Hydrogen Supply Chains in the Netherlands

A techno-economic and socio-political performance analysis

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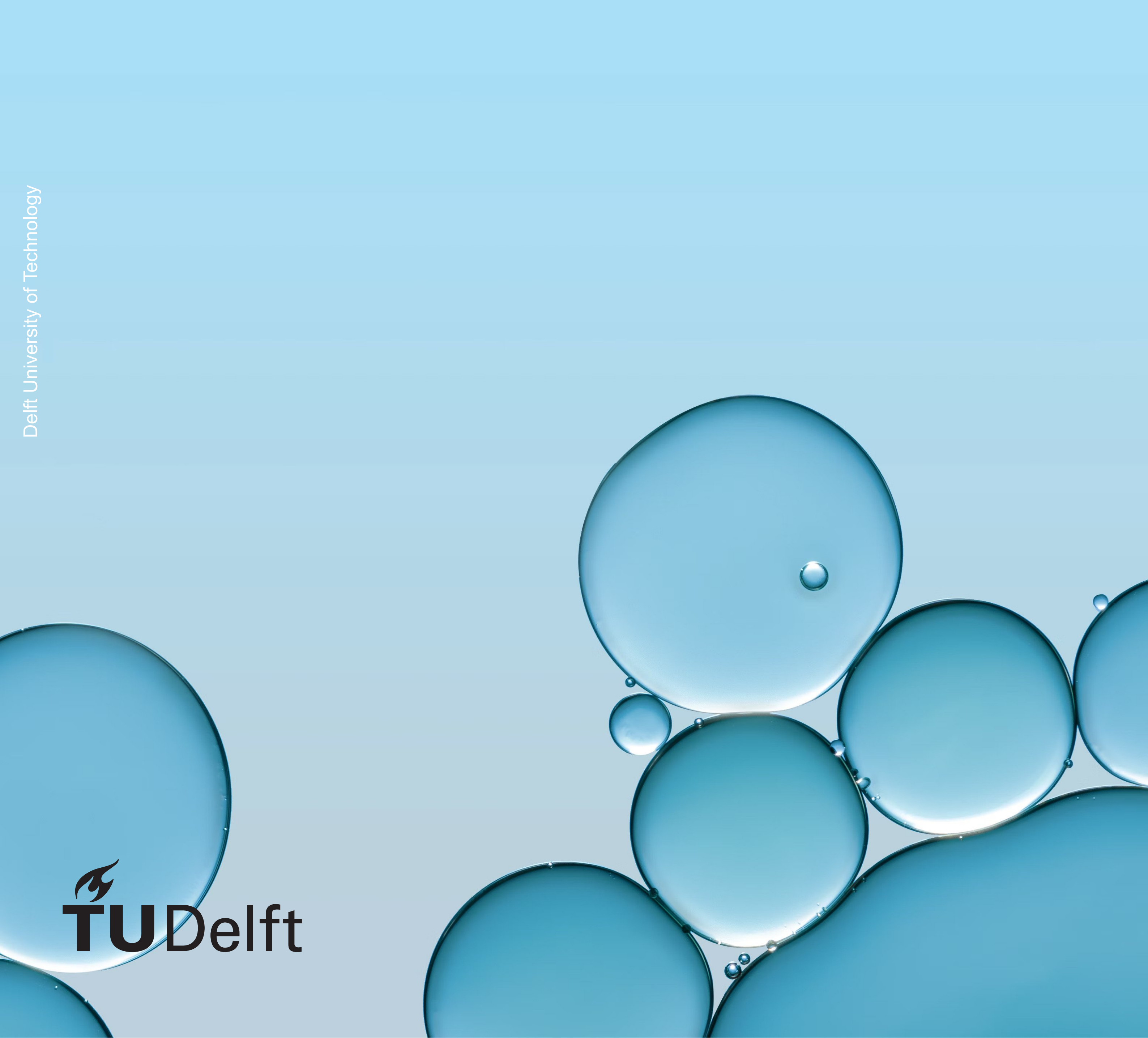

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Hydrogen Supply Chains in the Netherlands

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Summary

The Netherlands has committed to reducing greenhouse gas emissions by 95% by 2050. In this respect, hydrogen is a promising part of the pathway to meeting climate targets. However, there is a knowledge gap regarding the potential domestic and global supply chains in the Netherlands and their techno-economic and socio-political performance under current technology, market and energy policy conditions.

The following thesis aims to identify the key trade-offs of future hydrogen supply chain portfolios that meet stakeholders' objectives in the Netherlands. First, the drivers, barriers, and facilitators for hydrogen supply chains in the Netherlands are identified. Then, possible technology combinations that can form domestic and global hydrogen supply chains, including resulting portfolios, are created. Finally, the techno-economic and socio-political performance is assessed, and trade-offs are identified.

The results were derived from literature studies on hydrogen supply chain components and technologies, performance criteria, and hydrogen supply chains in the Netherlands. Additional expert interviews provided country-specific insights on the strategies, utilization, and evaluation of hydrogen supply chains in the near future (2030). A system analysis applying Geels' (2002) multi-level perspective framework identified drivers, barriers, and facilitators for hydrogen supply chains in the Netherlands. Mature hydrogen supply chain technologies for operation in 2030 and technologies with a low carbon footprint were used along with the characteristics of the Netherlands to create and select domestic and global supply chains. For the performance analysis, the criteria frequently mentioned in literature and interviews were selected. For the techno-economic analysis, a supply chain model was created to calculate hydrogen costs, and for the socio-political analysis, a qualitative analysis of social and political acceptance per supply chain component was performed.

The system analysis on hydrogen supply chains showed that the socio-technical landscape, regime, and niche levels contain drivers, barriers, and facilitators to their adoption. The main drivers for hydrogen supply chains in the Netherlands are affordability, sustainability, and acceptability. When considering the performance of the supply chains according to the performance criteria, it becomes apparent that there is no universal supply chain portfolio that can fulfill all stakeholders' objectives in the Netherlands. The key trade-off identified is that higher sustainability comes with higher acceptability but leads to lower affordability.

Comparable results in literature confirm that each supply chain has trade-offs on a techno-economic and socio-political dimension that need to be weighed by stakeholders depending on the use case and objective. To accelerate the implementation of hydrogen in the Netherlands, additional strategies and governmental support schemes are needed, especially to overcome the existing barrier and uncertainties for conversion, transport, and reconversion components. Therefore, a policy analysis is recommended to identify coordination issues and derive concrete policy recommendations. Moreover, the impacts and risks for society, hydrogen demand and supply, and emissions when importing hydrogen must be further analyzed. It is recommended to investigate technology and market developments of hydrogen supply chain components and compare the potential import countries for the Netherlands to secure hydrogen supply in the future.

The research adds to the discussion on the selection, performance, and development of hydrogen supply chains in the Netherlands. It thus makes a scientific contribution to the state of knowledge in that field. It also advances hydrogen supply chain studies by providing a holistic supply chain assessment methodology that includes techno-economic and socio-political criteria and domestic and global supply chains. The research also contributes to society by providing stakeholders with knowledge about the technical, economic, environmental, social, and political performance of hydrogen supply chains and country-specific drivers, barriers, and facilitators, including stakeholders' opinions and concerns about supply chain components. This may lead to better-informed policy and decision-making.

Acknowledgments

"A magic dwells in each beginning". This quote from the poem "Stufen" ("Steps") by Hermann Hesse always reminds me that life is about the steps we take, the changes that occur, and how we deal with them. Exactly three years ago, my journey at TU Delft started. During my bachelor thesis, I visited TU Delft to participate in the Joint Interdisciplinary Project. I investigated business challenges for sustainable energy carriers, such as hydrogen for aircraft. What fascinated me about hydrogen were the numerous application options in different sectors. However, I realized that the implementation of hydrogen as an energy carrier was not proceeding or only very slowly due to a complex energy system. The urgency of the climate crisis and my enthusiasm for sustainable and innovative solutions motivated me two years ago to start my master's in Complex Systems Engineering and Management at TU Delft specializing in the track Energy. Now, I completed my thesis on hydrogen supply chains in the Netherlands, which is my first (but certainly not last) contribution to implementing innovations for a future sustainable energy system.

The completion of my thesis would not have been possible without the support of various people whom I would like to thank at this point.

First, I would like to thank my supervisors for their guidance, expertise, and perspectives. Thank you, Andrea, for giving me the opportunity to write this thesis with you. You taught me to reflect critically on my work and to always choose my words carefully. Your feedback kept me busy, pushing my work to greater quality. I would also like to thank Jafar for your methodological and terminological input on supply chains and your feedback not to lose sight of the practical applicability. I learned a lot from it and it improved the overall quality of my work. Moreover, I would like to thank Svenja for your time and flexibility in meeting whenever I asked for feedback. Your encouraging words, advice, and support kept me motivated throughout the ups and downs of this project.

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Finally, with the successful completion of my studies, I have to think of my grandfather. Only a few days more and he could have witnessed this moment in person. I know he would be proud of me, his granddaughter, for becoming an engineer.

Maleen Hiestermann
Delft, October 2022

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List of Abbreviations

AF	Annuity factor
ATR	Autothermal reforming
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CO	Carbon monoxide
CO_2	Carbon dioxide
CoSEM	Complex Systems Engineering and Management
DEI+	Demonstratie Energie- en Klimaatinnovatie
EQ	Equation
EU	European Union
GHG	Greenhouse gas
H_2	Hydrogen
LH_2	Liquid hydrogen
LNG	Liquid natural gas
LOHC	Liquid organic hydrogen carrier
N_2	Nitrogen
NG	Natural gas
NH_3	Ammonia
NOx	Nitrogen oxides
O_2	Oxygen
OPEX	Operating expenditures
PEM	Proton exchange membrane
POX	Partial oxidation
PV	Photovoltaic
RQ	Research question
SDE++	Stimulering Duurzame Energietransitie
SMR	Steam methane reforming
SQ	Sub-question
WACC	Weighted cost of capital

1

Introduction

1.1. Context and motivation

In the Paris Agreement, 196 countries declared to significantly reduce greenhouse gas (GHG) emissions to keep the global average temperature rise below 2°C (United Nations, 2015). The European Union (EU), in particular, aims to achieve carbon neutrality by 2050 to become the first climate-neutral continent (European Commission, 2019). In this context, the Netherlands announced in the Dutch Climate Agreement of 2019 to reduce GHG emissions by 95% in 2050 relative to 1990 levels. To achieve this goal, the Netherlands intends to transition from a fossil-based to a renewable energy system, for example, by increasing the share of renewable electricity from 11% in 2020 to 100% by 2050 and switching to alternative energy carriers (Netherlands Ministry of Economic Affairs, 2019). In addition, the Dutch government declares to become independent of Russian fossil fuel imports (Rijksoverheid, 2022b). They are thus following the REPowerEU plan published by the European Commission in 2022, which aims to accelerate the energy transition, as Russia's invasion of Ukraine is negatively impacting the EU's energy security (European Commission, 2022b).

The use of hydrogen (H_2) is discussed as a promising pathway to meet climate targets and increase energy security due to its properties and diverse application options (European Commission, 2022b). H_2 can be used for heat and electricity generation, as a fuel or feedstock (IEA, 2019). It has the highest gravimetric energy density (120 MJ/kg), which is three times higher than conventional diesel fuel (45 MJ/kg) and a very low volumetric density (0.09 kg/m^3) (Møller et al., 2017). H_2 can be produced using (renewable) electricity or fossil fuels, stored in large volumes over time, transported via truck, rail, pipeline, or ship in pure form or in/on H_2 energy carriers to combat its low volumetric energy density. It is thus a versatile energy carrier that can replace fossil fuels in difficult to decarbonize and electrify industries or improve the energy system flexibility and reliability by serving as a feasible storage medium (Rijksoverheid, 2020a). Furthermore, if produced from renewables, the production is associated with zero-carbon emissions as no carbon dioxide (CO_2) is emitted at the point of use (Reuß et al., 2017).

Given these characteristics, the concept of a H_2 economy which Bockris (1977) defined as *"A system of industry, transportation, and household energy which depends on piped hydrogen [...]"* is gaining popularity in the Netherlands. In 2020, the Dutch government published a national H_2 strategy, which includes subsidy plans and research programs for ports, industry, mobility, and the built environment (Rijksoverheid, 2020a). Figure 1.1 illustrates the H_2 production trajectory in the Netherlands from 2020 to 2050. It focuses on low-carbon H_2 produced from electrolysis in the long term and natural gas (NG) reforming with carbon capture and storage (CCS) as an intermediate step. Over 100 projects have been announced and are developed to increase domestic H_2 production, storage and infrastructure (TKI Nieuw Gas, 2022). However, the Netherlands' H_2 production capability is limited due to seasonal and geographic characteristics such as limited renewable, fossil energy supply and accessible land. H_2 imports are thus considered from countries with abundant resources (Rijksoverheid, 2020a). In the REPowerEU plan, half of the announced 20 Mt H_2 for the EU in 2030 are planned to be imported (European Commission, 2022b) and 4.6 Mt of this delivered via the Port of Rotterdam (Port of Rotterdam, 2022b). For 2050, the Port of Rotterdam expects that imports will even cover about 85% of total H_2 consumption (Port of Rotterdam, 2022a). As a result, the Dutch government has already signed several memorandums of understanding with countries such as Chile (Rijksoverheid, 2022a), and the United Arab Emirates (Rijksoverheid, 2021) to establish collaboration for global H_2 infrastructures.

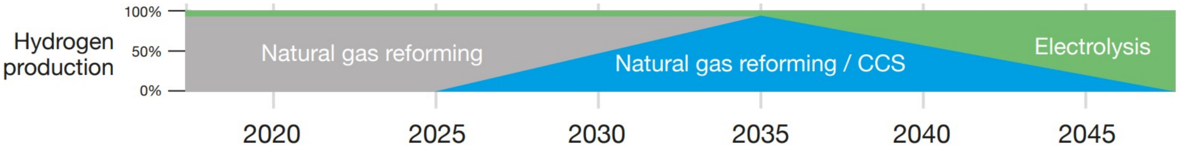


Figure 1.1: Trajectory of H_2 production routes in the Netherlands from 2020-2050 (Gigler & Marcel, 2018)

To establish a H_2 economy in the Netherlands, a detailed analysis of the entire supply chain is required, which van der Vorst (2000) defines as *"a set of activities linked by material and information flows that aim to deliver a product to the final consumer."* As the H_2 market is still at an early stage and the Dutch H_2 strategy only includes a trajectory of H_2 production but not for H_2 supply chains (Rijksoverheid, 2020a), it is difficult to identify the required measures needed to fulfil future H_2 demand for achieving country's climate targets. To overcome this, insights into the potential H_2 supply chain options for the Netherlands and their performance are required.

In this thesis, H_2 supply chains are divided into the following components according to IEA (2019) and HyChain (2022): Production, conversion, transport, reconversion, storage, and utilization. Furthermore, supply chains will be grouped into domestic and global supply chains. Domestic H_2 supply chains refer to H_2 produced, converted, transported and stored in the Netherlands. In contrast, global H_2 supply chains refer to H_2 produced and converted in another country and then transported to the Netherlands. The combination of a domestic and global supply chain will be called a supply chain portfolio.

1.2. State of the art and knowledge gaps

H_2 supply chain components

Previous studies focused on individual components of H_2 supply chains and analyzed mainly techno-economic criteria such as costs and GHG emissions. For example, components for conversion (Møller et al., 2017), transport (Yang & Ogden, 2007), and storage were studied (Andersson & Grönkvist, 2019). However, the main focus was on H_2 production, as economically competitive and environmentally friendly production methods are seen as a key factor for the H_2 economy (IEA, 2019). The studies include various technologies, such as gasification (Shayan et al., 2018; Midilli et al., 2021), reforming (Oni et al., 2022) and water electrolysis (Shiva-Kumar & Himabindu, 2019). A recent review of H_2 production methods by Yukesh-Kannah et al. (2021) showed that coal and NG remain the cheapest feedstock for H_2 production at about 1.25-3.5 USD/kgH_2. They concluded that low-carbon production such as steam methane reforming (SMR) with CCS will likely dominate H_2 supply in the short term. In the long term, renewable-generated H_2 will gradually displace low-carbon production as fossil fuel costs rise and technological developments lower the cost of renewable energy such as wind and solar power (Yukesh-Kannah et al., 2021).

H_2 supply chains

Many studies investigated H_2 supply chains with variations of chosen supply chain components or countries. Due to country and technology-specific differences, the results are not easily comparable and do not show an agreement on which supply chains are most beneficial. Nonetheless, they provide insight into the cost competitiveness and carbon footprint of different domestic or global H_2 supply chains for a specific country.

For domestic supply chains, numerous countries have been studied, such as Germany (Reuß et al., 2017), France (Robles et al., 2018) or the United Kingdom (Stockford et al., 2015). These studies combined production, transport and storage options and compared them in terms of total supply chain costs and GHG emissions. Their results showed that for large H_2 volumes and distances, storage and transport of gaseous H_2 in underground salt caverns and pipelines appears to be the solution that is most cost-effective and causes the lowest amount of GHG emissions.

For global supply chains, Japan (Ishimoto et al., 2020; Heuser et al., 2019), South Korea (Kim et al., 2021) and Germany (Sens et al., 2022) have been taken as frequent examples of H_2 importing countries due to their high energy demand and limited energy resources. Countries and regions with high renewable energy resources such as Norway (Ishimoto et al., 2020), North Africa (Sens et al., 2022), South America (Heuser et al., 2019), the Middle East (Kim et al., 2021) and Australia (IEA, 2019) are examples for exporting economies. The studies analysed different energy carriers such as liquid organic hydrogen carrier (LOHC) or ammonia (NH_3) and compared them to liquid H_2 (LH_2). Teichmann et al. (2012) compared the long-distance transport of H_2 via LOHC and LH_2 within the EU. They demonstrated that importing low-carbon H_2 in the form of LOHC from countries with significant renewable energy resources is economically advantageous compared to LH_2 generation via SMR. Ishimoto et al. (2020) studied the supply chains for renewable and NG-based H_2 from Norway to Japan. They showed that LH_2 could be a more efficient, environmentally and economically promising option for transporting and storing H_2 for long-distance transport than NH_3. They concluded that long-distance transport of H_2 from countries with significant renewable energy sources may be an economically viable option for energy supply when import prices for crude oil, petroleum derivatives, and NG increase. Kim et al. (2021) also came to the conclusion that using LH_2 for importing H_2 is the most economical choice because it does not require energy-intensive reconversion processes such as hydrogenation or cracking. In contrast, studies published by IEA (2019) and IRENA (2022) concluded that NH_3 is more cost-effective if the price of renewable energy falls from today's average of 0.048 €/kWh to 0.02 €/kWh.

H_2 supply chains for the Netherlands

Murthy Konda et al. (2011) analyzed the transition routes for domestic H_2 supply chains in the Dutch transport sector. The authors included the topology of the domestic H_2 infrastructure, a quantitative and qualitative comparison of three H_2 production alternatives, and a qualitative assessment of the Dutch CCS potential. They concluded that SMR with CCS would be the most economical low-carbon production route given the significant potential for CCS, low energy and feedstock prices in the Netherlands. However, they also emphasized that this could change due to developments in material costs and the availability of new technologies. For example, the co-production of electricity and H_2 was mentioned to be a cost-effective solution. Weimann et al. (2021) determined the optimal system configuration for minimized H_2 production cost of water electrolysis powered by electricity from wind energy and solar power for the Netherlands, which resulted in H_2 cost of 9 €/kgH_2. Ishimoto et al. (2020) studied importing H_2 from Norway to the Netherlands by ship and found that the cost and CO_2 emission for importing LH_2 is lower compared to NH_3 with 5 €/kgH_2 instead of 6 €/kgH_2 and 20 kgCO_2/MWh instead of 76 kgCO_2/MWh. In addition to techno-economic studies, a recent system analysis on the future role of H_2 in the Netherlands was performed by Detz et al. (2019). The authors concluded that the demand for H_2 will increase in different sectors, but the exact amount varies due to different key assumptions in studies that are not explicitly and adequately addressed. The main modeling parameters influencing the role of H_2 were identified as the technical availability of the technology, the economic feasibility, the availability and supply of renewable energy, and the CO_2 reduction target (Detz et al., 2019).

Knowledge gaps

From the variety of H_2 supply chain studies that were analyzed, the following knowledge gaps could be identified:

1. *H_2 supply chain performance*: Studies focus mainly on techno-economic criteria. Socio-political criteria are often not assessed when comparing H_2 supply chains. However, if they are included, they are country- and time-dependent, so their results cannot be easily generalized to the Netherlands. Hence, there is a knowledge gap regarding the country-specific socio-political performance of H_2 supply chains in the Netherlands under current developments. The country-specific performance of H_2 supply chains is important for decision making to achieve the national H_2 and climate targets. Furthermore, socio-political aspects are important to consider in any energy transition analysis as they influence economics, implementation processes, resources, and technologies used (Upham et al., 2015).
2. *H_2 supply chain portfolios*: Domestic and global supply chains for the Netherlands have been analyzed in separate studies but it is yet unclear which supply chain portfolios are possible in the Netherlands and whether and how domestic and global supply chains influence each other. These insights are important in order to understand how both types of supply chains contribute to meeting the increasing national H_2 supply and demand in the future.

1.3. Research questions

The literature review shows that research in H_2 supply chains is still evolving. More countries are being studied, and analyses include more supply chain components to obtain a holistic understanding. To address the identified knowledge gaps, this thesis presents a comprehensive analysis of H_2 supply chains that focuses on and includes techno-economic and socio-political aspects of a combination of domestic and global H_2 supply chains for the Netherlands in the near future (2030). There are several reasons why the Netherlands was selected for the study. First, the country is considered an important transit and trading hub for energy due to its large oil refining and chemical industries. Second, it aims to maintain its key role in European energy markets in the future (International Energy Agency, 2020). Third, no detailed case study on the Netherlands under current technology, market and energy policy conditions is available in literature.

This thesis addresses the following main research question (RQ):

What are the key trade-offs of future H_2 supply chain portfolios that meet stakeholders' objectives in the Netherlands?

To answer the main research question, three sub-questions (SQ) have been identified:

1. What are the drivers, barriers, and facilitators for H_2 supply chains in the Netherlands?
2. Which technology combinations can form H_2 supply chains, and how would resulting portfolios look like?
3. How do H_2 supply chains and portfolios compare in terms of their techno-economic and socio-political performance?

1.4. Contribution

Investigating the key trade-offs of H_2 supply chain portfolios that meet stakeholders' objectives in the Netherlands is of added value from a scientific and societal perspective. The findings and recommendations of this thesis are useful for all stakeholders interested or involved in H_2 supply chains.

From a *scientific perspective*, this research will advance the field of H_2 supply chain studies by (1) providing a holistic methodology for assessing H_2 supply chains. The methodology will include techno-economic and socio-political criteria. Socio-political criteria have become more important to governments, the energy industry, and academia alike as they are increasingly seen as an aspect that determines the successful implementation of new developments and policies (Upham et al., 2015). Therefore, including both types of criteria allows for a holistic performance analysis to identify more comprehensive trade-offs. In addition, domestic and global supply chains that use fossil fuels or renewable energy are analyzed as not all countries can fully supply the amount of H_2 they demand. Including both supply chains helps to analyse whether and how they affect each other and provides a comprehensive overview of possible portfolios. (2) The study will add to the body of knowledge in the field of H_2 supply chains in the Netherlands as country-specific data is included. Thus, it contributes to the scientific discussion on performance, choice and development of H_2 supply chains in the country.

From a *societal perspective*, the research contributes to more informed policy and decision-making by providing stakeholders with knowledge about (1) the technical, economic, environmental, social, and political performance of H_2 supply chains and (2) country-specific drivers, barriers, and facilitators which includes stakeholders' opinion and concerns on supply chain components. At the government level, these insights could guide Dutch policymakers to adjust or expand their H_2 strategy, policies and support programs. At the company level, the insights could be used to make informed decisions about supply chain choices to remain competitive and fulfil national climate targets.

1.5. Link to study program

Analyzing H_2 supply chains and investigating their trade-offs in the Netherlands aligns with the research criteria of the Complex Systems Engineering and Management (CoSEM) master's program. The investigated system of this study is H_2 supply chains in the Netherlands. It is a multidisciplinary system involving technologies, societal and environmental impacts, governance, laws and regulations. Thus, the system is embedded and affected not only by the interactions of its technical components but also by external aspects. The system's complexity can be shown by the involvement of several stakeholders, interdependencies between technologies, and unpredictable societal, environmental or political events. H_2 supply chains can, for example, directly impact society regarding energy security or environmental impact. At the same time, changing energy markets, societal trends, or political decisions may alter the profitability, acceptance, or utilization of H_2 supply chains (Rijksoverheid, 2020a). The system under investigation can therefore be described as a complex social-technical system which is the system in focus of the CoSEM master's program.

1.6. Thesis outline

Chapter 1 introduced the problem, the state of the art and knowledge gaps of H_2 supply chains, RQs, and the scope of the study. Chapter 2 describes the methodology that was adopted to answer the RQs. The methodology is applied in Chapter 3, which presents the results of two literature reviews, stakeholder interviews and the resulting supply chain portfolios. The first literature review focused on H_2 supply chains in the Netherlands to identify their drivers, barriers, and facilitators. The second one focused on H_2 supply chain components to configure potential supply chains for the Netherlands. Chapter 4 describes the identification and selection of techno-economic and socio-political criteria and analyzes the performance of each supply chain. The results determine which portfolios meet stakeholders' objectives best and what trade-offs they entail. Chapter 5 discusses and reflects on the key findings and methodology of the study. Chapter 6 concludes this thesis by answering the research questions and provides recommendations for further research.

2

Methodology

2.1. Research Flow Diagram

The methodology of this thesis is visualized in the research flow diagram displayed in Figure 2.1.

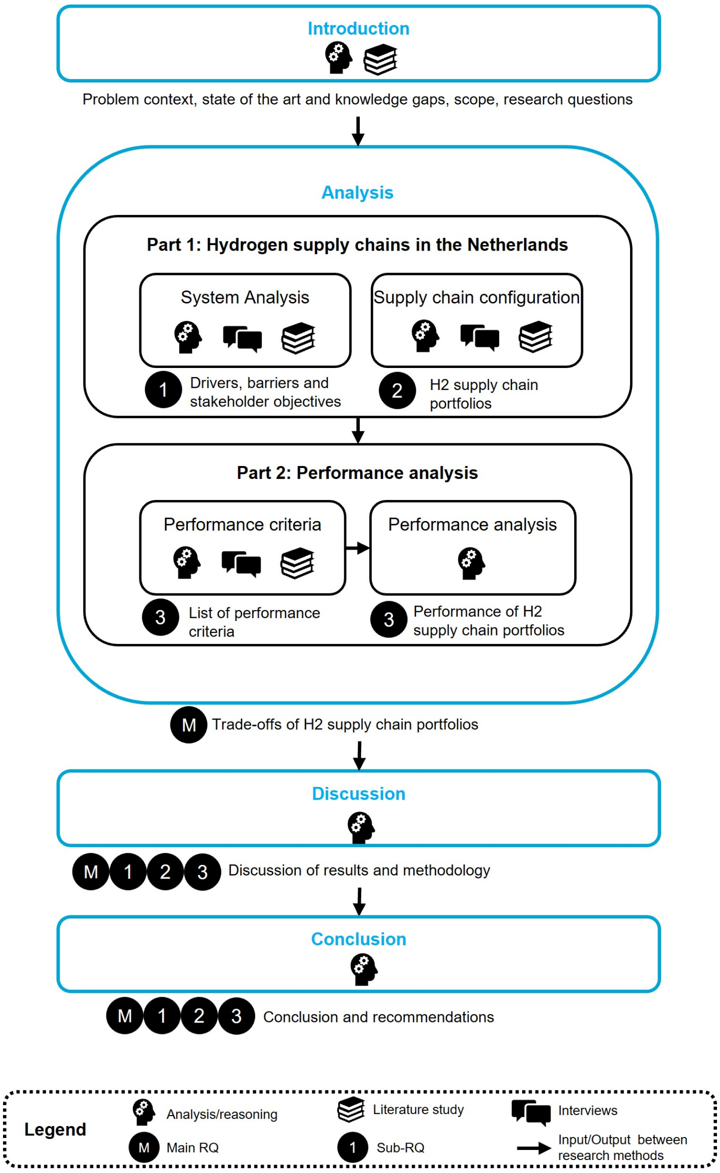


Figure 2.1: Research flow diagram

The figure shows that the introduction to the topic described in Chapter 1 is based on a literature study and identifies the context of the problem, the scope, the state of the art and knowledge gaps, and the RQ. The results serve as input for the analysis step, which is divided into two parts:

Part one refers to H_2 supply chains in the Netherlands in Chapter 3. The first results are the drivers, barriers and facilitators of H_2 supply chains in the Netherlands. The results answer SQ1 and are found reviewing literature and analyzing interviews regarding (1) H_2 supply, (2) H_2 utilization, (3) H_2 infrastructure, (4) legislation and regulation, and (5) stakeholders involved. The information gathered is structured according to the multi-level perspective framework of Geels (2002). Next, H_2 supply chain components are analyzed based on data from literature and interviews. Subsequently, selected components are combined into H_2 supply chain portfolios. The results answer SQ2.

