholders in the value chain as well as conducting a literature review. By conducting the interview with questions based on the diagnostic system functions (Appendix B, Figure A.3), the interviewees were invited to share their perspectives on the main drivers and barriers in the system. The outputs are system functions with variables that most actors see as the main driver or barrier, or at least as variables that need to undergo change to change the status of the innovation system. These are concluded qualitatively by cross checking interviews and literature.

A qualitative approach is suitable for this individual case as it could highlight the exact conditions for this system (Mahoney & Goertz, 2006). The stakeholders view on the most important influences of the system allowed us to recognize which variables in the system would be most influential in the current years and years to come. These discussions provided valuable viewpoints on which aspects of the innovation system are currently fostering progress or, conversely, impeding the desired direction of innovation. This integration ensures that the qualitative structural analysis and functional analysis form the foundational basis of the scenario development.

The goal was not to score the system functions and overcome the obstacles for the policy goals, which is the target of a TIS analysis (Hekkert et al., 2011); it was to use the structural and functional analysis parts, which provide the necessary tools for understanding the system, and be able to conclude what processes and dynamics are most influential on the system. The functional analysis of the TIS analysis provided a structured method from which parts are introduced within this thesis, as well as structure for the interview questions.

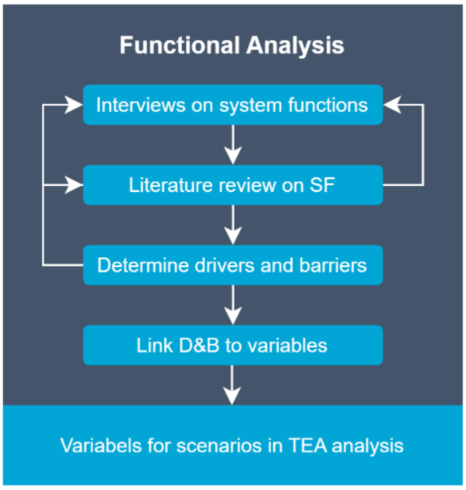

Figure 3.3: Functional analysis flow

3.4 Techno-economic Analysis

A quantitative techno-economic spreadsheet model was developed to facilitate a comparative analysis of the levelized costs of various hydrogen value chains. By clarifying the distinctions in techno-economic performance among these alternatives, the model directly contributes to addressing SQ 3: "*How do the different green hydrogen alternatives compare in techno-economic performance?*"

The comprehensive nature of this model allows for an in-depth assessment, bridging the gap between qualitative and quantitative. The framework proposed by Zimmermann et al. (2020) was adapted within this TEA to have a method for the conceptualization and design of the model and aligns with the mixed-method character of this research, as well as providing structure in the execution of the research. The phases are goal and scope definition, inventory data collection, indicator calculation, interpretation, and reporting. The phases shall be explained below, along with the method used in each specific phase.

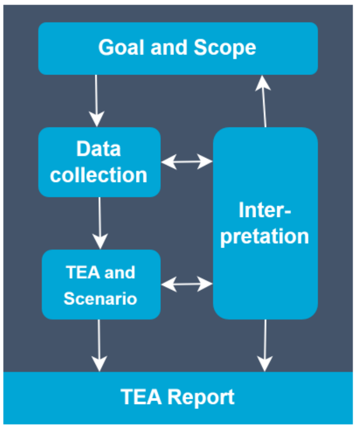

Figure 3.4: Phases of techno-economic assessment adapted from Zimmermann et al. (2020)

3.4.1 Goal and Scope

In this part of the analysis, the goal and scope were set for the TEA. In this research, the goal and scope were set by the research gap and the structural and functional analysis.

The goal was defined through the study context. The main focus of the goal is to create a fair comparison, to make sure apples are compared to apples, and the comparison will make sense for the goal of the research. Firstly, it will entail not only the object the original case is compared to but also the location, time horizon, scale, and partners in the research, including the scenarios. Secondly, the reason for conducting the research will be explained, as will the application it is intended to have. Lastly, the limitations will be highlighted (Zimmermann et al., 2020).

The research scope encompasses several critical aspects to assess the technology and its comparison with other technologies. Initially, the focus was on identifying the technology application – the specific subject of the analysis. Following this, the dimension of comparison with other technologies was determined, which included establishing the functional unit (the basis of comparison) and the reference flow (the number of comparisons to be made). Additionally, the system elements were carefully outlined, specifying which elements were included and excluded in the comparison, thereby defining the system boundaries. Benchmark systems for comparison were then selected, and the maturity levels of the technology were assessed to ascertain potential exclusions, a step already addressed in the structural analysis. Lastly, the parameters and measures used in the study are identified, covering the criteria and indicators, to provide a well-rounded and comprehensive scope for the research (Zimmermann et al., 2020).

3.4.2 Data collection

The inventory analysis had the goal of collecting relevant data for the techno-economic model. This relates to the data of the relevant technical systems and the overall system. When breaking down the indicators, there was a selection of higher-level parameters that were central to the overall comparison between different systems. Therefore, below is introduced as a manual for them to collect data. In this figure, it can be seen what the main cost components for every hydrogen production plant will be. The goal of the assessment indicators is to calculate the LCOH at the end. The data collected can be related to technical, economical, or techno-economic indicators.

The data related to hydrogen production was gathered through an examination of recent literature, with a focus on different value chains. The emphasis was placed on identifying clear distinctions between hydrogen production methods and their specifications. The desk research, accompanied by the interviews, provides more insight into the boundaries of the systems.

3.4.3 Economic Assessment

The calculation of the indicators is the phase of the TEA where the cost assessment is made. Excel, a spreadsheet modeling program, was used to process the collected data into results. The model provides the user with an interface that allows them to systematically fill out the data. The model allows the user to directly determine the cost per component of hydrogen production, creating an overview of the total costs per unit for hydrogen production.

3.4.3.1 Levelized Cost of Hydrogen

The LCOH is used in this end calculation, allowing for an apple-to-apple comparison between different hydrogen production methods and their value chains. The LCOH is calculated by dividing the Net Present Value (NPV) of the total costs by the NPV of the total hydrogen production, as seen in Equation (2). The discount rate and lifetime used are based on literature and assumed to be the same for all different production technologies. The Weighted Average Cost of Capital (WACC) or Technologies' financing cost, was the discount rate used for LCOH. This WACC is the opportunity cost of the money invested in the technology; in other words, the return on the money when this money would have been invested in a project with the same amount of risk (BEIS-UK, 2021). Therefore, this WACC is the minimum required return. In Equations (3) and (4), the NPV's of both the total costs, and hydrogen production can be found (BEIS-UK, 2021). The NPV's are summations of all cash flows throughout the lifetime of the project. This results in a unit measure expressed in euros per kilogram of hydrogen (€/kgH_2).

$$LCOH_{production} = \frac{NPV_{total\ costs}}{NPV_{hydrogen}} \tag{2}$$

$$NPV_{total\ costs} = \sum_{n} \frac{Total\ costs_n}{(1+WACC)^n} \quad n = time\ period \tag{3}$$

$$NPV_{hydrogen} = \sum_{n} \frac{Hydrogen\ Production_n}{(1+WACC)^n} \quad n = time\ period \tag{4}$$

3.4.3.2 Total costs

Total costs encompass both capital expenditure (CapEx) and operational expenditure (OpEx). CapEx primarily includes costs associated with property, plant, and equipment, which constitute the fixed assets, and other intangible assets such as patents (ROSS, 2023). In this calculation, the investment cost and stack replacement cost will be used. The OpEx (€) covers a range of recurring expenses necessary for ongoing operations, such as fuel costs, operational and maintenance expenses, and additional costs like research and development, which are essential for sustaining business operations (ROSS, 2023).

To compare the techno-economic performance, the LCOH is calculated per cost component and added up. The total costs can be expressed as the LCOH sum of the CapEx and the OpEx. CapEx does exist out of the investment costs of the plant as well as stack replacement costs when the plant is an electrolyser. OpEx exists out of the cost of O&M, the energy costs, and the CO_2 costs, when applicable. All these costs combined form the total cost. Below are the functions.

In cases where total investment costs were known, such as in the case of electrolysers, the total cost was calculated by multiplying the price per capacity by the capacity of the plant.

$$Cost_{Investment} = Capacity_{plant} * Price_{Capacity} \tag{5}$$

The cost of the stack replacement was calculated by multiplying the capacity of the plant by the price of the stack.

$$Cost_{Stack} = Capacity_{plant} * Price_{stack} \tag{6}$$

The cost of O&M was calculated by multiplying the capacity of the plant by the price of O&M.

$$Cost_{O\&M} = Capacity_{plant} * Price_{O\&M} \tag{7}$$

The cost of energy was calculated by multiplying the amount of energy used, be it natural gas or electricity, times the price of that energy source.

$$Cost_{Energy} = Consumption_{Energy} * Price_{Energy} \tag{8}$$

The cost of CO_2 was calculated by multiplying the consumption of energy, natural gas, by the emission rate of that energy, and then multiplying it by the price of CO_2.

$$Cost_{CO2} = Consumption_{Energy} * Emission_{Energy} * Price_{CO2} \tag{9}$$

In the calculation of the total cost, production technology and energy sources are used. The cost will be expressed in euros (€) and can be calculated per cost component. When dividing through the LCOH of each cost component, it could be calculated. The CapEx is separated into two different parts. The normal CapEx and Stack replacement costs. The CapEx is provided in total or adjusted to the size of the plant. Stack replacements are dependent on CapEx and are a percentage every time they have to be replaced. The hydrogen production will be set at 100 m3 per year. But to calculate the total costs, the capacity must be calculated. The energy consumption exists outside of the theoretical energy consumption, and the efficiencies hamper the production method of reaching that theoretical total.

$$Capacity\ plant = \frac{Hydrogen\ production * Energy\ consumption}{Electrolyzer\ utilization} \tag{10}$$

3.4.4 Scenario analysis

The scenario analysis was used to understand how the most important and expected scenarios would influence the result, the LCOH. The scenarios are depicted by the functional analysis, whereby the variables that are most likely to change in those scenarios will be adjusted and compared to see what the possible futures for the hydrogen system could be. This combination allowed for more insightful information, which allowed for numbers with context given to the user.

3.4.5 Interpretation and implications

As can be seen in the overview of the methods, this method was an iterative process where constant interpretation could enhance the model through multiple rounds of iteration. Throughout the project, expert validation helped, helped confirming the model provided realistic outcomes with the assumptions made. In the end a discussion was also held on the applicability of socio-technical research.

3.4.5.1 Model validation

Expert validation and benchmarking were used to verify the data from the model. The model structure was validated with benchmarks, measured data, and other data from similar systems. This helped verify the numbers found in the literature research for compatibility with the model. A number of experts, each with specialized knowledge in the field of hydrogen energy systems, were consulted in multiple states. Their insights were invaluable in identifying any potential oversights and suggesting adjustments to enhance the model's accuracy and applicability.

3.4.5.2 Model visualization

For data visualization, the model's interpretation process and overall design were centered on the accessibility and readability of crucial numerical data for drawing conclusions. A specific model design was developed to visually represent the results. The primary objective of this model was to facilitate a high-level comparison of different hydrogen value chains. The model was structured to provide straightforward insights into the various costs and their composition within each value chain, thereby simplifying the iterative interpretation process for the user. This approach enabled users to promptly evaluate the impacts of different variables on the final outcome, streamlining the comparative analysis. Such a method of visualization proved to be an effective tool for making the assessment of complex data more user-friendly and intuitive.

The prices for each component in the hydrogen source comparison were chosen to clearly highlight the biggest differences in costs in bar charts. By presenting these prices side by side, the analysis offered an overview that facilitated a direct comparison and insight into their competitiveness.

Additionally, depicting these costs as percentages in pie charts helped in understanding which production process components constituted the largest portion of the cost, thereby offering a clearer view of the key cost drivers in hydrogen production. Down below, in Figure 3.5 and Figure 3.6, examples are presented.

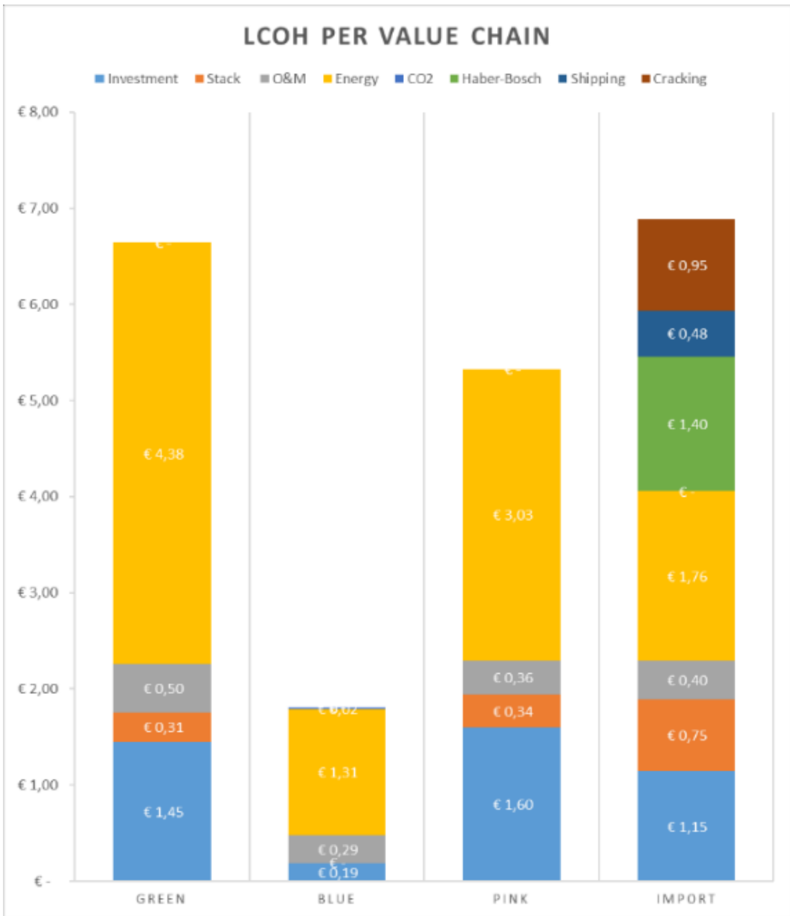

Figure 3.5: Bar chart of LCOH per value chain example

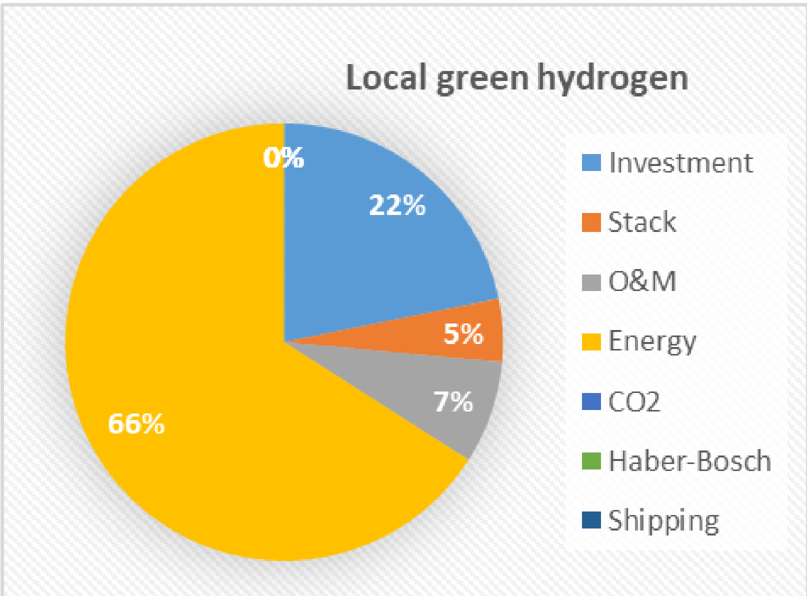

Figure 3.6: Pie chart of LCOH Example

4
Results
Socio-technical System Analysis

This chapter will provide the first part of the results, where the focus lies on the socio-technical system analysis. In Section 4.1, the socio-technical analysis shall begin with identifying the system structure and dynamics, which will determine the scope of the system. The hydrogen variations that are feasible in the current European hydrogen system are determined by assessing the production varieties that are viable for the future European hydrogen system. Then in Section 4.2, the discussion and conclusion of the structural analysis are present, answering the first sub-question: *How are the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe configured?* In Section 4.3, a functional analysis allows the recognition of the biggest drivers and barriers of the system, which could be translated into variables for the techno-economic analysis. Lastly, in Section 4.4, the chapter is concluded, and the second sub question is answered: *How do the stakeholders in the European hydrogen system perceive the main system functions of that system, as drivers or barriers?*

4.1 Structural analysis

Section 4.1 examines the structure of the European green hydrogen system, focusing on its key components: actors, institutions, networks, and technological developments. This analysis lays the groundwork for understanding the sector's structure, which is crucial for evaluating the hydrogen system. Structural analysis as presented in the manual for TIS analysis by Hekkert et al. (2011). A simplified version is used where the main actors shall be highlighted, and focus shall be laid on their influence on the value chain and the possible hydrogen solutions in Europe. Within the value chain, or the industry, a more in-depth analysis shall be made to make sure this is understood.

4.1.1 Actors Analysis

This subsection delves into the diverse array of system actors and stakeholders within the European green hydrogen system. The term “actors” in this context refers to a broad spectrum of organizations and stakeholders that contribute to the technology's development, adoption, or facilitation. This group encompasses developers, adopters, regulators, financiers, and others. The variety of these actors is extensive, ranging from private entities to public institutions, each playing a vital role in the generation, diffusion, and utilization of technologies (Hekkert et al., 2011). These actors are intrinsically linked to networks, providing varied interactions across different stakeholder groups. The nature of these interactions is important in understanding the dynamics within the green hydrogen system. The following sections identify and categorize these stakeholders into distinct groups, providing a clearer picture of the system and the roles each actor plays within it.

4.1.1.1 Research & Education

Knowledge institutes and universities play a vital role in advancing green hydrogen technologies. These entities, including research institutions, are at the forefront of conducting essential research and development in the green hydrogen sector (Hekkert et al., 2011). It also includes private research organizations, associations, and R&D companies. The primary objective of knowledge institutes and universities is to enhance the understanding of the fundamental technical aspects of these technologies (EC6). By demonstrating the feasibility and potential of diverse green hydrogen technologies, they become instrumental in drawing the attention of not just policymakers but also potential investors (EC3, EC6). The critical function of these knowledge institutes extends beyond research and development. They also serve a consultative role for other stakeholder groups, particularly governmental bodies and the hydrogen industry. Their expertise is crucial in advising on the practical possibilities of hydrogen use. Moreover, they emphasize the strategic application of hydrogen, advocating for its focused utilization in industries where it yields the most benefit and necessity (EC4). This dual role of research and consultation positions knowledge institutes as key stakeholders in shaping the future landscape of green hydrogen technologies.

4.1.1.2 Industry – Supply & demand

Industry is the part of this structure that focuses most on the hydrogen value chain, the supply and demand. This ranges from the energy providers, the hydrogen producers, industrial plant manufacturers and operators, and transport operators, ending in the final utilization inside the sectors. While the scope includes various hydrogen production methods and energy sources, the current focus is on green hydrogen. Consequently, competitors utilizing other methods are not considered in this detailed structure. Should they be included, their respective manufacturers and additional elements of the value chain would also be analyzed. However, for illustrative purposes, this discussion is tailored to the example of green hydrogen. For green hydrogen, the most important stakeholders are the hydrogen producers and electrolyser manufacturers, as well as the hydrogen off takers, the electricity producers, and the government (Jesse et al., 2024).

A problem the hard-to-abate industries find themselves in is that climate targets are pressuring the industry to decarbonize, which pushes the industry to use low-carbon alternatives, but there are alternatives to green hydrogen (EC1). This is challenging the competitiveness of the green hydrogen industry against the currently acceptable (EC1), more emitting alternatives because the production of green hydrogen is more expensive (PwC, 2023). A clear level of cooperation can be seen in the hydrogen value chains as buyers and producers stress the need for action and incentives from governmental bodies, lobbying for possible beneficial regulatory frameworks (EC8). The problem now is that hydrogen-dependent projects, the hard-to-abate industries, are awaiting hydrogen supply development, while again, hydrogen producers need the hard-to-abate industries to adopt hydrogen for them to create supply (EC7), creating an impasse in the hydrogen value chain. The hard-to-abate industries, the demand side, which is in this impasse, but also the supply side, in the energy providers, have a chicken and egg problem where the supply and demand sides are embedded in (EC1; EC4; EC7; EC8). This allows the full industry, the demand side with the hard-to-abate industries and direct consumers of hydrogen, and the supply side, all different sorts of hydrogen, to be in an unclear state.

4.1.1.3 Governmental bodies

There are the present government bodies that set the policies, hard institutions (laws, regulations, standards, and rules) (Hekkert et al., 2011). The government body is the international authority, which is the European Commission and the European Parliament. As the focus lies on Europe, the national governments do have interplay with the system, meaning that they cannot be forgotten; however, the overall institutions are set by the European Union and its governmental bodies. The governmental bodies set the rules of the game and are able to create a level playing field with carrots, incentives, or sticks, taxes, both policy instruments (EC1; Jesse et al., 2024). As Expert Consultation 5 states, *“A policy or subsidy can make or break the economic viability of such a project.”* They are the stakeholder group that creates the institutional framework in which the other stakeholder groups can conduct business. According to the research of Jesse et al. (2024), the government influences the system indirectly in many ways; however, they can take two roles in the future. On the one hand, they set regulations and targets, incentivizing a demand pull, while on the other hand, the still not yet fully clear institutions can have a hindering effect on the investments in green hydrogen, having the opposite effect. The institutions shall be explained more in depth in the institutional analysis in subsection 4.1.2.

4.1.1.4 Supportive organizations

The supporting bodies, like financial institutions, non-governmental organizations, and society, but also platforms, support the hydrogen value chain directly and indirectly. Where the supporting organizations, which are all parts of society, actually elect the governmental bodies in Europe, they indirectly have influence on the possible future regulations. They also form the hydrogen value chain by setting constraints in their search for environmentally friendly alternatives that are secure, affordable, and reliable, the three main points again translated in the REPowerEU plan (European Commission, 2022).