Part two refers to the performance of H_2 supply chains in Chapter 3. The output is, first, a list of criteria to analyze the performance of H_2 supply chains. This corresponds to SQ3 and is generated through a literature study and stakeholder interviews. The list of criteria is the input for the performance analysis. The results answer SQ3 and form the input for the trade-offs of H_2 supply chain portfolios. They are generated by comparing the performance, which answers the main RQ.

The output from the analysis step is the input for the discussion in Chapter 5. It relates to all RQs. The outcome is a discussion of the results and methodology, which includes a sensitivity analysis and a comparison with literature. This forms the input for the final step, the conclusion in Chapter 6. The output responds to all RQs and recommendations.

2.2. Literature study

The literature study in this thesis has three objectives: (1) Identify H_2 supply chain components to configure supply chains and portfolios in Chapter 3. (2) Analyze the current H_2 supply chains in the Netherlands to identify drivers, barriers, and facilitators in Chapter 3. (3) Identify performance criteria to analyze H_2 supply chains in Chapter 4.

According to Leech and Onwuegbuzie (2010), literature studies enable the extraction of information from multiple sources, and its synthesis generates new insights into a topic. Moreover, literature research can improve credibility and helps to identify potential contradictions or inconsistencies through syntheses. The main advantages of a literature study are thus representation and legitimization. Peer-reviewed literature has high credibility and academic rigor but it is also advantageous from a methodological perspective as its standard format facilitates the search, selection and content analysis of relevant articles. According to Paez (2017), grey literature can increase the scope of the search by including a wide range of sources. As there is a long time period between submission and publication of papers, grey literature provides the most current context of the rapidly evolving topic of H_2 supply chains (Paez, 2017; Frankowska et al., 2022). However, the quality of the literature review decreases with time, as not all studies relevant to the topic can be reviewed (Leech & Onwuegbuzie, 2010). Analyzing grey literature can be time-consuming as there is no word limit, standardized presentation format, and usually no abstract. Lastly, grey literature is not peer-reviewed, which can question the reliability and quality of publications (Paez, 2017).

For *H_2 supply chain components*, the literature study was conducted as follows. First, the term ”hydrogen supply chain” resulted in 219 articles on Scopus. Then, the search was reduced to articles from the last five years (2018-2022) to increase the relevance to the research topic and reduce the number of articles. As the topic of H_2 supply chains has evolved rapidly in recent years, it is assumed that more recent articles will provide an accurate overview of the characteristics of the technologies. Review papers were selected as their authors conducted a literature review themselves and thus contained a larger, more complete overview. This resulted in 19 articles whose title, abstract, and conclusion were read to assess whether the articles met the following two selection criteria: First, H_2 supply chains are the subject of the review, and, second, the review describes various H_2 production, conversion, storage, and transport components and their technology alternatives. This resulted in five papers. Since the results were limited in number, backward snowballing was performed to find additional papers that met the selection criteria. In this way, five more papers were found. Table A.1 in Appendix A provides an overview of the considered articles.

For *H_2 supply chain performance criteria*, a second literature study in Scopus was conducted. First, the initial string ”hydrogen supply chain” and ”assessment” OR ”analysis” yielded 63 articles. To improve the quality of the results, keywords including ”multi*” were added so that the papers obtained with the query were more likely to contain techno-economic and socio-political performance criteria. After performing several exploratory queries, the final string used was (hydrogen supply chains AND assessment OR analysis AND criteria OR objective AND ”multi*”), which yielded 18 articles. The title, abstract, and conclusion were read to assess whether the articles met the following selection criteria: First, H_2 supply chains are the paper’s topic. Second, the criteria list includes at least two of the following categories: Technological, economic, environmental, and socio-political. This resulted in ten articles. Backward snowballing using the same selection criteria was then applied to include relevant articles that could be excluded based on the chosen database. Four additional papers were added, leading to fourteen selected articles. Table A.2 in Appendix A provides an overview of the articles considered.

For *H_2 supply chains in the Netherlands*, grey literature was included as an initial search for peer-reviewed literature led to no relevant papers. Grey literature was obtained from Google Scholar by searching for reports and white papers about the Dutch H_2 economy and H_2 supply chains. Various document types were considered when selecting which documents to include in the analysis to provide a broad perspective. The selection criteria were, first, that the H_2 economy in the Netherlands is the paper’s main topic and, second, it considers a holistic system perspective, i.e. on technical, economic, environmental, social and political aspects. Seven papers were found. Table A.3 in Appendix A provides an overview of the papers considered.

2.3. Expert interviews

The interviews aim to capture stakeholder’s drivers, barriers, and facilitators for H_2 supply chains in Chapter 3. In addition, the goal is to compare the information from literature (Section 2.2) with those to be considered in the Netherlands in Chapters 3 and 4.

Interviews are commonly used in exploratory studies to collect empirical data or validate findings (Adams, 2015). They have the advantage of allowing the researcher to obtain a higher level of detail by asking interviewees to elaborate on specific topics compared to literature studies. Semi-structured interviews were selected as they promote a relaxed setting in which the interviewee can respond in their own words (Myers & Newman, 2007). They are used to discuss topics rather than answer a fixed list of questions. Semi-structured interviews have a certain degree of predetermined order but allow for more open interaction when conducting interviews and flexibility in how the interviewee addresses the issue and in adapting questions to experts’ responses and varying levels of expertise (Longhurst, 2003). Individual online interviews were chosen instead of in-person or focus group interviews as it is easier to schedule a meeting individually. Furthermore, it guarantees that different perspectives are presented independently. An online meeting is neutral, quiet, easily accessible and provides the possibility to record the conversion so that the interviewer can focus on and listen to the conversion instead of losing focus due to writing notes (Longhurst, 2003).

The disadvantages include that the data quality in an interview depends on the interview design and the interviewer’s skill. The interviewee might not understand the question or is influenced by the interviewer’s responses (Adams, 2015). The interviewer is thus not a neutral entry but influences the respondent’s behavior (Myers & Newman, 2007). Moreover, time pressure when answering the questions can lead to missing information (Myers & Newman, 2007). Processing semi-structured interviews takes more time than structured interviews as open-ended questions do not have a uniform answer scheme (Myers & Newman, 2007). However, as fewer stakeholders are interviewed, who differ significantly from each other, this does not pose a problem (Myers & Newman, 2007). The recruitment process to find interview partners can also be very time consuming. Lastly, online interviews make it difficult to read body language (Longhurst, 2003).

The interview approach for semi-structured interviews is based on Myers and Newman (2007). The steps are shown in Figure 2.2 and explained in detail afterwards.

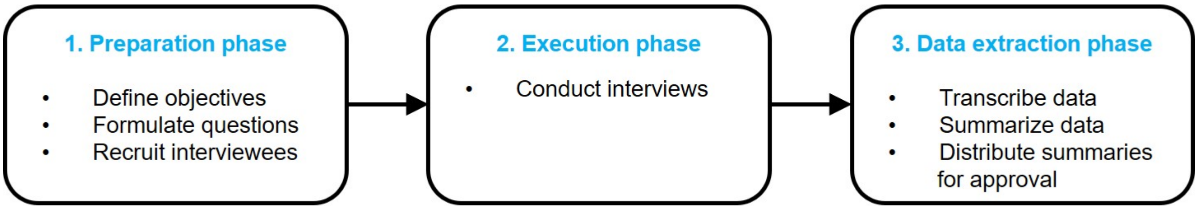


Figure 2.2: Interview process based on Myers and Newman (2007)

The *preparation phase* begins with defining the objective of the interview, in this case identifying stakeholder objectives and validating H_2 supply chains and performance criteria. With this objective in mind, an interview protocol is created, which can be found in Appendix B. It was noted according to the model of the qualitative interview by Myers and Newman (2007). The steps are as follows: Preparing the opening, the introduction, the key questions, and the closing. Then, based on the stakeholder groups identified in the literature study (Section 2.2), companies were selected based on their involvement in Dutch H_2 supply chains. People with knowledge in H_2 supply chains were chosen, which was demonstrated by working on projects related to H_2 supply chains. The interviewees were found through personal contacts and participation in conferences such as the ”World Hydrogen Summit 2022” in Rotterdam and the ”TU Delft Sustainable Transport event” and contacted electronically which made it easier and faster to find and reach the desired person in a large organization. In addition, respondents can be spoken to beforehand in an unconstrained manner to confirm that they are knowledgeable about the topic. From each identified stakeholder group, at least one stakeholder was interviewed. An overview of the interviews can be found in Table 2.1.

In the *execution phase*, interviews are conducted. All interviews were individual and online conducted through Microsoft Teams following the storyline according to the model by Myers and Newman (2007): First, the topic, goal, procedure and important definitions and assumptions of the thesis were explained to ensure a common understanding. Then, a general question was asked about H_2 supply chains to start the conversation and to assess the interviewee’s knowledge about H_2 supply chains in the Netherlands. Afterwards, more specific questions were asked to elicit information that could not be easily found in literature based on the interviewee’s practical experiences. All questions were open-ended and not in a specific order. The questions can be found in Appendix B. Lastly, the interview was concluded by thanking the interviewee and asking about possible confidentiality.

The *data extraction phase* consists of creating interview summaries. The data processing method started by transcribing interviews using the Microsoft Teams transcription function. Then, the transcript was fully read in parallel with the audio recording to verify its accuracy and to make necessary corrections. After finalizing the transcript, the sentences were summarized and structured according to the questions. The summaries can be found in Appendix C and was provided to all interviewees to ensure the accuracy of the content.

Table 2.1: Overview of conducted interviews

Interview	Stakeholder group	Job description
1	Energy producer	Business Developer
2	Hydrogen producer	Business Developer
3	Transport and storage operator	Advisor
4	Built environment	Consultant
5	Industrial sector	Consultant
6	Transport sector	Business Developer
7	Local government	Advisor
8	National government	Program manager
9	Research and Development	Researcher
10	Research and Development	Researcher

2.4. System analysis

A system analysis is performed to identify drivers, barriers, and facilitators of H_2 supply chains in the Netherlands, which answers SQ1: *What are the drivers, barriers, and facilitators for H_2 supply chains in the Netherlands?*

Adapting the supply chain management terminology by Lambert (2010), *drivers* are defined as the compelling reasons to stakeholders for H_2 supply chains i.e. their objectives. They set the expectations for H_2 supply chains performance. *Barriers* are defined as obstacles that hinder the implementation of H_2 supply chains. *Facilitators* are defined as supportive environmental factors that enhance the H_2 supply chain implementation.

To identify the drivers, barriers and facilitators, the findings from the literature study (Section 2.2) and interviews (Section 2.3) are placed in the multi-level perspective framework by Geels (2002) depicted in Figure 2.3. It is a commonly used framework for comprehending transitions in the CoSEM study program with which the author is already familiar. It places current and prevalent technologies into broader systems, i.e. including networks, tacit knowledge, infrastructure, stakeholder preferences, and institutional frameworks to extract relevant information from different sources (Geels, 2002). Thus, applying the framework structures the insights into how the transition to H_2 supply chains is socially and technically motivated in a larger context.

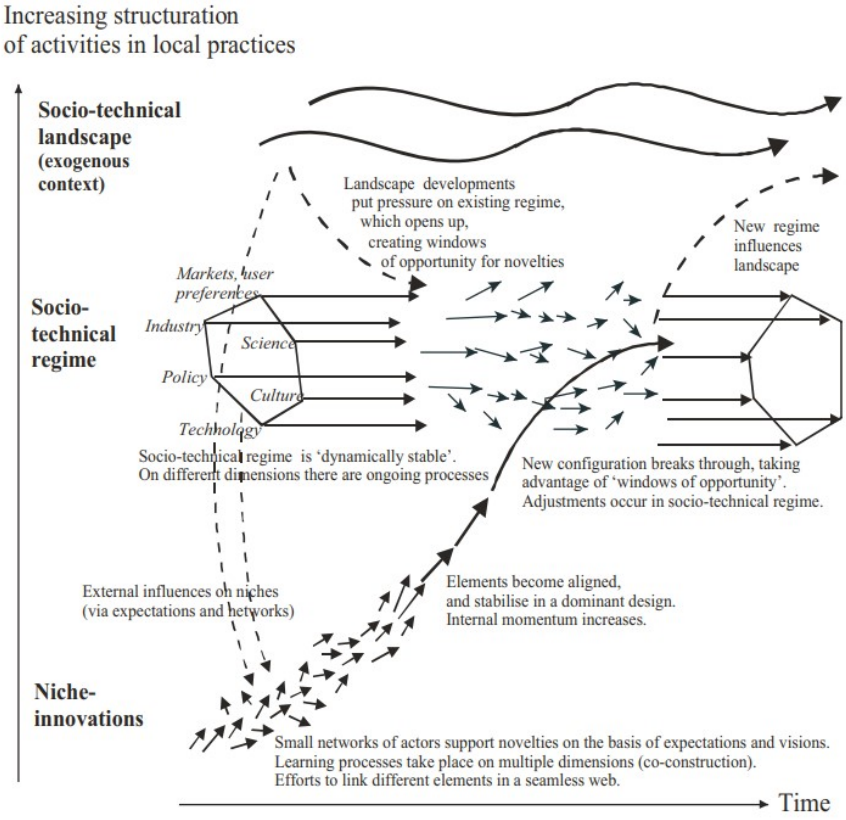


Figure 2.3: Multi-level perspective framework by (Geels, 2011)

The framework presented in Figure 2.3 will be explained in the following:

- The *landscape level* consists of the overarching long-term structural set of trends and developments of H_2 that either stabilize or puts pressure on the existing regime of H_2 supply chains. Landscape characteristics should be seen as facilitators that can considerably impact the regime and niche levels but cannot be changed by the stakeholders involved at these levels. These facilitators can vary (i.e. demography and the natural environment, political culture, social beliefs and values) (Geels, 2002).

- The *regime level* includes factors that provide a framework and guidelines for the decision-making and actions of stakeholders within those levels that stakeholders can influence. These factors include the status quo, such as stabilized or dominant H_2 supply chain technologies, stakeholders, and other rules of the game. In general, regime characteristics are difficult to change due to their stability. On the contrary, a transition is characterized in particular by adjustment of the regime level (Geels, 2002).
- The *niche level* consists of controlled environments or protected sub-systems where innovations are nurtured and enabled to thrive. Niches provide shelters against established H_2-technologies and frameworks, with which the development of new technologies, behaviors and structures may not be able to compete. In a transition to a H_2 economy, a complex interaction arises between regime adjustments that accelerate the uptake of innovations from a niche level and innovations that themselves lead to social-economic changes at the regime level (Geels, 2002).

2.5. Supply chain configuration

The goal of the supply chain configuration is to create H_2 supply chains and portfolios to answer SQ2: *Which technology combinations can form H_2 supply chains, and how would resulting portfolios look like?*

The approach to configure H_2 supply chain portfolios is as follows: First, selection criteria are applied to narrow down the optional components for H_2 supply chains in the Netherlands. These include: (1) Technologies that have a low carbon footprint to adhere to the Dutch climate targets and (2) technologies with a Technology Readiness Level of 7 and above (i.e. demonstration or commercially available) are considered since they are regarded mature enough for operation in 2030. Once the technologies are identified for each component, they are combined into technically feasible domestic and global supply chains following the standardized supply chain sequence based on IEA (2019) and HyChain (2022). Based on the identified advantages and disadvantages of the technologies and the characteristics of the Netherlands (adhered from literature and the interview series), the domestic and global H_2 supply chains for the Netherlands in this thesis are selected without specifying the utilization. Then, portfolios are created, combining each domestic with a global supply chain. Lastly, countries eligible to export H_2 to the Netherlands were selected based on their (1) existing and planned energy resource capacity for NG and renewable electricity and (2) valid or potential cooperation with the Netherlands to establish export-import corridors in accordance with published memoranda of understanding.

The advantage to configure H_2 supply chains using a standardized sequence of components is to improve comparability and to limit the possible supply chain options. Furthermore, not specifying the utilization of H_2 provides an overview of all potential supply chains, which is in line with the scope of the thesis. Using selection criteria to narrow down technology options, as well as using literature and stakeholder interviews in the configuration process, helps to develop H_2 supply chains that take into account country-specific characteristics but are also scientifically credible. However, applying selection criteria may exclude technologies with high but undiscovered potential, and stakeholder may have incomplete knowledge or are biased when selecting a component. In addition, a standardized sequence of components without considering the exact utilization can give stakeholders some insight into supply chains but it cannot reflect the system's complexity as a whole. Including the utilization can change supply chain preference per sector/application, if, for example, H_2 is needed as a fuel rather than a feedstock, other energy sources become interesting to consider. Differentiating the utilization of H_2 is therefore beyond the scope and goal of this thesis which focuses H_2 supply on the Netherlands as a whole.

2.6. Performance criteria

The performance criteria selection aims to derive at list of criteria which are used in the performance analysis (Section 2.7) to answer SQ3: *How do H_2 supply chains and portfolios compare in terms of their technical-economic and socio-political performance?*.

To derive a list of performance criteria, first, the most frequently mentioned criteria in literature (Section 2.2) and interviews (Section 2.3) are identified and visualized in a bar chart. The categories include technological, economic, environmental, and socio-political criteria. Then, the drivers identified in the system analysis (Section 2.4) are applied as selection criteria to narrow down and categorize the options. Lastly, the most frequently mentioned criteria for each driver are selected for further analysis and defined with their metric and methodology.

Determining performance criteria based on a literature study and interviews has the advantage of choosing country-specific but also scientifically credible criteria that the Dutch stakeholders focus on when selecting H_2 supply chains. A disadvantage of using literature and interviews to identify performance criteria is the possible different definitions and determination of the criteria, which must be considered when assessing which criteria were mentioned most frequently. In addition, selecting the most frequently mentioned performance criteria is a disadvantage, as a few criteria can only represent a limited part of the stakeholders' objectives.

2.7. Performance analysis

A performance analysis is conducted to analyze and compare the performance of H_2 supply chains to answer SQ3: *How do H_2 supply chains and portfolios compare in terms of their techno-economic and socio-political performance?*. Based on this, the trade-offs are derived, which answers the main RQ: *What are the trade-offs of future H_2 supply chain portfolios that meet stakeholders' objectives in the Netherlands?*

To compare the performance of the configured supply chains (Section 2.5), the selected and defined techno-economic and socio-political performance criteria (Section 2.6) are analyzed. Two analyses are performed: (1) A quantitative techno-economic analysis (Section 2.7.1) to calculate the economic and environmental performance. (2) A qualitative socio-political analysis (Section 2.7.2) to analyse the social and political acceptance. The analyses are conducted using information from literature (Section 2.2) and stakeholder interviews (Section 2.3). Per criterion, each component of the supply chain is evaluated. Then, the results for a supply chain are compiled to give an overview of the performance, compare supply chains and determine the trade-offs per supply chain. Finally, the results are compared to literature.

Analysing the performance based on literature and stakeholder interviews has the advantage of choosing country-specific but also scientifically credible data and information to calculate and assess H_2 supply chains in the Netherlands. Comparing the results to literature puts the results in context with other findings to understand discrepancies and agreements. However, comparing the results with other studies can be difficult because the studies H_2 define supply chains differently and analyze different aspects. Also, the analyses are based on different data, assumptions and calculations, e.g. for different countries or technologies. If these are not apparent or accessible, comparing the results is difficult. According to Edmonds et al. (2019), another disadvantages is that the results are not a 1:1 representation of what is observed but only a representation of the supply chain components that are defined in this study. For simplicity and to better understand the complex nature of H_2 supply chains, not all aspects of the supply chain, as well as its flexibility, and H_2 capacity are included. This leads to a bias in the representations, since it cannot be accurately assessed whether the supply chains and portfolios may not be able to meet the required supply. However, this would add an additional complexity in modeling which is beyond the scope of the thesis, which has the goal to provide explanatory insights rather than predictions. Finally, the reader may not understand the limitations and may make incorrect assumptions about the generality of the results (Edmonds et al., 2019).

2.7.1. Techno-economic analysis

To perform a techno-economic analysis, first, current techno-economic data and calculations were defined for each selected component of the supply chain, and information on country-specific energy prices and transportation distance for each export country to the Netherlands was determined based on the largest port in the country. Second, based on the data and calculations, a model is developed to calculate the economic and environmental performance, i.e. the total H_2 costs, CO_2 emissions, NOx emissions and land requirement per kg H_2. Third, a sensitivity analysis is performed to account for uncertainties in assumptions and data and their impact on performance.

Economic analysis

To compare the economic performance of H_2 supply chains, the costs per kg of H_2 are estimated per supply chain component.

Production costs

The H_2 production costs for domestic and global supply chains are estimated using the selected production technology and energy source. The costs per kg H_2 can be expressed as the sum of $CAPEX$, $OPEX_{fix}$ and $OPEX_{var}$ as presented in EQ 1.

$$Cost_{H_2} = CAPEX + OPEX_{fix} + OPEX_{var}, \tag{1}$$

where $CAPEX$ are investment cost such as plant construction and equipment costs, $OPEX_{fix}$ are the fixed labor, maintenance and general administrative costs, and $OPEX_{var}$ are the variable operational costs such as electricity, fuel, and carbon tax.

The specific annual $CAPEX$ per kg H_2 are calculated by first multiplying the total investment cost by an Annuity factor (AF) defined in EQ 2 and then dividing it by the annual H_2 $throughput$ as presented in EQ 3. The AF is a ratio for determining the present value and annualizing the investment costs to determine the share of total investment costs per kg H_2 produced. According to Reuß et al. (2017) it is based on the Weighted cost of capital (WACC) of 8% and the depreciation period N, which is assumed to be equal to the life of the production facility.

$$AF = \frac{(1 + WACC)^N * WACC}{(1 + WACC)^N - 1} \tag{2}$$

$$CAPEX = \left(\frac{Invest_{total} * AF}{throughput}\right) \tag{3}$$

$OPEX_{fix}$ is represented by an operation and maintenance (OM) factor per supply chain component and related to the total investment costs. It is calculated similarly to $CAPEX$ as presented in EQ 4.

$$OPEX_{fix} = \left(\frac{Invest_{total} * OM}{throughput}\right) \tag{4}$$

To estimate $OPEX_{var}$, the emission costs are added to the energy consumption costs i.e. the energy consumed multiplied by the country-specific energy price as presented in EQ 5. The $Cost_{emission}$ defined in EQ 6 are based on the energy consumption per supply chain component multiplied by the country-specific carbon emission factor per energy type and the carbon emission price applicable in the Netherlands. For 2030, a CO_2 price of 100 €/tCO_2 according to Brändle et al. (2021) is assumed.

$$OPEX_{var} = Consumption_{energy} * Price_{energy} + Cost_{emission} \tag{5}$$

$$Cost_{emission} = Consumption_{energy} * Emission_{energy} * Price_{carbon} \tag{6}$$

Conversion and reconversion costs

For calculating conversion and reconversion costs, EQs 1-6 were used, with the required data for the conversion and reconversion technology and energy source used.

The $throughput$ is adjusted as shown in EQ 7 by an overcapacity factor f_{cap} = 1.1 and an overproduction factor $f_{prod} = \frac{8760h}{FLH}$ to consider flexible operational hours and losses of H_2 across the supply chain (Reuß et al., 2017). Furthermore, it is assumed that conversion and reconversion facilities operate at full load over 8000 hours per year to provide a reliable supply for all utilization cases.

$$throughput = throughput_{base} * f_{prod} * f_{cap} \tag{7}$$

The conversion of H_2 takes place in the selected exporting country. Therefore, the country-specific energy costs of the same energy type applied to calculate the production costs are assumed for the conversion costs.

The reconversion of H_2 takes place in the Netherlands. Therefore, the Dutch energy costs of the same energy type applied to calculate the production costs are assumed for the reconversion costs.

Transportation costs
For calculating transport costs, EQs 1-6 were used, with the required data for the transport technology and energy source used.

For shipping, $OPEX_{fix}$ and $OPEX_{var}$ are related to the $Time_{Roundtrip}$ which is the shipping time that relates to the transport distance and speed. $OPEX_{fix}$ and $OPEX_{var}$ are adapted by the shipping time as shown in EQs 9 and 10 which is based on the average shipping distance from the exporting country to the Netherlands. A speed of 10 knots was assumed according to Kim et al. (2021). Furthermore, heavy fuel oil is assumed for ship transport and boil-off losses during the transport time are included in the $throughput$ (which in this case refers to the maximum ship loading).

$$Time_{Roundtrip} = \frac{Distance}{Speed} * 2 \tag{8}$$

$$OPEX_{fix} = \left(\frac{Invest_{total} * OM * Time_{Roundtrip}}{throughput} \right) \tag{9}$$

$$OPEX_{var} = Consumption_{fuel} * Time_{Roundtrip} * Price_{fuel} + Cost_{emission} \tag{10}$$

For pipelines, the cost are assumed to be constant over time and grid electricity is assumed as an energy source. The pipeline's diameter is the main parameter for cost calculations and depends on the required $throughput$ and the transport distance (Reuß et al., 2017). The $throughput$ was calculated based on the diameter and distance using the HyChain (2022) supply chain tool. $Invest_{base}$ and $Invest_{total}$ is thus adjusted according to Reuß et al. (2017) shown in EQs 11 and 12.

$$Invest_{base} = 0.0022 \frac{€}{mm^2} * D^2 + 0.86 \frac{€}{mm} * D + 247.5€ \tag{11}$$

$$Invest_{total} = Invest_{base} * Distance_{pipeline} \tag{12}$$

where D is the diameter which depends on the selected energy carrier used per supply chain and $Distance_{pipeline}$ for domestic pipelines is assumed to be 1400 km based on the H_2 backbone (Gasunie, 2022).

Storage costs
For calculating storage costs, EQs 1-6 were used, with the required data of the selected storage technology.