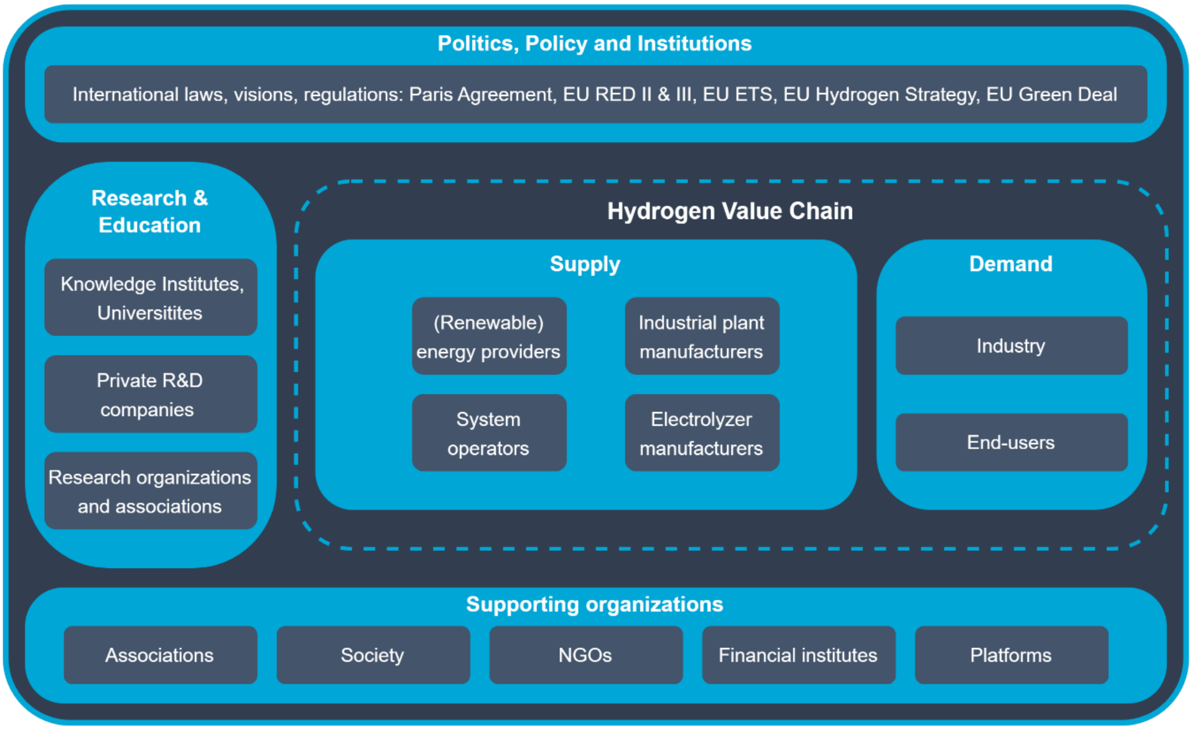

Figure 4.1: Green Hydrogen system actors based on Hekkert et al. (2011)

4.1.2 Institutional analysis

This section delves into the institutional frameworks, often referred to as the 'rules of the game,' which are fundamental to the innovation system. As described by Hekkert et al. (2011, p.5), these are *'humanly made constraints that shape human interaction.'* Specifically, this discussion centers on the pivotal European legislation, rules, policies, and mandates that play a crucial role in guiding the development of green hydrogen projects. It is important to distinguish between soft and hard institutions. Soft institutions, encompassing norms, culture, and values, present challenges in terms of coordinated mapping due to their intangible nature. Consequently, the focus will be primarily on hard institutions, which are more tangible and measurable in the context of policy and legislative frameworks.

4.1.2.1 EU Green Deal - EU Hydrogen Strategy

The EU green deal and the EU hydrogen strategy both have the objective of reaching climate neutrality by 2050. The EU green deal is a combination of legislative and non-legislative acts focused on reaching the objectives of the Paris agreement. Notably, the “Fit for 55” package targets a reduction of GHG by 55% from 1990 levels by 2030 (European Commission, 2019). Within this comprehensive structure, the EU hydrogen strategy plays a central role. It outlines a phased approach to developing renewable hydrogen technologies, especially important for decarbonizing sectors where direct electrification is challenging. This strategy is broken down into three distinct phases, each with escalating targets for electrolyser capacity and hydrogen production. Initially focusing on industrial applications, the strategy encompasses broader energy storage and balancing roles, aiming to integrate hydrogen into various sectors, including heating and transport (European Commission, 2020a). Under this strategy, the goal was to create a comprehensive system where relevant policy instruments and legislation could guide the EU towards climate neutrality, the instruments of which are explained below.

4.1.2.2 European Legislative Framework and Targets

Integral to this system and the strategy is the Renewable Energy Directive II (RED), now revised to RED III to increase renewable energy targets in line with the evolving ambitions (European Commission, 2021c). Complementing this, the recent REPowerEU plan further raised the bar. This plan seeks to accelerate the energy transition and reduce dependency on non-renewable energy sources. The concept of Renewable Fuels of Non-Biological Origin (RFNBOs) was introduced and defined in the Delegated Act to support the RED’s (European Commission, 2023c). This category was created to promote the synthesis of clean fuels using renewable electricity, such as green hydrogen, contributing to the EU’s goals. RED II and III and the delegated act have thus cleared the path for green hydrogen to be acknowledged as a vital component in meeting the EU's renewable energy ambitions. Additionally, the strategy and the Fit for 55 package incorporate specific mandates for renewable energy use in the transport and aviation sectors, like the ReFuelEU Aviation initiative (European Council, 2023). In this regulation, there are again mandates included that, for example, allow nuclear energy to produce hydrogen, as that falls within the reduction requirements (EC2). These mandates are critical for increasing the production and uptake of sustainable aviation fuels (SAFs). This type of legislation has been designed with a degree of flexibility to facilitate a smoother transition for these industries. Under the RED, nuclear energy is not considered renewable. The EU's decarbonisation package suggests "low-carbon hydrogen" can be made from non-renewables like nuclear if it cuts greenhouse gas emissions by at least 70% compared to fossil gas. Details on measuring these savings will be finalized by the end of 2024 (European Commission, 2023d).

The directive, which reflects the EU's aim for a more integrated energy system, is anticipated to strengthen the commitment to green hydrogen by establishing higher obligatory targets for RFNBOs (Directorate-General for Energy, 2023). The inclusion of RFNBOs serves multiple purposes, including boosting innovation in the European energy sector and guaranteeing energy security (European Commission, 2018). Supporting this is also a reliable certification system, making sure that, for example, RFNBOs like green hydrogen are actually certified and a hydrogen trade is possible. This European certification scheme is used so that the hydrogen used is indeed green hydrogen and is part of the European hydrogen strategy as it would allow the development of green hydrogen as it would make the use of green hydrogen certain, not confusing it with other types of hydrogen (European Commission, n.d.-b).

4.1.2.3 European Fund and Market Mechanisms

The successful implementation of these strategies relies heavily on robust financial support and market mechanisms, as the current market has not been developed yet. Programs like the IPCEI (Important Projects of Common European Interest), InvestEU, Horizon Europe, and the Innovation Fund all play a vital role in providing necessary funds and support (European Commission, n.d.-d, 2020b, 2021b, 2021a). The IPCEI approved over 5.4 billion euros in funding for hydrogen-related projects in July 2022 (IEA, 2023d). These schemes are designed to bridge the gap between current technologies and the desired future technology, facilitating research, development, and large-scale implementation.

In addition to these financial initiatives, the EU Emissions Trading Scheme (EU ETS) stands out as a key market mechanism. The EU ETS operates by setting a cap on the total amount of carbon dioxide emissions allowed from all participating installations (European Commission, n.d.-c). Within this cap, companies are allocated or can purchase emission allowances, each of which permits them to emit one tonne of CO_2 equivalent. This system creates a flexible choice for installations: they can either invest in reducing their emissions to avoid purchasing additional allowances or opt to pay for their emissions through buying allowances. This cap-and-trade principle incentivizes companies towards decarbonization by making emission reductions financially beneficial (European Commission, n.d.-c). Complementing this is the Carbon Border Adjustment Mechanism (CBAM), which aims to level the playing field between EU producers subject to ETS costs and non-EU producers, mitigating the risk of carbon leakage. If a non-EU producer has already incurred a cost for the carbon emissions during production, this amount can be deducted by the EU importer from the CBAM charge (European Commission, 2023a). This mechanism is set to be introduced gradually, initially focusing on products at high risk of carbon leakage, such as iron, steel, cement, fertilizer, aluminum, and electricity generation. The gradual introduction and sector-specific focus of CBAM are designed to prevent carbon leakage and ensure that European and non-European producers operate under similar carbon cost structures (European Commission, 2023a).

4.1.3 Network analysis

The networks in the European hydrogen system, especially for the actors around the value chain, were identified through a literature review. The network is not about the different stakeholders, their roles, and their interactions, as this is already discussed in subsection 4.1.1, but rather the possible networks that could form in the future around the globe. The value chains that exist out of supply and demand, whether domestic or worldwide.

Multiple agencies stress the future of green hydrogen being with imports from outside of Europe. Global hydrogen trade is a subject that is driven by the cost differential over time between importing and local production (IEA, 2023a; IRENA, 2022b). There is a serious trade-off between domestic production and hydrogen imports, as the cost over time could differ. At the moment, domestic production is still a viable option, but with costs for imports, such as transportation and conversion costs, deemed to go down, the potential for trade flows becomes clear (IRENA, 2022b).

The Hydrogen Council & McKinsey and Company (2022) argue that global hydrogen trade can accelerate the transition into the hydrogen economy. They argue that in the years beyond 2030, trade flows will become apparent throughout the whole globe, with the first trade routes being established in the first years of 2030. The reports of Deloitte (2023) and Roland Berger (2023) agree with them and provide even more claims that Europe will become self-sustaining without governmental incentives from then on and will be a huge demand and production center for green hydrogen. This demand is also agreed upon by the IRENA (2022b). They see an expanding growth in the demand for hydrogen in Europe, meaning that trade flows from all over the world, as can be seen in Figure 4.2 below.

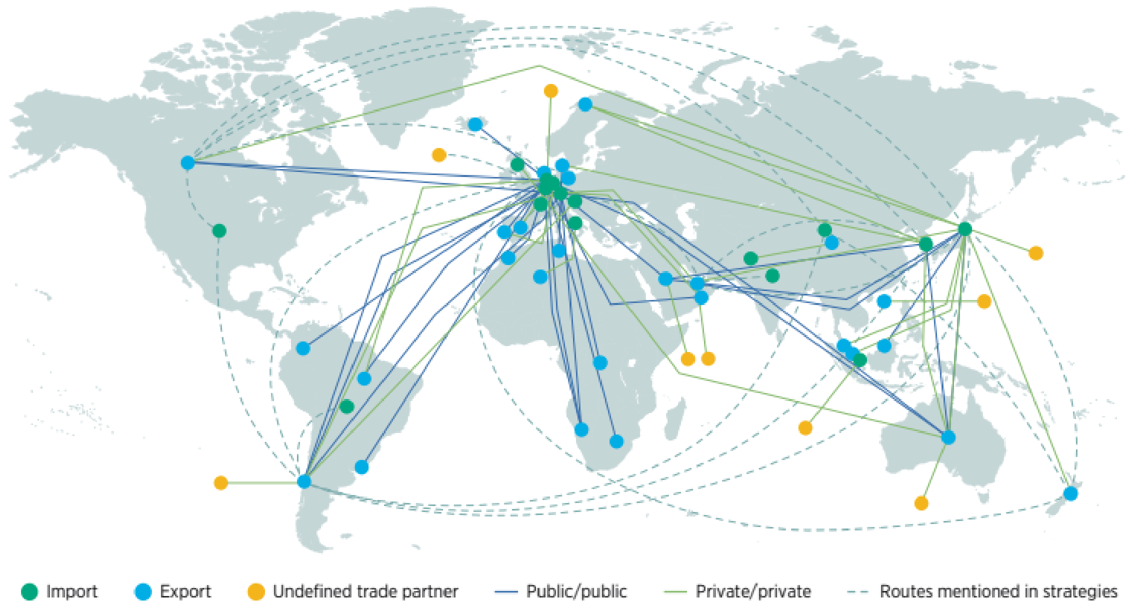

Figure 4.2: Pathways for low-carbon hydrogen import to Europe by (IRENA, 2022b)

The dynamics of production are also greatly influenced by geographic considerations. Green hydrogen production is more cost-effective in areas with a wealth of renewable resources, which might have an impact on global trade patterns for hydrogen and its derivatives. Regional hydrogen hubs that take advantage of available gas infrastructure and local renewable energy resources will be a key feature of the technology's evolution (Hydrogen Council, 2020).

In the EU, arguments arise from different agencies about whether it is smart to produce green hydrogen because of the price difference in production with other countries. As demand surpasses the supply of green hydrogen (Dejonghe et al., 2023), agencies like the International Renewable Energy Agency and the International Energy Agency provide reports every year containing credited evaluations (IEA, 2023a; IRENA, 2022a). Due to decreasing prices of renewable energy, however, green hydrogen is expected to be competitive in 2030 (World Energy Council, 2018); however, there needs to be a reduction in price due to economies of scale, innovation, and efficiency gains of electrolyzes. At the moment, because of this price difference, many countries still opt for the cheaper alternative, blue hydrogen (Deloitte, 2022).

4.1.4 Technology analysis

As the main colors that are the main hydrogen production methods are already explained in Section 2.2, no further explanation on the processes and energy sources is needed. More clarification can be given on the most-used technologies per value chain. The production methods that are explained are the methods that are used widely and in combination with other technologies to make blue, green and pink hydrogen, the value chains that are suitable in the European institutional system. In Figure 4.3 below, an oversight of the different energy production methods are given. For fossil fuel-based hydrogen the hydrocarbon reforming method is most used and for renewable and nuclear based hydrogen is water splitting method is most used. These shall be elaborated below to highlight the technological process that has been made throughout the last years on hydrogen production.

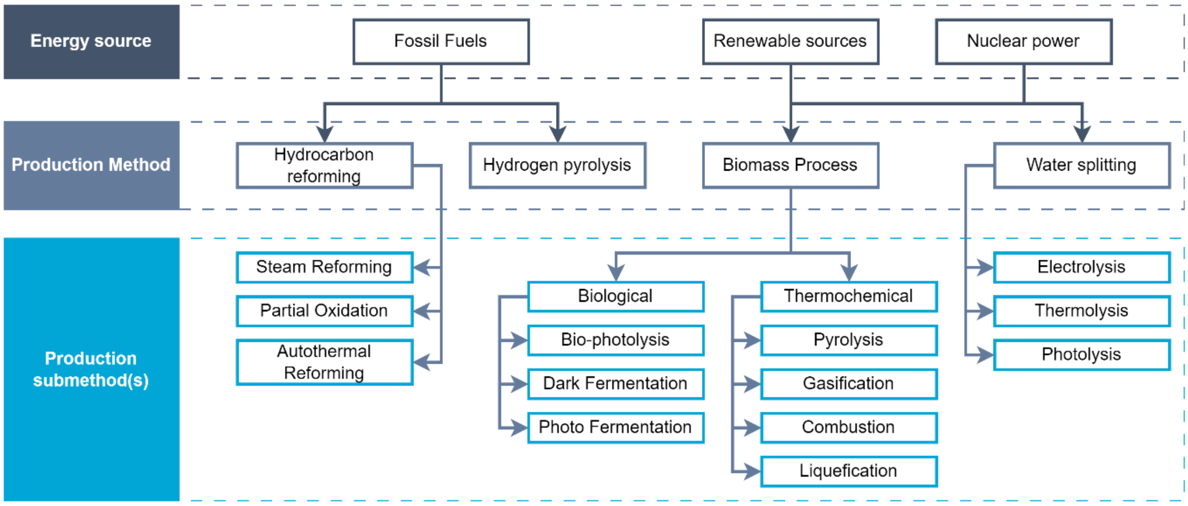

Figure 4.3: Hydrogen production methods adapted from Zainal et al. (2024)

4.1.4.1 Water splitting

Water electrolysis is an electrochemical method that allows for the splitting of water molecules with the help of electricity. Utilizing electricity in the process allows for the possibility of an emission-free technology when using emission-free electricity. The process requires a direct electric current that splits the atoms into separate atoms of oxygen (O_2) and hydrogen (H_2) (Shiva Kumar & Lim, 2022). At present, a spectrum of electrolysis technologies is employed for hydrogen production with water splitting. The most well-known technologies range from low-temperature systems such as Alkaline Electrolysis Cells (AECs) and Proton Exchange Membrane Electrolysis Cells (PEMs), to high-temperature systems like Solid Oxide Electrolysis Cells (SOECs). Each of these technologies has its own unique set of strengths and weaknesses (KGAL, 2022). Notably, while low-temperature electrolyzers are more established in terms of commercial development, high-temperature electrolyzers offer superior efficiency (Nami et al., 2022).

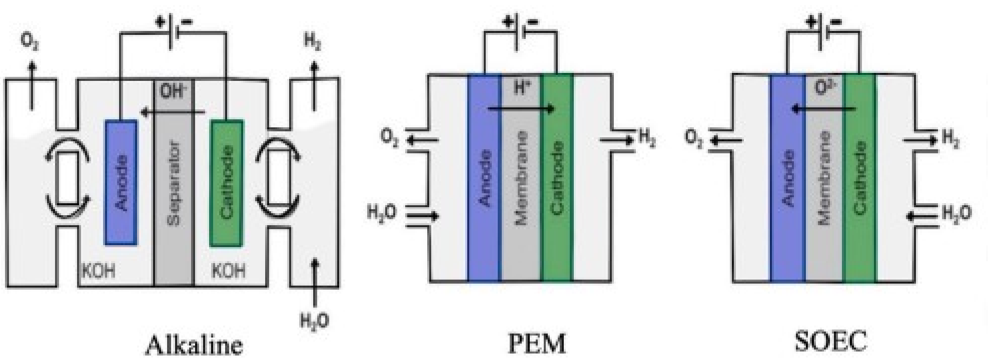

Figure 4.4: Conceptual set-up of three electrolysis cell technologies by (Zainal et al., 2024)

TU Delft

The first one is alkaline water electrolysis; this type of electrolyser is a well-established technology that has proven to be commercially applicable for industrial applications. The relative low costs, the long-term stability, and the other attributes make the electrolyzer technology a solid choice for green hydrogen (Shiva Kumar & Lim, 2022). The second one is the Proton Exchange Membrane water electrolysis (PEM), a recently commercialized electrolyzer that is also ready for commercial application and has the benefit of a quick response time in comparison to the other technologies, yet the components used in this type of electrolyser are expensive (Shiva Kumar & Lim, 2022). The third and last one is the Solid oxide electrolyzer (SOEC), a high-temperature electrolyzer with high efficiency potential as it operates with water in the form of steam (Shiva Kumar & Lim, 2022). This type of electrolyser is especially suitable for hard-to-abate industries with waste heat (Corbeau & Merz, 2023; Leo, 2023). Solix oxide electrolyzer is seen as a dark horse that could be used in the future (Parkes, 2023).

4.1.4.2 Hydrocarbon reforming

There are multiple reforming technologies utilized for the generation of hydrogen from hydrocarbon fuels; however, there is one method that is widely used: Steam methane reforming. Reforming is a method that allows the chemical process of hydrocarbon reforming to reform gaseous hydrocarbons, typically a natural gas converted to hydrogen and carbon monoxide using steam (Zainal et al., 2024). SMR is highly efficient and has been the backbone of the hydrogen industry for decades. It inherently produces CO2 as a byproduct, thus posing challenges in the context of decarbonization efforts. Here, carbon capture and storage come into place, adding a vital dimension to the SMR process.

The CCS, or CCUS where utilization is included, allows the captured CO_2 that is produced during the reforming process to be stored underground in geological formations, or to be used in other industrial applications (Zainal et al., 2024). This integration allows for this process to be more in line with the overall decarbonization goals. The combination of SMR with CCS offers a transitional pathway to cleaner hydrogen production, leveraging existing infrastructure and technology while significantly mitigating greenhouse gas emissions (Durakovic et al., 2023).

4.2 Discussion and Conclusion structural analysis

This combined section gives an answer to the first sub question: *How are the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe configured?*

4.2.1 Discussion

The main takeaway of the actor analysis is the fact that the different stakeholder groups influence the other groups. Their interactions form the structure in which interactions between green hydrogen and its competitors can take place. As at the moment the main theme is the decarbonization of the industry, the focus lies in the interaction setting boundaries on which technologies are able to be used in the future. The institutions can be seen as the set boundaries that are now present, meaning that these will form the boundaries on which exact technologies can be competitors in the future of green hydrogen.

The main takeaway from the institutional analysis is the emphasis on the EU Green Deal and the hydrogen strategy in the current EU's REPowerEU plan, where affordability, security, and sustainability emerge as main pillars. This strategy highlights the diversification of hydrogen sources as essential for ensuring both affordability and security. This approach aligns with the broader EU directives aimed at a sustainable energy transition, reinforcing the role of low-carbon hydrogen alongside green hydrogen. By prioritizing these pillars, the EU underlines the importance of developing a robust hydrogen market that can contribute to climate neutrality goals while also addressing immediate energy needs and reducing dependency on non-renewable energy sources. As the goal of the research is to compare the techno-economic viability, two criteria, which are based on the pillars of REPowerEU, are created for the selection of suitable production methods. The maturity of the technology provides the necessary safety and possibilities for diversification of energy sources, and the production method is low-carbon to aid in the energy transition.(European Commission, 2022).

The key insight from the network analysis is that global trade, driven by the interplay of supply and demand, is crucial for Europe's hydrogen economy. The future of green hydrogen in Europe is expected to lean towards imports, with cost differences between domestic production and imports shaping strategic decisions. Reports predict Europe as a significant hub for green hydrogen demand and production beyond 2030, with trade flows intensifying due to decreasing import logistics costs. Geographic advantages and technological advancements are highlighted as essential for making green hydrogen cost-competitive by 2030. This analysis underscores the importance of strategic investments in production and international trade to address the growing demand for green hydrogen in Europe.

The key conclusion from the technology analysis is that in water splitting, there are three distinct types of electrolyzers in use, each suited to different applications, with one type often being more fitting than the others depending on the context. In the realm of hydrocarbon reforming, the primary method for hydrogen production, Steam Methane Reforming (SMR) emerges as the predominant choice (Zainal et al., 2024). However, a significant downside is its GHG emissions. Consequently, integrating a carbon capture and storage (CCS) system can mitigate the environmental impact (Zainal et al., 2024), aligning the process with European regulatory standards.

Therefore, the discussion on the inclusion of alternatives is performed. Green hydrogen, which is distinguished by its carbon-free generation process, marks a paradigm shift in sustainable energy sources. The process avoids the carbon emissions connected with conventional hydrogen generation technologies, such as steam methane reforming with grey hydrogen or coal gasification with black hydrogen. The environmental implications of green hydrogen production are significant (Ajanovic et al., 2022; Arcos & Santos, 2023; IRENA, 2023b). Therefore, black and grey hydrogen are excluded from the selection. Yellow hydrogen is also debatable as it typically is produced using electricity from non-renewable sources (Ajanovic et al., 2022), failing to meet certain low-carbon criteria, meaning it is also excluded from the selection. The emphasis in the criterion is on low carbon emissions, meaning pink hydrogen, albeit producing nuclear waste, also fits within the low-carbon production methods, while also promising cost-effective numbers (El-Emam et al., 2020). Therefore, it is kept in the selection.

4.2.2 Conclusion

To conclude, the REPowerEU plan serves as the foundational framework for this selection, outlining the system's boundaries within which actors operate. With security and sustainability as its core objectives, the REPowerEU plan requires that potential alternatives be identifiable as low-carbon. This criterion excludes overly experimental technologies, favoring those with high potential and necessitating diversification in the selection process. The international value chain is named that way because imports are not calculated solely based on the production costs in another country. Accordingly, the chosen options are as follows:

1. An Alkaline electrolyzer powered by local renewable energy, selected for its compatibility with sustainable energy sources and adherence to environmental sustainability criteria in Europe.
2. Blue hydrogen produced via Steam Methane Reforming (SMR) with Carbon Capture and Storage (CCS), representing a standard yet secure supply option that aligns with the plan's sustainability and security goals. Allowing for comparison between competing technologies.
3. A Solid Oxide Electrolyzer Cell (SOEC) paired with local nuclear power is chosen for diversification because of its high efficiency potential when combined with waste heat, such as in a nuclear plant, highlighting the importance of leveraging diverse energy sources. Allowing for comparison of a technology and energy source combination with high efficiency potential.
4. Green hydrogen is produced in Saudi-Arabia using an Alkaline electrolyzer. This choice is justified by existing agreements for future alkaline electrolyzer projects in Saudi Arabia, enhancing the comparability and relevance of the analysis. Allowing for a direct comparison of the results of the same technology in different circumstances (ThyssenKrupp, 2021).