The costs are determined based on the required volume and losses over time. $Invest_{total}$ is thus adjusted as shown in EQ 13. The investment costs for underground storage are assumed to decrease with increasing volume. For above-ground storage, a fixed specific investment amount per volume is assumed.

$$Invest_{total} = Invest_{base} * \left(\frac{volume}{volume_{compare}} \right)^{Invest_{scale}} \tag{13}$$

The $volume$ for storage is based on the H_2 $throughput$ in the Dutch pipeline network per year, a storage factor $f_{store} = \frac{storagedays}{365days}$ and the volumetric energy density of gaseous H_2 as presented in EQ 14. It is based on the Institute of Electrochemical Process Engineering energy concept 2.0 that estimates a storage amount of 90 TWh = 60 days given a 5300h electrolyser supplied by renewable energy (Reuß et al., 2017). Grid electricity is assumed as an energy source.

$$Volume = \left(\frac{throughput_{pipelines} * f_{store}}{VDensity_{H2}} \right) \tag{14}$$

Environmental analysis

To compare the environmental performance of H_2 supply chains, CO_2 emissions, NOx emissions, and the land requirement are estimated per supply chain component.

Emissions

CO_2 and NOx emissions are calculated based on the energy consumption of each supply chain component during the operation and the emissions of the energy source used as presented in EQ 15. Life cycle emissions of the energy source and the supply chain component, i.e., construction of the facility or end of life, are not considered.

$$Emission_{type} = Consumption_{energy} * Emission_{energy} \tag{15}$$

Land requirement

The land requirement of a supply chain is calculated based on the operational energy consumption per component and the land requirement of the energy source used as presented in EQ 16. For grid electricity, the country-specific share of renewable and fossil energy sources in the electricity grid was used. NG is taken as the fossil energy source and the average of offshore wind and solar PV as the renewable energy source.

$$Land = Consumption_{energy} * Land_{energy} \tag{16}$$

Sensitivity analysis

To understand how input variables and assumptions influence the results of the techno-economic analysis, a sensitivity analysis is performed by varying selected input parameters in the model and calculating the new output variable leaving all other assumptions unchanged. Then, the sensitivity, i.e. robustness of the results from these changes, is calculated by dividing the change in the output variable by the change in the input variable (Pichery, 2014).

A selection of parameters is made for which a range of values was set. Three scenarios were selected for the analysis, a high, base- and low-price scenario. For the economic results, the parameters $Invest_{total}$, $Price_{energy}$, and $Price_{carbon}$ were varied as these are subject to high uncertainties due to energy market and technology developments. For the $Price_{carbon}$, the projected prices according to Brändle et al. (2021) for 2020 and 2050 are taken to see the effect of a changing carbon tax policy. For the $Price_{energy}$, the average NG price before the recent energy crisis is taken for the low-price scenario and the highest NG price prediction until 2030 is taken both for the United States and the Netherlands for the high-price scenario. For renewable electricity price, a change of ±40% is assumed according to IRENA (2021). For the $Invest_{total}$ of H_2 supply chain components, a change of ±40% is assumed according to IRENA (2021) H_2 technologies in the short term. For the environmental performance, no sensitivity is evaluated, as the emissions are based on the energy source which is not subject to a change per kWh used. Table 2.2 lists all values for each scenario examined in the analysis.

Table 2.2: Range of values parameters selected for sensitivity analysis.

Parameter	Unit	High	Base	Low	Reference
$Invest_{total}$	€/kgH_2	+ 40%	current price	- 40%	(IRENA, 2021)
$Price_{naturalgas}$ (Netherlands)	€/kWh	0.3	current price	0.04	(European Commission, 2022a)
$Price_{naturalgas}$ (United States)	€/kWh	0.03	current price	0.01	(EIA, 2022b).
$Price_{renewables}$	€/kWh	+ 40%	current price	- 40%	(IRENA, 2021).
$Price_{carbon}$	€/tCO_2	160	100	28	(Brändle et al., 2021).

2.7.2. Socio-political analysis

To perform the socio-political analysis, the findings from the literature study (Section 2.2) and interviews (Section 2.3) are analysed according to the definition of the criteria obtained in Section 2.6. Then, the social and political analysis of each supply chain component is conducted by analysing the social acceptance and political acceptance.

Social analysis

The social analysis studies the social acceptance defined as *“a favorable or positive response [...] by [f the general public (i.e. individual consumers and citizens without formal political objectives)] at the country level towards [H_2 supply chain components]”* (Upham et al., 2015) based on the alignment with societal values, familiarity with technology, and health and safety risks (Ruggero, 2014). A color scale indicates how H_2 supply chain components are viewed by the society. Red means that society is not familiar with the component, the component is not consistent with society’s values of sustainability, and it is very toxic, causing significant health and safety impacts. Yellow means that the society is either already familiar with the use of the component to a large extent, as it is already applied in such a way that the component is consistent with the sustainability values, or that it is non-toxic and thus has little impact on health and safety. Green means that the use of the component is widely known in society, is consistent with sustainability values, and has a low impact on health and safety.

Political analysis

The political analysis studies the political acceptance which is defined as *“a favorable or positive response [...] by [the government]” at the country level towards [H_2 supply chain components]* (Upham et al., 2015) based on the alignment with national H_2 strategy and the support the components receive from the governmental schemes (Fazli-Khalaf et al., 2020). A color scale indicates the level of acceptance of the government. Red indicates the absence of specific governmental support schemes and that the component is not mentioned in the Dutch H_2 strategy. Yellow signals that either the component is already mentioned as part of the Dutch H_2 strategy or specific governmental support schemes exist. Green means that the component is part of the Dutch H_2 strategy and there are governmental support schemes.

3

Hydrogen supply chains in the Netherlands

3.1. System analysis

3.1.1. Socio-technical landscape

The system analysis begins, as explained in Section 2.4, with the socio-technical landscape, i.e. overarching long-term trends and developments that influence the H_2 supply chains in the Netherlands. Three aspects are analyzed: (1) The existing energy system, (2) the energy transition, and (3) national H_2 developments. The drivers *(D)*, barriers *(B)* and facilitators *(F)* for H_2 supply chains are indicated in the text and summarized in Section 3.1.4.

The existing energy system

The Dutch energy system is dominated by fossil fuels. In 2021, 86% of the energy supply in the Netherlands was generated using fossil fuels, mainly NG (42%), oil (36%) and coal (8%). Renewable energy (11%) only accounted for a small share in the energy mix (CBS, 2021). The discovery of NG reserves in Groningen in 1959 made NG a widely available and affordable energy source in the Netherlands (Murthy Konda et al., 2011). Energy-intensive industries such as oil refineries and the chemical industry were established, leading to many jobs and an extensive continental and intercontinental oil and gas pipeline network. Today, the Netherlands have one of the largest concentrations of oil refineries, marine bunkers and liquid NG terminals in Europe. The existing infrastructure makes the country a vital transit and trading hub for fossil fuels in Europe (IEA, 2022b) which stabilizes the current fossil fuel-dominated energy system and creates a barrier for the introduction of other technologies *(B1)*. At the same time, years of research and business activities in the oil and gas industry provide the Netherlands with a high level of knowledge about industrial gases, advanced materials and chemical processes *(F1)*. This knowledge can facilitate the process of becoming a significant player in developing a regional and international H_2 market (Rijksoverheid, 2020a).

The energy transition

The transition to a renewable energy system has gained momentum in the Netherlands. In the Paris Agreement, the Netherlands committed to reducing GHG emissions to limit global warming to 1.5°C (United Nations, 2015). In 2018, the Renewable Energy Directive II came into effect, setting the 2030 renewable energy consumption targets (European Commission, 2019). To meet the targets and respond to the change in society's request towards more sustainable energy alternatives *(F2)*, in 2019, the Netherlands stipulated in the Dutch Climate Act to reduce GHG emissions by 49 % in 2030 and 95 % in 2050 (compared to 1990) *(F3)*. Based on the National Climate Agreement, the Dutch parliament decided to phase out coal by 2030 and NG by 2023, accelerate electricity generation from renewables, and kick-start the H_2 economy (Netherlands Ministry of Economic Affairs, 2019). However, the share of renewable energy in 2021 was 11 %, which is among the lowest share in the EU (Eurostat, 2022). Reasons for the lag in renewable energy production include weather and geographical conditions, limited available space and electric grid capacity (PBL, 2021). Offshore wind energy is one of the essential pillars of the Dutch climate policy, as it is widely available in the North Sea. In 2022, the Dutch Government raised the offshore wind energy target from 11.5 GW to about 21 GW in 2030 (about 16 % of total energy demand and 75% of the country's electricity needs) (RVO, 2022b). The complex and slow transition toward a new energy system *(B2)* while reducing domestic fossil fuel production led to high energy imports and, thus, increasing dependence on other countries (IEA, 2022b). In 2022, the Russian invasion of Ukraine highlighted the drawbacks of such dependencies, such as being confronted with high energy prices and energy insecurity *(F4)*. This put pressure on the existing energy system to expand and diversify its energy portfolio *(F5)* (Rijksoverheid, 2022b).

Dutch H_2 developments

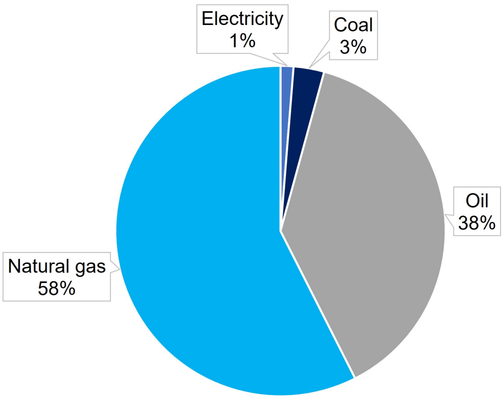
The Netherlands indicates in the National Climate Agreement that H_2 can link different sectors to increase the flexibility of a future low-carbon energy system. Where processes cannot be electrified for technical, spatial or financial reasons, H_2 is a scalable energy carrier that helps integrating intermittent renewable energy into the energy supply (Netherlands Ministry of Economic Affairs, 2019). In 2020, the Dutch H_2 strategy was presented. It focuses on renewable H_2 production using electrolysis with renewable electricity (500 MW in 2025 and 3-4 GW in 2030) but also considers H_2 generated from NG and CCS to accelerate the development of a H_2 system (Rijksoverheid, 2020a). The H_2 strategy thus provides a clear support signal to all Dutch and foreign companies to start their H_2 pilot and demonstration projects *(F3)*. However, there is no specific legislation for H_2 yet *(B3)* which means that the existing Dutch Gas Act applies in the context of H_2 projects (Rijksoverheid, 2020a). The lack of specific H_2 guidelines and standards makes implementation, especially on the local or small-scale level, difficult (Rijksoverheid, 2020a; Appendix C, Interview 5, 10). Furthermore, H_2 is still perceived with scepticism in society regarding its safety due to past events such as the Hindenburg explosion or unfamiliarity with the energy carrier *(B4)* (Ruggero, 2014; Appendix C, Interview 7, 10).

3.1.2. Socio-technical regime

The socio-technical regime, i.e. the status quo and the factors that provide the framework or guidelines for H_2 supply chains in the Netherlands (Section 2.4), is analyzed next. Five aspects are investigated: (1) production, (2) utilization, (3) infrastructure, (4) legislation and regulation, and (5) stakeholders.

H_2 production

The Netherlands is the second largest H_2 producer in Europe after Germany, with an estimated 180 PJ/year in 2019 (Detz et al., 2019). As seen in Figure 3.1, 99% of the H_2 in the Netherlands is currently produced from and with fossil fuels. As a result, more than 12.5 million tons of CO_2 were emitted in the same year, corresponding to 8% of the total CO_2 emissions in the Netherlands (TNO, 2022). The production processes are mainly located in Rotterdam and Zeeland and can be grouped into direct H_2 production and production as a by-product. Direct production alternatives include steam reforming of NG or natural-gas-rich residual gases, gasification of heavy residues from oil refining, or water electrolysis using electricity. As a by-product, H_2 is produced during catalytic reforming processes in oil refining, steam cracking of naphtha, chlorine production or coke production (Detz et al., 2019). The experience with existing H_2 production *(F6)* and the multiple production options from various energy sources is a driving force for H_2 supply chains *(F7)*. However, high H_2 production costs due to high energy and technology costs slow down the implementation *(B5)* (Appendix C, Interview 5). Depending on the regional energy prices, H_2 produced from renewable electricity is estimated at 3-8 USD/kgH_2, from NG at 0.5-1.7 USD/kgH_2, or NG with CCS at 1-2 USD/kgH_2 (IEA, 2022a). As of 2021, H_2 is therefore up to 2.5 times more expensive than NG per kWh considering an average annual price of 0.1 €/kWh (CBS, 2022). However, studies show that cost savings of 50-60% can be achieved for renewable H_2 production alternatives over the next ten years due to decreasing technology and renewable energy costs *(F8)* (Rijksoverheid, 2020a).



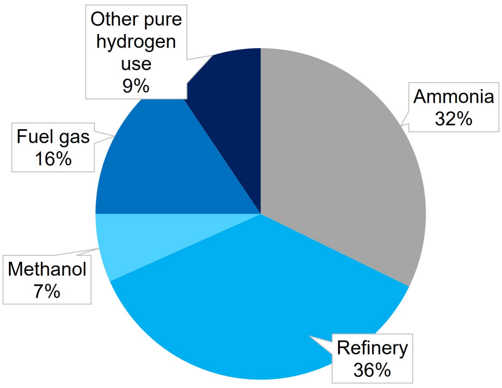
Energy source	**Estimated amount of H_2** [1]	
	kton/year	PJ/year
Natural gas	862	104
Oil	574	69
Coal	45	5
Electricity	19	2
Total	**1500**	**180**

Sources: [1] Detz et al. (2019)

Figure 3.1: Annual H_2 production by energy source in the Netherlands in 2019 based on Detz et al. (2019). H_2 is mainly produced from fossil fuels. The share of H_2 produced from non-fossil fuels is still low.

H_2 utilization

H_2 is mainly used in the Dutch chemical and refinery industry (Weeda & Segers, 2020). As seen in Figure 3.2, it is used as (1) feedstock for the production of NH_3 to make fertilizers or for the production of methanol, (2) as heat in refineries to desulphurize fuels and reprocess heavy petroleum fractions, (3) as fuel gas in the steam generation or co-generation or (4) as reducing agent and process gas for surface treatment in the glass, metal and semiconductor industry (Detz et al., 2019). The demand for H_2 is expected to increase due to numerous new applications for decarbonizing processes using H_2 (Rijksoverheid, 2020a). These include low-temperature heating in the built environment, fuel for diesel engines for heavy-duty transport, shipping or aviation in the transport sector, fuel for dispatchable electricity generation in the power sector or seasonal storage for the electricity, gas and heat sectors (Detz et al., 2019) *(F9)*. The increasing demand and application options are the driving force for developing H_2 supply chains. However, the exact demand is challenging to predict as many sectors are reluctant to commit yet because H_2 is expensive, and changing industrial processes can be difficult and costly *(B6)* (Weeda and Segers, 2020; Appendix C, Interview 2, 5, 9). An overview of the current and expected demand in the Netherlands is given in Figure 3.2. For comparison, primary energy consumption in the Netherlands was 3000 PJ in 2020 (Weeda & Segers, 2020).



Sector	**H_2 Demand** [PJ/year]	
	2020[1]	2050[2]
Industry	180	554
Built environment	0	34
Mobility	<1	160
Power	<1	332
Total	**180**	**1080**

Sources: [1] Weeda & Segers (2020); [2] Detz et al. (2019)

Figure 3.2: Annual H_2 demand by application type (left) and sector (right) in the Netherlands based on Detz et al. (2019). Today, H_2 is mainly used in the chemical and refinery industry. In 2050, more sectors are expected to use H_2.

H_2 infrastructure

The Netherlands already has an existing H_2 infrastructure consisting of pipelines and trucks. However, most H_2 is produced and consumed by industry directly on site (Rijksoverheid, 2020a). Trucks transport H_2 in small quantities in gaseous and liquid form over limited distances. The latter is done to a limited extent, as currently, only one facility for LH_2 in the Netherlands exists with a capacity of 5 tH_2/day (Weeda & Segers, 2020). H_2-rich residual gases are transported via pipelines to nearby companies, for example, between the two chemical companies DOW and YARA in Zeeland. 140 km of the H_2 pipeline network is located at the port of Rotterdam, 1000 km pipeline connects the port of Rotterdam to Northern France via Belgium, and 12 km are in Zeeland (Detz et al., 2019). Figure 3.3 provides an overview of the existing pipeline network. In addition, H_2 can also be injected into the existing NG grid to a limited extent: 2% with minor adjustments and 10-20% if further adjustments are taken (Rijksoverheid, 2020a). The H_2 Backbone i.e. the national H_2 pipeline network, is currently developed, which will consist of 85% existing NG pipelines and 15% new gas pipelines (Gasunie, 2022). For long-term H_2 storage, Gasunie explores the possible use of salt caverns and empty gas fields near Groningen with other companies. It is assumed that about 20.000 tons of H_2 can be stored in salt caverns in the future (RVO et al., 2021).

The existing H_2 and gas infrastructure is an essential driver for developing H_2 supply chains *(F10)*. However, there are unresolved regulatory questions around NG grid regulations and responsibilities and the allocation of cost to consumers, which create substantial uncertainty *(B7)* (Berger, 2021). The difference between the future H_2 and the existing H_2 pipelines is that for the latter, the supply and demand are agreed upon in advance. A contract guarantees that the pipeline operator can recoup its investment to set the transport tariff. In the future H_2 economy, the market will be open and dynamic with multiple suppliers and customers accessing the pipelines, which makes predicting H_2 flow and, thus, the tariff complex and business model difficult (Rijksoverheid, 2020a).

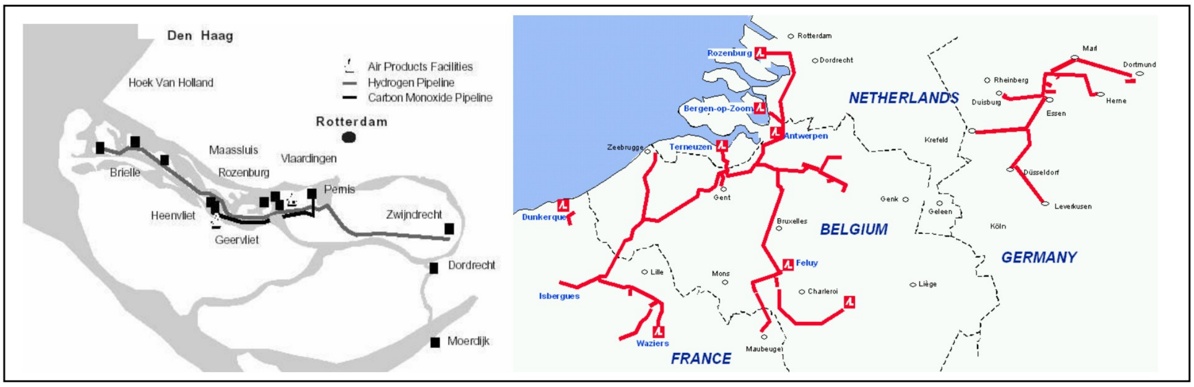


Figure 3.3: Existing H_2 pipeline network in the Netherlands (Detz et al., 2019). The Netherlands already has an extensive network within the port of Rotterdam and from the port to neighboring countries.

H_2 legislation and regulation

Legislation and regulation for H_2 supply chains are still at an early stage or in the planning phase in the Netherlands, as the Dutch Gas Act includes H_2 only on an industrial scale in central production facilities *(B8)* (Rijksoverheid, 2020a). However, together with the EU, the Netherlands proposes new laws and regulations *(F11)*, e.g., on common sustainability standards, guidelines for H_2 safety and quality, H_2 blending in gas networks, flexible market regulations, and adequate innovation support (Rijksoverheid, 2020a). Regarding the latter, the Dutch National Climate Agreement established legal and regulatory flexibility for cooperation with other market participants in implementing pilot projects under the general administrative regulation for temporary acquisitions (Netherlands Ministry of Economic Affairs, 2019). The national H_2 strategy describes the following five aspects of legislation and regulation:

- Use of the existing network to define stakeholder responsibilities
- Market regulation and preliminary tasks for network operators
- Guarantees of origin to facilitate a reliable market for carbon-free H_2
- Safety to determine the scope and effectively control the risks of new H_2 applications
- Energy infrastructure program to coordinate H_2 with the electric grid (Rijksoverheid, 2020a)

In addition to legislation and regulations, the government recognizes the importance of funding programs for research projects as well as the scale-up process in the H_2 strategy (Rijksoverheid, 2020a). H_2 projects are characterized by high initial investment costs but have difficulties to receive subsidies in the existing schemes for carbon-reduction technologies *(B9)* (Appendix C, Interview 5, 6). For instance, the Stimulering Duurzame Energietransitie (SDE++) subsidy in 2020 and 2021 only attracted three H_2 project applicants (Rijksoverheid, 2020a). To appeal to more applicants, the following financial support schemes are mentioned in the national H_2 strategy *(F11)*:

- SDE++ is a national subsidy program for emission reduction technologies and the first European example of carbon contracts for difference. It is awarded on a project basis and subsidizes the most cost-effective technologies. In 2022, SDE++ will feature H_2 production by electrolysis directly linked to a wind or solar farm as a new category to give market participants the necessary prospect of receiving support from the program (RVO, 2022d).
- Demonstratie Energie- en Klimaatinnovatie (DEI+) is a grant program for demonstration projects in industrial settings that use innovative technologies to reduce CO_2 emissions. Projects can receive a grant of 25% of eligible costs. Depending on the type of company, the amount can be up to 45% with a maximum of 15 million euros per project (RVO, 2022a).
- State aid for important projects of common European interest is an extended framework for state aid. It is complementary to SDE++ and DEI+ to accelerate cost reductions, so a cost-effective introduction of H_2 can occur earlier (European Commisson, 2022).

Stakeholders

Many stakeholders are already involved in H_2 supply chains in the Netherlands. The Ministry of Economic Affairs and Climate Policy has identified 250 companies near Arnhem but also Zeeland, South Holland, North Holland or the north of the Netherlands. Furthermore, they noted that on a smaller scale, various stakeholders such as municipalities, research institutes, small and medium enterprises, citizens, and grid operators are exploring innovative H_2 applications to exploit the economic opportunities related to local sustainability strategies (Rijksoverheid, 2020a). The interest and cooperation between stakeholders across the country are facilitators of developing H_2 supply chains *(F12)*. The implementation involves stakeholders with different roles: Energy producers, H_2 producers, transport/grid operators, end-use sectors, policymakers, society, and research institutes. The simplified relationship between them is illustrated along the H_2 supply chain in Figure 3.4. Their roles and drivers are explained below.

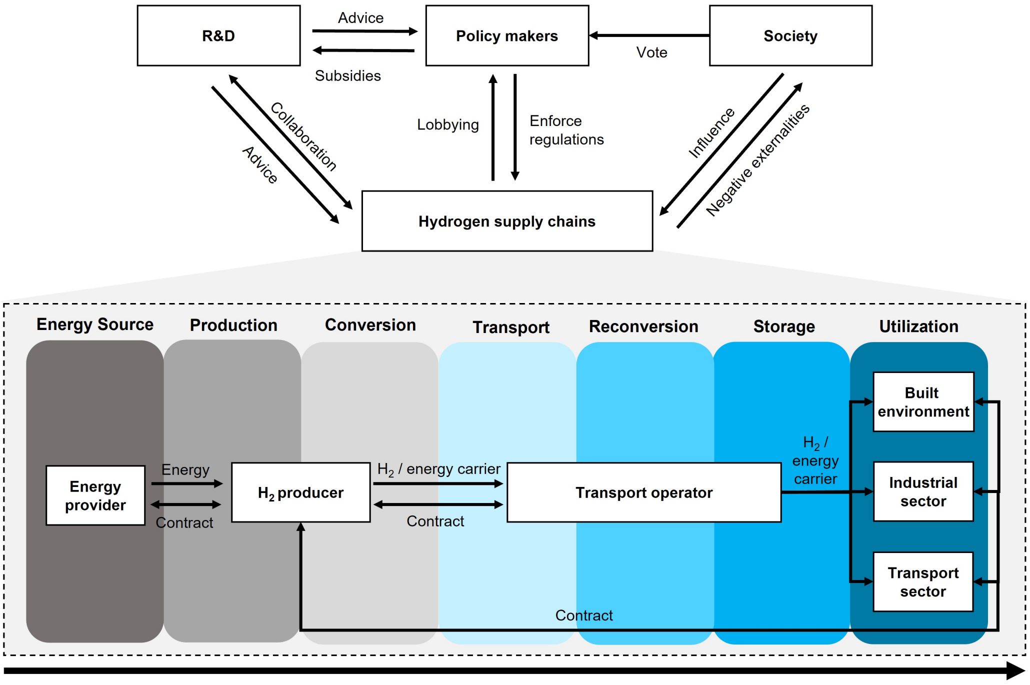


Figure 3.4: Stakeholders involved in H_2 supply chains and the relation between them. Stakeholders with different roles, drivers, and relations make the implementation of H_2 supply chains a complex endeavour.

Energy producers produce, process and trade fossil fuels and renewable energies, which they provide to society and industry reliably *(D1)* and in the required quality *(D2)* in return for payment (Appendix C, Interview 1). Due to the mentioned climate targets of the EU and the Dutch government, energy companies are obliged to reduce their carbon emissions *(D3)*. To achieve the reductions, H_2 is being considered in areas that are difficult to electrify with renewable energy. However, the transition must not jeopardize the company's competitiveness i.e. H_2 needs to be affordable *(D4)* (Rijksoverheid, 2020a). Similar considerations apply to H_2 generators that use energy to produce H_2. They, too, must meet emissions targets and do not want to lose economic competitiveness. At the same time, H_2 generators need to meet the increasing demand for H_2, so mature technologies with a convenient lead-in time *(D5)* for large-scale production *(D6)* are preferred (Appendix C, Interview 2). The H_2 produced is then converted, stored, or transported directly to the end user. As the application of H_2 expands into many new areas, a flexible *(D7)*, high-capacity storage and transportation network is needed that is accessible *(D8)* to market participants in a timely manner (Rijksoverheid, 2020a; Appendix C, Interview 3). For existing customers (industry), quality and cost are essential to continue producing their products reliably and reasonably priced (Appendix C, Interview 1, 2, 3). On the other hand, new users such as the built environment, transport, and other industrial sectors will use H_2 primarily to save emissions (Appendix C, Interview 4, 5, 6). Policymakers prioritize achieving climate goals and energy security in the Netherlands, as mentioned in Section 3.1.1. They advocate for systems that produce low-carbon emissions and are safe *(D9)* for society by creating regulations and financial support programs (Rijksoverheid, 2020a; Appendix C, Interview 7, 8). Safety, sustainability and efficient land use are important to society because the habitat is limited, and they are affected by the negative impacts of construction and operation (Section 3.1.1; Appendix C, Interview 8). Finally, private and public research institutions support the above stakeholders in their decisions by providing knowledge and advice or collaborating with them to develop new processes and technologies that are more affordable, efficient, and sustainable (Appendix C, Interview 9, 10).

Different stakeholder drivers may lead to conflicts. These include the environmental and societal impacts of the construction and operation of H_2 supply chains, which change rural infrastructure and may create potential health and safety problems for residents (Ruggero, 2014; Schönauer and Glanz, 2022). Furthermore, ethical conflicts could arise between H_2 producers and consumers over the transport or sourcing of H_2 from third countries (Appendix C, Interview 4, 8). At the same time, stricter government sustainability measures could affect the country's economic viability. The industry could decide to leave the Netherlands and move its production facilities to other countries with less stringent environmental regulations (Rijksoverheid, 2020a; Appendix C, Interview 1). A study by PwC (2019) examined the impact of, e.g. a national CO_2 tax. It concluded that such a measure would reduce the attractiveness of the Netherlands as a location for the industrial sector. Therefore, to keep industries in the country, companies must be able to purchase carbon-free energy sources at internationally competitive prices (Rijksoverheid, 2020a). A large number of stakeholders with different drivers can thus lead to a complex decision-making process with conflicts that are a barrier to implementing H_2 supply chains *(B10)*.