This selection process, aligned with the REPowerEU plan, emphasizes low-carbon technologies that promise security, sustainability, and technological feasibility. Through this approach, the analysis not only adheres to academic thoroughness but also aligns closely with the European Union's strategic energy objectives, ensuring a comprehensive and forward-looking comparison of hydrogen production methods.

4.3 Functional Analysis

The evaluation of the system functions. These key processes of the innovation system allow us to assess how the system is performing by assessing key stakeholders in the value chain. Expert consultants were the main input; their insights provided an overview of the aspects of the innovation system that are currently hampering or fostering that system, ergo the drivers or barriers. Other socio-technical literature was added to complete the reasoning.

4.3.1 SF 1 - Entrepreneurial Activities

System function 1 - entrepreneurial activities, mostly focuses on the actors present in the system responsible for entrepreneurial experimentation and production. Hydrogen currently has the wind in its sails and is destined for growth; there is even an overflow of new initiatives (EC4). The expert states that collaboration between all programs is crucial, and the goal is to facilitate more start-ups and create more low-TRL projects. Facilitate in the sense that all these new initiatives know how to navigate the fast-growing hydrogen system (EC4). Producers and users of hydrogen are in search of a business case for hydrogen and are experimenting with smaller projects to prove concepts (EC1). Concepts that illustrate how green hydrogen can become the best solution for the whole value chain (EC6). Entrepreneurial activities do not focus on new actors, as there are plenty, but rather on collaborations. Both the demand and supply sides are eager to start these collaborations, allowing them to share risks and costs among the whole value chain (EC6; EC7; Jesse et al., 2024). In combination with hydrogen having the wind in the sails, the system function of entrepreneurial activities is not seen as a barrier but as a driver. Actors recognize the need for hydrogen, do experiments, and are focusing on the next steps that need to be taken, realizing projects for the scale-up of green hydrogen.

4.3.2 SF 2 - Knowledge Development

System function 2 - Knowledge development, is key for the hydrogen system to thrive; it focuses on whether the quality and quantity of knowledge development are sufficient for the innovation system. There are two major themes in knowledge development that are discussed for the needs of the hydrogen system. The first one being that there is still no consensus in what exact sector hydrogen is most logical to use (EC3; EC6; EC7) and the second one focused on lowering the overall costs of green hydrogen and improving its economic viability (EC4; EC5; EC6). The body of knowledge that exists and has been developed should be sufficient for the development of the hydrogen system. The knowledge institutes are focusing fundamental research on the nuances and complexities that arise in the application of hydrogen within different end-uses and industries. Rationality should drive the system, and knowledge development could help in identifying the exact role hydrogen should and can play in the future energy system (EC3). Hydrogen should not be seen as a silver bullet for solving all energy problems; it is merely one of many means that help in the energy transition. That hydrogen has better suitable applications is shown by, for example, the prementioned hydrogen ladder (Liebreich, 2021). This and more literature begin to agree that the end use should be specialized to certain industries where direct electrification is not possible (Ajanovic et al., 2024).

Even though there seems to be clarity on the allocation of hydrogen, how it should be produced, used, and managed is still unclear (EC4). In every section of the value chain, there is unclarity, resulting in higher costs as there is no standard yet (Ramboll, 2023). Because universities allow for research on the theoretical limits of technologies, they are responsible for creating understanding among investors and industries about the economic viability and feasibility of the different technological alternatives. This drives the industry to fund new research delving deeper into the exact subjects they need. Industrial development can then be funded by industrial clusters (EC6).

The problem with knowledge development now is that there is a status quo because of the chicken and egg problem, creating a gap between what knowledge can be provided and what knowledge is needed (EC1; EC4; EC7; EC8). The chicken and egg problem: must there first be hydrogen demand or hydrogen supply? There is no first mover, making it impossible to see what the actual costs are of all the different parts of the value chain, as well as the lack of evaluation of the technology on a commercial scale. Learning-by-doing and economies of scale are therefore not present, meaning that the development of knowledge is hampered (Revinova et al., 2023). Both main themes are in full research; however, the research does remain solely theoretical. These arguments would say that this system function is partly driving but also hindering the hydrogen system; however, arguments can be made about whether this is the exact system function that proves to be the barrier or that it is a causality of other system functions hampering the innovation system. A complex feedback loop system where the learning effect could enhance other parts but is held back by the parts it should enhance (Jesse et al., 2024).

4.3.3 SF 3 - Knowledge Diffusion

In system function 3 – knowledge diffusion or exchange is key. As knowledge is necessary for the system to thrive, the focus should not only be on the development of knowledge but also on the diffusion and availability of that knowledge. An innovation system could perform significantly better when the knowledge gained is also able to be structurally diffused among other stakeholders. The focus lies on the networks here, which are able to exchange sufficient knowledge between business, government, and academia (EC3). The current status of the networks is deemed good (EC3; EC4). One of the examples is the fact that the European Commission is setting up many different initiatives to ensure collaboration is facilitated in the hydrogen system (n.d.-e). This hydrogen key action plan consists of actions facilitating international organizations' collaboration on the subject. Next to that, as already mentioned in SF 1 - Entrepreneurial Activities, knowledge diffusion should become easier as parties develop knowledge by starting hydrogen projects together, which forces open collaboration and knowledge sharing (EC3). These networks foster innovation and have a positive impact on the overall advancement of the sectors. Yet there is one downside at the moment. Initial painful steps must be taken by the first movers; however, setting that first step is unrewarding and economically illogical (EC7; EC8), pointing back again to the chicken and egg problem. Open collaboration and learning from past mistakes are both vital, with open communication, to set the base for knowledge for the rest of the industry (EC7).

Overall, the network and knowledge diffusion are performing adequately and are set up in such a way that they foster the innovation system; however, at the moment, there is an impasse with no stakeholder eager to take the first step in hydrogen production. The network is well connected and facilitates the diffusion of knowledge, but for that to happen, knowledge should be developed, and to develop knowledge, industry should start exploring real-life examples that are currently financially unattractive to choose from. So, overall, knowledge diffusion does not form a barrier; it is hampered by another system function. It could even be seen as a driver, as it does foster a good connection between stakeholders.

4.3.4 SF 4 - Guidance of the Search

The concept of system function 4—guidance of the search, is whether the regulations, visions, and expectations of the government and key actors are clear for the hydrogen system. As the system grows, more regulations, mandates, and directives are taking their place in the fit for 55 legislative packages as well as the hydrogen strategy. These legislative measures set the targets in the EU that drive the transition to renewable hydrogen (EC1). In total, of the industry's use, 42,5% must come from RFNBOs by 2023, a clear and ambitious target (European Commission, 2023b). RED III not only sets targets but also outlines measures to promote investment in and adoption of renewable energy technologies. It recognizes the critical role of green hydrogen in achieving decarbonization goals, especially in hard-to-abate industries. This also provides a guideline on how the industry should develop and take its stance within the market. The clear guidelines and support mechanisms stimulate the market for green hydrogen, ensuring its pivotal role in the energy transition for Europe. The introduction of RED III, where the definition of renewable hydrogen is finally agreed upon, and the inclusion of the different subsidy schemes and financial incentives are creating a demand-pull (EC4; EC8). This momentum that is being created by binding targets allows for the often-mentioned chicken and egg problem to start resolving itself.

There, however, are still uncertainties. The direction of the best technological design is still unclear (EC5), and in every part of the supply chain, from production to transport, it is still unclear what exact technology is the best; that is where academia could play an important role (EC4; EC5; EC6). Yet, the vision of all interviewees who are part of the hydrogen value chain is positive. Hydrogen is going to play a significant role in the energy transition (EC1; EC3; EC7); however, several steps need to be taken to make this technology competitive. Therefore, the stakeholders perceive this system as a driver.

4.3.5 SF 5 - Market Formation

The system function 5 - market formation focuses on the question of whether the current size of the market and the future size are sufficient. The current market for green hydrogen is characterized by its emergent nature, with several challenges and opportunities. Currently, the hydrogen industry and market are still in a nascent state (EC1), and at the moment there is no market for green hydrogen, as can be seen by the fact that there is no price set yet (EC3). The existence or expectation of demand not being met is usually a condition for the growth of supply, but at the moment there is no demand (Jesse et al., 2024). Because electricity prices can be so volatile, with electricity being one of the main cost contributors to the green hydrogen price (EC3), the investment risk is too high (EC1; EC5). The energy industry, and especially green hydrogen, is naturally dynamic, while financing is based on dependability and predictability (EC5). Key elements that could improve the market are the reliability of the technology, the existence of long-term contracts, and a supportive policy environment (EC5).

The EU has a big challenge with the absence of the market, again referring back to the chicken and egg problem, as there is no supply and demand. Yet, there seems to be a business case, as there are sectors that cannot decarbonize without the help of green hydrogen. That sets the basis for a future market that is expected to exist in the future; however, the current impasse is hard as there is a certain first-mover disadvantage. This disadvantage shows that for a project to find financing, there should be long-term contracts for off-take; otherwise, investors think there is too much risk attached. And the first price shall be higher than as there has been no learning yet, meaning that that offtake is stuck with a long-term contract with a high price, making it unfavorable to make the first step into a market (EC8).

The absence of a green hydrogen market is deemed a barrier. Suppliers do not have the off-take where they can sell their hydrogen, and the demand side does not have the supply from which they can acquire the green hydrogen. The market has not matured enough (EC1). This barrier is currently the primary target for the EU to resolve, as they are doing by introducing the RED III rules. However, in the short term, this could not have an impact. The introduction of a subsidy or penalty scheme could help the market evolve from its nascent state.

4.3.6 SF 6 - Resource mobilization

In system function 6 - resource mobilization, the focal point is around a sufficient number of resources. This could be in the form of human resources, financial resources, or physical resources, depending on whether the physical infrastructure is developed sufficiently for the innovation to diffuse. The focus here is on financial resources.

When discussing the financial side, the big problem with acquiring funding is that with green hydrogen projects it is difficult to present risk-free cost calculations (EC3). The expert from the financial institute confirms this statement, arguing financial insecurity does have negative effects on the funds that are available to the different green hydrogen creators (EC5). The problem is that for companies to invest in such projects, there needs to be security. Security of a stable supply with the same price, but also a security of demand making sure that the project has a stable cash flow, only the making it interesting to invest in (EC5; EC8). As the market is not yet developed, technical aspects are unclear, and regulatory uncertainty is present, the only tool for some stability and protection for the investor is long-term contracts. This typically results, and also in this case of hydrogen, in a risk premium leading to higher prices (EC3). Subsidies could play a vital role in the future by bridging the gap between costs and prices, thereby ensuring the financial viability of projects. However, the implementation of such subsidies remains uncertain at this time (EC3). As well as the current EU funding landscape being complex to navigate (EC2).

Stabilizing energy prices and offtake would enhance the possibility of funding. However, as there is no set price yet for green hydrogen, the cost calculations cannot yet be made precise enough for an investor to be comfortable with investing. Subsidies are necessary for green hydrogen to become economically viable (EC5; EC8). These are necessary for closing the 'feasibility gap' of green hydrogen in comparison to its competitors (EC8). Therefore, resource mobilization, or at least the funding side of resource mobilization, is definitely seen as a barrier in this system. Too much insecurity about whether there is demand blocks investors from investing in the supply, again making the demand side insecure because there is no supply.

4.3.7 SF 7 - Creation of Legitimacy

In system function 7—creation of legitimacy, or, in other words, counteracting resistance—the focus is on the resistance towards the new technology. The gut feeling for hydrogen should change from negative or neutral to positive, to being a vector that does indeed help the energy transition.

Currently, there are concerns among the public about the climate, which could be a positive reinforcement of their willingness for hydrogen; however, that reality still seems distant. The willingness to pay for sustainable services and products is still low (EC4). The users express their concerns primarily centered around rising electricity bills, having less interest in what type of energy would be more beneficial for sustainability (EC4). But the question here is whether to invest now or later, as the choice is whether prevention is better than cure financially, as the cost of keeping non-renewable resources could become high in the future with the EU plans (EC6).

The general public is also concerned because of the double efficiency loss when transforming renewable electricity hydrogen, and then possibly back, the academics could play a role by directing the green hydrogen to the right industries where no second transformation is necessary and where it has the biggest impact (EC4). Green hydrogen, or hydrogen in general, should be prevented from being seen as a cash cow (EC3). The regulatory framework around it could enhance its legitimacy, but therefore a consensus must be reached to use the hydrogen in the places where it is most logical (EC1; EC3). Skepticism about the feasibility and profitability of green hydrogen is one of the biggest barriers at the moment (EC6). The mindset on the shift towards technological and financial feasibility should change, creating a positive narrative from which other stakeholders can also start believing the transition can be done with the government, leading to this optimism (EC6).

Overall, this system function can be seen as a barrier; there is still resistance to change, and legitimacy must still be created for green hydrogen to become the status it ought to be. The primary gut feeling does show that it has potential, but that potential still has to become reality before that gut feeling changes.

4.4 Discussion & Conclusion - Functional analysis

First, the conclusion shall be presented, as these are the core findings of the sub-question. This way, the discussion is able to elaborate on the findings without emphasizing too much on the answer to the sub-question. The main takeaway is more directed toward an overarching theme than a main system function; therefore, the discussion is more suitable after the conclusion.

4.4.1 Conclusion

The socio-technical functional analysis was used to answer the following sub-question: *How do the stakeholders in the European hydrogen system perceive the main system functions of that system as, drivers or barriers?*

The expert consultations, which were held as semi-structured interviews, were used to shed light on the green hydrogen system in Europe, allowing us to gain insight into where the system is lacking and where it is not. The study revealed that the stakeholders do perceive the system functions as drivers or barriers but see another overarching theme as the barrier that should be solved for the total system to grow, or, in other words, for green hydrogen to start diffusing, but that will be part of the discussion in the next subsection. Below a table is the result. The drivers are the system functions that are deemed to motivate the system, and the barriers are the system functions that hamper the system.

Table 4.1: System functions of the hydrogen system

# System Function	1 Entrepreneurial activities	2 Knowledge creation	3 Knowledge diffusion	4 Guidance of the search	5 Market formation	6 Resource mobilization	7 Legitimacy creation
Barrier		x			x	x	x
Driver	x		x	x			

4.4.2 Discussion

The results indicate that there are several functions performing as drivers and several as barriers; however, these functions are all interconnected, meaning that there are several main themes throughout these functions that are considered overall barriers and drivers. It should be noted that the barriers and drivers identified in this study reflect the current situation. However, due to the dynamic nature of the system, these findings could change significantly following this research. This dynamic aspect underscores the complexity of the hydrogen market and the interconnectedness of various factors influencing its development.

Overall, there is a complex system of negative and positive feedback loops, making it evident that the system functions are not to be seen as individual functions but rather as interdependent factors in the development of green hydrogen. Now the goal was not to define this feedback loop system but to identify what system functions are seen as drivers and barriers, to see what exact variables are most likely to change in the future. There is one main argument coming back throughout the system functions: the overall cost being too high, which is caused by multiple system functions, and by the chicken-and-egg problem, which is also mentioned multiple times in the Expert Consultations.

There is one big theme that comes back in every aspect of hydrogen production: the costs of hydrogen. The costs of green hydrogen are too high at the moment, making it uncompetitive with the other fossil-fueled versions. Because of this price difference, there is no market, and because there is no market, there is no supply. Most stakeholders point to policymakers as the ones who should be able to solve the issue through governmental intervention. They are already implementing different targets and legislation on the use of green hydrogen, creating a demand pull. There should also be a mechanism by which the prices of renewable energy-based hydrogen and fossil fuel-based hydrogen can become more competitive. When this mechanism is in place, the functions that are currently less performing should be able to overcome their problems, or at least partly, and be able to have the hydrogen innovation system start to grow. A push in the right direction could start the complex feedback loop situation from having its effect.

The two most promising solutions, according to most system functions, are the influence of the government leveling the playing field and technological development lowering overall costs. For each barrier, one of these arguments is given for the complex system to start resolving its issues. Therefore, these are seen as the barriers that will receive the most attention for being resolved, or the ones with the most potential.

5 Results Techno-economic Modelling

Within this chapter, the results of the techno-economic model are presented. In Section 5.1, the goal and scope of the TEA are elaborated on. In Section 5.2, the techno-economic data is presented, as well as assumptions made about the data. Then, in Section 5.3, the techno-economic analysis will be performed to answer SQ 3: *How do the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe compare in techno-economic performance?* In Section 5.4, the scenarios set up as well as the parameters and their future predictions are mentioned. And finally, in Section 5.5, the scenario analysis based on the drivers and barriers is performed.

5.1 Goal and scope

5.1.1 Research perspective

The goal of the research is guided by perspective. Each perspective raises its own set of questions, which are vital in determining the goal of specific research. Perspectives for a TEA are research and development, corporate, or market, and each targets a specific audience. In this case, the market perspective is adapted as this TEA forms an explorative market research market (Zimmermann et al., 2020).

The goal is to compare different hydrogen value chains and prove that this TEA allows for a socio-technical and techno-economic combination of research methods. This leads to an analysis of the market and how the new concepts influence the hydrogen market. The goal is not to compare exact numbers but to give insight into how the value chains compare and what influences the prices per value chain the most.

5.1.1 Scope of the TEA

The scope of this analysis is the production of hydrogen through a low-carbon production method. The methods, or value chains, are all able to comply with a rule, mandate, directive, or initiative of the European legislation in the EU green deal, as analyzed in Subsection 3.3.1 under institutional analysis. A comparison will be made between the total costs of the different value chains. In this comparison, the components creating the CapEx and the components creating the OpEx will be calculated to highlight which cost components affect the price per value chain the most. So, a final comparison will be made in the following functional unit: The production of one kg of pure low-carbon hydrogen, in the year 2025.

The reference flow represents the value chains that are used for the techno-economic analysis. The four value chains were already mentioned in Subsection 4.2.2, but down blow the concentrated versions.

1. The production of one kg of pure low-carbon hydrogen produced from renewable energy using an alkaline electrolyser in Europe in the year 2025.
2. The production of one kg of pure low-carbon hydrogen produced from natural gas using steam methane reforming and carbon capture and storage in offshore gas fields in Europe in the year 2025.
3. The production of one kg of pure low-carbon hydrogen produced from nuclear power using a SOEC electrolyser in Europe in the year 2025.
4. The production of one kg of pure low-carbon hydrogen produced from renewable energy power using an alkaline electrolyser in Saudi-Arabia in the year 2025.

The boundaries of the systems are presented in Figure 5.1 below; they form the scope in which the value chains are compared based on the reference flows. As can be seen, only the production methods and the energy sources are included.

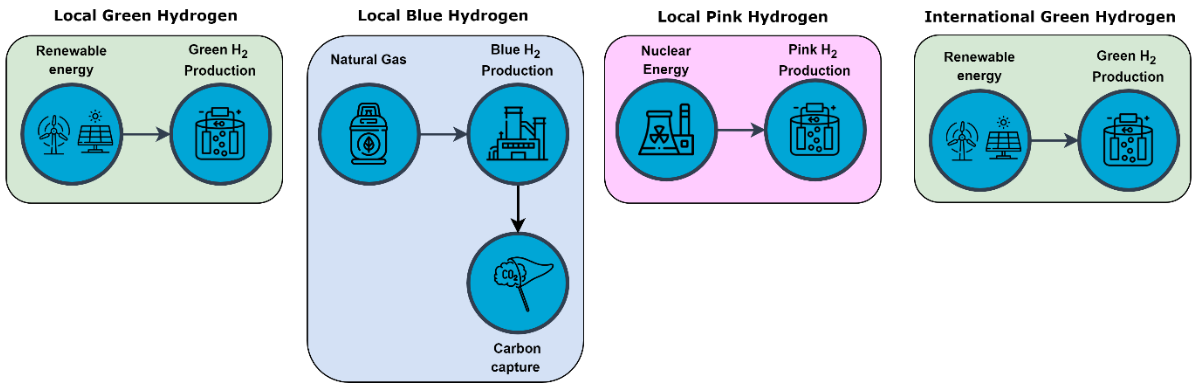

Figure 5.1: System boundaries per value chain

5.2 Data collection

The collected data and the assumptions will be discussed in this section. The selected data is as recent as possible. The data on the invested components is taken from the most recent years, as these technologies will be applied in the construction. The energy source data, like fuel and energy, are taken from the year 2025. First, the overall system assumptions, and then, per value chain, more in-depth techno-economic data.

5.2.1 Overall system assumptions

- ***The discount rate:*** or the WACC is set at 8% for all projects, balancing the lower risk associated with renewable energy projects at 6% WACC and the higher risk at 10% WACC. This rate is applied to electrolysis as well as SMR and CCS plant projects, acknowledging the developmental stage of CCS technology (BCG, 2023; IRENA, 2020b).
- ***The operational lifetime:*** All projects are assumed to have a 20-year operational lifetime, providing a standardized timeframe for evaluating viability and financial outcomes across different technologies.
- ***The Inflation rate:*** is assumed to be two percent for all projects. The reason for including the inflation rate In the cash flows, when not included, the costs would be undervalued, which would mean that the 8 percent WACC could not be reached as the costs would become higher in real life than the calculation would present. The outcome will be an average LCOH over all years that accounts for inflation. An inflation rate of 2% is factored into all projects to ensure

costs are realistically evaluated over time, adjusting the Levelized Cost of Hydrogen (LCOH) to reflect true financial implications and support the 8% WACC target.

- ***Hydrogen production***: Hydrogen production capacity is uniformly assumed at 100 mega tons (MtH2) per year for each plant, regardless of size, with the capability achieved through multiple (smaller) plants to reach the necessary total capacity.

Table 5.1: Overall assumptions for all value chains

Parameter	Value	Unit
Discount rate (WACC)	8	%
Operational lifetime	20	years
Inflation rate	2	%
Hydrogen production	100	MtH_2/year

5.2.2 Local green hydrogen

Local green hydrogen based on an alkaline electrolyser. This electrolyser suits is the most commercialized and therefore chosen in this example. Down below the economic and technological parameters.

5.2.2.1 Economic parameters

- ***Investment costs:*** The local hydrogen production is assumed to be performed by a western-made alkaline electrolyser. This electrolyser is assumed to be onshore, and the costs include the balance of the plant. The cost is assumed to be 1200 €/kW. This first investment cost is assumed to have the first stack costs included. The costs range between 500 and 1400 €/kW. Yet, as in the expert interviews as well as the stakeholder interviews by Jesse et al. (2024), tend towards the range of 1400 €/kW, which is more likely than the range of 500 €/kW. The costs are assumed to be 1200 €/kW, which is also on the conservative side for possible strategic decisions (Brändle et al., 2021; Corbeau & Merz, 2023; IEA, 2019; Jesse et al., 2024; Krishnan et al., 2023; van 't Noordende & Ripson, 2022; Webb et al., 2023).
- ***Stack replacement costs:*** The stack replacement costs for an alkaline electrolyser is assumed to be 30% of the CapEx, based on the number 242 to 388 €/kW (Krishnan et al., 2023).
- **O&M costs:** O&M is assumed to be 3% of CapEx the alkaline electrolyser. This is assumed to be without electricity costs (Brändle et al., 2021; Hydrogen Council, 2020; Ishaq et al., 2022).
- **The *electricity costs:*** as the report is from an energy company perspective, the cost of 65 €/MWh in 2030 is assumed to be feasible for the duration of the whole time for renewable energy (BCG, 2023; María Villarreal Vives et al., 2023). This price is assumed to be logical for the northwestern European region.