3.1.3. Niche level

The niche level, i.e. the controlled and protected environments for innovations that can change the regime level of H_2 supply chains in the Netherlands (Section 2.4), are considered last. Two aspects are studied: (1) Structure and behavior and (2) research and projects.

Structure and behavior

The Dutch government supports knowledge structures that promote initiatives and stimulate market developments. Since innovations involve high investment costs, the process of development and commercialization requires time and might initially perform worse than established technologies *(B11)* (Schot & Steinmueller, 2018). The Netherlands invests, for example, in a growth fund and subsidy programs and introduces several policy instruments, such as those mentioned in Section 3.1.2. The goal is to learn from the projects and experiments, raise awareness, create a support base for new technologies and remain competitive. Knowledge structures are based on fundamental research to make processes and applications more efficient, sustainable and affordable and applied research to realize new and improved technologies and applications in collaboration with the industry (Nasiri et al., 2013). An example of the latter is the Topconsortium voor Kennis Nieuw Gas – Energy Top Sector, which focuses on innovations in industrial production and application of H_2 together with offshore wind energy development H_2 (TKI Nieuw Gas, 2022). The established knowledge structure and research behaviour in the Netherlands that aims to be at the forefront in this H_2 segment encourages the development of the niche *(F13)* (Rijksoverheid, 2020a). However, it is uncertain whether innovations meet the quality standard(s), required financial performance and time constraints. In addition, innovations might not attract enough buyers/customers *(B12)* (Schot & Steinmueller, 2018).

Research and projects

Until 2030, predominately local (research) projects have already been initiated which serve as an facilitator for H_2 supply chains *(F14)* to improve the technologies and identify the necessary legislation and regulation. These can be categorized per sector.

- Industrial sector: Porthos is a project focused on capturing CO_2 in the existing H_2 production in the Port of Rotterdam (RVO et al., 2021). Together with the H-Vision project, which focuses on the production of low-carbon H_2 using NG and refinery fuel gas, large-scale low-CO_2 H_2 production is targeted to reduce emissions by 2030 (RVO et al., 2021). This is expected to pave the way for large-scale integration of renewable H_2 (Rijksoverheid, 2020a). At the same time, Shell has taken the final investment decision to build Holland Hydrogen I, which will be Europe's largest renewable H_2 plant in 2025 (Shell, 2022).
- Transport sector: National network operators and TU Delft investigate reusing the NG network by analyzing its performance and necessary safety measures, such as new working methods and tools. North Sea Wind Power Hub is another transport project investigating the hub-and-spoke concept in the North Sea. Here, interconnectors connect offshore wind farms with neighbouring North Sea countries to facilitate sector coupling by converting electricity into H_2 (RVO et al., 2021).
- Mobility sector: Several H_2 projects have already been rolled out for using H_2 fuel cell vehicles and refuelling stations across the country. At the same time, there is research on using H_2 as a fuel in aircraft or the marine sectors.
- Built environment, there are some H_2 heating projects in Rozenburg or Stad aan 't Haringvliet planned for 2020 to 2025, followed by larger pilot projects by 2030.
- Energy sector: Initiatives at local and regional levels started to combine local generation with the production, use and storage of H_2. This can help avoiding electricity grid congestion, increasing the number of opportunities for integrating locally and regionally generated renewable energy (Rijksoverheid, 2020a; RVO et al., 2021).

3.1.4. Drivers, barriers and facilitators

Concluding the system analysis, drivers, barriers, and facilitators for H_2 supply chains in the Netherlands were identified and are summarized in Table 3.1.

Table 3.1: Drivers, barriers, and facilitators of H_2 supply chains in the Netherlands identified using the multi-level perspective framework by Geels (2002)

Level	Drivers		Barriers		Facilitators	
Socio-technical landscape			**B1**	Existing fossil fuel infrastructure	**F1**	Experience in industrial gases & chemical processes
			B2	Limited space & electricity grid capacity	**F2**	Society's climate change awareness
			B3	No specific H_2 legislation	**F3**	Clear governmental targets for an energy transition and H_2 economy
			B4	Social skepticism towards H_2	**F4**	High fossil fuel & low renewable energy prices
					F5	Energy diversification to ensure energy security
Socio-technical regime	**D1**	Reliability	**B5**	High H_2 production costs	**F6**	Experience in H_2 production
	D2	Quality	**B6**	Lack of H_2 demand	**F7**	Many production alternatives
	D3	Sustainability	**B7**	Lack of governance for H_2 infrastructure	**F8**	Projected technology cost reduction
	D4	Affordability	**B8**	Laws & regulations for H_2 in early stage	**F9**	Diverse H_2 application options
	D5	Maturity	**B9**	Only few H_2 subsidies	**F10**	Existing natural gas & H_2 infrastructure
	D6	Scalability	**B10**	Complex decision making (many stakeholders with conflicting objectives)	**F11**	Concrete proposals on missing laws and regulations (including H_2 subsidies)
	D7	Flexibility				
	D8	Accessibility			**F12**	Many cooperations between stakeholders
	D9	Acceptability				
Niche level			**B11**	High investment costs, long development & commercialization time	**F13**	Existing knowledge structure & ambition to become leader in H_2 sector
			B12	Operational, commercial & financial risks	**F14**	High level of research activity

Drivers

The literature review and stakeholder interviews revealed stakeholders' drivers for H_2 supply chains. Figure 3.5 shows the frequently mentioned drivers per stakeholder.

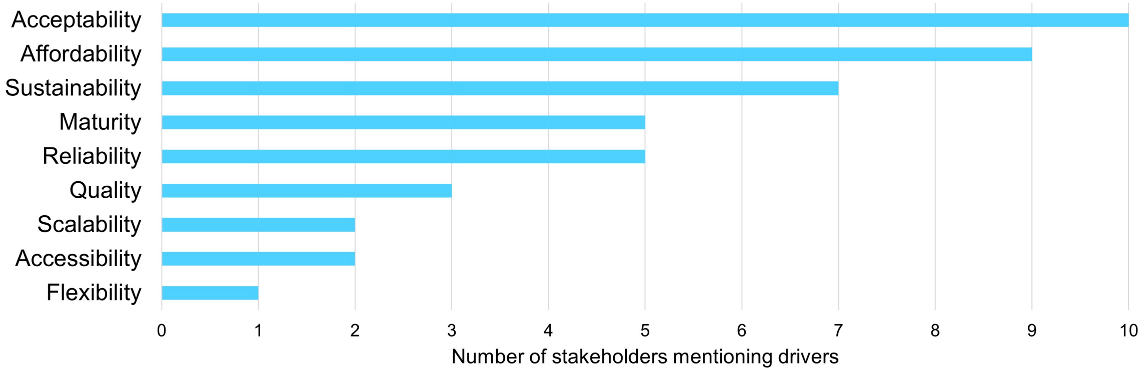


Figure 3.5: Drivers for H_2 supply chains in the Netherlands based on conducted interviews

The most frequently mentioned drivers are acceptability, affordability, and sustainability which are defined in the following:

- *Acceptability*: The implementation and use of new energy technologies is related to their impact on society and how society will react to them (Upham et al., 2015). Acceptable H_2 supply chains are pursued that have *"a favorable or positive response (attitude, intention, behaviour) [...] by members of a given social unit (country, community, organization)"* (Upham et al., 2015).
- *Affordability*: The transition to a new energy carrier involves additional costs that can jeopardize the user's competitiveness. Therefore, affordable H_2 supply chains are sought that *"[secure] some given standard of [operation] at a price [...] which does not impose [...] an unreasonable burden on [stakeholders]"* (Maclennan & Williams, 1990)
- *Sustainability*: Increasing awareness of environmental impacts and changing consumer preferences led to regulatory emission targets and raised interest in sustainable solutions (Netherlands Ministry of Economic Affairs, 2019). As a results, sustainable H_2 supply chains are targeted that *"meet the [energy] needs of the present without compromising the ability of future generations to meet their own [energy] needs or [climate of future generations]"* (United Nations, 1983).

Barriers and facilitators

In addition to drivers, barriers and facilitators for H_2 supply chains in the Netherlands were identified at the landscape, regime, and niche level.

- *At the landscape level*, H_2 supply chains in the Netherlands benefit from societal pressure to reduce fossil fuels, government goals for an energy transition toward renewables, and energy instability in Europe. Given these developments and the experience with industrial gases and chemical processes, there is growing interest in further expanding the existing H_2 supply chains despite scepticism and limited capacity and land.
- *At the regime level*, the production experience, the existing H_2 infrastructure, and its diverse production and application capabilities are increasing stakeholder interest in using H_2. As a result, numerous collaborations and projects between stakeholders have already been established, and additional government subsidy schemes have been developed to implement H_2 supply chains. However, large-scale expansion and use of H_2 are still slow due to high production costs, high system conversion costs, and the lack of concrete laws, regulations and subsidies. The uncertainty of sufficient H_2 supply, lack of business cases, and complex decision-making result in low demand on the user side and hesitant expansion on the production side.
- *At the niche level*, there is substantial research on H_2 technologies, e.g., to reduce costs and increase efficiency to commercialize them on a large scale. The Netherlands' existing knowledge structure supports these efforts, intending to become a leader in the H_2 segment. However, innovations involve high investment costs, long development times, and the risk of disinvestment, which slows down the implementation of H_2 supply chains.

3.2. Supply chain configuration

3.2.1. Components

H_2 supply chains consist of various components to deliver H_2 or a H_2 energy carrier to end users. IEA (2019) and HyChain (2022) distinguish the following components: Production, conversion, transport, reconversion, storage, and utilization. The approach was adopted because it differentiates H_2 storage by the conversion to a chemical energy carrier, physical storage mediums of H_2, and reconversion alternatives. It allows for a more detailed comparison of supply chain components. The conceptual H_2 supply chains are shown in Figure 3.6. It illustrates the general flow and interconnection of the components and the various alternatives, which are described in more detail in the following sections.

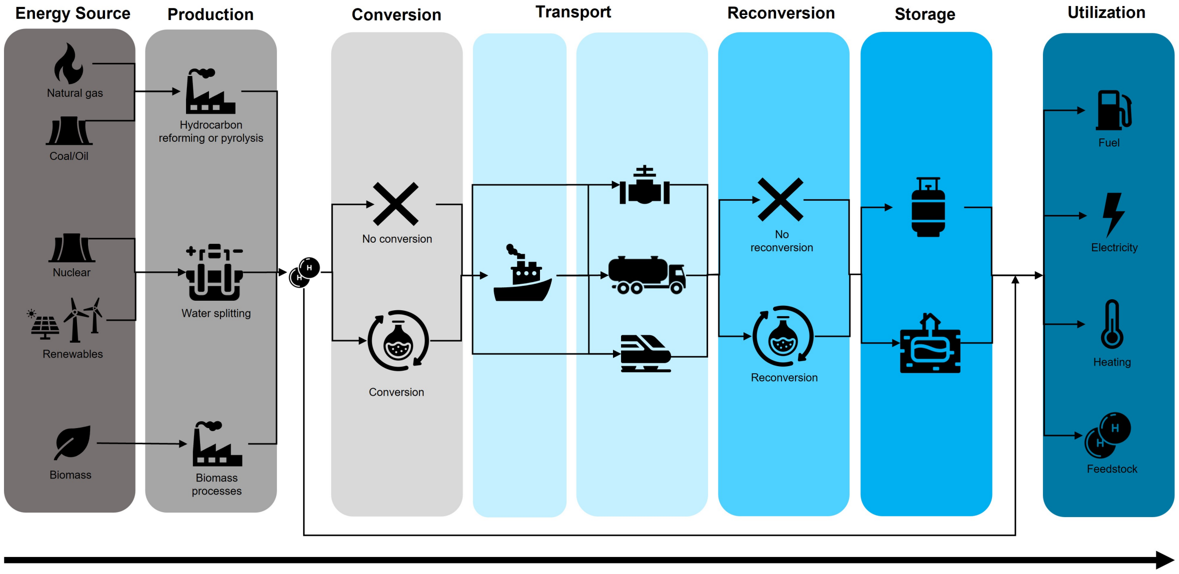
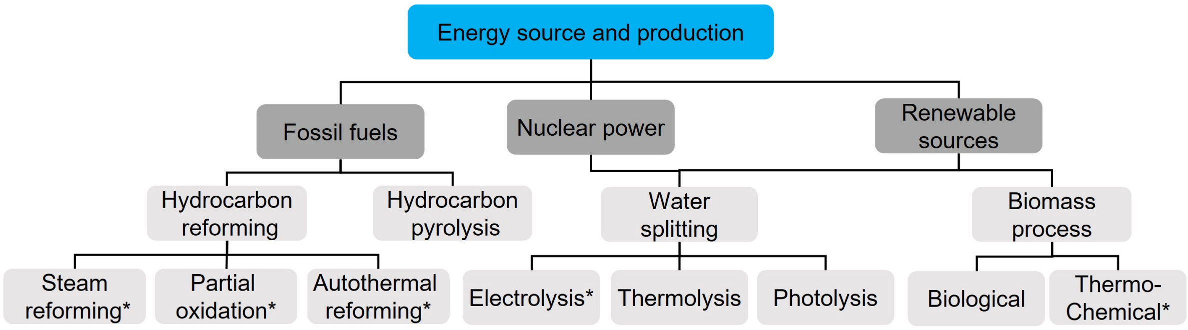


Figure 3.6: Conceptual H_2 supply chains based on IEA (2019) and HyChain (2022).

Energy source and production

H_2 in pure form is not a natural source. However, it is found in many molecules, such as water or NG, which is why it can be produced by various chemical reactions (Agyekum et al., 2022). There are numerous alternative H_2 production methods, which can be distinguished according to the energy source used. Figure 3.7 shows an extract of the alternatives frequently mentioned in literature. The alternatives marked with an asterisk are described in the following. They are available for commercial production and consistent with the Dutch H_2 strategy and climate targets mentioned in Section 3.1. Table 3.2 summarizes the characteristics, advantages and disadvantages of each production alternative.



* Production alternative aligned with selection criteria and described further

Figure 3.7: Overview H_2 production alternatives.

Hydrocarbon reforming is a chemical process in which gaseous hydrocarbons are converted to H_2 using steam (steam reforming), Oxygen (O_2) (partial oxidation), or a combination of both (autothermal reaction) (Ji & Wang, 2021). SMR is currently the most economical and widely used method for large-scale production of H_2 (Robles et al., 2018). In this process, NG is mixed with steam under high pressure and temperature to form syngas (a mixture of H_2 and Carbon monoxide (CO) in various ratios). The CO obtained reacts with steam to produce H_2 and CO_2. NG is used due to its high H_2 to carbon ratio within the group of hydrocarbons (Faye et al., 2022). Another reforming method is Partial oxidation (POX) with hydrocarbons such as NG or fuel oil. In this process, hydrocarbons are mixed with O_2 and then partially combusted in a reformer to produce syngas from which H_2 can be removed. The process is faster and requires less external heat than SMR. However, the required O_2 leads to higher investment costs, as an additional air separation unit and a desulfurization stage are required (Abdin et al., 2020). Autothermal reforming (ATR) is a combination of SMR and POX. It uses O_2 and CO_2 or steam in a reaction with NG to form syngas, which takes place in a single chamber. ATR has the lowest process temperature requirement, does not require external heat, and can have a high H_2 yield as the syngas NG content can be tailored by adjusting the reformer outlet temperature. The limited experience for large-scale production and the high costs for the required O_2 plant are drawbacks of this production method Faye et al., 2022; Agyekum et al., 2022). Hydrocarbon reforming emits significant amounts of up to 9.3 $kgCO_2eq/kgH_2$ (Hydrogen Council, 2021). It can be combined with CCS to capture up to 90% of the CO_2. However, this requires additional CO_2 infrastructure, which increases the cost of the alternatives (Abdin et al., 2020).

Water splitting is a process in which water is split into H_2 and O_2. Electrolysis applies a direct electric current to do so (Ji & Wang, 2021). Alkaline and Proton exchange membrane (PEM) electrolysis are the two most mature electrolysis processes used for commercial purposes to split water (Agyekum et al., 2022). In alkaline electrolysis, two electrodes are immersed in a highly concentrated alkaline solution. In contrast, PEM electrolysis involves the same electrochemical reaction with an acidic polymer membrane as the solid electrolyte (Ji & Wang, 2021). PEM electrolysis enables a high current density and, thus, a compact system design. At the same time, PEM electrolysis can better compensate for fluctuating renewables because it can start within seconds and adjust its output more quickly. However, PEM electrolyzers require expensive noble metals as electrodes, such as iridium or platinum, while alkaline electrolyzers use less expensive nickel- or iron-based electrodes. In addition, the lifetime of PEM electrolyzers is shorter due to the decomposition of the electrolyte during operation, so alkaline electrolyzers have an economic advantage (Faye et al., 2022).

Thermo-chemical biomass processes such as gasification are processes in which biomass (liquid or solid feedstock such as wood, grass, plant or animal waste) is oxidized using air, steam, O_2, or a combination thereof to form syngas from which H_2 can be removed (Ji & Wang, 2021). Compared to conventional coal gasification, this process is more sustainable because biomass can be produced from renewable sources such as plants and waste that can be continuously replenished. Furthermore, the plants that are the source of biomass for energy capture almost the same amount of CO2 through photosynthesis while growing as is released when biomass is burned, which can make biomass a carbon-neutral energy source (EIA, 2022). However, the process efficiency is low at 50%, and the complex composition of the different biomasses leads to H_2 impurities (Faye et al., 2022). In particular, the formation of tars can lead to plugging, equipment wear, and catalyst failures, limiting large-scale commercialization and making production more expensive than other renewable, low-carbon alternatives. Finally, biomass availability is limited, and its use is ethically critical due to its effects on the environment (land use), food security, and prices (Agyekum et al., 2022).

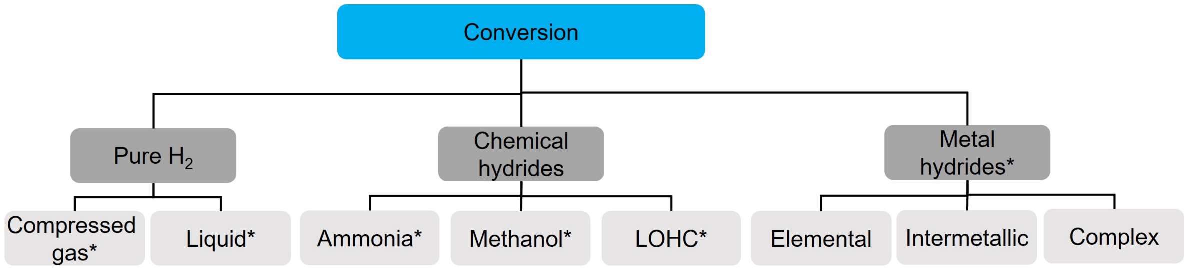
Table 3.2: Characteristics, advantages and disadvantages of H_2 production alternatives.

	Hydrocarbon reforming: Steam methane [1, 2]	**Hydrocarbon Reforming: Partial oxidation** [1,2]	**Hydrocarbon Reforming: Autothermal** [1, 2]	**Water splitting: Alkaline electrolysis** [1, 2]	**Water splitting: PEM electrolysis** [1, 2]	**Thermal-chemical biomass process: Gasification** [1, 2]
Main feedstock	Natural gas & water	Hydrocarbons & O_2	Hydrocarbons & water / O_2	Electricity & water	Electricity & water	Various biomass & water / O_2
Critical material	Ni or Ni-alloys or noble metals	-	-	NaOH/KOH & Ni or Ni-alloys	Polymer(s) & noble metals	-
Efficiency [%]	70-85	55-75	60-75	62-82	67-84	50
Temperature [°C]	700-1100	950-1500	700-1000	60-90	50-90	700-1200
Current density [A/cm^2]	-	-	-	0.2-0.5	1-2	-
H_2 production costs	Low-Medium	Medium	Low	High	High	Low-Medium
Lifetime [years]	20-30 [3]	-	-	20-30	10-20	-
Maturity level	Commercial	Commercial	Commercial	Commercial	Commercial	Commercial
Advantages	• High H_2 yield • High maturity • Low costs	• Fast start-up time • No external heat	• Fast start-up time • No external heat • High H_2 yield	• Long lifetime • High maturity • Low pollution	• Compact design • High load flexibility • Low pollution	• Low costs • Diverse, abundant feedstocks
Disadvantages	• High pollution • High external heat demand	• Low H_2 yield • Higher costs • High pollution	• Low maturity for large scale • Low H_2 purity control	• Low current density • Limited flexibility	• Short lifetime • Costly materials • Low maturity for large scale	• High H_2 impurities • Ethical conflicts [4] • Low maturity for large scale

Sources: [1] Faye et al. (2022); [2] Ji & Wang (2021); [3] Reuß et al. (2017); [4] Agyekum et al. (2022)
Notes: PEM = Proton exchange membrane

Conversion and reconversion

H_2 has the highest gravimetric but one of the lowest volumetric densities, i.e. it requires space but is very light. Therefore, it must be compressed, liquefied, or converted to another energy carrier to improve its transportability and storage size (Abdin et al., 2020). Numerous alternatives are found in literature to process or convert H_2, which can be divided depending on their chemical energy carrier (Andersson & Grönkvist, 2019). Figure 3.8 shows the commonly mentioned carriers in literature. Table 3.3 summarizes the characteristics, advantages and disadvantages per energy carrier.



* Conversion alternative aligned with selection criteria and described further

Figure 3.8: Overview of H_2 conversion and reconversion alternatives.

Compressed hydrogen gas is currently the most commonly used form of H_2 with high density values. The maximum pressure at which H_2 can be stored varies from 100-700 bar at atmospheric temperatures (Robles et al., 2018). Compressed H_2 can be stored above-ground, and underground and transported in trucks, pipelines or trains. Furthermore, it can directly be used without reconversion (Andersson & Grönkvist, 2019). H_2 gas compressors are a well-established technology at an industrial scale. It uses commercially available and relatively inexpensive tanks or existing infrastructure of NG pipelines (Berger, 2021). However, compressed H_2 has a low volumetric energy density compared to other energy carriers. It requires high volumes which makes compressed H_2 unsuitable for shipping. Other drawbacks are safety issues due to the rapid loss of H_2 in case of leakage as low concentrations of H_2 in air are explosive already (Abdin et al., 2020).

Liquefied hydrogen has a higher volumetric density than compressed H_2. However, it must be cooled to temperatures below -253°C to liquefy. After liquefaction, H_2 is stored in insulated tanks to limit boil-off losses due to evaporation. LH_2 can be transported via trucks or ships. At the destination, it is vaporized into its gaseous form before use (Berger, 2021). Liquefaction is a well-established technology at a small scale, does not require energy-intensive reconversion and provides high purity H_2. However, the liquefaction process is energy-intensive, and storage and transportation are more cost-intensive than other carriers due to the required energy for cooling and boil-off losses. In addition, large-scale transportation via ship is still in the demonstration phase, leading to substantial investment costs (Andersson & Grönkvist, 2019; Berger, 2021).

Ammonia is an inorganic chemical carrier mainly used as a chemical feedstock to produce fertilizers today. It is produced by reacting H_2 and nitrogen derived from the air through an air separation unit. It can be liquefied at temperatures below -33°C and has a volumetric energy density almost 50% higher than LH_2 (Berger, 2021). Liquid NH_3 can be stored and transported in refrigerated tanks via trucks, rail, ships, and pipelines. Once it reaches its destination, NH_3 can be used directly as a feedstock or energy carrier for fuel or heating. However, it can also be reconverted to H_2 through cracking. The conversion from H_2 to NH_3 is a well-established process which is why the infrastructure for storing, transporting and handling NH_3 is already commercially mature (Andersson & Grönkvist, 2019). However, NH_3 is a toxic fluid and precursor to air pollution. It can negatively affect human health, soil and water quality if released. The conversion and reconversion processes are very energy intensive leading to high costs. In addition, the NH_3 cracking process is at a very early stage of technological development for large-scale applications (Berger, 2021).

Methanol is an organic chemical carrier mainly used as an intermediate chemical for producing chemicals such as propylene or ethylene (Andersson & Grönkvist, 2019). It can be produced differently from syngas and is liquid under ambient conditions. It has a high volumetric density and can be stored and transported in tanks at atmospheric temperatures via trucks, rail, ships, and pipelines (Abdin et al., 2020). Once it reaches its destination, methanol can be used directly as a feedstock, heating or fuel. However, it can also be reconverted to H_2 through hydrocarbon reforming processes. The conversion from H_2 to methanol is a well-established process which is why the infrastructure for storing, transporting and handling methanol is already commercially mature and partly available. The ambient conditions make storage and transportation in conventional tankers easy. Furthermore, since the required CO_2 content of syngas feed to the reactor should be high, the methanol process is perceived as a CO_2 utilization process alternative to reduce or delay CO_2 emissions (Abdin et al., 2020). However, if released, methanol is a toxic fluid that can negatively affect human health and soil and water quality. Especially the reconversion process is energy intensive leading to high operational costs (Berger, 2021).

Liquid organic hydrogen carriers are chemical compounds that can absorb and release H_2 through a chemical reaction (Brändle et al., 2021). The conversion (hydrogenation) process involves chemically binding H_2 to the liquid compound so that it can be transported at atmospheric pressure in tanks via ships, trucks or rail. To release H_2, LOHC is reconverted at the destination via an endothermic dehydrogenation process. The dehydrogenated LOHC can then be transported back to the H_2 source for reuse. Due to their oil-like properties, LOHCs can use the existing infrastructure for storage and transport. In addition, LOHCs do not incur H_2 losses, allowing long storage duration and storage of large volumes. However, the reconversion requires very high temperatures and thus high operational energy costs. Furthermore, LOHCs are often expensive and add to the overall H_2 costs when reused and shipped back. The long-term viability of LOHC is also yet to be proven as the technology development is still at a demonstration level (Berger, 2021; Andersson & Grönkvist, 2019).

Metal hydrides are metals that can absorb H_2 atoms using chemical bonding into their inner crystal structure or dissociate H_2 molecules on their surface to increase the volumetric energy density further (Abdin et al., 2020). As a solid, they can be stored in barrels and transported at atmospheric pressure via trucks, rail, or ships. At the destination, the H_2 is released in high purity via an hydrolysis process (Berger, 2021). Metal hydrides have low reactivity and large H_2 storage densities, making them valuable for long-term storage. It is considered safe due to the low pressure and relatively slow kinetic rates of H_2 release. However, the comparatively heavy weight and high costs are the most significant drawbacks. Reconversion of H_2 requires, for example, high temperatures and has thus process cost (Abdin et al., 2020).

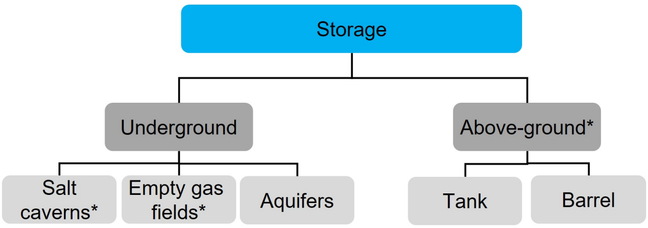
Table 3.3: Characteristics, advantages, and disadvantages of H_2 conversion and reconversion alternatives

	Compressed hydrogen [1,2,3,4]	**Liquified hydrogen** [2,3]	**Ammonia** [2,3]	**Methanol** [1,2,3]	**Liquid Organic** [2,3] **Hydrogen Carriers***	**Metal** [1,2,3] **Hydrides****
Volumetric density [kgH_2/m^3]	7.8	70	123	99	47	68
Gravimetric density [wt% H_2]	5-7.5	10	17.7	12.5	6.1	9.1
Pressure [bar]	100-700	-	250	50	150	50
Temperature [°C]	-	-253	400	250	30	350
Energy conv. [kWh/kgH_2]	1-1.6	6	2-4	1.3-1.8	0.7	0.8
Energy reconv. [kWh/kgH_2]	-	0.6 [5]	4.2	6.7	11.2	6.4
Maturity conv.	Commercial	Commercial	Commercial	Commercial	Commercial	Commercial
Maturity reconv.	-	Commercial	Commercial	Commercial	Demonstration	Commercial
Advantages	• High maturity • Low energy demand • Not toxic • Multiple storage and transport options	• High energy density • Not toxic • High purity	• High storage capacity • High maturity (conv., transport, storage)	• High storage capacity • High maturity (conv., transport, storage) • Additional CO_2 reduction	• Existing infrastructure • Low toxicity, non-explosive • Long storage duration and volumes	• Large storage density • High safety (low reactivity) • High H_2 purity
Disadvantages	• Highly explosive • Low volumetric density	• High energy demand (conv.) • Low maturity for large scale conv. • Complex storage and transport • High costs	• High energy demand • Toxic • High environ. impact • Low maturity for large scale reconv.	• High energy demand • Toxic • High environ. impact • Low maturity for large scale reconv.	• High energy demand (reconv.) • Low maturity for large scale reconv. • High environ. impact • Costly materials	• High energy demand (reconv.) • Low maturity for large scale reconv. • Toxic

Sources: [1] Abdin et al. (2020); [2] Andersson & Grönkvist (2019); [3] Berger (2021); [4] Robles et al. (2018)
Notes: Conv. = conversion; reconv. = reconversion; environ. = environment
* = Depends on liquid organic hydrogen carrier used, here based on methylcyclohexane and toluene
** = Depends on metal hydride used, here based on lithium borohydride and magnesium hydride

Storage

To store the previously compressed, liquefied H_2 or converted energy carrier, numerous physical storage alternatives are discussed in literature, which can be divided into two categories: Above- and underground storage. Figure 3.9 shows an extract of the alternatives commonly mentioned in literature. The alternatives that are available for large-scale storage in the Netherlands are described. Table 3.4 summarizes the mentioned characteristics, advantages, and disadvantages per storage method.



* Storage alternative aligned with selection criteria and described further

Figure 3.9: Overview of H_2 storage alternatives.

Underground storage are large-volume storage facilities for gases at depths of more than hundreds of meters below ground. Therefore, on the one hand, they are space-saving but can only be constructed at sites with favorable geological conditions. They offer protection against physical impacts and weathering and have a long service life. However, inspection is complicated, and construction involves significant intervention, so they are subject to public acceptance, which can lead to delays (Muhammed et al., 2022). As salt caverns and depleted gas reservoirs frequently occur in the Dutch subsurface (Rijksoverheid, 2020a), they are discussed in more detail below:

- Salt caverns are artificially created chambers in salt domes or stratified salt deposits. A typical salt cavern can have a volume of 0.001 billion m^3, allowing for ample storage volumes compared to above-ground storage. Due to the mechanical stability of salt domes, pressure changes allow for rapid injection and extraction processes at a rate of 5 million m^3/day. Therefore, they are suitable for medium- and short-term storage of H_2. Moreover, since salt layers surround the H_2, there is a low risk of H_2 leakage into the atmosphere (Visser, 2020). The high salt content also makes caverns less likely to contaminate H_2 by biological activities of microorganisms or other chemical reactions. However, salt caverns require construction, such as infrastructure requirements for large pipelines for transportation (Muhammed et al., 2022; Olabi et al., 2021). The cost of building a new salt cavern, including the necessary infrastructure for cyclic storage, is estimated at €334/MWh, and storage costs for cyclic storage at 17 €/MWh per year (Visser, 2020).

- Depleted gas reservoirs are porous and permeable hydrocarbon reservoirs located kilometres below the earth's surface and have a storage volume of 1-10 billion m^3. They were a conventional storage medium for NG, so pipeline infrastructure is already in place. Building a new infrastructure would cost 280 - 424 €/MWh, depending on the reservoir size. Reusing existing NG infrastructure could be a financial advantage compared to salt caverns. However, the costs of cyclic storage in depleted gas reservoirs are higher at 51 - 76 €/MWh (Visser, 2020). Furthermore, the production rate in depleted reservoirs is only 1 million m^3/day. The geological formation, the wells and other materials used for oil and gas production are not necessarily suitable for H_2 storage, which could result in leakage. The reservoirs may contain sulfurous gas, minerals, or other residues, which can cause chemical reactions with H_2 that produce highly toxic gases and compromise the purity of the injected H_2 (Muhammed et al., 2022; Olabi et al., 2021)

Above-ground storage in tanks (gases and liquids) and barrels (solids) is a commercially mature method for H_2 and all other H_2 carriers. Typically, the design of the tank or barrel is specific to the energy carrier but must be compact, lightweight, and safe (Robles et al., 2018). The chosen design and material help prevent contamination by environmental factors and keep the quality of the stored product high (Abdin et al., 2020). Compared to large-scale underground H_2 storage, the capital and operating costs are significantly higher and depend on the energy carrier used (Olabi et al., 2021). For example, pressure tanks incur high costs due to their limited energy density, and cryogenic tanks require expensive materials suitable for low temperatures. In addition, they offer limited storage time due to the evaporation losses required to maintain an acceptable pressure level. An intermediate solution here is cryo-compressed storage, which combines the abovementioned alternatives and allows for a longer storage time (IEA, 2015). Nevertheless, the smaller volume and, thus, the larger space requirement on the already densely populated surface are a disadvantage of above-ground storage compared to underground storage (Reuß et al., 2017).

Table 3.4: Characteristics, advantages, and disadvantages of H_2 storage alternatives

	Underground storage: Salt caverns [2,3,5]	**Underground storage: Depleted gas reservoirs** [2,3,5]	**Above-ground storage: Tank/Barrel** [1,3.4]
Usability purpose	Frequent	Seasonal	Frequent
Capacity [billion m^3]	~0.001	~1-10	<0.001
Discharge rate [million m^3/day]	5	1	Various*
Investment costs [€/MWh]	334	280-424	Various*
Operational costs [€/MWh/year]	17	51-76	
Maturity	Demonstration	Demonstration	Commercial
Advantages	• Low leakage rates • High discharge rate • Low contamination risk • Low operational costs	• Large volumes • Low investment costs	• High maturity • Low contamination • Applicable for gaseous, liquid and solid energy carriers
Disadvantages	• Need to dispose massive amounts of salt brine • Only H_2-rich gaseous energy carriers	• Low discharge rate • High contamination • Only H_2-rich gaseous energy carriers	• Low spatial storage capacity • High costs • Risk of leakage*

Sources: [1] Abdin et al. (2020); [2] Muhammed et al. (2022); [3] Olabi et al. (2021); [4] Robles et al. (2018); [5] Visser (2020)
* = Depends on energy carrier stored

Transport

Different transport alternatives can be found in literature for compressed and liquefied H_2 and converted H_2 energy carriers. The alternatives are described below, and Table 3.5 summarizes the characteristics, advantages, and disadvantages per transport method.

Trucks are a commercially used medium that can flexibly transport all of the previously mentioned energy carriers and pure H_2 in gaseous, liquid or solid form to different endpoints and routes. Tube trailers are suitable for small H_2 quantities of up to 1150 kgH_2 in gaseous form at high capital costs above 1 million €. For larger quantities, other alternatives such as LH_2 tankers with a capacity of up to 4500 kgH_2 per trailer or LOHC with a capacity of up to 1680 kgH_2 can be used (Reuß et al., 2017). Standard steel tanks already used for diesel and gasoline delivery can be used, whereas, for LH_2, special cryogenic tank designs are required which have high capital costs due to the specific material and required to operate at low and high temperatures are required. Trucks, however, are limited by their maximum allowable volume and weight and are only used for short distances of up to a few hundred kilometres (Robles et al., 2018; Olabi et al., 2021).

Rail transport is similar to trucks as it can transport all the energy carriers mentioned and pure H_2 theoretically using similar tanks. The difference is, however, its ability to transport larger quantities over long distances. Compared to pipelines, the quantity is still limited, and transportation can be restricted due to possible disruptions and tightly timed rail traffic. The form of transportation is also not mature enough for extensive scale application, as the infrastructure at rail stations for further distribution to end users has not yet been developed (Robles et al., 2018). The development would require high initial investment costs and complex permitting processes leading to long lead times (Berger, 2021).

Pipelines are a commercially proven medium for transporting gaseous H_2 or liquid NH_3. For transport, H_2 is mechanically compressed to the pipeline operating pressure and then compressed along the pipeline. In comparison, pumps are used to transport NH_3. Existing NG pipelines can be repurposed for H_2 transport, or H_2 can be injected into the existing gas network at up to 20% (Abdin et al., 2020). H_2 and NH_3 pipelines have low operating costs, long lifetimes and carry high volumes over several thousand kilometres. Reusing existing pipelines has a lower environmental impact and is also beneficial regarding public acceptance and cost. The disadvantages are similar to rail transport: High capital costs, long lead times of several years, and complex permitting processes. In addition, large volumes of H_2 are required to achieve acceptable utilization rates. Because of fixed routing, many consumers not located at the pipeline cannot be served without additional investment in distribution infrastructure (Berger, 2021). Finally, there are still concerns about reusing old NG pipelines due to material compatibility, leading to embrittlement and the need for retrofits such as coatings (Robles et al., 2018).

Shipping can transport H_2 or H_2 carriers over long distances where pipeline transport is not feasible. It offers high transport capacity and multiple import options from countries worldwide (Abdin et al., 2020). LH_2 is a potential energy carrier due to its high gravimetric density. There are currently no ships that could be used commercially on a large scale. However, liquefied NG transport ships that have on-board re-liquefaction systems show a possibility for the future transport of LH_2 by ship, even if this involves additional capital costs (Abdin et al., 2020). Transportation of H_2 carriers such as NH_3, or LOHC is already more mature, as they benefit from existing infrastructure and ships for large-scale transportation. They also have a high volumetric density, which means that ships of the same size theoretically need less cargo than LH_2 to transport the same amount of energy (Berger, 2021). Lastly, transporting H_2 in ships that use diesel for a several-week trip causes pollution and environmental damage, which is contrary to the idea of importing renewable H_2 from overseas (Abdin et al., 2020).

Table 3.5: Characteristics, advantages, and disadvantages of H_2 transport alternatives

	Truck [3,4,5]	**Rail** [2, 5]	**Pipeline** [1,2,5]	**Shipping** [1,2]
Capacity	Low	Medium	High	High
Energy carrier	Various	Various	H_2 (g) and NH_3 (l)	Various liquids and solids
Distance	Short	Medium	Long	Long
Energy loss	Various*	Various*	Low	Low*
Investment costs	Medium	High	High	High
Operational costs	Medium	Medium	Low	Medium
Maturity	Commercial	Commercial	Commercial	Commercial
Advantages	• Flexible and last mile delivery • All energy carriers • High maturity	• High quantities • Long distances • All energy carriers	• High quantities • Long distances • Low operational costs • High maturity	• High quantities • Long distances • Flexible infrastructure
Disadvantages	• Small quantities • Short distances	• High capital costs • Low maturity for large scale • Complex construction • No last mile delivery	• High investment costs • Limited energy carriers • Complex construction • No last mile delivery	• High costs • Low maturity for large scale* • No last mile delivery • High pollution

Sources: [1] Abdin et al. (2020); [2] Berger (2021); [3] Olabi etal. (2021); [4] Reuß et al. (2017); [5] Robles et al. (2018)
Notes: g = gaseous; l = liquid
* = Depends on the energy carrier used

Utilization

H_2 can be used in many different applications and sectors, as mentioned in Section 3.1.1. Two utilization categories can be distinguished: H_2 as a feedstock or energy carrier. Detz et al. (2019) and Rijksoverheid (2020a) differentiate between the following applications:

- *Feedstock*: The (petro)chemical industry requires H_2 as a raw material for the production of various products such as fertilizers, fossil-fuel refining, iron and steel, chemicals and plastics.
- *High-temperature heating*: Industrial processes that require high-temperature heating cannot be electrified. H_2 can be used as an energy carrier in pure form or as an admixture to the NG grid to provide high-temperature heat.
- *Low-temperature heating*: In the built environment, H_2 can be used in combination with electric and gas systems or, in the longer term, in combination with a boiler or fuel cell to support electrification and emissions reduction.
- *Fuel*: Various modes of transportation such as heavy-duty vehicles, shipping, or (large) aircraft are technically challenging to electrify. H_2 can directly serve as fuel or feedstock for producing synthetic fuels.
- *Electricity (storage and generation)*: H_2 can be used to store renewable electricity on a large scale for the long term and then convert it back into electricity, for example, with fuel cells or gas turbines. This way, daily and seasonal fluctuations in electricity generation from renewable energy sources can be balanced.

Due to its wide range of applications, H_2 can link multiple energy sectors and transport networks to each other, as seen in Figure 3.10 to increase the reliability and flexibility of future low-carbon energy systems. Coupling systems has the advantage that one system can balance weak elements in another. This can make the energy system more reliable and affordable as H_2 can store electricity from renewable energy sources and transport it at a lower cost than electricity (IEA, 2015).

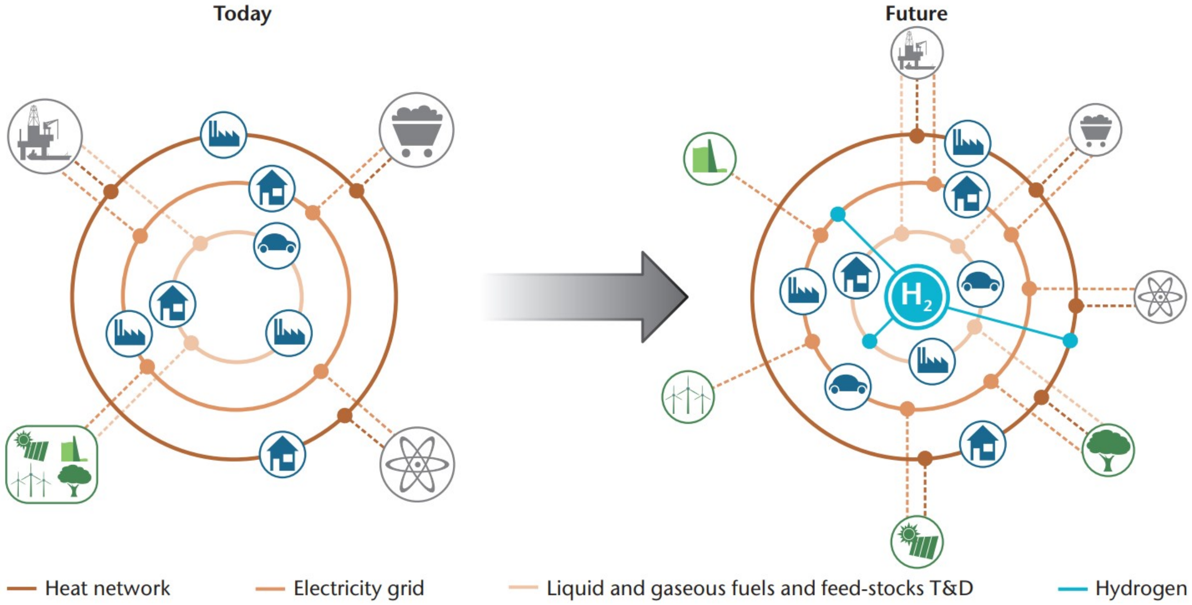


Figure 3.10: Conceptual energy system today and in the future. Figure taken from IEA, 2015. H_2 can be an important link between several energy sectors and transport networks due to its wide range of applications.

3.2.2. Hydrogen supply chain portfolios

Section 3.2.1 described different alternatives for each H_2 supply chain component. These can be combined to form supply chains, resulting in a large number of possible supply chains. Figure 3.11 shows the possible domestic and Figure 3.12 the global supply chains. The alternatives selected for each component and the resulting supply chains considered further are described and justified below.

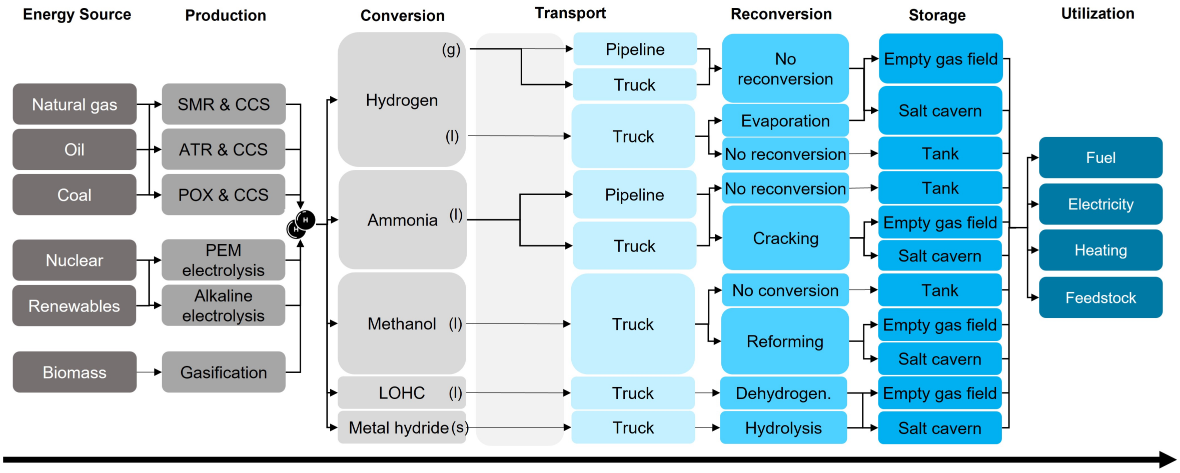


Figure 3.11: Overview of domestic H_2 supply chain alternatives.

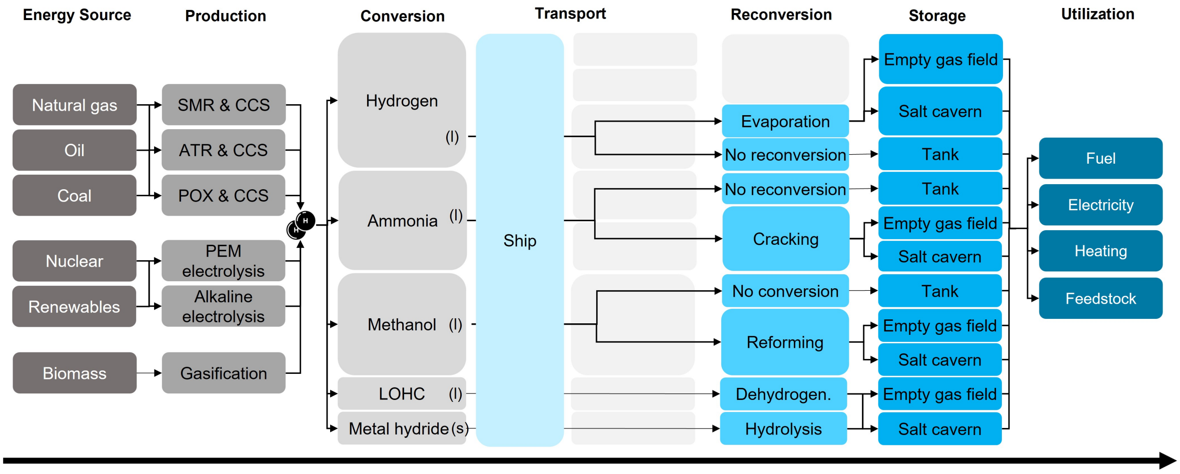


Figure 3.12: Overview of global H_2 supply chain alternatives.

Two alternatives were chosen for production. First, SMR, as this is the most commonly used method for large-scale H_2 production in the Netherlands (Detz et al., 2019). The process is therefore already established and can reliably produce large quantities of H_2 in the future. The combination with CCS makes it a low-carbon method, ensuring consistency with the Dutch climate targets and is already mentioned as a transition method in the strategy (Rijksoverheid, 2020a). The second production method is water electrolysis with renewable energy, also mentioned by the Dutch government in the H_2 strategy and supported by industry and society due to its emission reduction potential. PEM electrolysis was selected because it is more suitable for intermittent electricity input than alkaline electrolysis. For the domestic supply chain, offshore wind was chosen as the primary energy source because it is widely available in the Netherlands and will contribute to 75% of the electricity demand in 2030 (RVO, 2022b). All renewable energy sources are considered for the global supply chains since different energy sources are available depending on the selected production country. Biomass gasification is not considered further due to the high ethical conflicts associated with biomass use and cultivation and the scaling problems that still exist. Finally, this study does not consider nuclear energy due to limited development, acceptance, and available capacity in the Netherlands (CBS, 2021).

For conversion, three different processes are considered. Compressed H_2 is selected for domestic supply chains because it is the most commonly used and mature process that is easier to integrate into the existing infrastructure on a large scale. NH_3 was selected for global supply chains because it has the highest volumetric density of the energy carriers described. Also, there is a mature transportation, conversion, and storage infrastructure in the Netherlands and worldwide. It can be used as a H_2 energy carrier but also directly in various applications. Besides NH_3, LH_2 was chosen for comparison due to its high purity, efficiency and low environmental impact. Furthermore, it is subject of numerous discussions and research projects (Appendix C), but it is not yet commercially available as it requires complex storage and transport alternatives.

Two transport alternatives are considered. First, pipelines have been chosen as the domestic transport method for gaseous H_2. It is the most economical method for transporting H_2 over long distances and at large volumes, considering the low operating costs and the already extensive NG network in the Netherlands. Trucks and trains can, in principle, be used, especially for last-mile delivery. However, due to their limited volume and the risk of delivery bottlenecks due to time delays or accidents, they are neglected as the primary means of transport in this thesis. Second, ships are considered for global transport as they allow the transport of large volumes over long distances from several countries worldwide. Infrastructure and standards for some energy carriers already exist in the port of Rotterdam, making it a feasible option that can be implemented in a timely manner.

For storage, underground reservoirs were suitable for large-scale H_2 storage because they have lower costs and land requirements than above-ground reservoirs. Salt caverns were selected because they offer the highest cycle rates and have low losses due to chemical reactions and leakage, making them particularly suitable for short- and medium-term storage. In addition, they are more mature than depleted gas reservoirs and have lower safety and contamination risks. In addition, above-ground storage is considered for storing H_2 and energy carriers in non-gaseous form, despite higher cost and space requirements, because there are no other alternatives.

Figure 3.13 shows the two resulting domestic supply chains (D1 and D2). For global supply chains, four supply chains (G1 to G4) were defined that deliver H_2 as an end product and one supply chain (G5) that delivers NH_3, as seen in Figure 3.14. As G5 does not deliver H_2, it cannot be directly compared to G1-G4 when H_2 is needed as a feedstock. The comparison is nonetheless considered relevant as it provides insights into the differences between when H_2 is used for purposes other than a direct feedstock.

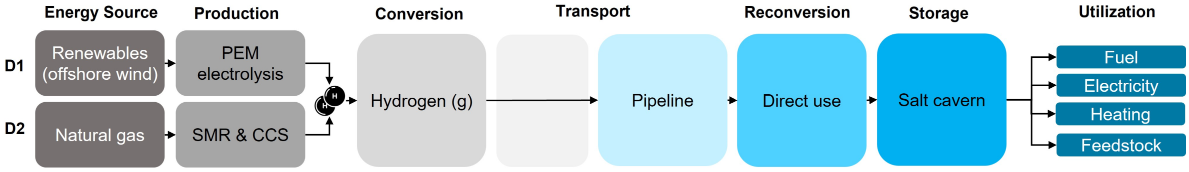


Figure 3.13: Selected domestic H_2 supply chains.

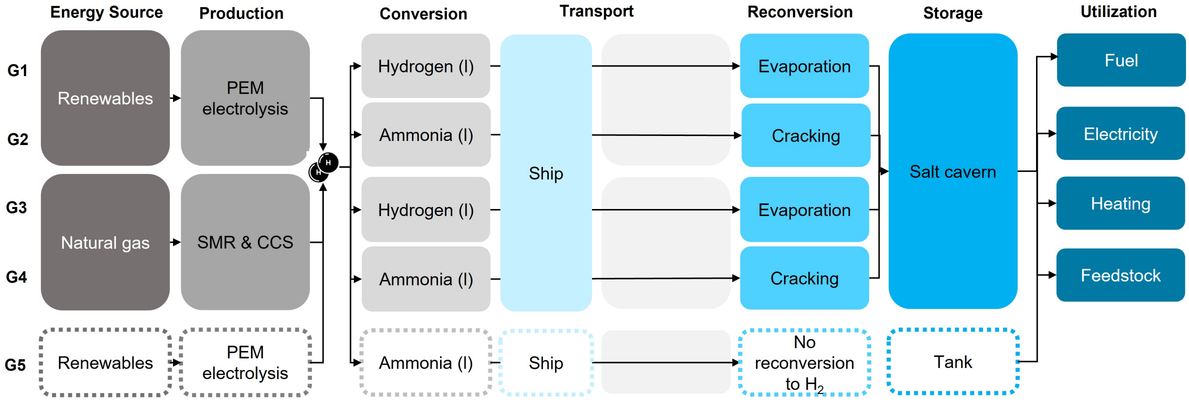


Figure 3.14: Selected global H_2 supply chains.

Eight portfolios (P1-P8) can be derived by combining each domestic supply chain with a global supply chain, as seen in Figure 3.15. Supply chains in green indicate the use of renewable electricity for production and conversion. In contrast, supply chains in blue indicate the use of NG and grid electricity.

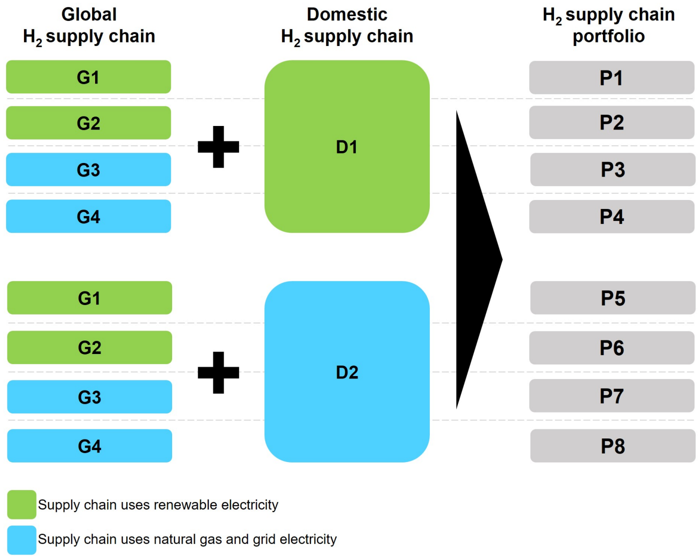


Figure 3.15: Potential H_2 supply chain portfolios in the Netherlands.

Finally, for exporting countries, the United States were selected as an example country for H_2 supply chains from NG as it is not only the largest NG producer (OEC, n.d.) but also the second-largest H_2 producer worldwide after China (IEA, 2022a). For supply chains using renewable electricity, the United Arab Emirates were selected as an example country as they are have the potential for large scale production of low-cost renewable solar electricity (Rijksoverheid, 2020a), have signed an memorandum of understanding with the Netherlands to establish export-import corridors for H_2 (Rijksoverheid, 2022a), are experienced in exporting liquid energy carriers such as LNG and have already started to scale up their renewable H_2 production capacities (IEA, 2022a).