5.2.2.2 Technological parameters

- ***Electricity consumption:*** The theoretical energy efficiency is 39,4 kWh/KgH_2 (EPCM, n.d.). The electrical efficiency and the system energy consumption are 51-82% (Ajanovic et al., 2022, 2024; AlHumaidan et al., 2023; Brändle et al., 2021; IEA, 2019). The total electrical efficiency can be seen as 57 to 69 kWh/KgH_2 (IRENA, 2020b). Therefore, a total value of 55 kWh/KgH_2 is assumed in this research. The percentages used are negligible, but the end total of 55 kWh/KgH_2 is seen as acceptable.
- ***Stack lifetime*:** the stack lifetime is between 60.000-100.000 hours (Corbeau & Merz, 2023; IRENA, 2020b; Ishaq et al., 2022; Sebbahi et al., 2022; Shiva Kumar & Lim, 2022). Therefore,

the stack lifetime is assumed to be 80.000 hours. The stack replacement is assumed to be performed at 90% stack efficiency (van 't Noordende & Ripson, 2022). Meaning that at 90%, the total lifetime hours have passed.

- ***The capacity factor/ electrolyzer utilization:*** represented as a percentage, reflects the actual operating time against the total possible hours in a year, summed up to 8760 hours. Electrolyzer utilization of 55%; however, this is the year 2023 (BCG, 2023). Current projects demonstrate a lower capacity factor, prompting an adjustment to a more realistic figure of 45% (Taminiau & van der Zwaan, 2022). This adjustment better aligns with the observed capacity factors of renewable energy sources, ensuring a more accurate representation of operational efficiency in the techno-economic analysis.

Table 5.2: Techno-economic data for local green hydrogen value chain

Technology	Parameter	Value	Unit
Electrolyser Alkaline			
	CapEx	1200	€/kW
	OpEx	3	% of CapEx
	Electricity consumption	39,4	kWh/KgH_2
	Stack lifetime	80.000	hours
	Stack replacement costs	30	% of CapEx
	Electrical efficiency	79	%
	System efficiency	91	%
	Electricity price - renewable	65	€/MWh
	Electrolyzer utilization	45	%

5.2.3 Local blue hydrogen

Local blue hydrogen is created in a blue hydrogen plant that combines steam methane reforming with carbon capture. This technology is seen as a bridging technology for the energy transition to green hydrogen. Despite the carbon capture technology, some CO_2 still gets emitted into the air, and its dependence on fossil fuels raises questions about its long-term viability (Ueckerdt et al., 2023). Down below the economic and technological parameters.

5.2.3.1 Economic parameters

- ***Investment costs:*** The costs are for the CCS and the SMR combined. 247 Million for an output of 78 MtH_2 per year. The is assumed, without economies of scale to be able to grow to 100 MtH_2 per year in the same ratio (Ali Khan et al., 2021; Kim et al., 2021)
- ***Stack costs:*** The SMR & CCS plant does not have stack, meaning that there are no stack costs.
- ***O&M costs:*** These are assumed to 6% with all necessary parts included per year (Mullen et al., 2023).
- ***Energy costs:*** The blue hydrogen plant is assumed to run both on electricity and on natural gas. As the Netherlands has proceeded with a final investment decision on blue hydrogen, including storage (ICSC, 2023; Martin, 2023b), their natural gas price will be taken, in 2025, which is estimated at around 27 €/MWh (ICE, 2024; MarketWatch, 2024). The electricity cost is assumed to be the same as for green hydrogen, so that there are no extra CO_2 emissions (BCG, 2023).

- ***CO_2 costs:*** The CO_2 price assumption is based on the EU's emissions trading system, suggesting that producers will make economically sound decisions by engaging with this system. When it becomes operational in 2025, the CO_2 price is expected to be around €85 per tonne based on the ETS (Twidale, 2024; Vitelli, 2023). The CO_2 costs for carbon capture are already encapsulated in the CapEx and OpEx of the SMR & CCS plant. The sole CO_2 emissions costs are based on the remaining CO_2 that is emitted into the atmosphere.

5.2.3.2 Technological parameters

- ***Natural gas consumption:*** The natural gas consumed is 434 MW/year for an output of 78 MtH_2 per year. It is assumed, without economies of scale, to be able to grow to 100 MtH_2 per year in the same ratio, becoming 556 MtH_2 per year (Ali Khan et al., 2021; Kim et al., 2021).
- ***Electricity consumption:*** The electricity consumed is 7,87 kWh/kgH_2 (Kim et al., 2021).
- ***Emissions:*** The emitted CO_2 by a SMR plant is around 8 to 12 kgCo2 per kg of H_2 (Blank & Molly, 2020), while with blue hydrogen, the SMR technology in combination with CCS, the emission is only still 1 $kgCO_2/kgH_2$ (AlHumaidan et al., 2023; Arcos & Santos, 2023). Therefore, the assumed emission of SMR is 10 kg CO_2 per kg H_2.
- ***Carbon capture rate:*** The SMR & CCS plant is assumed to have a carbon capture rate of 90 percent.
- ***The capacity factor*** for this energy source is assumed to be 90%. As it can self-control the capacity factor.

Table 5.3: Techno-economic data on local blue hydrogen value chain

Technology	Parameter	Value	Unit
Steam methane reformer & CCS			
	Operational life	20	years
	CapEx	1200	€/kW
	OpEx	4	% of CapEx
	Natural gas consumption	556	MW/year
	Electricity consumption (actual)	7,87	kWh/KgH_2
	Emissions	10	$kgCO_2/kWh$
	Carbon capture rate	90	%
	utilization	90	%
	Natural gas price	27	€/MWh
	Electricity price	65	€/MWh
	CO_2 price	85	€/tCO_2

5.2.4 Local pink hydrogen

For local pink hydrogen, the SOEC is chosen as the production technology. SOEC is a type of high temperature steam electrolysis that represents a innovative technology, offering enhanced thermal efficiency and more economical production costs compared to traditional low-temperature water electrolysis (Shiva Kumar & Lim, 2022). The combination of SOEC with a nuclear source has potential for enhanced efficiency (Leo, 2023), because of the high temperature that comes along with nuclear energy (Shiva Kumar & Lim, 2022). Nuclear energy has the pro that it offers stable, clean energy, mitigating GHG, but it also incurs higher costs, the risk of nuclear accidents, and the consequences of nuclear waste (Revankar, 2019). The numbers for this technology are taken on the experimental side to see how they would compare if the technology could perform in comparison to more commercial technologies.

5.2.4.1 Economic parameters

- ***Investment costs:*** The local hydrogen production is assumed to be performed by a western-made SOEC electrolyser. This electrolyser is assumed to be onshore, and the costs include Balance of Plant. The CapEx is around 2000 €/kW but could be upwards of that (Corbeau & Merz, 2023; IRENA, 2021; van 't Noordende et al., 2023).
- ***Stack costs:*** The stack costs are assumed to be 20% of the CapEx; 300 kW can be found, 15% of the CapEx, and 40% of the CapEx in the literature, therefore, also on the experimental side, 20% is taken (Bernuy-Lopez, 2023; Deloitte, 2021).
- ***O&M costs:*** The O&M is assumed to be 3%, the same as the other electrolysers. But it can be seen to have higher costs, around 5%. But for the more experimental numbers in this scenario, this is accepted (Deloitte, 2021)
- ***Energy costs:*** 70 €/MWh, which are French nuclear prices (Hummel & Thomas, 2023).
- ***CO_2 costs:*** assumed to be no emissions, so none.

5.2.4.2 Technological parameters

- ***Electricity consumption:*** All of these combined numbers taken are 33 kWh/kgH_2 for energy consumption, electrical stack efficiency is 100% stack efficiency, with 84% system efficiency, ending on 39 kWh/kgH_2 total energy consumption with balance of plant (van 't Noordende et al., 2023).
- ***Stack lifetime:*** The lifetime of the stack is between 20.000 and 90.000 hours. Therefore, the stack lifetime is assumed to be 45.000 hours, as these assumptions are already from 2022 and the numbers in this value chain are less conservative (Corbeau & Merz, 2023; IRENA, 2020b; Shiva Kumar & Lim, 2022). The stack replacement is assumed to be performed at 90% stack efficiency (van 't Noordende & Ripson, 2022). Meaning that at 90%, the total lifetime hours have passed. The stack is assumed to be replaced at 90% of its initial working capacity, depending on capacity hours, their stack lifetime, and how much change is necessary.
- ***Capacity factor:*** The capacity factor is assumed to be 90%, as it is assumed to be self-controlled by the direct power output of nuclear energy.

Table 5.4: Techno-economic data on local pink hydrogen value chain

Technology	Parameter	Value	Unit
Electrolyser Alkaline			
	CapEx	2000	€/kW
	OpEx	3	% of CapEx
	Energy consumption	33	kWh/KgH_2
	Stack lifetime	45.000	hours
	Stack replacement costs	20	% of CapEx
	Electrical efficiency (stack)	100	%
	System efficiency	84	%
	Electricity price - nuclear	70	€/MWh
	Electrolyzer utilization	90	%

5.2.5 International green hydrogen

For international green hydrogen, the same characteristics for the electrolysers are chosen, as for the local green hydrogen. International green hydrogen is based on an alkaline electrolyser. This electrolyser suits is the most commercialized and therefore chosen in this example. Down below the economic and technological parameters.

5.2.5.1 Economic parameters

- ***Investment cost:*** Same as local green hydrogen, see subsection 5.2.2.1.
- ***Stack costs:*** Same as local green hydrogen, see subsection 5.2.2.1.
- ***O&M costs:*** Same as local green hydrogen, see subsection 5.2.2.1.
- ***Energy costs:*** The electricity price for Saudi Arabia is the benchmark price in Saudi Arabia's power purchase agreements for solar projects and wind projects. The price is 18,3 $/MWh or 19,9 $/MWh, although reforming this with an exchange rate of 1€ being 1,09$ (ECB, 2023), to be more conservative, as this is for an investor decision, 20 €/MWh is assumed (Hasan & Shabaneh, 2021).

5.2.5.2 Technological parameters

- ***Electricity consumption:*** Same as local green hydrogen, see subsection 5.2.2.2.
- ***Stack lifetime:*** Same as local green hydrogen, see subsection 5.2.2.2.
- ***The capacity factor***: The capacity factor, or capacity utilization rate, is 60% on average in Saudi Arabia (Hasan & Shabaneh, 2021).

Table 5.5: Techno-economic data on international green hydrogen value chain

Technology	Parameter	Value	Unit
Electrolyser Alkaline			
	CapEx	1200	€/kW
	OpEx	3	% of CapEx
	Energy consumption	39,4	kWh/KgH_2
	Stack lifetime	65.000	hours
	Stack replacement costs	30	% of CapEx
	Electrical efficiency	79	%
	System efficiency	91	%
	Electricity price - renewable	20	€/MWh
	Electrolyser utilization	60	%

5.3 Techno-economic analysis

The techno-economic analysis of the chosen local and international hydrogen value chains involves calculating the levelized cost of hydrogen (LCOH) for each cost component and adding these to a LCOH total. A comprehensive account of the techno-economic data related to each component of the value chain is located below in Figure 5.2, with a breakdown of the costs per value chain. The value chains included are defined as follows: green, for local green hydrogen; blue, for local blue hydrogen; pink, for local pink hydrogen; and international, for international green hydrogen.

The figure below shows the results of the techno-economic analysis for the different hydrogen value chains. The third sub question shall be answered here: *How does the key competing value chain of* *green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe compare in terms of techno-economic performance?*

For all electrolysers, the magnitude of the electricity costs can be seen. Where the local production has much higher electricity prices, this also translates into a much higher LCOH in the end. Local green hydrogen has a LCOH of 6,84 €/kgH_2, local blue hydrogen has a LCOH of 2,65 €/kgH_2, local pink hydrogen has a LCOH of 5,06 €/kgH_2, and lastly, international green hydrogen has a LCOH of 3,23 €/kgH_2. These are all levelized costs over a time span of 20 years with an inflation rate of 2% and a WACC of 8%.

Figure 5.2: LCOH per value chain

5.3.1 Local Green Hydrogen

In the case of the production of one kg of pure low-carbon hydrogen produced from renewable wind power using an alkaline electrolyser in Europe in the year 2025, the levelized cost of hydrogen is 6,84 €/kgH_2. The investment cost used was 1200 €/kW, resulting in a component price of the investment costs of 1,71 €/kgH_2, which is 25% of the total costs. The stack replacement costs were 30% of the investment costs; with a one-time stack replacement, the stack costs were 0,21 €/kgH_2, which is 3% of the total costs. The electricity cost used was 65 €/MWh, which resulted in a component price of 4,33 €/kgH_2, which is 63% of the total costs. The O&M used was 3% of the CapEx per year, resulting in a component price of 0,59 €/kgH_2, which is 9% of the total costs.

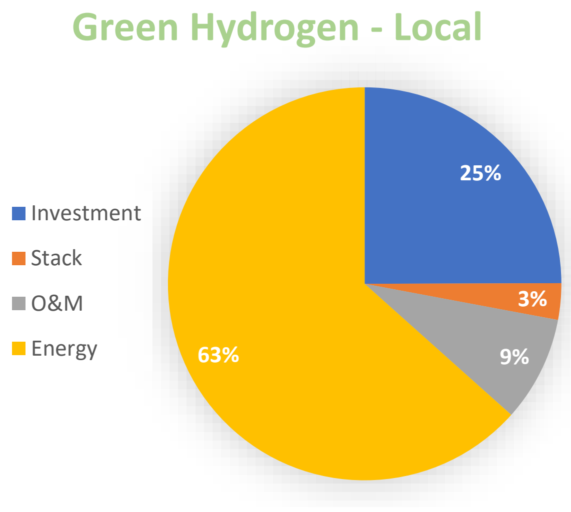

Figure 5.3: Local green hydrogen cost break down

5.3.2 Local Blue Hydrogen

In the case of the production of one kg of pure low-carbon hydrogen produced from natural gas using steam methane reforming + carbon capture and storage (90%) in Europe in the year 2025, the levelized cost of hydrogen is 2,65 €/kgH_2. The total investment costs were € 317 million, resulting in a component price of 0,32 €/kgH_2, which is 12% of the total costs. The energy cost used was 65 €/MWh for electricity and 27 €/MWh for natural gas, which resulted in a component price of 2,00 €/kgH_2, which is 76 percent of the total costs. The O&M used was 6% of the CapEx per year, resulting in a component price of 0,22 €/kgH_2, which is 8% of the total costs. The CO_2 costs were based on a CO_2 price of 85 €/tonne, resulting in a component price of 0,10 €/kgH_2, which is 4% of the total costs.

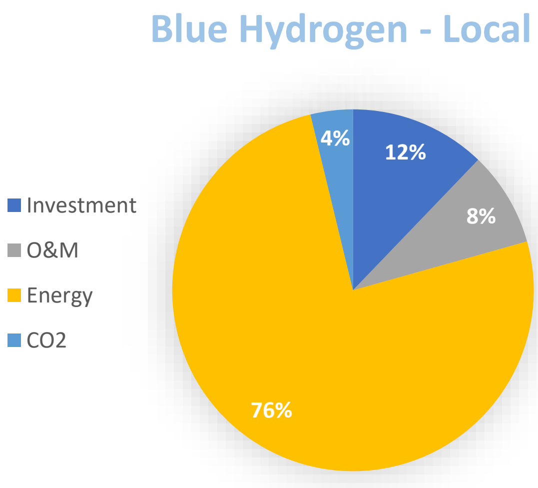

Figure 5.4: Local blue hydrogen cost breakdown

5.3.3 Local Pink Hydrogen

The production of one kg of pure low-carbon hydrogen produced from nuclear power using a SOEC electrolyser in Europe in the year 2025 will cost 5,06 €/kgH_2. The CapEx used was 2000 €/kW, resulting in a component price of 1,02 €/kgH_2, which is 20% of the total costs. The stack replacement costs were 20% of the investment costs. With three stack replacements, the stack costs were 0,33 €/kgH_2, which is 7% of the total costs. The electricity cost used was 70 €/MWh, which resulted in a component price of 3,36 €/kgH_2, which is 66% of the total costs. The O&M used was 3% of the CapEx per year, resulting in a component price of 0,35 €/kgH_2, which is 7% of the total costs.

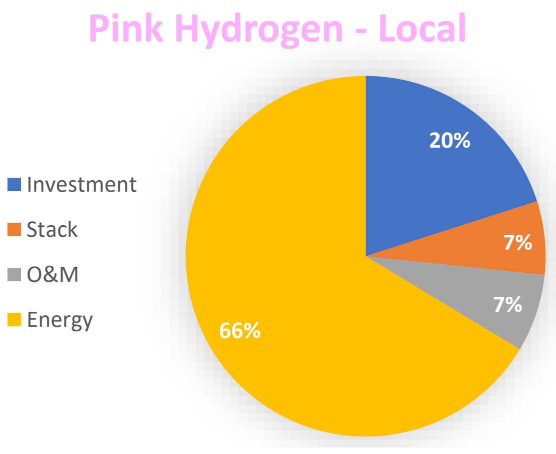

Figure 5.5: Local pink hydrogen cost breakdown

5.3.4 International Green Hydrogen

The production of one kg of pure low-carbon hydrogen produced from renewable energy using an alkaline electrolyser in Saudi Arabia in 2025 will cost 3,23 €/kgH_2. The investment cost used was 1200 €/kW, resulting in a component price of the investment costs of 1,27 €/kgH_2, which is 39% of the total costs. The stack replacement costs were 30% of the investment costs; with a one-time stack replacement, the stack costs were 0,18 €/kgH_2, which is 6% of the total costs. The electricity cost used was 20 €/MWh, which resulted in a component price of 1,33 €/kgH_2, which is 41% of the total costs. The O&M used was 3% of the CapEx per year, resulting in a component price of 0.44 €/kgH_2, which is 14% of the total costs.

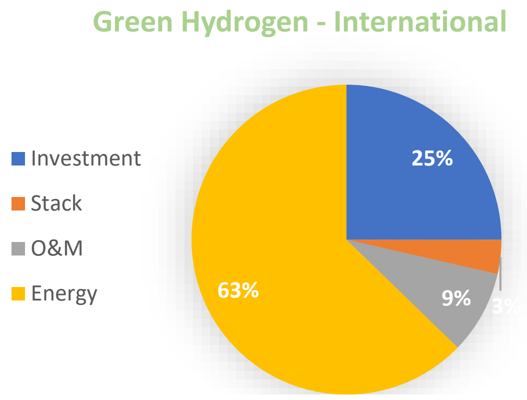

Figure 5.6: International green hydrogen cost breakdown

5.4 Scenario set-up

This segment explains various scenarios presented in this thesis, incorporating insights based on the most frequently discussed theme from the functional analysis. These scenarios serve as additional input for the discussion. Down below in Figure 5.7, there are four separate scenarios based on the main theme that comes back in every system function of the green hydrogen production method: the costs of hydrogen.

The costs of green hydrogen are too high at the moment, being uncompetitive with the other fossil-fueled versions, and because of the impasse that has become the current status of the system, the chicken-and-egg problem, a solution is necessary to resolve that impasse. According to most system functions, the two most promising solutions are the government's influence in leveling the playing field and technological developments that lower total costs. Therefore, the scenarios are based on these possible solutions. Down below in Figure 5.7, the scenarios, and below the figure, further explanation of the scenario's.

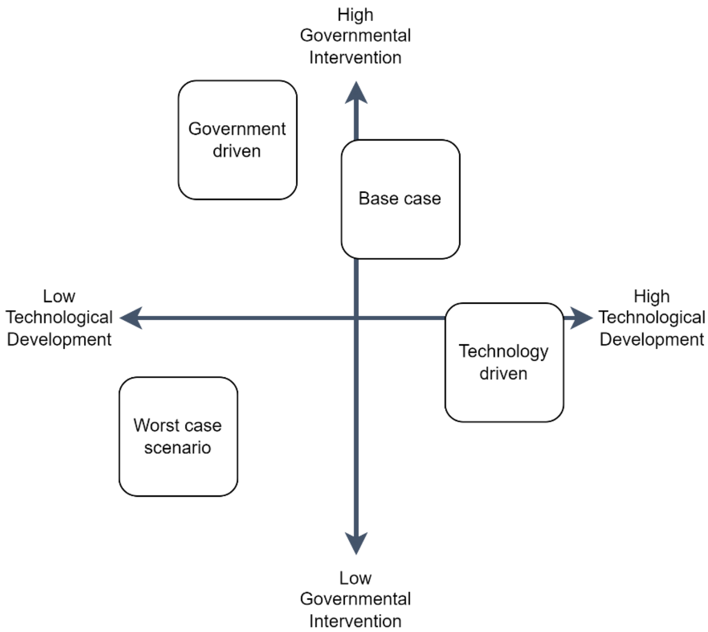

Figure 5.7: Scenario's based on barriers

Base Case Scenario: This scenario represents the current state of affairs, characterized by existing levels of governmental intervention and technological development. It serves as the reference point against which the other scenarios are compared, providing a grounded perspective on the status quo of the hydrogen production industry. The base case shows above middle governmental intervention, as there are, for example, initiatives under the EU Green Deal, that set binding and non-binding targets, such as the RED III (van Ahee, 2023). The technological development is still not optimal but does have a positive outlook.

Government-driven: High Governmental Intervention with a Low Technological Development Scenario. This scenario examines the impact of substantial governmental support through policies, subsidies, and incentives on the hydrogen economy, assuming that significant technological advancements do not materialize as expected. The analysis here is centered on understanding how policy-driven measures can influence the market dynamics, investment landscape, and overall competitiveness of hydrogen production in the absence of rapid technological progress.

Technology-driven: Low- to middle-level government intervention with a high technological development scenario Conversely, this scenario explores the hydrogen sector's evolution under conditions of medium governmental support but with significant breakthroughs in technology. It focuses on how advancements in hydrogen production technology, leading to reduced CapEx, which directly lowers O&M and stack replacements, can drive the sector forward. The scenario aims to gauge the potential for market-driven innovation and cost reductions to stimulate the growth and adoption of hydrogen technologies without relying heavily on government intervention. This scenario is the goal of the system, as it aims to become a market without the government having to intervene; however, some supervision is still necessary.

Worst-case: The worst-case scenario is where both the governmental intervention has stopped and the technological development is in a worse state than thought at the moment, for example, through unknown conditions or just overall little experience in current times with system builders. The electricity prices rise, and the CapEx turns out to be higher than before.

Table 5.6: Parameters and ranges for scenario analysis

Parameter	Unit	Base case	Low GI High TD	High GI Low TD	low GI low TD
CapEx Alk	€/kW	1200	500	1200	1800
CapEx SOEC	€/kW	2000	1400	2000	2800
Price local electricity	€/MWh	Local green - 65 Local pink - 70	65 70	58,5 (-10%) 63 (-10%)	71,5 (+10%) 77 (+10%)
ETS - CO_2 price	€/tCO_2	85	85	150	85

The chosen numbers are based on previous literature reviews. The CapEx is taken in the higher end and lower end, prices of these sorts, referring back to the data collection. The renewable energy price is adjusted by a 10%, just to see the influence on the total price. The CO_2 is based on possible future prospects, around 150 €/tCO_2 (Glushchenko, 2023).

5.5 Scenario analysis

The scenario's research is shown below. In the discussion, the effects shall be discussed, and here the main takeaways are given. The main takeaways are based on how the value chain compares and, in different scenarios, if they compare differently than in the base case. Therefore, the base case is shown below first.

Figure 5.8: Base case scenario results of TEA

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5.5.1 Technology driven

Low governmental intervention with high technological development. The LCOH of local green hydrogen has dropped by 1,46 €/kg, a cost reduction of more than 20% due to a CapEx change from 1200 to 500 €/kW, or almost 60%. The same change applied to international green hydrogen has caused a LCOH drop of 1,11 €/kgH_2, a drop of 34%. The last change has happened in pink hydrogen, which has a LCOH drop of 0,51 €/kgH_2, around 11% less than original due to a CapEx change from 2000 to 1400 €/kW, a change of 30%.

Figure 5.9: Technology driven scenario results of TEA

5.5.2 Governmental driven

High governmental intervention with low technological development. The LCOH of local green hydrogen has dropped by 0,37 €/kgH_2, a cost reduction of more than 5% due to a renewable price change of -10%. The same change applied to local pink hydrogen has caused a LCOH drop of 0,34 €/kgH_2, a drop of almost 7%. The last change has happened in blue hydrogen, which has a LCOH rise of 0,07 €/kgH_2, around 2,5% more than the original.

Figure 5.10: Governmental driven scenario results of TEA

5.5.3 Worst-case scenario

Low governmental intervention and low technological development. The LCOH of local green hydrogen has risen by 1,68 €/kgH_2, a cost increase of almost 25% due to a renewable price change of +10% and the CapEx increase from 1200 to 1800 €/kW. A cost increase of 1,02 €/kg because of a CapEx increase from 2000 to 2800 €/kW, 40%, and a renewable price increase of 10%. The last change has happened in international hydrogen, with a LCOH increase of 1,42 €/kgH_2, an increase of 66% due to a CapEx change of 40%.

Figure 5.11: Worst-case scenario results of TEA

6 Discussion

First, the results are interpreted in Section 6.1, where the outcomes of the techno-economic analysis are situated in the broader literature and socio-technical context. Following this, in Section 6.2, the limitations are discussed. Lastly, in Section 6.3, suggestions for future research are made based on the limitations of this research.

6.1 Interpretation of Results

6.1.1 Interpretation of LCOH

The techno-economic analysis in this thesis revealed that, in comparing the different key competing value chains of green hydrogen in Northwestern Europe, the local blue hydrogen value chain was the most cost-effective with a LCOH of 2,65 €/kgH_2, and local green hydrogen was the least cost-effective with a LCOH of 6,84 €/kgH_2.

The results of the scenario analysis, especially under the drivers and barriers of the hydrogen system, show that blue hydrogen consistently remains the cheapest local production method and that local green hydrogen is the most expensive option. Only international green hydrogen in one scenario is cheaper than local blue hydrogen. Comparing these results to previous literature, the LCOH for all value chains ranges from 2,12–8,52 €/kgH_2 in the scenarios. The literature reviewed offers a range of costs, indicating prices of 1,5–3 €/kgH_2 for SMR with CCS and 2,5–8,5 €/kgH_2 for electrolyser-based hydrogen production (Ajanovic et al., 2024; AlHumaidan et al., 2023; Durakovic et al., 2023; Mio et al., 2024; Noussan et al., 2020; Shirizadeh & Quirion, 2023; Zainal et al., 2024). The further named LCOH values are already compared to existing literature; therefore, no further source or explanation shall be given in the subsections.

The variation in prices can be attributed to the absence of a standardized metric for direct, apples-to-apples, comparison between hydrogen value chains, as highlighted in the literature review. This issue is intensified by differences in assumptions regarding operating hours and energy costs (Ajanovic et al., 2022). The diversity in the steps included within each value chain further contributes to this variance. Nonetheless, the TEA findings align with these price ranges. After adjusting for inflation, the costs remain within the expected spectrum, a consistency that, coupled with expert validation throughout the research process, affirms that the figures are within a realistic range. Therefore, the metric used is seen as viable for the purpose of comparison, including both levelized cost over time and inflation. It must be noted that calculations are made from an investor perspective. The inclusion of levelized costs and inflation is key for their decision-making and thus is included and consists of solely the production method and the energy source.

These results do inform the user well, yet these results should not lead to decision-making, as the dynamic and complex nature of the energy market and its components can constantly influence the outcome of this comparison. The scenario analysis focused on barriers and drivers identified by stakeholders across the value chain. It translated the main barriers into scenarios by adjusting variables accordingly in Section 5.4 to clarify the influence of drivers and barriers on analysis outcomes. This created more robust outcomes; however, context on the matter should be created per value chain, understanding the current status, outlook, and associated risks, to improve TEA as a comprehensive decision-making tool. The context is given in the next subsection to provide the user with a full overview.

6.1.2 Interpretation of cost components

The TEA revealed that in both the electrolyser-based production methods and the SMR-based production method, the energy cost and the CapEx are the components that make up most of the price, forming 78–87% of the total LCOH in all value chains. With stack costs included, which in other TEAs are seen as part of the CapEx, these percentages are all upwards of 80%. This aligns with the results from the functional analysis in Subsection 4.4.2, as well as the literature (Ajanovic et al., 2022, 2024; Webb et al., 2023). The stakeholders, as well as existing literature, outline the effect electricity and natural gas prices have on the final LCOH, displaying their importance in making green hydrogen more cost-competitive. Next to the influence of the capacity factor and capital cost, they are also of great impact on the LCOH (Ajanovic et al., 2022, 2024; Hasan & Shabaneh, 2021; Webb et al., 2023).

The TEA revealed that the capacity factor and energy price are a duo of parameters that have a big influence on the LCOH. These two are the only parameters that differ in the comparison between international and local green hydrogen, highlighting a price for local green hydrogen (5,38-8,52 €/kgH_2) being around twice as expensive as international green hydrogen (2,12-4,18 €/kgH_2) in all scenarios. It was also revealed that the natural gas-based production method is more cost-effective than the electricity-based ones. The TEA gave the insight that with the current prices for renewable energy and nuclear energy, as well as the efficiency of electrolysers, it is difficult to compete with the prices of SMR because of the better efficiencies of the SMR technology and the lower price of natural gas.

This highlights the importance of these parameters and, thus, the great influence they have on the LCOH. For renewable hydrogen to become competitive, an electricity price of 30 €/MWh is suggested (Lagioia et al., 2023). A place like Saudi Arabia, with better capacity factors and lower energy prices, is more likely to reach those numbers than Europe (Griffiths et al., 2021; Noussan et al., 2020; Webb et al., 2023). A comparison of the results with the literature supports the finding that the high energy consumption of the electrolyser-based value chains is one of the main components that contribute to the LCOH. The contribution of the electricity price is one of the biggest components of the total price (Ajanovic et al., 2024; Brändle et al., 2021). Therefore, the literature does align with the results of the TEA on the cost components.

6.1.3 Interpretation of competing value chains

6.1.3.1 International green hydrogen

The techno-economic analysis showed that international green hydrogen has the potential to become the cheapest value chain of all sorts. With technological developments, the LCOH ranges from 2,12 to 4,18 €/kgH2. With the Middle East as an example, it has a major advantage because of its lower electricity costs (Hasan & Shabaneh, 2021). This aligns with the discussion on why some places around the world have better meteorological advantages over others, as a LCOH difference of 3,17–4,34 €/kgH2 with locally produced green hydrogen is substantial, being double the cost.

As this research is focused solely on the production method and energy source in the value chain, import logistics and their costs fall out of scope. The socio-technical analysis revealed that import logistics, which consist of the storage, conversion, and transport of hydrogen, currently exhibit low TRLS. The absence of standardized processes and technologies contributes to higher costs (Griffiths et al., 2021). If transport can fill that gap lower than that difference in price, the costs associated with it could be justified. A fair reasoning could be given on exactly why international green hydrogen is necessary, but also the other way around. As the electricity price is such a big part of the costs of local hydrogen production, policy should focus on lowering that price, or at least give some form of compensation that the local hydrogen producers could compete with, especially with the diversification of energy sources in mind.

For green hydrogen to become competitive, it should overcome the costs associated with import logistics, conversion, reconversion, and transport (Genge et al., 2023). However, international green hydrogen has a budget of 3,17–4,34 €/kgH_2, which is substantial. Otherwise, solutions must be found in technological developments, such as lowering the electricity price or improving the electrolyser utilization/capacity factor. Based solely on the production method, there is no preference, especially as REPowerEU plans to diversify the energy sources. It would even mean that both could exist, as local hydrogen production could be preferred as it means the independence of other countries, which was already a subject in another geopolitical discussion (European Commission, 2022).

6.1.3.2 Local pink hydrogen

The TEA revealed that pink hydrogen, in all scenarios, is more expensive than blue and international green hydrogen. However, it is always less expensive than locally produced green hydrogen. With a LCOH of 4,55-6,07 €/kgH_2, this type of hydrogen does remain the cheapest local, non-emitting hydrogen source. Pink hydrogen does have the advantage over green hydrogen in that the efficiencies are higher, as well as higher electrolyzer utilization (Shirizadeh & Quirion, 2023). High-temperature electrolysis is more suitable than low-temperature electrolysis for nuclear energy (Ajanovic et al., 2022). The Solid Oxide Electrolyzer, capable of operating at high temperatures, demonstrates improved efficiency under these conditions. However, scalability remains a challenge for SOEC technology, hindering its widespread application (AlHumaidan et al., 2023).

A further socio-technical analysis of pink hydrogen has highlighted certain challenges. Pink hydrogen does not comply with the qualifications of the RFNBO standards, as it is not renewable. This limits its applicability across various industries, meaning that it cannot be applied in every industry (Schelling, 2023). This restriction means pink hydrogen can primarily be utilized in sectors where mandates or initiatives explicitly support the adoption of low-carbon fuels. This compliance issue, coupled with country-specific stances on nuclear energy, underscores the challenges pink hydrogen faces in achieving wider acceptance and deployment. The concerns over nuclear waste and safety perceptions limit pink hydrogen's appeal, making it an unlikely choice for a Europe-wide hydrogen solution despite its possible technical merits (Griffiths et al., 2021). One positive note is that the capacity factor is higher as well as that it can be used in places where renewable energy is scarce (Corbeau & Merz, 2023). However, this is assumed not to be the case in Northwestern Europe in this analysis.

For green hydrogen to become competitive, it should overcome the price difference, which is between 0,83 and 2,45 €/kgH2. However, pink hydrogen has the downsides that it does have lower technical readiness and scalability, as well as nuclear energy having low social acceptance. When green hydrogen would become competitive is hard to tell, but overall, solely based on numbers, the choice would have been made easy, yet the inclusion of context could convince the user to decide in one or the other direction.

6.1.3.3 Local blue hydrogen

The techno-economic analysis also showed that blue hydrogen, in all scenarios compared to the other value chains, is the cheapest. Even with subsidies on the CapEx of electrolysers and possible higher prices for CO_2, blue hydrogen still remains the cheapest alternative. With a value between 2,65 and 2,72 €/kgH_2, it remains the most cost-competitive of the alternatives. Blue hydrogen is the cheapest technology at the moment because of its lower energy costs, and the SMR and CCS technologies are cheaper than the electrolysers. There is a discussion on whether blue hydrogen is competitive or complementary to green hydrogen in a future decarbonized hydrogen system (Durakovic et al., 2023).

The question with blue hydrogen is whether, in the future, this technology will still have a place in the energy system, as it still emits CO_2 and runs on natural gas and could become obsolete (Durakovic et al., 2023). A further socio-technical analysis of the drivers and barriers of blue hydrogen shows that geologic carbon storage potential is geographically specific. Which may cause it to not achieve high levels of employment (Griffiths et al., 2021). A barrier is the need for CO_2 infrastructure, as this is still lacking (Seck et al., 2022). These notes make the outcome of blue hydrogen costs also unpredictable, as the prices of CO_2 and natural gas could be higher than now assumed throughout the lifetime. The reliance on blue hydrogen carries the risk of facing substantial costs related to CO_2 emissions and surging natural gas prices, making the cost projections for blue hydrogen uncertain over its operational lifetime.

Yet, the cost gap of 2,73 to 5,87 €/kgH_2 could help in overcoming one of the first challenges green hydrogen has: forming a market, as it is a cheaper low-carbon version of hydrogen, allowing for the uptake of hydrogen in marginal demand sectors. Allowing the transportation network of hydrogen to start unraveling. However, as said before, there are still issues with CO_2 transport, which raises the question of whether these will hinder others' development (Carbon Limits & DNV, 2021). Overall, for local hydrogen to become competitive, it will need to address the cost gap. Only when there are stricter regulations on the emission of GHG will it become competitive, as the efficiency of the SMR process is better and the cost of natural gas is lower.

6.1.4 Interpretation of local green hydrogen

The techno-economic analysis has established that, across all evaluated scenarios, local green hydrogen remains the costliest option compared to other hydrogen value chains. The analysis identified a price range for green hydrogen between 5,84 and 8,52 €/kgH_2, marking it as not competitive with alternative value chains. A significant finding from the TEA is the cost differential that local green hydrogen must bridge to become competitive in the European market. The difference with blue hydrogen ranges from 2,73 to 5,87 €/kgH_2 when compared to blue hydrogen, the least expensive key competing value chain. This raises critical questions about the feasibility of narrowing this gap and the strategies required to achieve cost parity.

Subsequent socio-technical analysis has underscored the existing hurdles. Namely, the costs, which are validated by the results of the TEA, and the need for technological advancements (Griffiths et al., 2021). For green hydrogen costs to decrease, a combination of governmental policies and technological progress is essential. The path to lower costs is seen to lie in the adoption of hydrogen projects, driven by learning-by-doing and achieving economies of scale, necessitating proactive governmental measures to address the current impasse. This conclusion aligns with insights from expert consultations in the functional analysis and literature, pointing towards the necessity of an integrated approach involving policy support and technological development to enhance the competitiveness of local green hydrogen production (Ajanovic et al., 2022, 2024; Lagioia et al., 2023; Webb et al., 2023).

The functional analysis showed that the initiation of learning-by-doing and the realization of economies of scale hinge on the launch of projects, a milestone not yet achieved due to the challenge of securing project funding. This challenge can be identified by the lack of investors and funds. Which are deterred by the risks tied to the cost-competitiveness of the technology (EC5). The absence of demand consequently leads to a lack of supply. Investment becomes feasible only when demand is formalized in contracts and when energy prices for the supply side are established, creating a reliable stream of cash flow for investors.

6.1.4.1 The chicken-and-egg problem

The chicken-and-egg problem, or the supply and demand side of the hydrogen chain not making the first move on the market, is seen as a main problem by the functional analysis. The socio-technical analysis conducted in this research contrasts with the existing literature, particularly highlighting a first-mover disadvantage in the green hydrogen sector, a difference from the first-mover advantage (Jesse et al., 2024). Existing literature suggests that early entrants into a market can secure political backing and accumulate invaluable operational experience. Nonetheless, insights from the expert consultation reveal a different narrative: stakeholders perceive early adoption as risky, preferring others to navigate the initial hurdles and learn from their mistakes rather than being the pioneers themselves (EC7). This cautious stance among the stakeholders, especially in the value chain, underscores the reluctance to commit to sharing results and learning openly from early failures, despite such transparency being crucial for sector-wide advancement.

The stakeholders mention that a main challenge revolves around the reluctance to be pioneers, especially with the risk of facing early obstacles and the complexities involved in establishing long-term contracts (EC8). Industries face a significant dilemma in committing to long-term contracts associated with hydrogen supply. Such commitments may lock the industries into a contract or technology that could fall out of favor due to evolving regulatory landscapes and incentives aimed at reducing the costs of green hydrogen or technological developments, lowering overall costs (EC8). Waiting for green hydrogen to become more economically viable could ensure compliance with future regulations and potentially result in lower operational costs. This situation reinforces the deadlock as stakeholders from both supply and demand perspectives hold back, cautious of entering agreements that might not reflect the economic landscape down the line. Next to that, the insecurity over the existence and accessibility of funds and subsidies makes the reluctance to invest even higher (EC8).

Overcoming the impasse, or the so-called chicken-and-egg problem, is a crucial step towards establishing a sustainable green hydrogen economy. This dilemma, wherein the lack of supply stems from insufficient demand and vice versa, requires strategic interventions to break the cycle. The socio-technical analysis reveals the European hydrogen system is characterized by intricate connections and feedback loops, demonstrating how changes in one variable can lead to unpredictable adjustments across many others. This analysis made it clear that tackling the issue is not as straightforward as adjusting a few variables. However, the analysis showed that stakeholders agree that government intervention is key, whatever variable they may tackle (EC1).

The stakeholders recognize that while the industry aims to meet ambitious environmental targets, this goal must also be economically feasible. Current price barriers highlight a gap between policy aspirations and market realities, underscoring the essential role of government in facilitating a cost-effective transition to green hydrogen. The goal is for local green hydrogen to become competitive. A possibility of becoming competitive is by addressing the cost gap between local blue and local green hydrogen. This cost gap, ranging from 2,73 to 5,87 €/kgH_2, presents a significant challenge but also an opportunity for strategic interventions. This cost gap could be overcome by collective efforts within the hydrogen value chain to share costs, reduce prices, and disseminate knowledge (EC7). However, the primary solution lies in effective governmental intervention.

A note here could be given to the fact that green hydrogen could need a competing alternative like blue hydrogen to overcome the current status quo. This low-carbon alternative could help the demand side of hydrogen grow, facilitating the uptake of hydrogen in marginal demand sectors and starting to create the necessary infrastructure. The functional analysis highlighted the fact that blue hydrogen could replace green hydrogen in the system, yet a main goal of governmental intervention should solve that problem, as well as the growing demand for hydrogen in the future (Durakovic et al., 2023).

6.1.4.2 Governmental intervention

As the economics of green hydrogen are unfavorable, governmental intervention is a necessity. The governmental intervention does not have to overcome cost differences when companies are willing to pay a premium. A premium that comes forward out of the expected lower prices in the future for green hydrogen, or even the necessity of zero carbon emissions, makes blue hydrogen obsolete. However, as this premium is not calculated, in this case, the cost difference will be overcome.

For local green hydrogen to become competitive in the short term, the cost difference should be overcome. As of now, the current legislation allows companies to use other versions of hydrogen; this cost difference should be taken as the willingness-to-pay boundary. The willingness-to-pay is set by the blue hydrogen, as this falls under the EU regulations and thus sets the price. Therefore, the goal for green hydrogen is to bridge the gap to the price level of blue hydrogen. Governmental instruments ensuring lower prices for renewable energy, Electrolyzer CapEx funding, or other OpEx funds could all help in reducing the LCOH.

The functional analysis revealed that to overcome the chicken-and-egg problem, governmental intervention is necessary. This solution is proposed by most actors in the system. However, there is a problem with government intervention. One instrument is not as suitable as the other. The scenario analysis unraveled the techno-economic interplay between the cost components of the different value chains, as well as the interplay between the value chains. In these scenarios, governmental intervention was seen as a main barrier and was used as a scenario. The main takeaway from the analysis of governmental intervention was the application of the right intervention to the right cost aspect for the desired effect. For example, the price of ETS was raised from 85 to 150 €/tonne CO_2. However, a change of more than 40% only influenced the price of blue hydrogen by 2.5%. This shows that when governmental intervention is not applied to the right cost component, in this case a CO_2 price, it has little effect on the outcome.

In order for green hydrogen to have price reductions, questions could be asked about whether the focus should be on technological development and not on the electricity price, which accounts for more than half of the price. The price of electricity does impact the LCOH for electrolysis; this shows not only that the companies investing should focus more on lowering the electricity costs but also that whenever the policies are necessary to make green hydrogen competitive with its alternatives, great improvements could be made in the case of producing green energy at lower prices, overall positively impacting the overall emission reductions.

The ultimate objective, from the standpoint of the green hydrogen market, is to bridge the cost differential and discern which governmental interventions might facilitate this process. Or at least facilitate bridging the gap so that investors and demand sides are willing to invest and take on long-term contracts. When there are expected advancements in technology to reduce green hydrogen's cost relative to blue hydrogen, various strategic initiatives could be explored. The advocacy efforts of hydrogen value chain lobbyists, which are the supply side and demand side of green hydrogen combined, play a crucial role in this context. Either the costs are shared enough to lower the costs, or effective government intervention in tackling the chicken-and-egg issue could unlock funding for green hydrogen projects. This breakthrough would accelerate technological improvements, enhance hands-on learning, and leverage economies of scale (Revinova et al., 2023). Consequently, green hydrogen technology could evolve to become self-sustaining, driving competitive market dynamics and fostering widespread adoption.

These lobbyists are pivotal in highlighting the impact of diverse government policies on green hydrogen pricing and advocating the adoption of the most effective measures. Additionally, there is a need for comprehensive scenario analyses that map out the full spectrum of policy interventions, offering a clear picture of potential strategies. Understanding the variables that these interventions influence is invaluable, suggesting that detailed analyses of complex systems could shed light on both the current state and future possibilities of the hydrogen market. Such insights could significantly enhance decision-making capabilities, tailoring the analytical tool more precisely to user requirements and thus adding substantial value. The methodology has demonstrated its effectiveness, providing a foundation for further exploration. By incorporating additional scenarios and value chains, users can expand their understanding of the system, enriching the analysis with more nuanced insights.

6.2 Reflection on the method

In conducting this study, several limitations emerged that affected the scope and method of the research. This part of the discussion aims to unpack these limitations, explain the decisions made in the research process, and reflect upon them. The question with the reflection is whether the results are reproducible when another person tries to answer the same questions. The limitations, especially in this mixed-method research, are crucial in setting a clear scope for the research. Understanding the limitations allows for a clear picture of the challenges encountered and shows the thought process behind narrowing down the study's perspective.

6.2.1 Methodology

This research used a mixed method of qualitative and quantitative methods to assess hydrogen value chains in the northwestern part of Europe, a system analysis. This method, to the extent of the authors' knowledge, is the first that performs an apples-to-apples comparison of local and international value chains, with attention to their socio-technical status and outlook. The goal of the methods is to see if this method allows for a comprehensive overview, but the goal of the TEA is to assess when and whether green hydrogen could become competitive. This combination of socio-technical and techno-economic analyses led to a more comprehensive assessment of the hydrogen value chains in the European hydrogen system, allowing for a better-informed decision-making process for stakeholders.

The research has been conducted from the perspective of a company interested in green hydrogen. This gave insights into the complexity of the system where green hydrogen is currently; however, this also meant that the socio-technical discussion had more in-depth knowledge on this exact technology than the other technologies. The structural analysis set the demarcation for the limited value chains considered. The European legislation sets the boundaries within which these technologies should take their place. The exclusion of high-potential other technologies could be seen as a limitation, but as the goal of the research was to prove the workings of the model from a higher level, this is not seen as a limitation but as an opportunity for possible future research. This methodology assumed the value chain was just the energy source and the production technology, limiting the overall application, as it does leave out several value chain steps. This limitation could restrict the applicability of the findings to a broader context.