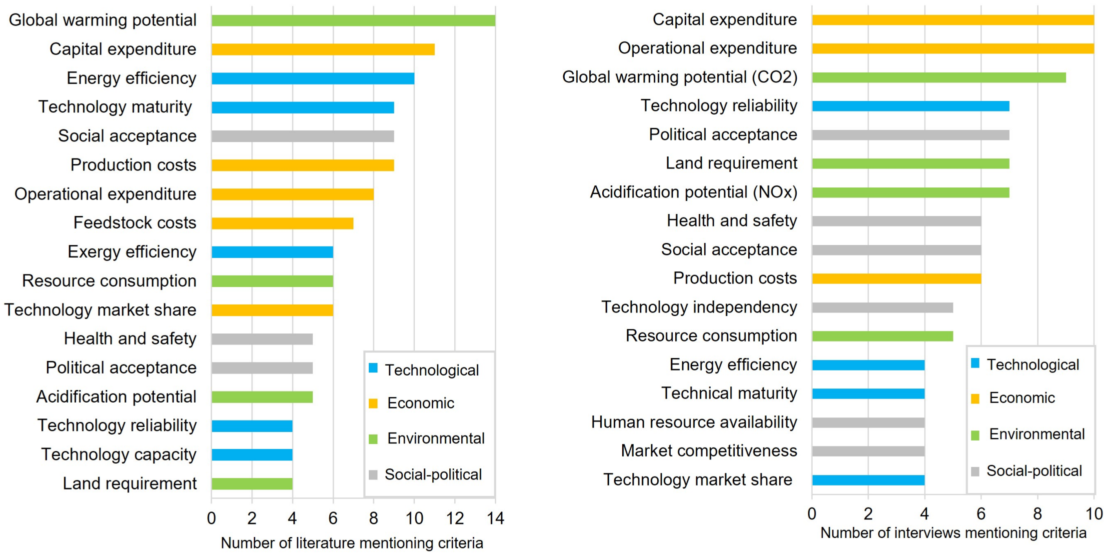
4

Performance analysis

4.1. Performance criteria

Criteria identification

To identify suitable criteria for the performance analysis of H_2 supply chains in the Netherlands, literature was reviewed (Section 2.2), and interviews with Dutch stakeholders were conducted (Section 2.3). An overview of the criteria frequently analyzed in (a) literature and (b) mentioned in interviews can be seen in Figure 4.1. The criteria can be divided into four categories: technological, economic, environmental, and socio-political.



(a) Literature

(b) Interviews

Figure 4.1: List of performance criteria for H_2 supply chains from (a) literature and (b) interviews, sorted by the number of mentions and color-coded by category.

Criteria comparison

Comparing the criteria lists shows that in literature, mainly technological and economic criteria (10 out of 17 criteria) are analyzed. This supports the observation in Section 1.2 that literature pays more attention to techno-economic than socio-political criteria. Global warming potential is, however, the most frequently mentioned criterion as the use of H_2 is discussed as a promising pathway to meet climate targets (Rijksoverheid, 2020a). In contrast to literature, participants mainly mention socio-political criteria (6 out of 17 criteria), which underlines the increasing need to include them in research. Capital expenditures (CAPEX) and Operating expenditures (OPEX) are the most frequently mentioned criteria in interviews emphasizing that implementing a new energy carrier must also be economically justified. Finally, country-specific environmental criteria are named, such as acidification emissions due to the high Nitrogen (N_2) pollution in the Netherlands (Rijksoverheid, 2020b) and land requirement due to limited space availability in the Netherlands (IEA, 2022b).

The comparison of criteria from literature with interviews shows that similar criteria are addressed, but their relevance for the performance analysis of H_2 supply chains is different.

Criteria selection

To select criteria for the performance analysis in this thesis, the stakeholder objectives identified in Section 3.1.4 are combined with the criteria identified in the previous section. The objective tree in Figure 4.2 summarizes the objectives, the selected criteria, and metrics, which will be described in more detail below.

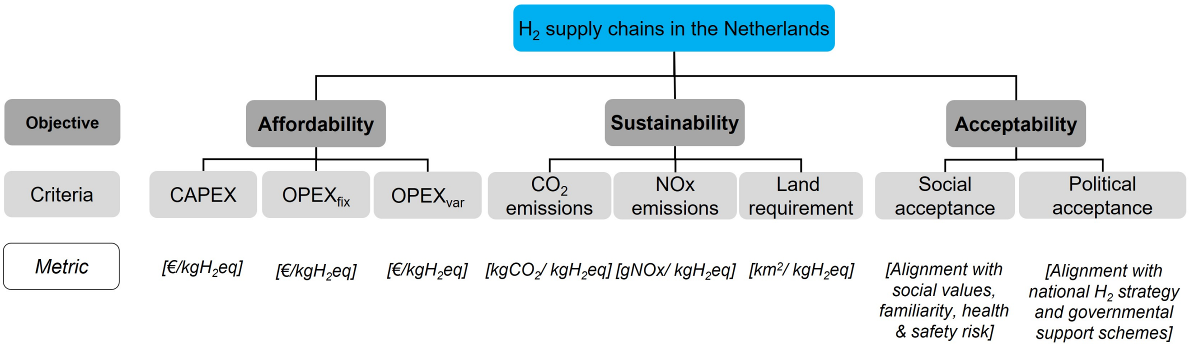


Figure 4.2: Selected performance criteria for H_2 supply chains in the Netherlands related to the three stakeholder objectives identified in Section 3.1.4

The affordability objective relates to the economic criteria. The most frequently mentioned economic criteria in both literature and interviews are CAPEX, OPEX and H_2 production cost per kg H_2. The latter is not selected as a separate criterion, as the cost results from the production component's CAPEX and OPEX. Therefore, the following criteria result according to the definition of Reuß et al. (2017):

- CAPEX [€/kgH_2eq]: Investment cost such as plant construction and equipment costs
- $OPEX_{fix}$ [€/kgH_2eq]: Fixed labor, maintenance and general administrative costs
- $OPEX_{var}$ [€/kgH_2eq]: Variable operational costs such as electricity, fuel, and carbon emissions

The sustainability objective relates to environmental criteria. The most frequently mentioned criteria in both literature and interviews are global warming potential, acidification potential, and land requirement. The interviews further specified CO_2 emissions for global warming potential and NOx emissions for acidification potential. As this study focuses on H_2 supply chains in the Netherlands, the more specific interview criteria are selected:

- CO_2 emissions [kgCO_2/kgH_2eq]
- NOx emissions [gNOx/kgH_2eq]
- Land requirement [km^2/kgH_2eq]

The acceptability objective relates to socio-political criteria. The most frequently mentioned socio-political criteria in literature and interviews are social acceptance, political acceptance, and health and safety. The latter can contribute to social acceptance (Ruggero, 2014), and is thus not analyzed separately. This results in the following criteria:

- Social acceptance [color scale]: *"[The] favorable or positive response [...] by [the general public (i.e., individual consumers and citizens without formal political objectives)] at the country level towards [H_2 supply chain components]"* (Upham et al., 2015) based on the alignment with societal values, familiarity with technology, and health and safety risks (Ruggero, 2014).
- Political acceptance [color scale]: *"[The] favourable or positive response [...] by [the government]" at the country level towards [H_2 supply chain components]* (Upham et al., 2015) based on the alignment with national H_2 strategy and the support the components receive from the governmental schemes (Fazli-Khalaf et al., 2020).

4.2. Techno-economic analysis

4.2.1. Economic performance

To analyze the economic performance of the selected domestic and global H_2 supply chains, CAPEX, $OPEX_{fix}$, and $OPEX_{var}$ are calculated. A detailed description of the techno-economic data for each supply chain component, energy prices per country, and the results per supply chain component be found in Appendix D. The main results are presented in the following.

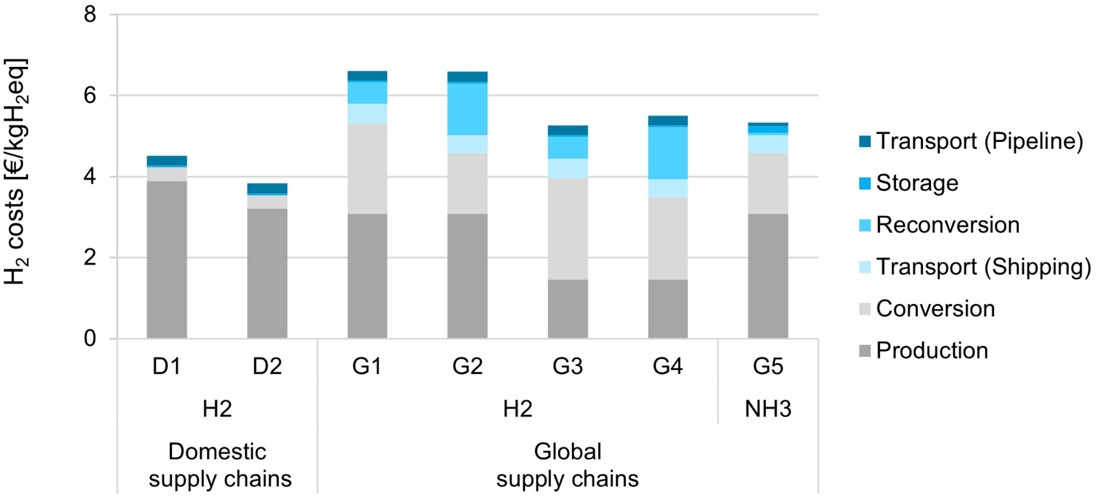


Figure 4.3: H_2 costs per domestic and global supply chain.

Figure 4.3 shows the cost of H_2 for different domestic and global supply chains and the cost contribution of each component. A detailed overview of the costs per supply chain, component, and performance criterion can be found in Table D.10 in Appendix D.

For domestic H_2 supply chains, costs are dominated by production costs due to the high energy consumption. D2 is the most economical domestic supply chain at 3.83 €/kgH_2eq. It produces H_2 with SMR and CCS and costs 15 % less than D1 which uses the more energy and capital-intensive PEM electrolysis (4.52 €/kgH_2eq).

For global H_2 supply chains, costs are dominated by production, conversion, and reconversion costs due to their high energy consumption. H_2 supply chains using renewable electricity have 23% time higher costs than their direct SMR and CCS counterparts mainly due to higher production costs. G3 has the lowest costs of global H_2 supply chains at 5.27 €/kgH_2eq using the less energy and capital intensive SMR with CCS alternative and the overall less energy-intensive conversion and reconversion LH_2 compared to NH_3. However, if NH_3 produced from renewable electricity is used directly i.e. without reconverting it to H_2, the supply chain G5 leads to 5.34 €/kgH_2eq. G5 has thus a more comparable price to G3 when considering both H_2 and NH_3 for the final utilization.

Comparing domestic and global H_2 supply chains shows that, on average, global supply chains lead to 1.5 times higher costs even though global supply chains have up to 55% lower production costs. Conversion, transport, and reconversion cost account for 50-67% of total costs.

4.2.2. Environmental performance

To analyze the environmental performance of domestic and global H_2 supply chains, CO_2 emissions, NOx emissions, and land requirements are calculated per supply chain component. A detailed description of the techno-economic data and results per supply chain can be found in Appendix D. The main results are presented in the following.

CO_2 emissions

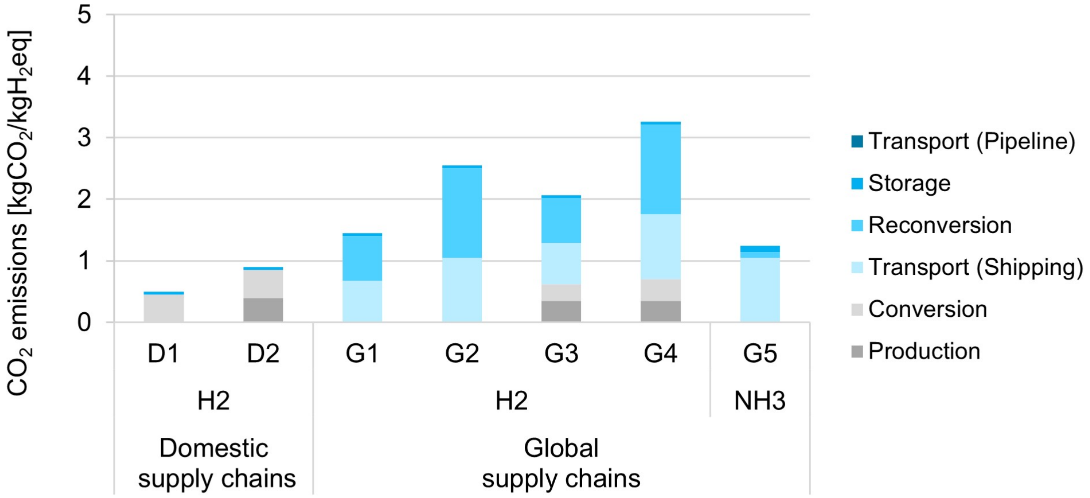


Figure 4.4: CO_2 emissions for domestic and global supply chain.

Figure 4.4 shows the CO_2 emissions per domestic and global H_2 supply chains. A detailed overview of the CO_2 emissions per supply chain, component, and performance criterion can be found in Table D.10 in Appendix D.

For domestic H_2 supply chains, CO_2 emissions are mainly emitted during the production and when H_2 is compressed for transport. D1 is the domestic supply chain with the lowest CO_2 emissions at 0.5 $kgCO_2/kgH_2eq$. It uses renewable electricity for production and emits thus three times less CO_2 than D2, which uses NG and grid electricity.

For global H_2 supply chains, CO_2 emissions are mainly emitted during transport and reconversion. H_2 supply chains using renewable electricity have approx. 1.5 - 2 times lower emissions than their direct SMR and CCS counterparts, as these emit additional emissions during production and conversion. G1 has the lowest CO_2 emissions of global H_2 supply chains at 1.4 $kgCO_2/kgH_2$ due to the renewable electricity for production and conversion and a less energy-intensive transport and reconversion of LH_2 compared to NH_3. However, if NH_3 is used directly i.e. without reconverting it to H_2, the supply chain leads to only 1.2 $kgCO_2/kgH_2eq$. G5 is thus the global supply chain with the lowest emissions when considering both H_2 and NH_3 for the final utilization.

Comparing domestic and global H_2 supply chains shows that on average, global supply chains emit 3 times more CO_2 than domestic supply chains due to the energy-intensive transport by ship using heavy fuel oil and reconversion processes without an additional CO_2 capture technology. However,H_2 produced from renewable electricity and converted to LH_2 in G1, emissions are comparable to domestically produced H_2 using NG, even with additional conversion, transport and reconversion components.

NOx emissions

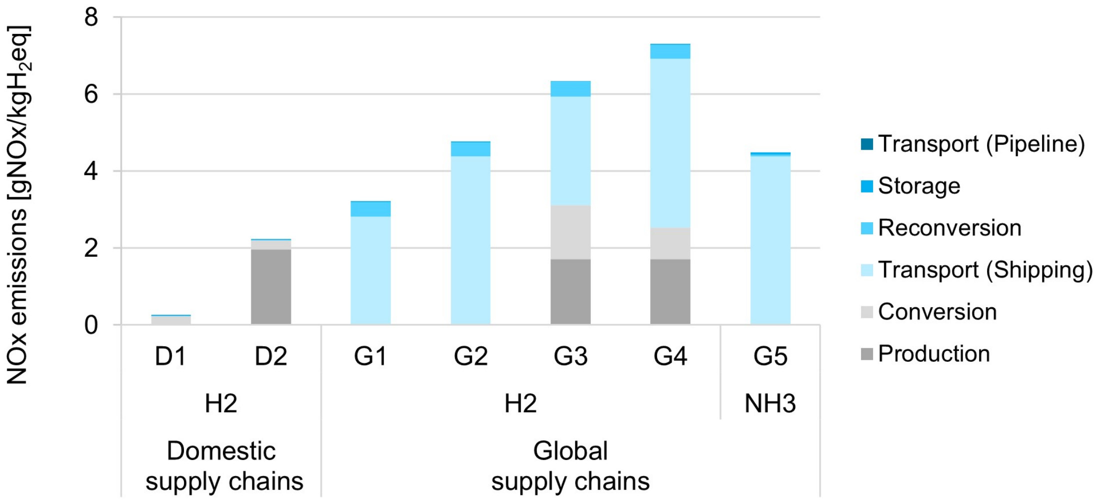


Figure 4.5: NOx emissions per domestic and global supply chain.

Figure 4.5 shows the NOx emissions per domestic and global H_2 supply chain. A detailed overview of the NOx emissions per supply chain, component, and performance criterion can be found in Table D.10 in Appendix D.

For domestic H_2 supply chains, NOx emissions are mainly emitted during the production using SMR with CCS. Storage and conversion play a minor role, as the electricity grid emits little NOx. D1 is the domestic supply chain with the lowest NOx emissions at 0.3 gNOx/kgH_2eq. It uses renewable electricity for production and thus emits eight times less NOx than D2, which uses NG and grid electricity.

For global H_2 supply chains, NOx emissions are mainly emitted during shipping using heavy fuel oil. Similar to CO_2 emissions, H_2 supply chains using renewable electricity have 1.5-2 times lower NOx emissions than their direct SMR and CCS counterparts as these emit additional emissions during production and conversion. G1 has the lowest NOx emissions of global H_2 supply chains at 3.2 gNOx/kgH_2 due to the renewable electricity for production and conversion and a less energy-intensive transport and reconversion of LH_2 compared to NH_3. If NH_3 is used directly, the supply chain leads to 4.5 gNOx/kgH_2eq which is still higher than G1. This differs from the results obtained from the analysis of CO_2 emissions. It can be explained by the fact that NOx are mainly emitted during shipping. Hence, excluding the reconversion has no significant effect on the reduction of NOx emissions.

Comparing domestic and global H_2 supply chains shows that, on average, global supply chains emit 4.5 times more NOx than domestic supply chains due to the high NOx content of heavy fuel oil used during transport by ship. However, for H_2 produced from renewable electricity and converted to LH_2 in G1, emissions are only 32% higher than domestically produced H_2 using NG, even with additional conversion, transport and reconversion components.

Land requirement

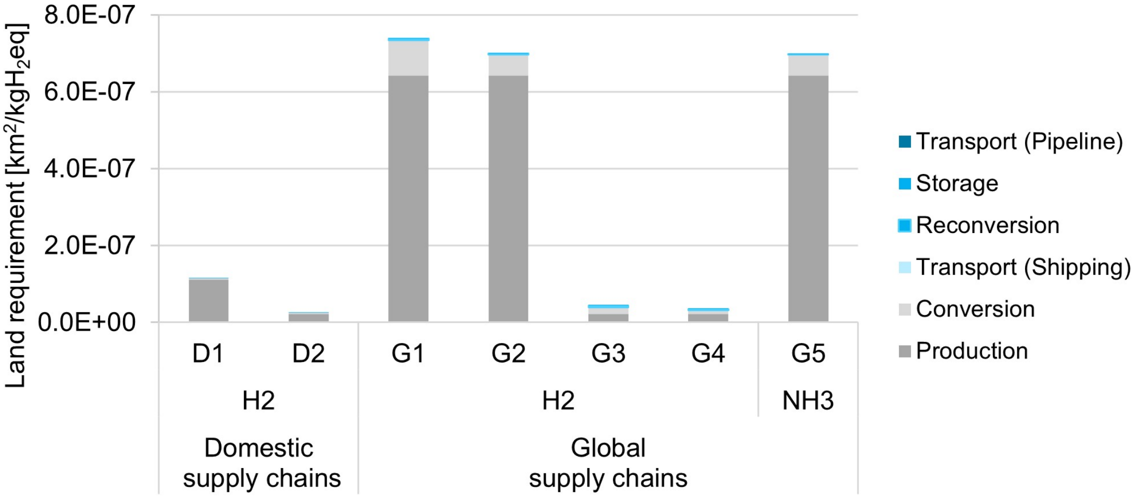


Figure 4.6: Land requirement per domestic and global supply chain.

Figure 4.6 displays the land requirement per domestic and global H_2 supply chain. A detailed overview of the land requirement per supply chain, component, and performance criterion can be found in Table D.10 in Appendix D.

For domestic H_2 supply chains, the land requirement is mainly caused by the production. Other supply chain components play a minor role, as they consume grid electricity which contains mainly fossil fuels with low land requirement per kWh (see Table D.9 in Appendix D). D2 is the domestic supply chain that requires the least land at 2E-08 km^2/kgH$_2$eq. It uses NG and grid electricity for production and requires thus five times less area than D1, which uses renewable electricity from offshore wind and energy-intensive PEM elecrolysis.

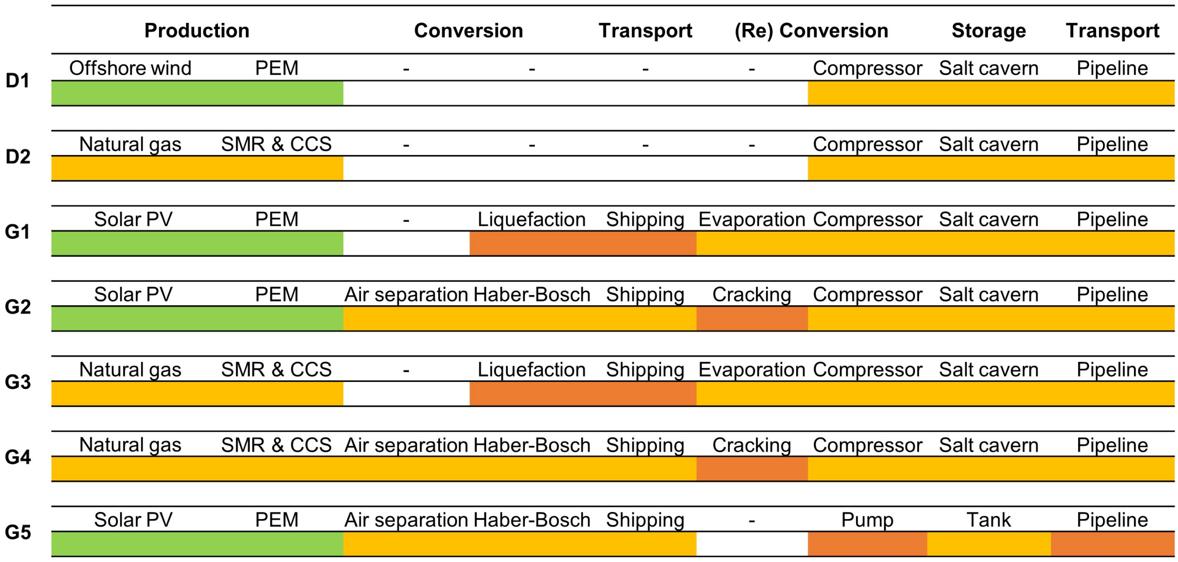
For global H_2 supply chains, the land requirement is mainly caused by production and conversion using renewable electricity. H_2 supply chains using renewable electricity require 50 times more land than their direct SMR and CCS counterparts due to the high energy demand for electrolysis and the large area needed for solar power generation. G3 requires the least land at 4E-08 km^2/kgH$_2$eq of global H_2 supply chains due to the use of NG, grid electricity, and the overall less energy-intensive production, conversion and reconversion of LH_2 compared to NH_3. If NH_3 is used directly, no significant change is seen as NG is used for reconversion, which has a low land requirement.

Comparing domestic and global H_2 supply chains shows that, on average, domestic supply chains require over 150 times less land than global supply chains due to the energy source used. Electricity from solar power is assumed as an energy source for production and conversion in global supply chains, whereas offshore wind is used for domestic production and conversion. Offshore wind requires six times less land than solar power (Cheng & Hammond, 2016).

4.3. Socio-political analysis

4.3.1. Social acceptance

For the social analysis of the selected domestic and global H_2 supply chains, the social acceptance is analysed. Figure 4.7 shows the estimate for social acceptance for domestic and global H_2 supply chains. The main results are presented in the following.



	Production		**Conversion**		**Transport**	**(Re) Conversion**		**Storage**	**Transport**
D1	Offshore wind	PEM	-	-	-	-	Compressor	Salt cavern	Pipeline
	🟩	🟩					🟨	🟨	🟨
D2	Natural gas	SMR & CCS	-	-	-	-	Compressor	Salt cavern	Pipeline
	🟨	🟨					🟨	🟨	🟨
G1	Solar PV	PEM	-	Liquefaction	Shipping	Evaporation	Compressor	Salt cavern	Pipeline
	🟩	🟩		🟧	🟧	🟨	🟨	🟨	🟨
G2	Solar PV	PEM	Air separation	Haber-Bosch	Shipping	Cracking	Compressor	Salt cavern	Pipeline
	🟩	🟩	🟨	🟨	🟨	🟧	🟨	🟨	🟨
G3	Natural gas	SMR & CCS	-	Liquefaction	Shipping	Evaporation	Compressor	Salt cavern	Pipeline
	🟨	🟨		🟧	🟧	🟨	🟨	🟨	🟨
G4	Natural gas	SMR & CCS	Air separation	Haber-Bosch	Shipping	Cracking	Compressor	Salt cavern	Pipeline
	🟨	🟨	🟨	🟨	🟨	🟧	🟨	🟨	🟨
G5	Solar PV	PEM	Air separation	Haber-Bosch	Shipping	-	Pump	Tank	Pipeline
	🟩	🟩	🟨	🟨	🟨		🟧	🟨	🟧

Figure 4.7: Social acceptance per domestic and global H_2 supply chain component.

Production with renewable energy sources is highly supported by society because they align with climate goals and society's sustainability values (Netherlands Ministry of Economic Affairs, 2019). SMR with CCS using NG, on the other hand, is a technology that society is familiar with but rejects for climate polluting reasons, but also because of safety reasons due to the Groningen earthquakes caused by the extraction of NG in 2010 (IEA, 2022b).

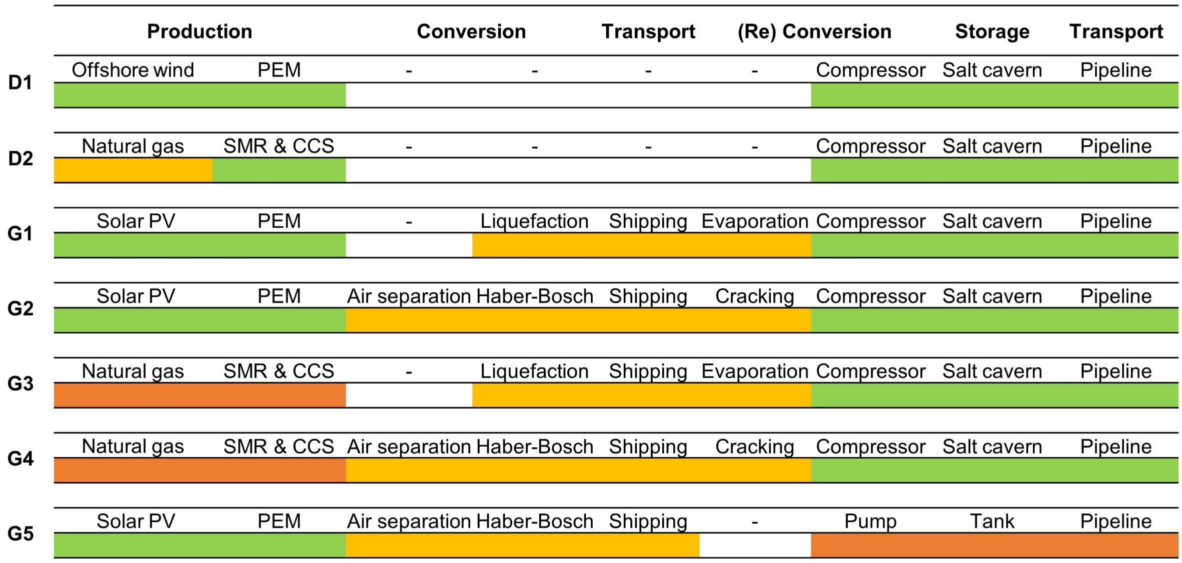
Conversion, shipping, and reconversion components have medium to low acceptance due to toxicity and society's low familiarity with these components. Conversion and transport are mature for supply chains using NH_3 as an energy source (Nayak-Luke et al., 2021). However, the toxicity of NH_3 and its impact on human health and the environment is of concern when transported in large quantities (Nayak-Luke et al., 2021; Appendix C). In addition, large-scale NH_3 cracking is not yet feasible and requires much fossil energy, which needs to be changed to renewable energy sources to meet society's sustainability values (Berger, 2021). There are also concerns about LH_2, as it is an explosive energy carrier and the technology to transport and convert it on a large scale is not yet mature (Andersson & Grönkvist, 2019). Thus, transport and conversion still raise safety concerns even though it is a non-toxic energy carrier. The risk uncertainty and unfamiliarity with the large-scale conversion, transport, and reconversion of H_2 energy carriers prove to be an obstacle.