A more in-depth discussion of the pink hydrogen technology could have presented more insights. Also, the inclusion of turquoise, for example, could have helped in creating a more insightful model. However, for the purpose of this research, with the maturity of electrolysers seen as higher, even though SOEC is still in the experimental phase, the choice was justified. More value chains, international places, or technologies could have been added. But for the purpose of proving the concept of this mixed-method system analysis, this limitation was accepted.

This whole discussion is not based on what value chain is most cost-effective, but rather on the stakeholders that use the designed tool and present these stakeholders with the information, and whether they have the tool to make more informed decisions. As the literature is in line with the outcomes, the methodology can be seen functioning for the purpose it is deemed to serve. Understanding the fact that some cost differences should not have to be overcome in a certain manner but rather understood and understanding what the system deems necessary could help with informed decision-making.

The idea from the TIS analysis is to use a structural-functional analysis to allow for the use of structural and functional analysis as tools for investigating the system, allowing for a structured method. Then the integration of the qualitative data into the quantitative analysis requires careful methodological planning without biasing one to the other. The scenario analysis is based on the drivers and barriers depicted in the functional analysis. Although these scenarios' present insights into the possible futures and the techno-economic comparison of that future, other variables could have been chosen to adjust. The chosen variables were within ranges of found literature, aiming to minimize the effect of bias. As these variables could be based on literature, and others were not able to be found in literature in scenarios, these variables were accepted as the ones used in the scenarios.

The drivers and barriers of the European hydrogen system were identified based on stakeholders in the hydrogen value chain. Selecting other experts for the stakeholder interviews could have resulted in different drivers and barriers. However, the open discussions reached through the semi-structured discussions helped in understanding the drivers and barriers that were seen sector-wide. Also, these stakeholders do represent the value chain in current times, meaning they also represent the current train of thought.

Artificial intelligence language programs were utilized to refine and enhance the clarity, coherence, and quality of academic writing, aiding in identifying grammatical errors and suggesting stylistic improvements, thereby streamlining the editing process. However, the program's limitations in recognizing academic jargon and terminology, along with its tendency to suggest more complex language than necessary, highlighted the irreplaceable value of human judgment in the editing process.

6.2.2 Data limitations

The collected data and analysis were conducted in accordance with relevant literature and validated where necessary through experts and comparison. The limitations of the data impacted the results of the research; by discussing these, the research is put into perspective, allowing the reader to understand the limitations.

A limitation applicable to all data in this work is due to the dynamic nature of the hydrogen system. The ever-changing European hydrogen system, with new technologies, new institutions, new projects, or other influences ever on the horizon, could make the data and analysis slightly outdated. As the system is so dynamic, data does get outdated quickly, limiting the trustworthiness of the quality of the data. Even upon the release of this research, the analysis could already be partly outdated, especially with the sources that are older than one year. The expert consultations were found through the networks of the researcher.

Time limitations were allowed solely for the interview of eight experts, which may not fully represent the breadth of perspectives in the field. The interviews and literature set a good base; however, because of the dynamic environment when performing the research, this must be checked as every new adjustment will make sure that new conclusions can be drawn.

The techno-economic analysis that was conducted was subject to several assumptions, simplifying the overall calculations. These assumptions could be more experimental, or more progressive. The reason for doing so was to identify whether, with fewer details, the same conclusion could be drawn. However, some limitations must be mentioned. For all value chains, the assumption was that there was a sufficient supply of solely the necessary energy source; in real life, this most certainly is not the case, yet for the ease of this model and to get better insight into the costs, this limitation was accepted. These assumptions, which sometimes seem high or low, did not impact the overall conclusions of the project. But for final decision making in projects, more advanced models should be used and more in-depth and realistic data. The objective was to demonstrate that by sifting through diverse online data sources, it is possible to construct a model that provides initial strategic insights for market exploration, enriched with contextual understanding. This approach underscores the value of integrating scattered data into a coherent framework for informed decision-making.

Some data assumptions were made to allow for easier comparison between the value chains. Such as the operating lifetime and the WACC values. Also, the factors of learning by doing and economies of scale were not implemented. Furthermore, the international price of green hydrogen was calculated in the production process of green hydrogen; however, it is likely that other types of fuel are directly produced, like ammonia (Martin, 2023a).

6.3 Future Research

Based on the comprehensive analysis performed in this study, along with the valuable experience gained throughout the investigation of this topic, key recommendations and insights for future research can be proposed to build further upon the findings of this study.

Given the objective of offering a high-level overview of various hydrogen options within the European hydrogen landscape, it is inherent that further research is necessary to enhance our understanding of specific subjects. The recommendations provided stem from identified limitations, aiming to enrich insights into the European system at a more detailed level.

From a company perspective, it can be interesting to discover what governmental interventions have the desired effect on the hydrogen market. According to the socio-technical analysis, the chicken-and-egg problem was deemed the biggest barrier to the European hydrogen system. Also, according to the socio-technical analysis, most stakeholders saw a pivotal role for the government in resolving this chicken-and-egg problem. Therefore, a dedicated study of the possible governmental interventions could be valuable. To understand what interventions could help, we could fill a significant knowledge gap on what exact policy measures have good potential for helping to overcome this impasse.

The exploration of scaling and learning curves for different technological components represents a promising avenue for future research. Understanding how the costs of these technologies evolve over time is crucial, as price development significantly influences the final cost of hydrogen. Investigating these price trajectories can provide deeper insights into the hydrogen value chain, potentially leading to more accurate and credible projections of hydrogen economics. Such analysis could not only enhance the understanding of how technological advancements and economies of scale affect hydrogen production costs but also inform strategic decisions in technology adoption and policy formulation.

Another interesting research subject is to analyze the national institutions and ambitions more in depth per country. While some nations exhibit a strong inclination towards pink hydrogen, others lean towards blue hydrogen, indicating distinct drivers and barriers within each national context. This diversity underscores the importance of customizing research to address the specific conditions and policy environments of individual countries. Understanding individual countries' institutional environments could help understand the overall market better.

A promising area for investigation is the economic and logistical feasibility of importing green hydrogen. It is proven that there is a significant cost gap in local production and high potential in international locations. It would therefore be interesting to research whether the remaining cost difference, or budget in this case, is sufficient to justify the supply chain logistics and clarify whether the imports are a really competitive alternative. This exploration could reveal whether and how international green hydrogen can indeed offer a cost-effective solution for green hydrogen in the energy transition.

7
Conclusions

Within this thesis, a combination of socio-technical and techno-economic methodology was used to identify the performance of different hydrogen value chains in North-Western Europe under the conditions of the innovation system. This is to identify whether this mixed method would allow for a better insight into the complex and dynamic hydrogen system. To conclude the different findings from the research questions, the sub-research questions shall first be repeated and answered, whereafter the main research question shall be answered.

SQ 1: How are green hydrogen competing value chains for decarbonizing hard-to-abate industries in Europe configured?

The data for this sub-question was collected through semi-structured expert consultations as well as a literature review on the European hydrogen system and its hydrogen value chains. The data was processed and analyzed according to a socio-technical structural system analysis based on the TIS framework by Hekkert et al. (2011).

The analysis revealed a complex interplay of factors, with governmental bodies emerging as the pivotal influencers. The competitors' value chains were identified by demarcating the scope in which competitors for green hydrogen within the future hydrogen network in Europe could take their place. The factor that was mentioned most in forming the future of green hydrogen as well as setting the scope were the governmental bodies. The EU's Green Deal and the 'fit-for-55' package of different targets, mandates, and other instruments set the scope for hydrogen in the future to only be low-carbon. The scope, therefore, was identified as being set by the REPowerEU institutions, which set three pillars that the future energy mix needs to adhere to. In this scope, the two main competing value chains were pink and blue hydrogen. The key insight from the network analysis is that global trade, driven by the interplay of supply and demand, is necessary for Europe's hydrogen economy. The future of green hydrogen in Europe is expected to lean towards a combination of local production and imports, with cost differences between domestic production and imports shaping strategic decisions.

In the end, four suitable value chains were selected, all with their own characteristics, which allowed for better comparison between the cost components of the value chains. The value chains resulted in the local production of blue, pink, and green hydrogen and the value chain of high-potential foreign green hydrogen.

SQ 2: How do the stakeholders in the European hydrogen system perceive the main system functions of that system, as drivers or barriers?

The data for this sub-question was collected through semi-structured expert consultations with stakeholders from the hydrogen value chain as well as a literature review on the European hydrogen system and its drivers and barriers. The data was collected and processed according to a socio-technical functional system analysis based on the TIS analysis by Hekkert et al (2011).

The analysis revealed that the system functions in the case of the European hydrogen system are all related in a complex system, where the system functions are connected via positive and negative feedback loops. This makes it clear that these functions should not be seen as individual but as interdependent factors in the hydrogen system. The entrepreneurial activities, knowledge diffusion, and guidance of the search were perceived as drivers, motivating the system. Knowledge creation, market formation, resource mobilization, and legitimacy creation were perceived as barriers hampering the system.

The stakeholders in the system clarified that one of the main overarching themes in the barriers is the cost of green hydrogen being too high in comparison to other versions. As the costs are too high, there is no demand for green hydrogen, as this would make the industry lose its own competitiveness. As there is no demand for green hydrogen, there is also no supply, so there is no green hydrogen market as the producers of green hydrogen have no industry that currently needs it. Because there is no production, there is no learning by doing, and there are no economies of scale, lowering the costs of hydrogen. Also, because there is no demand from investors for green hydrogen projects, the investors in green projects have no interest in investing as the risk is too evident. There is no demand, so there is no supply—the chicken-and-egg problem.

The costs of green hydrogen are too high at the moment, making it uncompetitive with the other fossil-fueled versions. Because of this price difference, there is no market, and because there is no market, there is no supply. Most stakeholders point to policymakers as the ones who should be able to solve the issue. Overall, there is a complex loop of negative and positive feedback loops, making it evident that the system functions are not to be seen as individual functions but rather as interdependent factors in the development of green hydrogen. The two most obvious solutions, according to most system functions, are the influence of the government, leveling the playing field with suitable interventions, and technological development, lowering overall costs.

For each barrier, one of these arguments is given for the complex system to start resolving its issues. Therefore, these are seen as the barriers that will receive the most attention for being resolved, or the ones with the most potential. When one of these mechanisms is in place, the functions that are currently less performing should be able to overcome their problems, or at least partly, and be able to have the hydrogen innovation system start to grow. A push in the right direction could start the complex feedback loop situation from having its effect. Therefore, concluding the question on the main system functions being perceived as drivers or barriers, the main system functions are being seen as barriers; however, they could become seen as drivers when solutions are implemented.

SQ 3: How do the key competing value chains of green hydrogen for decarbonizing hard-to-abate industries in Northwestern Europe compare in techno-economic performance?

The data for this sub-question was gathered through a literature review and techno-economic modeling. To be able to compare the different competitors' value chains, a comprehensive metric was selected. The LCOH allows for an apples-to-apples comparison that considers the value of time in the calculation as well, allowing for more insight into the realistic costs.

The analysis showed that in current conditions, blue hydrogen, or SMR with CCS, is the cheapest version of hydrogen in the comparison. This comes down to around 2,65 €/kgH_2, while the first competitor is the international green hydrogen with a LCOH of 2,76 €/kgH_2. The locally produced green hydrogen showed a LCOH of 6,84 €/kgH_2, and the local pink hydrogen had a LCOH of 5,06 €/kgH2. But further investigation into the cost breakdown of these prices revealed the biggest cost components. In all value chains, the biggest component is the energy price, which makes up 48% to 66% of the LCOH. The price of renewable electricity accounts for almost 48% of the international green value chain but for 63% of the local green hydrogen value chain. 15% difference, as the only difference is the capacity factor and the electricity. The cost of hydrogen produced by electrolyzers is dominated by energy prices, with electricity accounting for a minimum of 50 percent of the total costs.

The results showed that in terms of techno-economic performance, local blue hydrogen is the most affordable hydrogen value chain, even when governmental intervention influences the cost price of CO_2. The results also show that local green hydrogen is the least affordable hydrogen value chain, even with technological development lowering the overall costs. However, to understand the context around the different types of hydrogen, the conditions of the drivers and barriers of the innovation system should be included.

How do the key competing value chains of green hydrogen, destined for decarbonizing hard-to-abate industries in Northwestern Europe, perform in a techno-economic analysis under the conditions of the drivers and barriers of the innovation system?

This study unraveled the complex interplay between techno-economic factors and socio-technical influences in a dynamic European hydrogen system. The different value chains that are part of the different production methods, energy sources, and location combinations are complex systems that are each influenced by technological trends, different energy prices, and the conditions set by each country's specific mindsets. This research has shown that there is a higher-level way to create an apples-to-apples comparison between competitive hydrogen value chains in and around Europe. It has been shown that the combination of techno-economic research with socio-technical context provides a comprehensive overview of the current status and the expected outlook of the system.

Local blue hydrogen and international green hydrogen have an economic advantage over local green and local pink hydrogen. The techno-economic advantage of local blue hydrogen production stems from the lower natural gas price and the technological maturity of SMR, which has lower energy consumption as well as lower investment costs. The higher costs for the two local electricity-based value chains are due to the high electricity price, which accounts for more than half the costs. International green hydrogen does have a lower production cost, but further research should point out whether that is worth the investment, as the comparison can only be made when import logistics costs are included. For now, this research has confirmed the techno-economic result, as the competing technologies, in all scenarios, have lower LCOH values. But notes should be given to these results as the exact reason for socio-technical system analysis, as this provides context to the question. Where blue hydrogen is cheaper, it still emits CO_2, meaning that it is not a future-proof technology, as well as the fact that carbon storage and transport are still lacking. While pink hydrogen has trouble with low social acceptance, By analyzing various hydrogen value chains alongside their socio-technical frameworks, strategic approaches can be devised. Addressing the cost gap may also involve considering the negative externalities associated with each value chain, thereby aligning economic incentives with environmental and social objectives set by the market and the European Commission.

The stakeholders in the hydrogen system aim for the fact that governmental intervention is necessary to allow the chicken-and-egg problem to be resolved, yet not all interventions have the desired effect. Where the CO_2 price does not have the desired effect in the scope of the research, another governmental intervention is necessary for other hydrogen types to overcome the cost difference. This could be in the form of an overall subsidy, lowering capital, energy, or O&M costs and allowing for per-unit cost reductions. Further research into what exact subsidy could enhance the performance of local green hydrogen in the comparison under the conditions of the innovation system would allow for a better understanding of the status and outlook of the system. Instead of just solely relying on techno-economic numbers. But as of the current state, green hydrogen is not yet competitive, even under the conditions of the innovation system. If governmental intervention successfully addresses the chicken-and-egg dilemma, it could pave the way for resolving the funding challenges that green hydrogen projects currently face. Such intervention could catalyze technological advancement, foster learning-by-doing, and encourage economies of scale, thereby setting the stage for the technology to become more competitive independently. This progress might initiate the formation of a robust market for green hydrogen, facilitating its broader adoption and integration for the decarbonization of hard-to-abate industries.

The European hydrogen system is a complex system where if one variable changes, an unexpected number of variables, in different magnitudes, change as well. This newly formed systematic approach has aimed to provide a tool, in combination with context, to guide a company, or academics, through that complex landscape and demonstrate that conclusions should not only be drawn on quantitative grounds but on qualitative grounds as well. This strategic tool allows companies, to fill in their own exact specifications and gives them the first insight into how the LCOH and its cost components compare to other value chains, while also giving insight into the technical, institutional, and social aspects. The companies can use this tool to understand their position in the hydrogen market as well as get insight on what actions could be beneficial for the development of green hydrogen, allowing them to focus on specific cost components, along with contextual understanding, to enhance their strategic decision-making.

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Appendices

Appendix A Structured Literature Review

The structured literature review was conducted to identify the context in which different hydrogen production methods are placed and analyzed. The articles are systemically searched in Scopus with a focus on the increasingly developing field of hydrogen. Key articles were initially identified by employing a variety of keywords, which were refined through an initial scan of diverse sources. The inclusion criteria were restricted to English-language articles published between 2021 and 2024, aligning with the study's aim to capture the latest developments in hydrogen technology. The selection process involved a two-step screening of articles based on title, keywords, and abstract, using specific subject criteria. This ensured the relevance and alignment of the articles with the research objectives. The chosen articles were also subjected to an unstructured reverse-and-forward snowballing process. Using the references of the first articles that were selected, this strategy helped find more relevant research, collecting important works that would have gone unnoticed in the database search because of keyword and database limitations.

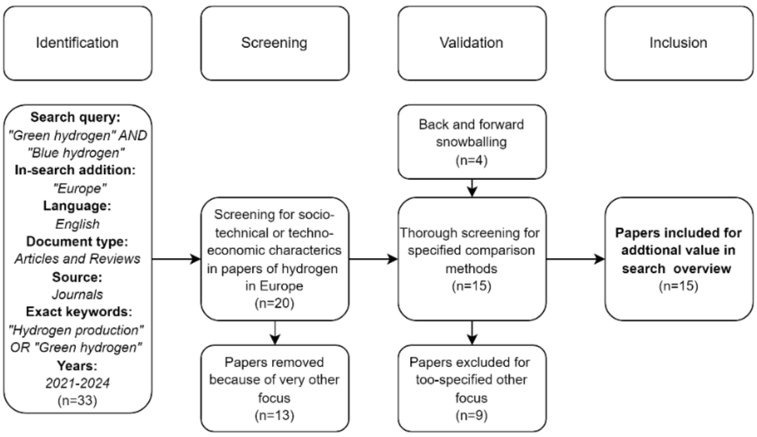

Figure A.1: Structured literature search and selection process

Table A.1: Selected articles for structure literature review

# *Snowballed	Author	Year
1	Ajanovic et al.	2024
2	Zainal et al.	2024
3	Webb et al.	2023
4	Durakovic et al.	2023
5	AlHumaidan et al.	2023
6	Shirizadeh & Quirion	2023
7	Mio et al.	2023
8	Lagioia et al.	2023
9	Shin, J.	2022
10	Ajanovic et al.	2022
11	Cheng & Lee	2022
12*	Noussan et al.	2020
13*	Seck et al.	2022
14*	Griffiths et al.	2021
15*	Genge et al.	2023

Appendix B Structural analysis components

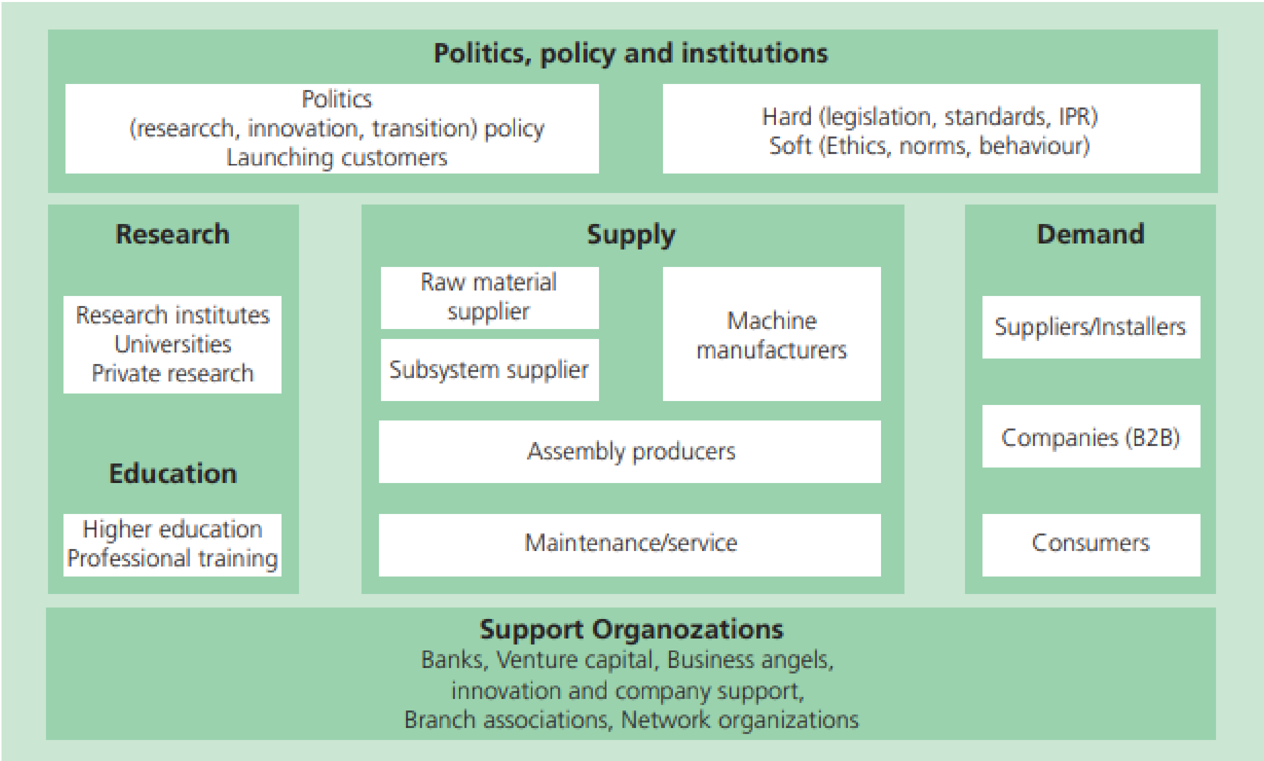

Figure A.2: Structure of innovation system by Hekkert et al. (2011)

Appendix C Functional analysis components

Functions and indicators	Diagnostic questions
F1 - Entrepreneurial Experimentation and production - Actors present in industry (from structural analysis)	- Are these the most relevant actors? - are there sufficient industrial actors in the innovation system? - do the industrial actors innovate sufficiently? - do the industrial actors focus sufficiently on large sale production? - Does the experimentation and production by entrepreneurs form a barrier for the Innovation System to move to the next phase?
F2 - Knowledge Development - Amount of patents and publications (from structural analysis)	- Is the amount of knowledge development sufficient for the development of the innovation system? - Is the quality of knowledge development sufficient for the development of the innovation system? - Does the type of knowledge developed fit with the knowledge needs within the innovation system - Does the quality and/or quantity of knowledge development form a barrier for the TIS to move to the next
F3 - Knowledge exchange - Type and amount of networks	- Is there enough knowledge exchange between science and industry? - Is there enough knowledge exchange between users and industry? - Is there sufficient knowledge exchange across geographical borders? - Are there problematic parts of the innovation system in terms of knowledge exchange? - Is knowledge exchange forming a barrier for the IS to move to the next phase?
F4 - Guidance of the Search - Regulations, Visions, Expectations of Government and key actors	- Is there a clear vision on how the industry and market should develop? - In terms of growth - In terms of technological design - What are the expectations regarding the technological field? - Are there clear policy goals regarding this technological field? - Are these goals regarded as reliable? - Are the visions and expectations of actors involved sufficiently aligned to reduce uncertainties? - Does this (lack of) shared vision block the development of the TIS?
F5 - Market Formation - Projects installed (e.g. wind parks planned, site allocation and constructed)	- Is the current and expected future market size sufficient? - Does market size form a barrier for the development of the innovation system?
F6 - Resource Mobilization - Physical resources (infrastructure, material etc) - Human resources (skilled labor) - Financial resources (investments, venture capital, subsidies etc)	- Are there sufficient human resources? If not, does that form a barrier? - Are there sufficient financial resources? If not, does that form a barrier? - Are there expected physical resource constraints that may hamper technology diffusion? - Is the physical infrastructure developed well enough to support the diffusion of technology?
F7 - Counteract resistance to change/legitimacy creation - Length of projects from application to installation to production	- What is the average length of a project? Is there a lot of resistance towards the new technology, the set up of projects/permit procedure? - If yes, does it form a barrier?