Compressor, pipelines, and storage technologies for H_2 have medium acceptance as society is less familiar in terms of use in large-scale H_2 supply chains but knows these components from other energy systems, such as in the gas network (Appendix C). However, the transport (pipeline and pumps) of NH_3 has low acceptance, as a new pipeline network would be required, which society is not familiar with, especially concerning the potential risks, it would have on human health and the environment.

Overall, H_2 supply chains that use electricity from renewable sources are more accepted by society due to society's awareness of climate change and support for renewable energy. Large-scale H_2 supply chains are relatively new or (in the case of LH_2 transport and conversion or reconversion of NH_3) have not yet been proven on a large scale. Furthermore, the risks of the energy carriers during conversion, transport, reconversion, and storage and its impact on human health and the environment are poorly understood by society.

4.3.2. Political acceptance

For the political analysis of the selected domestic and global H_2 supply chains, the political acceptance is analysed. Figure 4.8 shows the political acceptance for domestic and global H_2 supply chains. The main results are presented in the following.



	Production		Conversion		Transport	(Re) Conversion		Storage	Transport
D1	Offshore wind	PEM	-	-	-	-	Compressor	Salt cavern	Pipeline
	🟩	🟩					🟩	🟩	🟩
D2	Natural gas	SMR & CCS	-	-	-	-	Compressor	Salt cavern	Pipeline
	🟨	🟩					🟩	🟩	🟩
G1	Solar PV	PEM	-	Liquefaction	Shipping	Evaporation	Compressor	Salt cavern	Pipeline
	🟩	🟩		🟨	🟨	🟨	🟩	🟩	🟩
G2	Solar PV	PEM	Air separation	Haber-Bosch	Shipping	Cracking	Compressor	Salt cavern	Pipeline
	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟩
G3	Natural gas	SMR & CCS	-	Liquefaction	Shipping	Evaporation	Compressor	Salt cavern	Pipeline
	🟧	🟧		🟨	🟨	🟨	🟩	🟩	🟩
G4	Natural gas	SMR & CCS	Air separation	Haber-Bosch	Shipping	Cracking	Compressor	Salt cavern	Pipeline
	🟧	🟧	🟨	🟨	🟨	🟨	🟩	🟩	🟩
G5	Solar PV	PEM	Air separation	Haber-Bosch	Shipping	-	Pump	Tank	Pipeline
	🟩	🟩	🟨	🟨	🟨		🟧	🟧	🟧

Figure 4.8: Political acceptance per domestic and global H_2 supply chain component.

Production with renewable energy sources for domestic and global supply chains is politically more accepted than NG due to the announced reduction of NG in the Netherlands by 2023 (Netherlands Ministry of Economic Affairs, 2019) and the ambition to transition to a renewable energy system to achieve climate goals. However, NG is also mentioned as a potential energy source in the Dutch H_2 strategy for the H_2 production when combined with a CCS technology for domestic production. NG has thus a medium acceptance for domestic supply chains as it is mentioned in the H_2 strategy but not supported by governmental support schemes. For global supply chains NG has a low acceptance as the strategy aims for import of H_2 produced from renewable energy (Rijksoverheid, 2020a). Renewables are highly accepted as they are mentioned in the H_2 strategy and supported by various subsidy schemes and the Dutch climate goals (Section 3.1.2). Electrolysis is named in the H_2 strategy as the long term goal for domestic H_2 production (Rijksoverheid, 2020a). Recently, the technology has also been added to the financial support scheme SDE++ (RVO, 2022d), which leads to a high political acceptance. SMR and CCS are already supported by the SDE++ subsidy scheme (Rijksoverheid, 2020a) and mentioned in the national H_2 strategy but only as a short and medium solution which is why it is indicated with medium acceptance.

Conversion, shipping, and reconversion components have a medium political acceptance. NH_3 and LH_2 are mentioned in the H_2 strategy as potential energy carriers, but no specific support schemes are driving the import of either one of them. The lack of concrete support schemes and strategies for a particular conversion and reconversion technology indicates a medium political acceptance. Shipping is mentioned in the H_2 strategy as an option for import, and it also receives governmental support indicated through the already signed several memorandums of understanding with potential H_2 exporting countries (see Section 1.1). However, there are no concrete support schemes for shipping NH_3 and LH_2, leading to a medium acceptance.

Compressor, pipelines, and salt caverns have a high political acceptance, as the H_2 strategy clearly states the use of them in the near future and has already started to financially support the construction of the H_2 backbone and salt cavern with 750 million € investment announced in June 2022 (Reuters, 2022; Appendix C, Interview 3). For NH_3, the domestic conversion, storage, and transport have a low acceptance, as no concrete support schemes exist and no concrete indication of using NH_3 as an energy carrier and building a pipeline network are mentioned in the national H_2 strategy.

Overall, H_2 supply chains that use renewable sources are more accepted due to the strategic focus on reducing emissions to achieve climate targets. Production and transport support schemes are already established, whereas a strategy and support schemes for a specific energy carrier, i.e., conversion, reconversion, and shipping, are missing.

4.4. Conclusion and trade-offs

The techno-economic and socio-political analysis assessed the performance of different domestic and global supply chains and identified those that satisfy the criteria best. Now, these supply chains are combined into portfolios to discuss their trade-offs regarding stakeholders' drivers identified in Section 3.1.4.

The *techno-economic analysis* assessed H_2 supply chains with regards to the affordability and sustainability drivers. Table 4.1 provides an overview of the estimated results for each supply chain, indicating in blue the lowest costs or environmental impact among domestic or global supply chains. The results show that D2 and G3 are the most economical supply chains in their respective supply chain, meeting the affordability driver the best. D1 and G1 have the lowest CO_2 and NOx emissions, and D2 and G3 have the lowest spatial footprint. Considering a similar weight for each of the sustainability criteria, the most sustainable supply chains are D1 and G1.

Table 4.1: Overview techno-economic performance results per H_2 supply chain. D2 and G3 are the most affordable, and D1 and G1 are the most sustainable supply chains.

Driver	Criteria	D1	D2	G1	G2	G3	G4	G5
Affordability	CAPEX [€/kgH_2eq]	0.8	0.5	2.1	2.2	1.7	1.8	1.9
	OPEX$_{fix}$ [€/kgH_2eq]	0.2	0.5	1.2	0.6	1.4	0.9	0.5
	OPEX$_{var}$ [€/kgH_2eq]	3.5	2.9	3.3	3.7	2.1	2.7	2.9
	H_2 costs [€/kgH_2eq]	4.52	3.83	6.61	6.59	5.27	5.50	5.34
Sustainability	CO_2 emissions [kgCO_2/kgH_2eq]	0.5	0.9	1.4	2.6	2.1	3.3	1.2
	NOx emissions [gNOx/kgH_2eq]	0.3	2.2	3.2	4.8	6.3	7.3	4.5
	Spatial footprint [km^2/kgH_2eq]	1E-07	2E-08	7E-07	7E-07	4E-08	4E-08	7E-07

Note: Blue indicates the lowest value per criteria separated for domestic and global supply chains

The *socio-political analysis* assessed H_2 supply chains with regards to the acceptability driver. Figures 4.7 and 4.8 provide an overview of the estimated results for each supply chain. The results show that supply chains using renewable electricity D1, G1, and G2 are the most accepted supply chains, meeting the acceptability objective the best.

Per supply chain, the following overall trade-offs can be made across all domestic and global supply chains based on the identified performance regarding their sustainability, affordability, or acceptability:

D1 Domestic supply chains using renewable electricity and electrolysis have high investment costs, energy consumption costs, and land requirement. However, they have the lowest CO_2 and NOx emissions and high social and political acceptance due to society's awareness of climate change and explicit governmental support schemes and strategies.

D2 Domestic supply chains using NG with SMR and CCS have lowest land requirement, investment and energy consumption costs. However, they come with high CO_2 and NOx emissions and low social and political acceptance due to the goal to reduce NG in the Netherlands.

G1 Global supply chains using renewable electricity, electrolysis, and LH_2 as an energy carrier have the highest land requirement and the second highest investment and energy consumption costs. However, they come with the lowest CO_2, and NOx emissions for global supply chains and one of the highest social and political acceptance as society and the government are aiming for the import of H_2 produced from renewable energy to achieve climate goals.

G2 Global supply chains using renewable electricity, electrolysis, and NH_3 as an energy carrier have the highest land requirement, investment, and energy consumption costs and the second highest CO_2 emissions for global supply chains. However, they come with the third lowest NOx emissions and one of the highest social and political acceptance as society and the government aim to import H_2 produced from renewable energy to achieve climate goals.

G3 Global supply chains using NG with SMR with CCS and LH_2 as an energy carrier have the lowest land requirement, investment and energy consumption costs. However, they have the third highest CO_2 emissions, second highest NOx emissions, and one of the lowest social and political acceptance due to society's concern of the risk and impact of LH_2 on the human health when implemented on a large scale and no H_2 strategy and governmental support schemes to import H_2 produced with fossil fuels.

G4 Supply chains using NG with SMR with CCS and NH_3 as an energy carrier have the second lowest investment and energy consumption costs and land requirement for global supply chains. However, they have the highest CO_2 and NOx emissions and one of the lowest social and political acceptance due to society's concern of the risk and impact of NH_3 on human health when implemented on a large scale and no H_2 strategy and governmental support schemes to import H_2 produced with fossil fuels.

G5 Global supply chains using renewable electricity, electrolysis and NH_3 for the end use have the second lowest H_2 costs, the second lowest CO_2 and NOx emissions. However, they come with one of the highest land requirements and the lowest social and political acceptance due to society's concerns and uncertainty about the impact and risk of NH_3 on human health and the environment when implemented on a large scale, and the missing support schemes from the government and mentions in the H_2 strategy.

Per portfolio, different trade-offs can be made based on the combination of the individual supply chains. The trade-offs of the portfolios that meet the sustainability, affordability, and acceptability objectives the best are explained in the following:

- *Portfolio 1*, a combination of D1 and G1, is the most sustainable and one of the most accepted supply chain portfolios. It has the lowest CO_2 and NOx emissions as the domestic and global supply chain use renewable energy for production and conversion. Thus, portfolio 1 aligns the most with societal sustainability values, governmental climate targets, the H_2 strategy, and the offered support schemes. However, it also comes with high costs due to the investment and energy-intensive PEM electrolysis. Furthermore, renewable electricity leads to the largest land requirement among the portfolios. Moreover, liquefaction and shipping of LH_2 are still at an early development stage which is why the risk associated with the components is less understood, raising concerns about potential societal risks and political support. A renewable supply chain portfolio using LH_2 comes thus with the main trade-offs of low emissions and high acceptability but high costs, land requirements, and development uncertainties.
- *Portfolio 7*, a combination of D2 and G3, is the most economical supply chain portfolio. It has the lowest costs as both domestic and global supply chain uses SMR with CCS for production. It uses mainly existing and established components that society is familiar with and requires little land due to the use of fossil fuels. However, the high CO_2 and NOx emissions lead to low social acceptance and alignment with the national climate targets. Even though SMR with CCS is mentioned in the H_2 strategy, it is less supported by governmental funding as it is only considered as an intermediate step. Similar to Portfolio 1, liquefaction and shipping of LH_2 faces further obstacles for this portfolio leading to the conclusion that a fossil fuel supply chain portfolio comes with several trade-offs regarding low acceptability and low sustainability in exchange for its low costs and established components.

In conclusion, the analysis results show that there is no supply chain or supply chain portfolio that meets all stakeholder objectives best. Each supply chain has trade-offs on a techno-economic and socio-political side that need to be considered when assessing which supply chain portfolio to choose. However, two portfolios were identified that come close to meeting stakeholder's objectives. They show that higher sustainability comes with higher acceptability but leads to lower affordability.

5

Discussion

5.1. Results

5.1.1. Affordability

The economic analysis of this thesis showed that domestic and global supply chains using fossil fuels and LH_2 for global transport are the most economical, with production, transport, and reconversion as the energy- and capital-intensive components. However, the results are subject to uncertainty as energy and technology prices change due to technology, market, and energy policy developments. To show the influences of price uncertainties in input values, a sensitivity analysis was performed as described in Section 2.7.1. Figure 5.1 shows the results for the selected domestic and global supply chains.

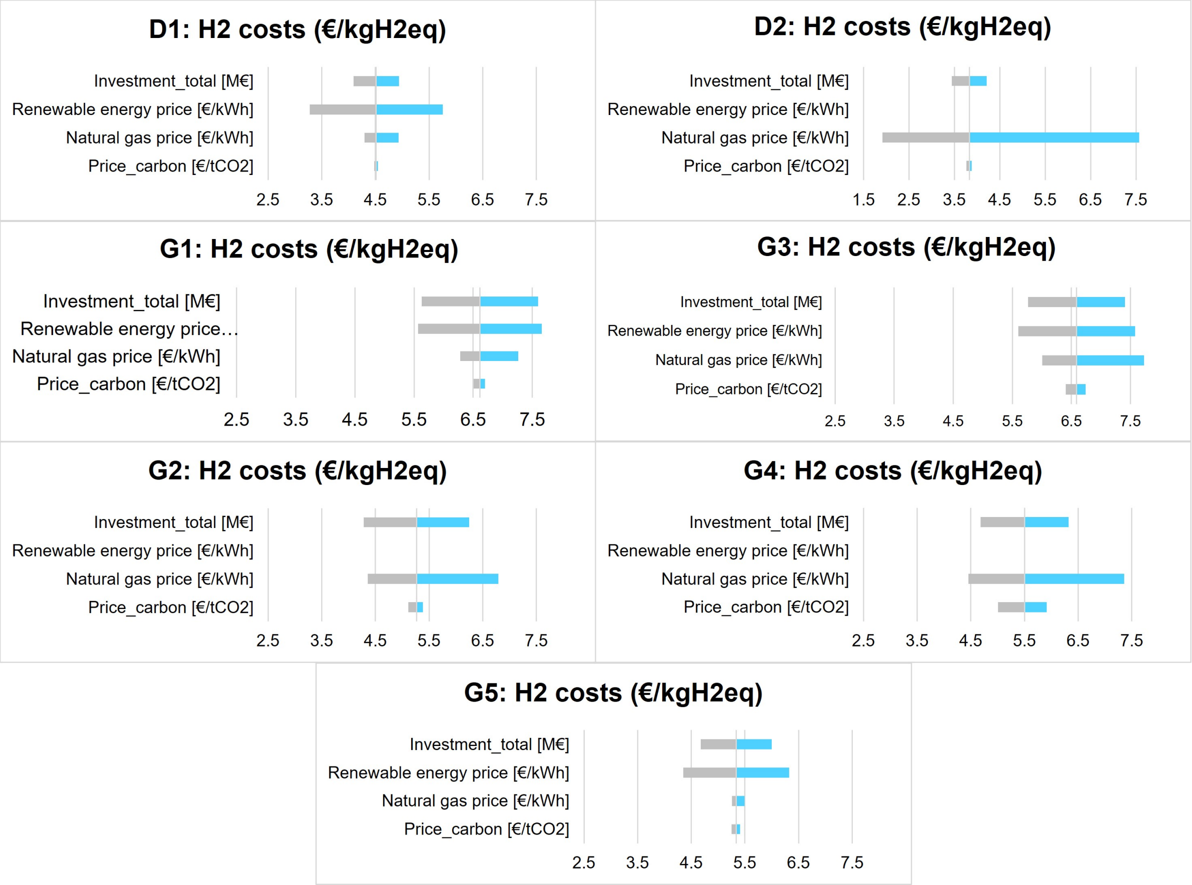


Figure 5.1: Sensitivity analysis of costs for domestic and global supply chains.

The sensitivity analysis shows that domestic supply chains are more sensitive to a change in energy prices due to their energy-intensive H_2 production. A change in the predicted or previous energy prices leads to a change of up to 50% in total costs. Global supply chains are also sensitive to changes in energy prices but to a lesser extent, as capital-intensive conversion, transport, and reconversion components also influence the total costs. A difference in energy costs leads to a ±15-20% change, and a ±40% change in investment costs leads to a ±15% change in H_2 costs. Finally, the analysis shows that carbon tax on emissions has little effect on price.

Comparing the most affordable H_2 supply chains and the results of the sensitivity analysis to previous literature supports the findings that the most influencing factors are production, conversion and reconversion costs due to the high energy consumptions (Brändle et al., 2021; IEA, 2019; Reuß et al., 2017; Ishimoto et al., 2020). These studies showed that comparing H_2 supply chains using renewable energy sources and NG, NG is most likely to be more cost-efficient then electrolysis in the medium term with costs around 2-2.5 €/kgH_2 for domestic and 5 €/kgH_2 for global supply chains. This is in line with Brändle et al. (2021), which estimated domestic production costs for Germany from renewables at 2.5 €/kgH_2. Ishimoto et al. (2020) estimated global supply chain costs from renewable produced H_2 and transported as LH_2 to the Netherlands at 6 €/kgH_2 and the IEA (2019) estimated global supply chains costs of LH_2 at 7 €/kgH_2. In the long term, however, H_2 is seen as potentially becoming cost competitive in regions with favorable wind or solar potentials, especially if investment costs for renewable energy sources and electrolysis decrease significantly (Brändle et al., 2021; IRENA, 2022).

Thus, the results found in literature are partially lower than those estimated in this study due to higher electricity and NG prices assumed in this study, less capital-intensive onshore wind for renewable electricity (Brändle et al., 2021), and higher import and export terminal costs for shipping (IEA, 2019). Since the beginning of 2022, the electricity and gas price increased (European Commission, 2022a), which further accelerates the development of renewable energy supply chains (RVO, 2022c). The validity of the results is therefore limited to the selected time frame, as strongly fluctuating energy prices and development prices for technologies change the costs significantly.

Reviewing the economic performance results of this study showed that the findings are in line with the overall H_2 supply chains research and proportions of how much components contribute to the overall H_2 costs. However, specific cost results differ due to country and time-specific energy price developments. New insights are thus provided into the cost-competitiveness of renewable with fossil fuel energy from global and domestic supply chains under the current conditions for the Netherlands, valid for price scenarios in 2030.

5.1.2. Sustainability

The sustainability of H_2 supply chains was assessed based on CO_2 and NOx emissions and land requirements. The results show that renewable domestic and global supply chains that transport LH_2 emit the least but require the most land. Transport and conversion are the drivers of the high emissions in this case. The use of renewable energy leads to high land requirements.

A comparison of the results with literature supports the finding that transport and conversion are the main drivers of emissions (Ishimoto et al., 2020; Reuß et al., 2017). The literature has shown that when comparing global supply chains transporting LH_2 and NH_3, LH_2 produces almost four times less CO_2 emissions due to emissions-intensive cracking (Andersson & Grönkvist, 2019). For domestic supply chains, Reuß et al. (2017) examined CO_2 emissions of 1.3 kg CO_2/kg H_2 for fossil H_2 production using a similar supply chain configuration. While CO_2 emissions for supply chains were analysed in literature, none of the literature studied for this research assessed NOx emissions or land requirements. This may be because NOx emissions and land requirements were identified as country-specific criteria and therefore are not particularly prominent by other countries.

Results from literature on CO_2 emissions show similar results due to the similar approach of including emissions based on the energy source used. Country-specific emission factors can explain differences between the emissions. Transport and conversion were identified as the most significant emission factors. This raises the question of importing H_2 by ship or not. Another point to note is that imported LH_2 produced from renewables was found to be high in CO_2 emissions in both literature and this study. Global LH_2 produced from renewables emits even more than domestically produced H_2 with SMR and

CCS. Suppose LH_2 is to be introduced to reduce emissions. In that case, additional measures will need to be taken to either offset the H_2 or to increase developments in conversion and transport methods.

Consideration of the sustainability performance of this study has shown that the results are consistent with previous research on H_2 supply chains. However, the specific CO_2 results differ due to country- and time-specific energy emissions and the components considered. This study only provided the environmental performance based on the energy source used. It is not directly related to the supply chain component process emissions and is only valid under current technology developments. Nevertheless, the results provide new insights into NOx emissions and the land requirement for H_2 supply of renewable with fossil energy from global and domestic supply chains.

5.1.3. Acceptability

Social acceptance
Social acceptance of H_2 supply chains in the Netherlands was overall found to be medium because society is unfamiliar with H_2 and supply chain components, not all technologies have yet been tested on a large scale, and H_2 energy carriers are toxic or explosive, raising concerns about risks and impacts on society. However, societal acceptance of supply chains that use renewable electricity is greater than that of supply chains using NG.

Comparing the results with literature on social acceptance of H_2 supply chains, a similar pattern emerges that large-scale infrastructure transitions experience low acceptance. Schönauer and Glanz (2022) conducted a study on the German population, which showed that H_2 enjoys a high level of acceptance in the country on a general level. However, regarding implementation in the participants' neighborhoods, acceptance drops drastically due to the lack of understanding of the impacts and consequences on their health and safety. Lack of familiarity was identified as one of the main reasons. Ruggero (2014) came to a similar conclusion, noting that H_2 is not yet widely used, making it difficult to anticipate its problems. He also points out that one of the challenges with new technologies is the controvert discussion that exists in the early stages because of the impact these technologies will have on society, as seen in the case of CCS or wind turbines.

Thus, the results from the literature on social acceptance of H_2supply chains are consistent with general research on the acceptance of renewable energy supply chains. H_2 acceptance exists at a general level but decreases when it comes to large-scale infrastructure implementation. The differences can be explained by the influence of culture and observed time. Countries with lower climate targets might reject supply chains more strongly or support other supply chains. In another time period, e.g. in a few years, the acceptance might change because supply chains have already been implemented and the risks have been researched. Therefore, the results may change in the future and are not directly transferable to other countries. However, this thesis provides a unique insight into the social acceptance of each supply chain component in the Netherlands.

Political acceptance
Political acceptance of H_2 supply chains in the Netherlands is higher than societal acceptance, as the government announced H_2 as an essential aspect of achieving climate goals and energy security (Rijksoverheid, 2020a). The H_2 strategy provides clear direction on which domestic energy sources, production, storage, and transport components should be used but lacks conversion, transport, and reconversion strategies or support schemes. Therefore, domestic supply chains' political acceptance is greater than global supply chains.

Comparing the results with literature on other countries' policy acceptance of H_2 supply chains supports the finding that global supply chains lack government support programs and strategies. Hydrogen Council (2021) analysed various government support programs and policies and concluded that, overall, policymakers are interested in low-carbon and renewable H_2 supply chains because of their key role in enabling greater and faster integration of renewables into the system. However, they also pointed out that there is a lack of policy development, which is needed to unlock the full potential of the deployment of H_2 supply chains. In particular, Hydrogen Council (2021) mentions the direct financial investment in components and transparent policy and regulatory frameworks in the early stages of market development.

Results from literature on the political acceptance show similar results as the results obtained in this study. H_2 is generally accepted but decreases when considering specific government support programs and policy regulations for global supply chains. The expanded criteria analyzed for policy acceptance in other studies explain the additional information. Similar to social acceptance, political acceptance is also culture- and time-dependent. Thus, the results may change in the future and are not generalized to other countries. Overall, however, the lack of policy measures and support schemes in the Netherlands is surprising, as imports are expected to play a crucial role for the Netherlands and its ambition to remain the energy hub of Europe by taking the leading role in H_2 trade (Rijksoverheid, 2020a). It is, therefore, questionable whether the Netherlands will achieve any of these goals without political leadership and support. Overall, the analysis analysed the political acceptance of supply chain components based on the governmental support schemes and their inclusion in the H_2 strategy. Hence, these results provide a unique insight into the acceptance of each component of the supply chain for the Netherlands.

5.1.4. Trade-offs

In this thesis, the main trade-offs of H_2 supply chains were that higher sustainability comes with higher acceptability but leads to lower affordability.

Reflecting on the previous Sections, affordability, acceptability, and sustainability may change over time as energy prices, technology development, and social-political acceptance evolve. The performance of supply chains in the short and long term will thus differ, leading to different trade-offs. Therefore, the short-term trade-offs in this study might not be valid in the long term. As fossil fuel prices are expected to increase and renewable energy prices to decrease, H_2 supply chains using renewable energy might become more affordable than supply chains using Natural gas (NG). According to IRENA (2022), this would make renewable supply chains the optimal supply chains across all drivers.

In the long term, however, other drivers than those identified in this study may be considered more important. In addition to sustainability and affordability, the conducted interviews and literature discussed capacity, timely implementation, and reliability (Appendix C; Rijksoverheid, 2020a). The studies and interviews conclude that timely implementation, reliability, and enough capacity come with the trade-off of low sustainability and affordability. However, this can be considered another short-term trade-off that will change in the future if renewable energy increases. In the long term, the expansion of renewables may lead to another trade-off within the sustainability driver such as between emission reduction versus material scarcity and dependence, given the production of renewable energy technologies such as wind mills or solar panels. Another element not considered with regards to renewable electricity, is that it may not be available in significant quantities for H_2 supply chains when additional renewable capacity is needed for other sectors (Brändle et al., 2021).

In reviewing the trade-offs of this study, it became apparent that the findings are only valid for a specific time and chosen drivers and will change in the future due to changes in technology, market and energy policy conditions. Other trade-offs, such as capacity, reliability, and timely implementation will also come into play. However, the results provides unique insight into the short term supply chain trade-offs for under current developments the Netherlands.

5.2. Methodology

This research used a combination of qualitative and quantitative methods to assess H_2 supply chains in the Netherlands. To the researcher's knowledge, this appears to be one of the first studies to combine domestic and global H_2 supply chains. This combination is relevant for countries with high energy demand, as they are not fully self-sufficient in supplying H_2. Consideration of domestic and global supply chains provides a comprehensive overview of the state of the art and performance of the various supply chains relative to each other. In addition, a combined techno-economic and socio-technical analysis was conducted with context-specific interview data. This leads to a more holistic assessment of the supply chain and results that increase the suitability of the analysis to inform stakeholders in the Netherlands.

However, the methodology used also has several limitations.

The supply chain configuration developed in this thesis was based on selection criteria that limited the technologies considered. In addition, the supply chain components were limited to production, conversion, transport, reconversion, and storage. Inlcuding additional components, such as storage and distribution in the exporting country and distribution and use in the Netherlands would result in supply chain costs tailored to the end user's needs.