Figure A.3: Diagnostic question for functional analysis by Hekkert et al. (2011)

Appendix D Informed Consent form

Your are being invited to participate in a master thesis research study titled: *Decarbonizing Hard-to-Abate Industries in Northern Europe: A socio-technical innovation system and techno-economic analysis on the most promising hydrogen sources.* This study is being done by Owen Thomson from TU Delft as a graduate intern from the company Vattenfall.

The purpose of this research study to gain knowledge about the functioning of the Northern European hydrogen system under the view of different expert stakeholders in this system, and will take approximately 45 minutes to complete. The data will be used for identifying the drivers, barriers and bottlenecks of the hydrogen innovation system in Northern Europe. We will be asking you (the expert) to answer questions about the European hydrogen system related to your own expertise, and where necessary for more value, more in depth questions can be asked about that particular subject.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing all data, being personal information, recordings, transcripts and summaries of transcripts, on the TU Delft OneDrive. This data is only available to the TU Delft research team. The confidentiality will be secured by providing the interviewee with an anonymous summary, making sure that the possibility of an alteration is there for the interviewee to adjust the summary as well as, to give an accord on what information of the interviewee can be published. When satisfactory for the interviewee, the summary can now be used in the thesis as consensus is reached between the interviewer and interviewee about the exact contents that can be published. The anonymized satisfactory summary will be added in the appendices of the master thesis, where other parties can see it as well. This master thesis is published, including the summary, in the TU Delft Repository, a publically available online database. All personal data, that is recording and transcript, will be deleted one month after the end of the project.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. For question or concern contact the responsible researcher via the email down below.

The corresponding researcher:	Owen Thomson	O.Thomson@student.tudelft.nl
The responsible researcher:	Gijsbert Korevaar	G.Korevaar@tudelft.nl

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐

Signatures

__________________________ __________________________ ________

Name of participant [printed] Signature Date

Appendix E Expert Consultation Summaries

Expert Consultation 1. EC1

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Power company
Job Description:	Business developer
Date:	Oct-23
Duration:	45 minutes

Questions:

1. **Can you discuss any ongoing green hydrogen projects in which you are currently involved? How do these projects exemplify your company's role in the green hydrogen sector?**

The group I work in, which is part of a power company, engages in several of them. One of the initiatives is offshore production of green hydrogen where the hydrogen is produced directly at the wind turbine offshore, supported by local government funding. Another project is about the direct decarbonization of a steel manufacturer, with the goal of setting a trend for industry-wide decarbonization efforts. Most initiatives of this power company are pilots with some projects being more mature. Currently, the green hydrogen Industry is still in its nascent state. The goal now is to prove concepts and to see what works and what not, in those pilots and to gain knowledge about these projects. Both projects show the commitment to decarbonization, each from a different perspective. A push however is required now from governments to put more pressure on environmental sustainability as the current production costs for green hydrogen are not competitive with natural gas. This push is necessary as the first movers need an incentive to engage in this forming market and take the risk to innovate along with partners, like the ones in the steel industry.

2. **What have been the most significant challenges in integrating green hydrogen with offshore wind energy? How has your company's learning and knowledge development processes contributed to addressing these challenges?**

I would first like to clarify that these are present challenges, not past ones because none of these exist yet on a large scale. There are almost no hydrogen production facilities, no liquid offtake market, and no infrastructure to transport and bring hydrogen to consumers on a large scale. The biggest challenge is the chicken and egg problem. There's no industry producing green hydrogen on a large scale, and there's no demand because there's nothing to buy. Overcoming this is the primary challenge: how do you solve the chicken and egg problem between no production and no demand? The ways we identify and seize opportunities vary. Some opportunities are very government-driven, especially in Northern European markets. Governments organize auctions for companies to bid on offshore wind tenders, and hydrogen or system integration is increasingly becoming a requirement to bid for these projects. Additionally, there are other projects where our partners want to explore decarbonization with hydrogen, and then the project consortium is formed by private industry. By actively learning from these pilot projects and engaging in these collaborative projects, new insights can be gained helping to finally integrate green hydrogen with offshore wind energy.

3. **From your perspective, what are the main drivers behind your company's interest in green hydrogen? How do these drivers guide the direction of innovation and research in the sector?**

There are multiple drivers. Firstly, there is a large availability of wind energy, especially offshore, which is very suitable for green hydrogen production. Secondly, there is a lot of industry in the Northern European region, especially heavy industry like steel and chemical production, which is hard to decarbonize with electricity alone. The overall driver here is the increasing demand for sustainable energy solutions and the climate goals, which form the need for hydrogen or other synthetic fuels. Additionally, there is existing infrastructure, especially in the Netherlands and Germany, for natural gas, that can be repurposed for the transport of hydrogen going forward.

The main factors driving decarbonization are the climate goals set by governments. Looking at the current production costs for green hydrogen, it is not competitive with grey hydrogen produced from natural gas. Therefore, the push for decarbonization primarily comes from government mandates. While electricity is often the first choice for decarbonization due to its efficiency, it is not possible to be used for decarbonization everywhere. In such cases, hydrogen is often the only viable solution for full decarbonization. However, there is a gap at the moment between what is feasible for a project and the price at which the produced hydrogen can be sold, given that buyers do not want a product that is significantly more expensive and cannot be sold on the world market. Governments need to ensure a level playing field globally, especially when it comes to products like steel traded globally. There is a need to either restrict or heavily tax products not aligned with green standards, a so-called stick, or in other cases, subsidies, the carrot.

4. **What do you perceive as the major barriers or bottlenecks to the development and adoption of green hydrogen technologies? How do these barriers challenge the legitimacy or acceptance of green hydrogen solutions?**

Market formation is currently a challenge in the EU. Again, just the chicken and the egg problem. Some sectors cannot decarbonize without green hydrogen, however at the moment green hydrogen is not competitive yet. To become competitive, subsidies are needed at the moment, and this could burden society with higher energy prices, making it unpopular. While subsidies can help drive the initial adoption of green technologies, the goal should be to establish a self-sustaining market. This can be achieved only if the market starts penalizing or restricting non-green alternatives. For instance, steel produced using coal needs to be pushed out of the market. This could be achieved by either prohibiting its sale or imposing heavy tariffs to level the playing field with green-produced steel.

5. **How do current market conditions impact the feasibility and profitability of green hydrogen projects? Are there specific collaborations, networks, or partnerships that have been influential in shaping these market conditions?**

Green hydrogen is influenced significantly by electricity prices. Electricity prices are volatile. This impacts the cost of green hydrogen, as electricity prices are not expected to decrease significantly in the near future. Green hydrogen is expensive because there is no established supply chain for essential components like electrolyzers. Although the market for electrolyzers is growing rapidly, it is not mature yet, causing high prices and shortage of supply. To make green hydrogen competitive, we need to reduce electricity prices by increasing renewable electricity production. Moreover, the electrolyzer supply chain must mature to a point where prices can come down.

6. **Considering the evolving energy landscape, where do you see green hydrogen fitting into Europe's energy mix in the next decade? How do you envision public perception and regulatory acceptance evolving?**

In Europe's evolving energy landscape, green hydrogen will play a crucial role, particularly for hard-to-abate sectors like heavy Industries, aviation and shipping. It is not just about producing hydrogen but also about creating a market for it. Currently, we have the technology to produce green hydrogen, but the market is not mature enough. Demand must grow in parallel with production. To achieve this, we need government intervention, either through subsidies for green hydrogen production or through penalizing non-green alternatives. A good thing is that the EU is setting steep targets for sector use of green hydrogen in the RED III directive, as this also provides a message to public perception as there is a need for more awareness. People should be made aware of why energy prices might increase due to investments in green technologies. This is a complex issue, and I would recommend discussing it with a public relations expert for better insights.

Expert Consultation 2. EC2

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Power company
Job Description:	Policy communicator
Date:	Nov-23
Duration:	45 minutes

Questions:

1. **Could you elaborate on your company's strategic approach to positioning itself within the green hydrogen market in Europe? And "How do these strategies align with the evolving EU policy landscape?**

The goal for us as an energy company is to be fossil free but to remain profitable. Sustainability is our business. Renewable hydrogen which is an option for abatement for some industries like aviation could be beneficial as this would be a low-carbon option, however for some industries it is about the energy content and the price whilst adhering to the guidelines of the EU. The RED (renewable energy directive) does not regulate nuclear energy, but there are other EU regulations such as the ReFuelEU Aviation Regulation, including its Sustainable Aviation Fuel mandate, which permits the use of low-carbon energy, including nuclear power, for its industrial processes. For instance, the ReFuelEU Aviation Regulation introduces a 70% reduction requirement which opens up the opportunity for the use of nuclear energy in this sector. One of the most recent initiatives in this regard is the European Small modular reactors alliance.

2. **How does your power company leverage EU policies to mobilize resources for green hydrogen projects? And are there particular EU funding mechanisms or partnerships that have been instrumental?**

For innovative projects involving renewable hydrogen, it is beneficial to search for EU policies and funding mechanisms to build a monetary foundation. One significant avenue is the EU Innovation fund, which plays a role in supporting low-carbon technologies. We are grateful to the European Commission for their support. As a side note, the EU funding landscape can be complex to navigate. The funds that the EU wants to allocate to projects that demonstrate high potential in innovation and carbon abatement.

3. **What initiatives has your power company undertaken to build public and political legitimacy for green hydrogen? And how do you address the varying levels of acceptance and support across different EU member states?**

To address the challenges of establishing public and political support for renewable hydrogen in the EU, the strategy for stakeholder outreach is to tailor the customized stakeholder engagement per market. This is necessary because of the varied energy policies and public opinions across the whole of Europe. For any of the markets we operate in, we obviously need to consider the national, regional and local regulatory frameworks and public opinion. By tailoring the approach to each country's unique energy conditions, challenges and objectives, we aim to find a business case to be created.

4. **What are your thoughts on the upcoming energy mix, mentioned by big consultancy firms and international agencies, who propose hydrogen as backbone; with blue hydrogen having the upper hand and green hydrogen slowly taking over through time?**

In line with the decarbonization of European power systems, it seems more likely that by mid 2030 we will see an uptake of renewable and low-carbon hydrogen solutions. Hydrogen produced with gas and CCS might play a role but if it is a dominant one needs to be seen since in light of the energy crisis and challenges arising with natural gas dependence, political support for such solutions might be lower.

Renewable and low-carbon hydrogen solutions – including synthetic fuels – will play a prominent role in hard to abate sectors whereas in for instance short-distance transport direct electrification will remain more efficient.

It however still is the question if local production of green hydrogen with the delegated acts would be more beneficial than production elsewhere. In the end only the transport cost would play a bigger role in the cost calculation because of those delegated acts, which could mean that -outside of Europe- hydrogen could be more beneficial cost-wise.

Expert Consultation 3. EC3

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Knowledge institute
Job Description:	Professor
Date:	Nov-23
Duration:	45 minutes

Questions:

1. **What role do you see for academic institutions in initiating and driving green hydrogen projects? And can you give an example of a successful or promising project in this domain?**

Academic institutions are essential in promoting the use of hydrogen in sectors where it is most logical and useful. For example, in sectors where direct electrification may not be possible, and there are not too many alternatives, most ground can be gained in terms of lowering the greenhouse gas emissions. Within the academic world the view on hydrogen there is a big division, on the one side the strong proponents of hydrogen and on the other side the skeptics. The role of the academics is to draw attention to the relevant sectors, informing policymakers, the public and businesses, and even correct any misconceptions. The reason I mention this misconception, is that when green hydrogen would be implemented, it would not mean that the universal solutions to all energy problems has arrived, it is rather a means that can help reach the end goal, but still there needs to be less demand of energy and less emission. It is seen as a silver bullet that solves all problems, but a sure role for academics is to make sure everyone understands what exact role hydrogen is going to have. It therefore is crucial for academics to now focus on the more realistic and practical applications of green hydrogen and create a balanced insight for all stakeholders on the potential but also its limitations. A goal for academics to initiate more projects is to focus on sectors where some consensus on the necessity of hydrogen already is already reached. Then steps could be made in for example the policy and the market maturing, as now and academics and those sectors themselves are pushing hydrogen.

2. **Which areas of green hydrogen technology do you think require more research and development? And how do you suggest academia and industry collaborate to address these knowledge gaps?**

In academia there is no consensus on the best use of hydrogen or green hydrogen specific. For me it would be logical to focus in the heavier industry which is hard to decarbonize. In these sectors the focus should be on creating an overall commitment on the necessity of hydrogen. At the moment there are discussions on the potential of hydrogen as storage medium and the long-term potential in a fully climate neutral energy system. The role of academia is to explore and clarify the nuances and complexities hydrogen brings in different applications within different industries as at this moment the focus is unclear on what, where and when hydrogen should and could be used. The focus is on building the system up from the bottom-up with rationality, and academics and industry together should cooperate in achieving that clear focus. Again, because hydrogen should not be seen as a silver bullet that solves all problems in 10 years, it is a long-term means that helps us in achieving the final goals.

3. **How do current policies and subsidies guide the research and development focus for green hydrogen? And what policy changes would you recommend to better direct this search?**

Europe, or the European Union in this case, has the task of setting the guidelines. They have a pivotal role in defining the concept of green hydrogen and setting the different targets and criteria. By 2030. 42% of all hydrogen used should be green within industries. This European definition of green hydrogen, where strict emission reduction goals are implemented, also influences global standards. Policies like emission trading system and CBAM steer the hydrogen market and production direction. Therefore, I would say most policies and other instruments are quite effective in reaching their final goals, be it a carrot or a stick, and do complement each other, and steer the import hydrogen in the right direction. Subsidies like the innovation fund, which are useful financial tools for the development of new energy generation possibilities, like electrolyzers. Europe is a great example in setting the standard, this can be seen by the United States researching similar standards at the moment. This could be the initiation of a global standard, but that is too early to tell. Some might say that the standards Europe implemented, the ones in RED and the delegated acts, are being implemented too slow, in a time where the clock is ticking. However, this also could be a good thing, as too high targets with a too quick implementation, could mean that the market finds it irrational, and they will lose their faith in the system. It is two-sided, great targets must be set to convince the industry this is the way forward, but not too far as the incredibility could lose the markets believe in the government setting the targets. At this moment there is even too much focus on hydrogen. It should not be seen as the silver bullet, solving all problems, even the ones with the dependence in Russia.

4. **What market conditions are necessary for the successful commercialization of green hydrogen? And how can these conditions be fostered through policy or industry action?**

This is a complex but there are at least a few key factors for hydrogen to have a successful commercialization. There should be a rapid deployment of renewable energy. Next to that the investment costs for electrolyzers should come down as this is even higher than most literature assumes; it could be up to 5 times more expensive than originally calculated. This is on the input side but on the output side the alternatives of the should be more expensive, for example high carbon dioxide prices. This would the more climate friendly alternatives cheaper and create a demand pull. An important aspect is the possibility of passing on the higher cost of green hydrogen to be passed on, for example in the cost of green steel in cars. However, the willingness of industry to bear these additional costs is still limited. Could an additional 100 euros for a car, made with green steel, persuade a customer to get that greener alternative? We do not know but at the moment the possibility is not even there yet. Also, for the market to grow is the differentiation of risk, so that not only the early movers and investors do have that risk but along the whole chain it can be mitigated. There should be a market design or instrument that shares that financial risk.

5. **What are the main challenges in securing funding for green hydrogen initiatives? And what strategies have proven effective in overcoming these challenges?**

As mentioned before, the biggest challenge to secure funding is the risk associated with these projects. As the electricity price is a big influence as well as the possible offtake, stability in those two could enhance the possible securing of funding. There currently is no set price for green hydrogen, it simply does not exist, meaning that a big variable is unsure in the cost calculations. A great example of a company that is comfortable investing is Shell who is investing in green hydrogen. They have an already set demand, a long-term contract with their own offtake, and a set electricity price in a power purchase agreement with their own renewable energy production, making the investment bearing less risk. When something is unsure, there is a risk premium and higher prices should be expected, which now is the case for hydrogen. This financial risk is a big barrier in the implementation of hydrogen, as well as policy risk as here also no solution is found for the financial problem. A crucial role in the future could be for subsidies as these could bridge cost-price gaps and ensure the viability of projects, however this for now is not set yet.

6. **How can the green hydrogen sector build legitimacy among policymakers and the public? And what resistance have you encountered towards green hydrogen adoption, and how can such resistance be effectively mitigated?**

This depends on how you define legitimacy. For now, it is crucial to prevent green hydrogen to be seen as greenwashing or as a subsidy cash cow. The current regulatory framework on the production of green hydrogen could help the build up the legitimacy. However, resistance may develop because of the industry's alleged special treatment while obtaining taxpayer-funded green electricity. When you define perception as more how the public and policymakers see the potential of green hydrogen, it should be made clear that the biggest potential lies in those industries like steel, but again, does the taxpayer want to fund that. They have already put millions in the industry by using steel and now also have to pay for making that industry greener.

7. **How important are networks in the diffusion of knowledge about green hydrogen? And could you provide an example of how these networks have facilitated a particular innovation or project?**

Networks are essential for disseminating information about green hydrogen. The creation and application of green hydrogen technologies depend heavily on efficient networking that unites business, government, and academia. The extent to which these networks are able to foster innovation and projects has a substantial impact on the overall advancement of the sector. The current status is good, and all is connected, but there is too much of a lobby at the moment for hydrogen. A lobby financed by the oil and gas sector, which raises questions about the neutrality of some organizations. The networks should be transparent and well informed and transparent information should be shared before making big investment in, for example, the whole hydrogen backbone.

Expert Consultation 4. EC4

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Knowledge Institute
Job Description:	Business developer
Date:	Nov-23
Duration:	60 minutes

Questions:

1. **What role do you see for academic institutions in initiating and driving green hydrogen projects? And can you give an example of a successful or promising project in this domain?**

In this but also other knowledge institutes there are platforms that facilitate and accelerate collaboration between public and private, this to solve specific challenges in the value chain. However, currently hydrogen has the wind in the sails so even without this platform more activities would have come over the past years. The collaborations between all parties are crucial in the development. One particular goal is to facilitate more start-ups, human capital and field labs, in addition to (low TRL) research programs. It eventually accelerates the transition to green hydrogen technologies. Examples of projects are airplane companies, and for example infrastructure projects at airports, this is because besides having some machines run on hydrogen, there also should be infrastructure to fuel those machines. But also, more in-depth on the technology with for example development of a new fuel cell technology, all projects in which this platform is involved. The projects vary, also showing the potential of hydrogen.

2. **Which areas of green hydrogen technology do you think require more research and development? And how do you suggest academia and industry collaborate to address these knowledge gaps?**

As it is the whole system in need of this research and development, it is a chicken or egg problem. There should be production and we should have the demand, which should be tied to each other, so it is about the whole system. Then there are sub questions which are needed for research and development in green hydrogen technology. Questions like the high cost of green hydrogen compared to its grey and blue alternatives, and technical issues in various sectors such as aviation and steel production, whilst all being subject to the question of the best transport of hydrogen as well. So, to pinpoint one exact field where more attention is needed is hard. The only thing to be sure is that in the end the price is too high at the moment and that should come down, the cost-effectiveness.

3. **How do current policies and subsidies guide the research and development focus for green hydrogen? And what policy changes would you recommend to better direct this search?**

The role of policy and subsidies steering the research and development in green hydrogen is substantial. Both the EU and national government provide substantial financial support, which subsequently causes there to be a significant amount of money and an, an overload of job opportunities in the field of hydrogen. Not only the EU but countries themselves as well are budgeting significantly for research on the subject, which shows the importance of the government support and financial tools for the development of green technologies. Next to that also the tax and tariffs on the emitting industries, also steer the companies in a more sustainable direction. So yes, the EU Green Deal is crucial with good ambitions that create an environment that stimulates to reach those ambitions and focus on green energy solutions like green hydrogen. So, on the driver's side, the ambition is good, only the laws and regulations are lacking, but this is with most cases.

4. **What market conditions are necessary for the successful commercialization of green hydrogen? And how can these conditions be fostered through policy or industry action?"**

The market conditions are going to be quite interesting as the costs do influence market formation. Another challenging aspect is the title 'green' for the hydrogen the off takers use. How do you separate the different hydrogen types within one backbone where the one is certified as green; how do you separate this from other colors? This complex process still has some challenges whilst also having to adhere to strict regulations, which also influences the type of system you want to set up for hydrogen. Where exactly do you want to electrify and where do you want to produce hydrogen and put it in the hydrogen backbone? Or even further with import, what type of transportation method and energy carrier. These questions will slowly be answered when there is sufficient demand, take Shell as an example. They can now invest in green hydrogen because they control the electricity price and the off take. If demand rises, the solutions will come, especially in places where there is abundant renewable energy at the moment such as in some wind parks.

5. **What are the main challenges in securing funding for green hydrogen initiatives? And what strategies have proven effective in overcoming these challenges?**

Securing funding for green hydrogen initiatives is a challenge. However, plenty of funds are made available by the EU, in the form of subsidies and funds for R&D&I. Funds for large scale implications may be lacking (and depend on the political landscape) These different resources are crucial for the research and development in the sector. The availability also shows the ambition and commitment of the EU whilst showing that there is a need for support and funding from the government to develop this technology and system of green hydrogen. In the end, the price of green hydrogen alternatives needs to go down, or the price of alternatives has to go up, to create a level playing field.

6. **How can the green hydrogen sector build legitimacy among policymakers and the public? And what resistance have you encountered towards green hydrogen adoption, and how can such resistance be effectively mitigated?**

There are certainly concerns about the climate among the general public, but hydrogen still seems like a distant reality. Indeed, the willingness to pay more for sustainable products and services appears to be low. They have their problems and have no interest in green hydrogen. The only thing they care about is their electricity bill or taxes becoming higher and higher. An argument against using hydrogen is the efficiency of converting it from electricity to hydrogen and back in some cases, however, I think as we had the car in the past, which had worse conversion rates of energy, we should not look at it that way. We should argue from the greenhouse gas emission perspective and hydrogen does help with that. The total costs are a valid argument, but let's first start using hydrogen and then try to reduce costs. It just should be logical for policymakers and also the public on where exactly electrification is used and where it should be converted to hydrogen for the biggest impact, as this creates that legitimacy.

7. **How important are networks in the diffusion of knowledge about green hydrogen? Could you provide an example of how these networks have facilitated a particular innovation or project?**

Networks play a crucial role in disseminating knowledge about green hydrogen. The bigger companies and universities are well connected and do possess the necessary knowledge, however, there is a lack of an overview of the whole sector due to the multitude of new initiatives. The part that needs more connection to the network is the Small- and medium enterprises which create that ever-needed demand pull. These Small- and medium enterprises, especially in the manufacturing industry, need guidance in the quickly developing hydrogen environment, for new hydrogen applications. There are some but overall, there is a lack of initiative to help those Small- and medium enterprises with a help desk, so they understand what steps to undertake with their network formation and knowledge exchange. Further down the line the laws and regulations for the products of these Small- and medium enterprises should be made, but first, there should be demand created and that could be helped by helping those smaller manufacturing companies.

Expert Consultation 5. EC5

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Financial Institution
Job Description:	Researcher - Energy Transition
Date:	Nov-23
Duration:	30 minutes

Questions:

1. **How does your bank assess the investment potential of green hydrogen projects? Can you provide an example of a project in which your bank has invested and what made this project attractive?**

Our main consideration when assessing the viability of green hydrogen projects for investment is their projected cash flows. Long-term contracts must exist that outline the volume of hydrogen to be produced and sold. These contracts offer a precise estimate of future revenues, which makes them the cornerstone of our decision-making process. For us, these financial flows' dependability and predictability are what make any project viable. We tend to invest in projects with substantial and stable long-term contracts, but I am unable to go into the specifics of any one project at this time. The basis for consistent revenue streams that these contracts offer is essential to our investment strategy. The energy industry, and green hydrogen in particular, is naturally dynamic and vulnerable to several concerns, such as viability in terms of technology and market demand. Thus, in an otherwise unstable market, having these contracts in place provides some stability and protection. As a result, our strategy involves more than just project financing; rather, it entails making calculated investments in businesses that offer long-term profitability and sustainability.

2. **What role does financial support play in the development of new green hydrogen technologies? And how does your bank collaborate with technology developers to assess and manage risks?"**

In the development of the technologies, there is also development in risk assessment and management, in collaboration with the technology developers. This is to gain knowledge on the technical, operational, and financial aspects of the projects and evaluate them, to ensure the feasibility and the viability of the project. The focus is not to create knowledge on the subject but to focus on technical due diligence, which involves a thorough examination of the reliability and the practicality of the technology. It is the commitment to fund sustainable projects, but projects should be identified as not only innovative but also grounded in practicality. It is important to understand that we are eager to invest in groundbreaking technologies, however, the commitment is to sustainable and reliable investments. As you do not want a great investment option, for which the electrolyzer breaks when you plug it in, the risk of the costs related to such a malfunction must also be mitigated. So, the financial support is, next to the books of legal paperwork, there, also for innovative projects, but the risks must be covered.

3. **How do current policy measures and subsidies influence your investment strategies in green hydrogen? And what policy changes do you think could stimulate investments in green hydrogen?**

Current policy measures do influence the investment strategy for green hydrogen technologies. The viability as well as the attractiveness of investing in the project are influenced by it. A policy or subsidy can make or break the economic viability of such a project. While there is no specific policy that could boost investments, it is evident that a stable and supportive policy is vital for the growth of green hydrogen. Especially for a financial institution, there is a focus on one of the two types of subsidies. There are CAPEX subsidies, with assistance to the investment, and OPEX subsidies, which are given based on the production over the years. An investor like us prefers the latter as this provides a guaranteed cash flow over years, stability, and predictability, again to mitigate risk. Whilst there are delegated acts and directives coming forth from the EU, as the big changes to what exactly green hydrogen is. The art is how to navigate through these regulations and make sure that subsidies are reached whilst also checking what exactly other parties are also eligible, again for risk mitigation. The only problem could be that policy measures will become too ambitious meaning that companies will go abroad to get their resources and, in that way, again loophole around the European system. Something that must be considered.

4. **What are, in your opinion, the key factors that will shape the green hydrogen market? And how does market uncertainty affect your investment decisions in this sector?**

The key elements forming the green hydrogen market will be based on the reliability of the technology, the existence of long-term contracts, and a supportive policy environment. The technological component is particularly important since the efficiency and reliability of the technology used to produce and distribute green hydrogen are key factors in determining the viability of the project. Long-term contracts offer a steady basis and predictable income stream. Another important aspect is the market uncertainty, as at the moment a volatile market is not of interest to invest in as there are too many risks attached. To reduce these problems and invest in projects, the reduction of risk is especially important. The projects that prove clear, stable revenue streams minimize uncertainties. Since most projects in green hydrogen are still in the early stages, the market is not yet developed, the technical aspects are unclear and regulatory uncertainty is present, the investment goal is to search for reduced-risk projects while capitalizing on the potential long-term benefits as a sustainable energy source. The main thing here that could help is long-term contracts both in demand and supply.

5. **What are the biggest challenges in financing green hydrogen projects? And what types of financial instruments or strategies do you see as most effective?**

Financing green hydrogen projects presents unique challenges, particularly due to the necessary long-term off-take contracts, the technical complexity, and the need risk assessments on different aspects. The complexity of the technology and its accompanying environment adds another layer of risk, which needs to be assessed and managed before any investment is made. The preferred financial strategy is senior financing, where repayment is prioritized based on the project's ability to generate cash flow. This minimizes risk to the investment however this does bring lower returns. With green hydrogen projects which are still in developing phases, and therefore inherent more risk, a finance strategy such as this is vital.

6. **How does your bank assess the social and ecological impact of green hydrogen projects? And how do you deal with public and political perceptions when assessing investments in this sector?"**

With the Paris agreement and the different goals set internationally and nationally. All different sectors must report, also financial institutions, and on the balance sheet a more sustainable development can be put in the reports of that financial institution.

Expert Consultation 6. EC6

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Power company
Job Description:	Innovation manager
Date:	Nov-23
Duration:	45 minutes

Questions:

1. **What is your role and the what role does your company play in driving green energy projects? And what scope is that in every scope?**

In my role, I focus on accelerating the green transition, particularly in green hydrogen technology. It's about balancing the high risks and costs against future profits. We invest in early-stage technologies, aiming for long-term returns. Our approach is to develop custom, innovative solutions, not off-the-shelf products, aligning with our strategic vision in green energy. The goal in the end is Our scope includes offshore wind and various technical innovations, covering the entire value chain. I have been involved in developing patents and implementing innovations across different scales. The methodology I apply is consistent, regardless of the project's scale, from designing turbine components to overhauling energy systems.

2. **Where do you think green hydrogen at the moment is lacking? Where does it need further research and development?**

Research on electrolyzer technology ideally starts in university settings, where the initial concepts for potential business applications are developed. Universities play a critical role in building a foundational technical understanding, which is vital for attracting financial investors by demonstrating the technology's feasibility and potential. This educational environment is suited for exploring the limits of technology, such as determining the maximum hydrogen output per kilowatt hour using various membrane technologies. While universities spearhead fundamental research, the scope of innovation extends beyond academic institutions. State funding is necessary for this foundational research, driving the industry forward. This funding should align with industry trends and market directions, ensuring that the research is relevant and contributes effectively to the industry's progress. When research is aimed at industrial development, industrial clusters can provide funding. This funding should be directed towards solutions that are emerging within the industry. Additionally, entities focused on large-scale integration and scaling up need to collaborate with companies to further develop and implement these technologies effectively. This approach ensures that the research is practical, industry-relevant, and contributes to significant advancements in the field.

3. **How do current European policies and subsidies direct your company's research and development focus in green hydrogen? How do you see that the current political agenda helps green hydrogen or could help green hydrogen?**

So, if the current mechanics are insufficient to achieve our goals, then politicians will alter them to ensure success. There are no other viable options. Politicians have committed themselves to the overarching green transition, investing their political capital to drive change. Thus, failure is not an option, as it would lead to a loss of face for all involved. They've reached a consensus and cannot backtrack now. The debate then shifts to who should fund these initiatives and in what order. In Denmark, for instance, discussions about offshore wind development focus on who should pay the most for a seabed lease. With the current market conditions in offshore wind, obtaining significant payments is challenging. In the UK, when no bids were received in the latest Contract for Difference round for offshore wind, they didn't abandon the project but instead revisited the subsidy scheme. I believe a similar approach will be adopted for green hydrogen, as it is the energy carrier the molecular world relies on, and there is substantial political support behind it. Funding availability will address a critical gap. I have seen various manufacturers' electrolyzer units, ranging from 1 to 5 megawatts, with costly components and standard converter systems. They are integrated into a container to support a large electrolyzer disk. This current setup is prohibitively expensive. To reduce electrolysis costs, the industry must shift from standard products to custom solutions tailored to specific functional needs, significantly differing from standard offerings.

4. **What market conditions do you believe are necessary for the successful commercialization of green hydrogen? Like financial institutions believing in the technology?**

The biggest barrier to green hydrogen innovation is skepticism about its feasibility and profitability. We need a mindset shift towards technical feasibility and financial viability. Optimism about green technology, particularly hydrogen, is essential. Government policies can foster this optimism, ensuring competitive fairness and promoting European manufacturing. Financially, while the technology has been proven, the focus now is on reducing costs and creating a narrative that green hydrogen is practical and beneficial. This approach mirrors Elon Musk's strategy with Tesla, where they started with a niche market through the Tesla Roadster, a high-end product with unique features. The industry has progressed beyond this initial phase, as demonstrated by the success of electrolysis based on green technology. Following Tesla's model, the next step involves transitioning to more accessible products, like the Model 3. This evolution from exclusive, luxury items to mass-market products is a common trend in various industries, including wind turbines with companies like Siemens and Vestas. The goal is to identify market segments that are willing to pay, starting small and then expanding. This is not just about pushing the product but offering something appealing to a specific part of the market, gradually broadening the appeal over time.

5. **What strategies have proven effective in overcoming these challenges? What is a good business model for green hydrogen especially compared to other varieties?**

The focus here is not on the comparison between different types of hydrogen like green, blue, or purple, but rather on competition within the green hydrogen sector itself. It is important to foster this internal competition to drive down prices continuously. In this context, there is a logical approach needed: hydrogen production should be as close to the source of energy as possible. This strategy is key for efficiency and cost-effectiveness in the green hydrogen industry, emphasizing the need for innovation and competition within the sector itself. If we base our future energy system on grid-connected electrolysis, it may result in inefficiencies. Adding production capacity through offshore and onshore wind, and solar power, creates imbalances in the grid, as these sources generate power simultaneously with other facilities. This leads to excess energy during high wind periods, presenting a business challenge. The solution might involve introducing balancing mechanisms like electrolyzers, storage facilities, or smart charging systems. However, relying on electrolyzers as the primary balancing method for large-scale grids, like a ten-gigawatt system, may not be the most effective strategy. We should develop wind farms that align better with future energy systems to avoid market deterioration and inefficiencies

6. **What do you think is one of the biggest barriers in the system right now?**

A primary obstacle now is skepticism towards future-focused investments, differing from the typical business case mindset. Many are realists wanting immediate returns, not future benefits. Such doubts can halt progress, leading to inaction. The dilemma is whether to invest now or later, to choose between flood-proofing a house or paying for potential damage. The responsibility for costs, whether through goods, taxes, or energy bills, falls on everyone. I have calculated that a minor increase in electricity costs in Denmark could fund a 100% green electrical system. The lack of action stems from unawareness of its feasibility.

7. **How does your company build legitimacy for green hydrogen and other hydrogen sources among the public?**

We need someone to start saying it is possible. I am one of those who, given the chance in the media, have begun to say just that: it can be done. Now, the focus is on making it financially viable and advancing step by step, without disadvantaging the EU competitively against other countries. I leave this responsibility to politicians, to ensure the environment supports this positive narrative. Then, industrial players will follow suit. Knowing we will not be outcompeted by cheap imported electricity or hydrogen, we can confidently make internal investments and gradually pass on the added costs to customers, who are likely to be receptive.

Expert Consultation 7. EC7

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Hard-to-abate industry
Job Description:	Analyst
Date:	Nov-23
Duration:	45 minutes

Questions:

1. **In what ways does your company promote the development and adoption of green hydrogen as a raw material for SAF? And what corporate strategies do you use to effectively integrate green hydrogen into your production processes?**

We try to collaborate with potential hydrogen partners, as we need hydrogen for SAF production ourselves. Financing these projects is often difficult because there's uncertainty about how everything works and what the best possibilities are, alongside the scale that still needs to be increased for the future. So, trying to make it possible together, you do better financially together than alone. Additionally, in the policy, we try to think along for solutions to the current problems in hydrogen production. The goal is ambitious objectives to make it easier for us, but with too ambitious objectives, which, for example, result in too strict regulation, you lose support again. You want the risks that are currently present in switching to hydrogen to be borne by others, however, everyone has that idea, which is logical. Everyone tries to push the risk like that, however, to achieve more success this should be spread over everyone. Agreements, for example, if you are going to produce hydrogen and we are going to produce SAF, we share the profit. There is a lot of hydrogen needed and at the moment there is not enough, but that will certainly come.

2. **What knowledge gaps exist around the use of green hydrogen in SAF and how does your company approach these challenges? And how can you collaborate with academic and research institutions to close these knowledge gaps?**

Currently, there are many questions. How should we store the energy, as electricity in a battery or as hydrogen, what is the best way of transport, is it better to produce centralized or not, each issue brings new questions with it. But I can say that these are all considerations. What is the best way in there, what actually works best for this SAF end market? And that is also another thing to answer your question. It is also sometimes unclear how other hydrogen-needing industries will develop. Because we saw that until a few years ago there was little interest in hydrogen from the chemical industry. The pharmaceutical industry too. Those are things that are now on the way to developing. You see it with Tata steel too. That has been held off for a long time. And now, that green steel is really becoming a thing. But then the question is, who is all going to share in that hydrogen pie? I think we should do as much as possible electrically where we can. And where that is not possible we have to look again at, how do you say that higher energy carriers. Like hydrogen or even fuel, so kerosene, in certain industries.

3. **How do current regulations and subsidies influence your approach to green hydrogen in SAF production? And what policy changes could accelerate or improve the use of green hydrogen in the SAF industry?**

Subsidies are necessary, especially as the political climate evolves. It is a bit of a chicken and egg situation where everyone waits on each other. Our hydrogen-dependent projects wait for hydrogen development, while hydrogen developers need customers. Subsidies can initiate this process. However, we must ensure affordability and customer payment. Substantial investments are required for factory-scale operations. The effectiveness of subsidies in these scenarios is uncertain. Majority funding must come from investors or banks who believe in the project. Subsidies can contribute, but they will not be decisive.

The CO_2 market is changing, differentiating between biogenic and fossil CO_2. Biogenic CO_2, from organic material, is used in SAF production, unlike fossil CO_2. The supply of biogenic CO_2 is becoming scarcer due to increased demand across industries. Also, capturing biogenic CO_2 in CCS projects creates negative emissions, offering a financial advantage. This leads to higher CO_2 prices, impacting SAF production costs and increasing the need for subsidies.

4. **What market dynamics do you see as crucial for the successful integration of green hydrogen in the SAF industry? And what role can government policy and industrial initiatives play in shaping this market?**

Creating a market for green hydrogen in the SAF industry requires considerable effort. Currently, numerous small projects with ten megawatt electrolyzers exist, but they lack widespread support and impact. Establishing a robust infrastructure, or 'backbone,' is vital, and government support could play a significant role in this development, providing a long-term vision for expansion and integration. Large oil companies like Shell and Exxon are transitioning towards sustainable practices, recognizing the profitability of this shift. However, newer, more innovative initiatives require long-term government support for stability, encompassing both subsidies and a consistent political approach in Europe. The formation of this market, influenced by these oil giants, demands faster political decision-making for success. The primary concern is the urgency of quicker decision-making to enable and facilitate this transition.

5. **What are the biggest financial and operational challenges in integrating green hydrogen into SAF, and how does your company address them?**

Operationally, the main challenge for a factory like ours is ensuring a consistent supply of hydrogen. In the Netherlands, solar and wind energy are variable, but our factory cannot just shut down when these energy sources are unavailable. This gap, known as the base load power issue, requires either back-up renewable fuel- hydrogen storage - to start up during low-energy phases or this could be solved by battery use. Additionally, while hydrogen might fuel short-range flights in the future, it is not efficient for long distances like crossing oceans, where kerosene remains essential. The challenges are hydrogen storage and costs. Subsidies provide temporary assistance, but a self-sustaining market is the ultimate goal. Hydrogen import is complex, raising questions about whether local production and use are preferable.

6. **How does your company build legitimacy and acceptance for the use of green hydrogen in SAF among various stakeholders? And what forms of resistance to this integration do you encounter and how do you deal with them?**

The goal is to drastically reduce CO_2 emissions in aviation, aiming for net zero by 2050. The company emphasizes flying less, using more efficient airplanes, and alternatives like trains. Electric flying and hydrogen are considered for short distances. SAF plays a significant role, estimated to contribute 60-65% towards achieving net zero. Green hydrogen is essential for this transition. Even in the short term, by 2030, green hydrogen has chances with current policies.

7. **How does your company utilize networks for the dissemination of knowledge and innovation regarding green hydrogen in SAF? Can you provide specific examples of how networks have facilitated the use of green hydrogen in your SAF projects?**

There are plenty of hydrogen initiatives, but optimization and collaboration are crucial. Central storage can reduce costs and enhance safety, but also makes projects interdependent. Announcements often yield few concrete results, complicating collaborations. Open collaboration and learning from past mistakes are vital. Taking the initial painful steps will aid progress within networks. Subsidies support risky, innovative projects, helping the industry progress collectively despite challenges and costs.

Expert Consultation 8. EC8

Interviewer:	Owen Thomson
Domain of activity Interviewee:	Hard-to-abate industry
Job Description:	Analyst
Date:	Nov-23
Duration:	30 minutes

Questions:

1. **Where are the main bottlenecks in green hydrogen development, especially in the hard-to-abate industry?**

The biggest problem is the chicken-egg problem—the buyers or the products. We want to purchase green hydrogen at cost-effective rates, but production is close to zero as they don't get financing. Financing electrolyzers requires long-term off-take contracts. There is a big gap between the willingness to invest and the ability of companies to purchase. The outlook for the real market prices in 2030 are multiples of the predictions by Bloomberg and McKinsey from one or two years ago. Increased electricity costs, due to government offshore tendering structure decisions and grid costs, are driving up hydrogen prices. Internationally, there are locations with lower electricity prices, but transporting hydrogen to the Netherlands is a challenge. Ammonia transport and storage are known, but cracking it is inefficient and costly, and the costs for this process are also still unknown.

2. **Despite clear regulations and incentives, the market for green hydrogen does not yet seem to be taking off. What is needed to break this deadlock and lower prices for consumers?**

The problem lies with hydrogen procurement. We have to commit to 15-year contracts at high prices based on current technology and costs. This makes buyers reluctant because there is a risk that prices will fall while we are locked into expensive contracts. This "first mover disadvantage" is a major obstacle. Without long contracts, projects won't get financing because investors want to have security. It requires at least 80% guaranteed sales of production to justify investment. All this makes it difficult for us to commit to hydrogen contracts, especially when future market dynamics are uncertain and technological developments can affect prices. So, the challenge is to strike a balance between encouraging new projects and mitigating risks for customers.

3. **Are there enough industry players and initiatives to drive green hydrogen development? Do you see examples of growth, or do activities still remain limited?**

It may seem a bit negative, but there are certainly developments underway. For example, there are some electrolyzers under construction, of which Shell's "Hydrogen one" is a notable example. This project can be seen as a status symbol and was even started without a subsidy. Another significant project is 'Neom,' which focuses on ammonia production. However, this falls outside the direct green hydrogen sector and involves a different branch of industry. Hydrogen is used directly for fertilizer production. However, these projects are exceptions and do not represent the full scope of the hydrogen market. Overall, there is a discrepancy between expected and actual investment and progress in the sector. Many initiatives are still in the early stages, and the large-scale adoption and implementation of green hydrogen remains a challenge.

4. **Are all parties in the green hydrogen value chain sufficiently connected, or is there still a lot of ambiguity and pointing at each other? What kind of solutions are there?**

A clear level of cooperation can be seen between buyers and producers, especially in the form of joint lobbying by governments. They stress the need for action and suggest incentives, such as tax increases on carbon or specific subsidy schemes. So, there is indeed an overlap and concerted effort in the sector. Those subsidies are crucial. There is a large "feasibility gap" between the current state of affairs and what should become feasible. Subsidies are essential to bridge this gap and make green hydrogen development economically viable.

5. **Do you think the current vision of the government and other stakeholders in Europe is well aligned when it comes to green hydrogen development?**

The current approach is inadequate. There is insufficient investment and off-take, so there is a need for tailored incentive packages. In Germany, for example, they have a subsidy pot for the steel industry with a "carbon contract for difference" in it. This kind of initiative should be more common. Large buyers should be encouraged to create a kind of flywheel effect; otherwise, the impasse will remain. In the Netherlands, companies like those in steel and chemistry could use incentives, and in Germany, the steel mills, chemical, and refinery sectors would also benefit from such measures.

6. **Realistically, green hydrogen prices are higher than expected. How do you deal with these higher costs? What is your approach?**

The reality is that we have to start accepting higher prices. It's a simple calculation that the government should also understand. I can't share the details, but I can talk about it. The cost structure of 1 kg of hydrogen in the Netherlands depends very much on the price of electricity. With a price of €45 per megawatt hour, 1 kg of hydrogen, considering efficiency losses, quickly exceeds €2, based on the electricity price alone. The assumption that the price will be around €3 in 2030 is simply not realistic. This understanding must also permeate governments; the current approach is not sufficient, and other schemes are needed to achieve the desired effect. Besides the high-power prices, which make up a large part of the costs, Capex and OpEx are still unclear and can be seen as a "black box." An important aspect is the revenue model the government uses on wind farms, where they want to make a profit. This element could easily be omitted, especially if the long-term goal is sustainability. Why should there be a profit motive if the ultimate goal is sustainability? This adds to the overall complexity and makes it difficult to reduce the true cost of green hydrogen. Thus, the government should reconsider how it deals with these aspects to make the transition to green energy feasible and affordable. While some improvement in price and efficiency is possible, there is limited room for significant reductions in the cost components of green hydrogen. Technological advances will offer some progress, but drastic cost reductions are unlikely without broader systemic changes.

7. **What variables must change for green hydrogen development to really take off?**

One crucial factor is the price of electricity, which accounts for a large part of the cost. Also, electrolyzers are currently extremely expensive. Although the cost of this is expected to eventually come down, it is uncertain to what extent this will happen. Another important factor is the CO2 price, which would have to be much higher to make green hydrogen more attractive. As CO2 prices rise, green hydrogen becomes more economically competitive. However, the exact scale of these changes is difficult to predict. I am not deeply enough immersed in it myself to make concrete predictions, but these elements are essential to the progress of green hydrogen.

8. **Where do you stand on the current challenges in the hydrogen market? Are you proactively anticipating future developments, or are you waiting and waiting? And what will it take to break the deadlock?**

There is certainly a realization that we need to become greener. There is a market movement where choices are being made about production methods, such as switching to electric furnaces for steel production. For us, the choice to continue producing high-quality steel is essential, and green hydrogen is the appropriate technology for that. Although we would like to switch to hydrogen, we are still reluctant to invest without clarity on subsidies. Concrete steps have already been taken in Germany, but not yet here. The issue of subsidies and the chicken-or-egg problem must be addressed to facilitate the transition to green hydrogen. There are also more noises about blue hydrogen because of its lower cost. The government has targets for the percentage of green hydrogen in the Netherlands, but if we switch to blue hydrogen, for example, achieving these targets becomes more complex. The government actually does not want us to use blue hydrogen, as it affects the calculation of the percentage of green hydrogen. We currently do not use hydrogen at all, so switching to blue hydrogen would increase the challenges for the government.