The identification of drivers was based on a limited number of stakeholders in the Netherlands. Thus, different drivers could have been selected. Adding or replacing drivers would result in new criteria and thus different trade-offs. However, the results for the criteria in this thesis would continue to apply for the given time period chosen. Changing the time period would change the results as the technology and market evolve, but also as the socio-political situation changes once the H_2 supply chains are in place.

The techno-economic analysis conducted is subject to several assumptions to simplify the cost, emissions, and land requirement calculations. First, the supply chain model estimated costs and emissions statically without considering the available energy capacity for H_2 production in the selected country. In reality, all supply chain components are integrated into the energy system. Meaning, renewable energy or NG is not infinitely available for use in the H_2 supply chains. Considering it in the model would lead to different results regarding which and how many portfolios need to be combined to meet the demand. Next, current investment costs were assumed without economies of scale as utilization was not considered. Including learning effects and specific demand for the Netherlands or a specific sector would increase the accuracy and applicability of the results. In addition, only sample countries were selected for import, limiting the cost and distance estimates to a specific region. Looking at other countries with different distances may result in price and emissions differences which changes the results. Finally, in the environmental analysis, emissions and land requirements were analyzed based on the energy source and consumption during operation rather than directly linked to the supply chain component. The results provide thus only a small insight and comparison between supply chains rather than the actual total emissions.

The socio-political analysis conducted is qualitative and subject to a limited set of criteria, literature, and stakeholder opinions. To better understand social acceptability, a representative survey of the Dutch public with varying levels of knowledge in H2 supply chains should be conducted to determine their concerns. For policy acceptance, limited criteria have been explored in this thesis. A detailed policy analysis, using Ostrom's Institutions and Development framework, could be conducted to understand and address governance issues around H2 supply chains better.

In summary, the methodology provides a holistic assessment of domestic and global supply chains. It is subject to the improvements described above but adds the assessment of country and time-specific socio-political performance and supply chain portfolios to previous literature.

6

Conclusion

6.1. Key findings

In this thesis, the techno-economic and socio-political performance of different domestic and global H_2 supply chains has been analyzed to identify the key trade-offs of H_2 supply chain portfolios that meet the objectives of stakeholders in the Netherlands. To conclude the findings, the research questions are repeated and answered below.

SQ 1: What are the drivers, barriers, and stakeholder objectives for H_2 supply chains in the Netherlands?

Data was collected by conducting a literature review on H_2 supply chains in the Netherlands and from ten semi-structured interviews with Dutch stakeholders from different parts of the H_2 supply chain. The data was analysed using Geels' (2002) multi-level perspective framework.

Multiple drivers (objectives) for H_2 supply chains in the Netherlands were identified, of which the following three were mentioned the most: Sustainability, affordability and acceptability. Sustainability is closely related to climate change and the energy transition at the landscape level. The climate targets set by the Dutch government and the societal pressure to reduce fossil fuels influence stakeholders to opt for low-emission supply chains. Affordability refers to the high transition costs when changing to a new energy carrier at the regime level which slows down the implementation of H_2 supply chains. The preservation of competitiveness is essential, which is why cost-effective H_2 supply chains are targeted. Finally, acceptability relates to all three levels. The introduction of H_2 supply chains has implications for society as a whole as it involves stakeholders on all three levels in the decision-making process.

In addition, several barriers and facilitators were addressed. At the landscape level, experience with industrial gases and chemical processes, increasing societal pressure to reduce fossil fuels, and governmental climate targets are facilitators for implementing H_2 supply chains. In addition, the current energy crisis in Europe further increases the interest in using H_2, despite societal scepticism and a lack of legislation. At the regime level, existing NG and H_2 infrastructure, experience with the production of H_2, and a wide range of application possibilities constitute an increasing incentive for cooperation between stakeholders. However, high production and system conversion costs, a lack of concrete governance and support schemes, and different stakeholder objectives lead to complex decision-making processes and a slow expansion of supply and demand. At the niche level, intensive research is being conducted on H_2 technologies, e.g. to reduce costs or increase efficiency. The research environment, public support programs and the ambition to become a leader in the H_2 segment announced by the Dutch government are facilitators against the high investment costs, long development times and risk of disinvestment accompanying H_2 innovations.

SQ 2: Which technology combinations can form H_2 supply chains, and how would resulting portfolios look like?

To configure H_2 supply chains and portfolios, the following supply chain components were defined: Production, conversion, transport, reconversion and storage. The literature was then searched for components that are, or are likely to be, suitable for large-scale deployment in 2030. This resulted in a plethora of feasible H_2 supply chains, which was divided into domestic (Figure 3.11) and global supply chains (Figure 3.12). Each component's characteristics, advantages and disadvantages were then compared to select the final supply chains and portfolios for the Netherlands.

Seven supply chains were selected: Two domestic (D1, D2), four global H_2 supply chains (G1-G4), and one global NH_3 supply chain (G5). The latter was added for comparison to alternative supply chains which provide the same utilization options (except for H_2 feedstock).

Domestic H_2 supply chains in the Netherlands produce H_2 either by SMR with CCS or by PEM electrolysis using renewable electricity from offshore wind. SMR is the most commonly used method for large-scale H_2 production in the Netherlands and combined with CCS, it is a low-carbon production alternative. PEM electrolysis using offshore wind power leads no CO_2 emissions during production. PEM electrolysis is best suited for dealing with fluctuating offshore wind, which is widely available in the Netherlands. H_2 is transported in a compressed form via pipelines and stored in salt caverns before being used. Compressed H_2 is most commonly used to transport and store H_2 as it is non-toxic and requires little process energy. Pipelines are a suitable alternative to transport H_2 over long distances and in large quantities, especially in the Netherlands as they have a large NG pipeline network which can be retrofitted for the transport of H_2. Salt caverns are a mature large-scale underground storage alternative with high production rates, high safety, low losses and contamination.

Global H_2 supply chains also produce H_2 by SMR with CCS or PEM electrolysis using renewable electricity. After converting H_2 to either NH_3 or LH_2 for transport by ship to the Netherlands, it is reconverted to H_2 before being stored and transported like domestic supply chains. NH_3 has the highest volumetric H_2 density and a mature worldwide transport, conversion and storage infrastructure. It is a H_2 energy carrier but can also be used directly in various applications. LH_2 is a much discussed and researched option due to its high purity, high volumetric H_2 density, and low toxicity. Ships can import large volumes over long distances from several countries worldwide. Infrastructures and import standards for several energy carriers already exist, making it a feasible option that can be implemented in a timely manner.

Finally, eight different portfolios (P1-P8) were obtained by combining each of the selected domestic (D1, D2) with a global H_2 supply chain (G1-G4) so that an answer to SQ 3 can be derived.

SQ 3: How do H_2 supply chains and portfolios compare in terms of their techno-economic and socio-political performance?

To compare H_2 supply chains and portfolios, techno-economic and socio-political criteria were selected that were most frequently mentioned in stakeholder interviews and literature and are consistent with the stakeholder objectives identified in SQ 1. The criteria analyzed were: CAPEX , OPEX , CO_2 and NOx emissions, land requirement, social acceptance, and political acceptance. The performance of each supply chain component for each criterion was determined creating a supply chain model with current literature data.

H_2 supply chains using SMR with CCS are the most affordable supply chains at 3.83 €/kgH_2eq for domestic (D2) and 5.3 €/kgH_2eq for global (G3) supply chains. They are less energy and capital intensive production compared to PEM electrolysis and renewable electricity which are on average 15-20% more expensive. H_2 supply chain costs are dominated by energy costs from production, conversion and reconversion, which is consistent with previous studies. However, the recent increases in grid electricity and NG prices lead to H_2 costs from SMR with CCS that are cost-competitive to supply chains using renewable energy.

H_2 supply chains using PEM electrolysis with renewable electricity are the most sustainable supply chains when considering their operational energy consumption. They emit 0.5 kgCO_2/kgH_2eq and 0.3 gNOx/kgH_2eq for domestic (D1) and 1.4 kgCO_2 /kgH_2eq and 3.2 gNOx/kgH_2eq for global (G1) supply chains. Thus, by using renewable electricity the supply chains emit up to 3 times less CO_2 and up to 8 times less NOx than comparable domestic and global H_2 supply chains using SMR with CCS. However, this study has shown that global H_2 supply chains using renewable electricity have similar or higher emissions than domestic supply chains using SMR with CCS due to the additional conversion, transport and reconversion. When considering land requirement for the energy consumption during operations, the H_2 supply chains using SMR and CCS are the most sustainable supply chains as renewable electricity can require up to 150 times more land than using fossil energy.

The analysis of the acceptability of H_2 supply chains revealed that the domestic (D1) and global supply chains (G1 and G2) using renewable energy to produce H_2 have the highest acceptance. They align with the social values of climate goals and are supported by the government with support schemes and mentioned in the H_2 strategy. It was also found that social acceptance of H_2 supply chains is overall lower than the political acceptance. H_2 supply chains have not yet been widely established and used in the Netherlands. In particular, the transport and conversion of LH_2 and the transport and reconversion of NH_3 have limited acceptance as they are not widely known, developed or tested for large scale H_2 supply chains. Therefore, society poorly understands the risks and impacts associated with H_2 supply chains on the environment and human health. This can lead to concerns and resistance that hinder the implementation. Political acceptance in the Netherlands is high for the domestic production, transport, and storage components, as specific support programs and H_2 strategies have already been presented. However, for global supply chains no support programs or strategies for a preferred energy carrier or transport medium were found. The lack of subsidies and strategies creates uncertainty and slows the implementation process.

Finally, the results show that the most affordable supply chain portfolio is P1, a combination of the most affordable H_2 supply chains D2 and G3. The most sustainable supply chain portfolio is P7, which is a combination of the most sustainable H_2 supply chains D1 and G1. Thus, there is no one supply chain or portfolio that performs best in every criterion. Different trade-offs must therefore be made.

What are the key trade-offs of future H_2 supply chain portfolios that meet stakeholders' objectives in the Netherlands?

The study showed that for stakeholders in the Netherlands, affordability, sustainability, and acceptability are the most important drivers for H_2 supply chains to meet their climate goals, remain competitive, and receive social and political acceptance for a smooth and rapid implementation. A combination of domestic and global supply chains will be essential to meet national energy needs in the future. Many configurations of H_2 supply chains are possible, whose performances differ mainly by the energy source and energy carrier used.

The key trade-off for these H_2 supply chain portfolios in the short term are low costs and a low land requirement versus low emissions and high acceptability.

Thus, no single supply chain portfolio can be selected to meet all targets best. Using established SMR and CCS facilities results in the highest emissions, thereby decreasing political and social acceptance. However, it has the lowest land requirement and cost for H_2 production, allowing for timely and economical implementation. H_2 from renewable electricity is more accepted due to low emissions and thus impact on climate. However, these supply chains have under current price and technology developments higher costs and require more land, making implementation difficult especially in densely populated countries such as the Netherlands. In the long term, the expected cost and efficiency learning curves, as well as possible cost reduction due to economies of scale can lead to lower investment and energy costs, allowing supply chains with PEM electrolysis fed with renewable electricity to compete with those using SMR with CCS in the future. Cost-competitiveness would also be given is the electricity price would go down to 0.02 €/kWh. In addition, social and political acceptance may change with the implementation of supply chains, new regulations and policies and cultural changes. The trade-offs identified are therefore time and country-dependent and need to be reconsidered when investigating a different time frame and country.

H_2 supply chains are complex systems embedded in the existing energy system. They are influenced by technology trends and energy prices and constrained by individual countries' spatial and climatic conditions, policies and societal mindsets. This research has shown that no universal supply chain portfolio can fulfill all objectives of stakeholder's in the Netherlands. Each supply chain has advantages and disadvantages that need to be weighed by stakeholders depending on the use case and objective. Nevertheless, to accelerate the implementation of H_2 to reach national climate targets and improve energy security, additional policies are needed in the Netherlands to overcome the existing barriers and uncertainties. In particular, policies need to define conversion, transport and reconversion strategies and support programs, while taking into account impacts and risks for society, and emissions from the entire supply chain when importing H_2.

6.2. Recommendations

Based on the analysis performed in this study and additional insights obtained while investigating this topic, the following recommendations on H_2 supply chains can be made.

The economic analysis showed that energy prices and investment costs for H_2 supply chains have a measurable impact on the total cost of H_2. Therefore, these parameters and their price development trends in the future should be further explored. Furthermore, the scaling and learning curve of the supply chain components should be investigated to improve the credibility of the results.

The sustainability analysis would benefit from extending the criteria, as in this study, only the energy consumption for CO_2, NOx, and land requirement were considered. A life cycle analysis of the individual H_2 supply chain components should be conducted to capture emissions for the direct supply chain. This would include emissions, toxicity, use and consumption of other materials such as rare earths, and end-of-life impacts. Furthermore, research should look into low-emission transport alternatives, as it was found that shipping accounts for more than half of the global supply chain's emissions.

The socio-political analysis would benefit from a quantification method of acceptability for better comparability of supply chain components. It is also suggested that the acceptability analysis be expanded to include additional parameters, such as a more detailed analysis of supply chain risks so that policymakers and stakeholders can better understand and thus better incorporate them into their policies. To better understand social acceptance, a representative survey of the Dutch public with varying levels of knowledge in H_2 supply chains should be conducted to determine their concerns. This can serve as a basis for further research on engaging society and understanding their concerns to develop more specific policies. In addition, a detailed policy analysis using Ostrom's institutional and development framework is proposed to identify and analyse the institutional barriers and policy instruments in more detail. The results would lead to identifying concrete coordination issues and proposing new policy recommendations. These could be compared to other countries to provide new insights into the effectiveness of policies to promote the implementation of the H_2 supply chain. This could help policymakers prioritize the most efficient interventions and potentially allow comparison with the efficiency of government interventions such as subsidies.

Further, it is recommended to add and investigate the Dutch H_2 demand, energy supply for H_2 and components operation capacity to the supply chain model as well as the specific sectors and transportation routes within the Netherlands to create a more detailed and flexible H_2 supply chain model. Extending the model can be used to study the optimal H_2 supply chains for each stakeholder considering their demand profile and objectives. This would result in more realistic and predictive results for the Netherlands.

The import of H_2 becomes increasingly important for the Netherlands. As a growing number of countries are considering H_2 in the future, this could lead to H_2 becoming highly competitive to acquire. It is thus recommended to analyse possible importing countries to give policymakers a better overview of the possible countries, their H_2 supply potential, and the advantages and disadvantages to build relationships with the right countries in the long term.

Lastly, this thesis provides stakeholders with knowledge about the technical, economic, environmental, social, and political performance of H_2 supply chains, country-specific drivers and barriers, and facilitators on supply chain components. It can serve as a basis for further research on how to agree on which H_2 supply chains to select for the Netherlands. Research into a decision-making process with all stakeholders involved is therefore recommended.

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A

Appendix: Literature review

Three literature studies were conducted to (1) identify H_2 supply chain components and the related technologies to configure H_2 supply chains and portfolios, (2) identify performance criteria to analyze H_2 supply chains, and (3) analyze the current H_2 supply chains in the Netherlands to identify drivers, barriers, and stakeholder objectives. Each literature study followed the four steps according to Van Wee (2021), as shown in Figure A.1-A.3.

First, relevant articles were identified by using Scopus or Google Scholar with different keywords obtained by scanning different articles and combining them in different ways. Due to increasing development and interest in H_2, only articles published in the English-language and, depending on the topic, from the last five (2018 to 2022) or ten years (from 2012 to 2022) were included in the study. After the identification step, articles were screened for eligibility in two iterations using subject-specific selection criteria. For this purpose, the title, keywords, and abstract were read. Finally, an unstructured backward snowballing using the same selection criteria was applied to include relevant articles that could be excluded based on the chosen database or keywords.

The final selection of literature served as input for Chapters 3 and 4. Figures A.1-A.3 show the conceptual literature search and selection process and Tables A.1-A.3 the selected articles for each literature study.

Literary study 1: H_2 supply chain components and technologies

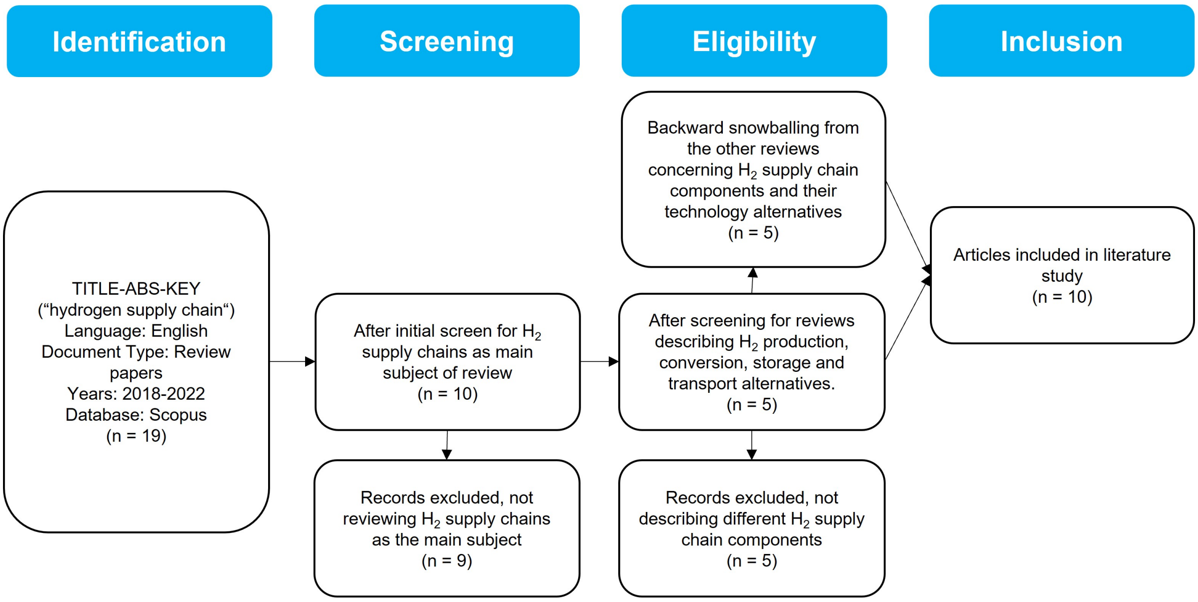


Figure A.1: Literature search and selection process for H_2 supply chain components and technologies

Table A.1: Selected articles for H_2 supply chain components and technologies

	Author(s)	Year
1	*IEA International Energy Agency	2015
2	Robles, J. Almaraz, S., Azzaro-Pantel, C.	2018
3	*Detz, R. J., Lenzmann, F. O., Sijm, J. P. M., Weeda, M.	2019
4	Abdin, Z., Zafaranloo, A., Rafiee, A., Merida, W., Lipinski, W.	2020
5	Ji, M., Wang, J	2021
6	*Berger, R.	2021
7	*Brändle, G., Schönfisch, M., Schulte, S.	2021
8	Olabi, A., Bahri, A., Abdelghafar, A., Baroutaji, A, Sayed, E., Alami, A.	2021
9	Faye, O., Szupunar, J., Eduok, U.	2022
10	Agyekum, E., Nutakor, C., Agwa, A., Kamel, S.	2022

*Literature retrieved from snowballing

Literary study 2: H_2 supply chain performance criteria

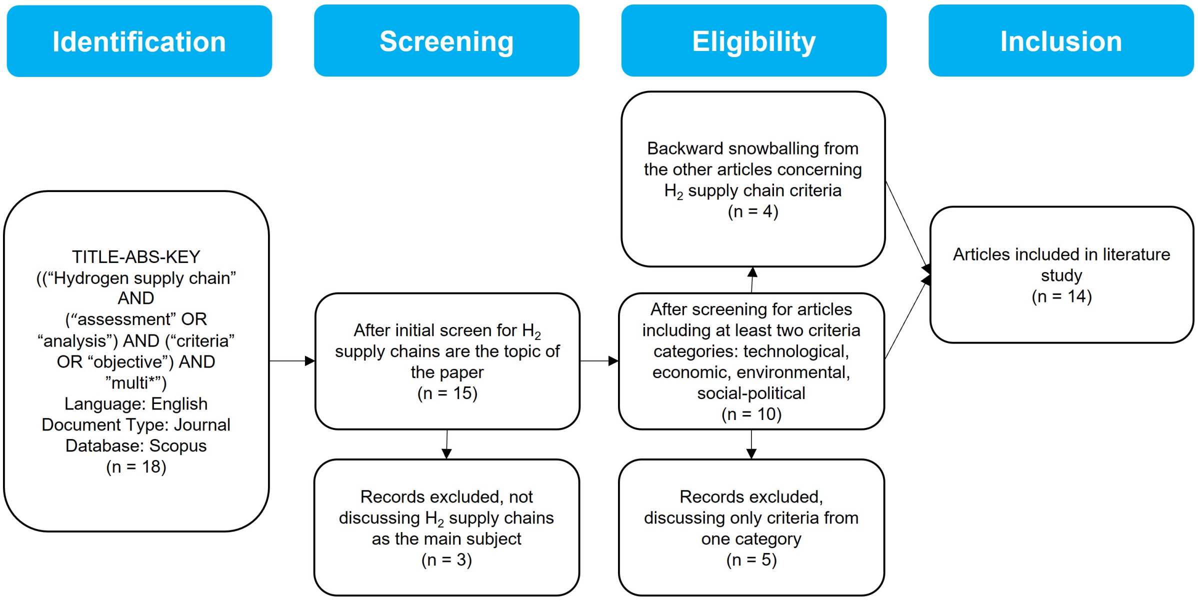


Figure A.2: Literature search and selection process for H_2 supply chain performance criteria

Table A.2: Selected articles for H_2 supply chain performance criteria

	Author(s)	Year
1	De-León Almaraz, S., Azzaro-Pantel, C., Montastruc, L., Boix, M.	2015
2	Almansoori, A.,Betancourt-Torcat, A.	2016
3	*Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., Stolten, D.	2017
4	Manzardo, A., Ren, J., Toniolo, S., Scipioni, A.	2017
5	Xu, J., Li, Q., Xie, H., Ni, T., Ouyang, C	2017
6	Acar, C., Beskese, A., Temur, G. T.	2018
7	Ren, J., Toniolo, S.	2018
8	Ochoa Bique, A., Maia, L. K. K., La Mantia, F., Manca, D., Zondervan, E.	2019
9	*Heuser, P.-M., Severin Ryberg, D., Grube, T., Robinius, M., Stolten, D.	2020
10	Robles, J. O., Almaraz, S. D. L., Azzaro-Pantel, C.	2020
11	Fazli-Khalaf, M., Naderi, B., Mohammadi, M., Pishvaee, M. S.	2020
12	Lin, R., Lu, S., Yang, A., Shen, W., Ren, J.	2021
13	*Kim, A., Kim, H., Lee, H., Lee, B., Lim, H.	2021
14	*Ishimoto, Y., Voldsund, M., Nekså, P., Roussanaly, S., Berstad, D., Gardarsdottir, S. O.	2022

*Literature retrieved from snowballing

Literary review 3: H_2 supply chains in the Netherlands

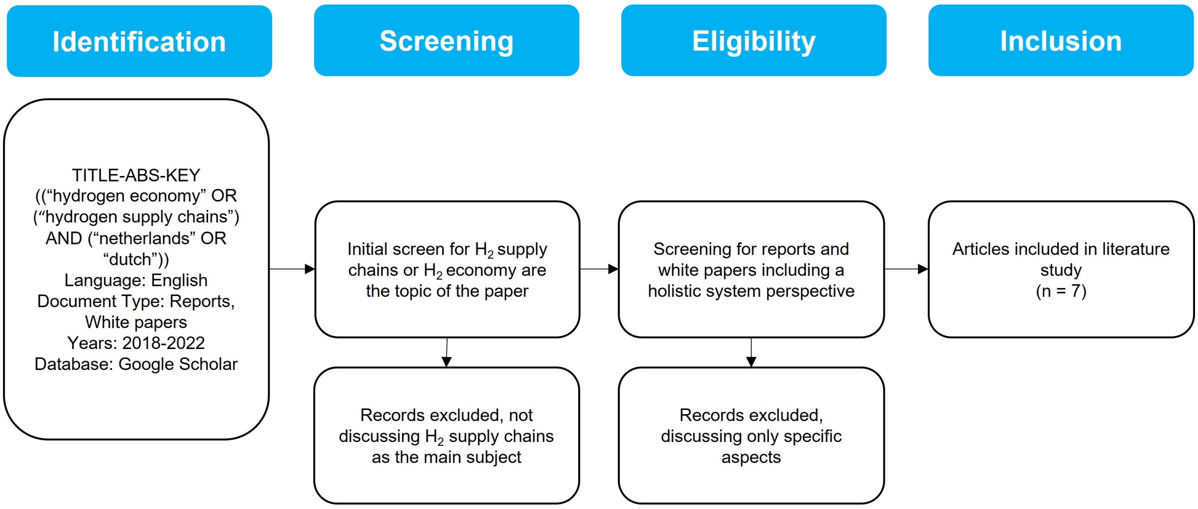


Figure A.3: Literature search and selection process for H_2 supply chains in the Netherlands

Table A.3: Selected articles for H_2 supply chains in the Netherlands

	Author(s)	Year
1	Weeda, M., Gigler, J.	2018
2	Mulder, M., Perey, P., Moraga, J.L.	2019
3	Detz, R. J., Lenzmann, F. O., Sijm, J. P. M., Weeda, M.	2019
4	Rijksoverheid	2020
5	IEA International Energy Agency	2020
6	RVO, FME, TKI Niew Gas	2021
7	PBL Netherlands Environmental Assessment Agency	2022

B
Appendix: Interview protocol

Opening

Objective: Identification of stakeholders' strategies, utilization, and assessment of Hydrogen (H_2) supply chains that will meet demand in the Netherlands in 2030.

Procedure: The introduction of the interview is followed by a narrative dialog. Finally, direct questions are asked about specific content, if it has not been mentioned in the interview so far.

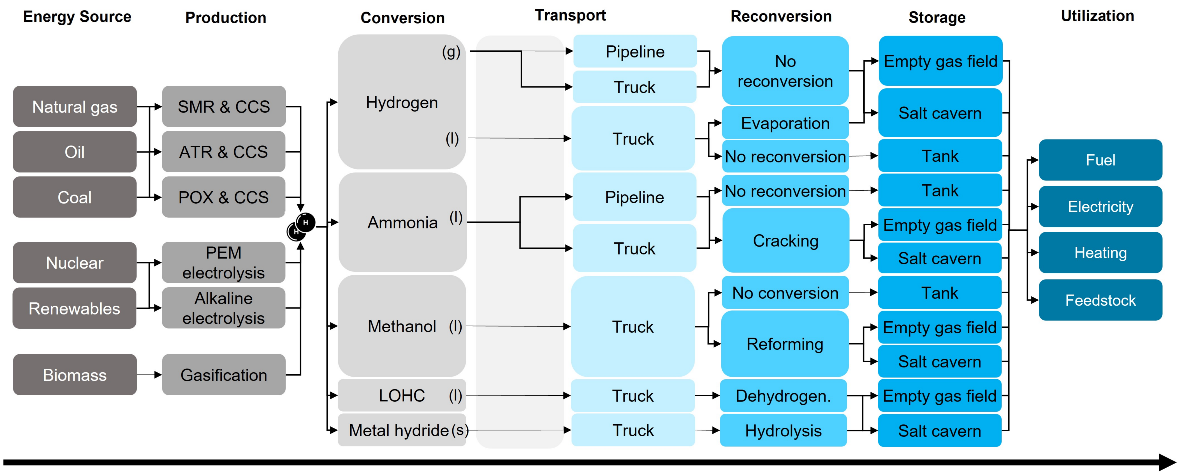
Introduction

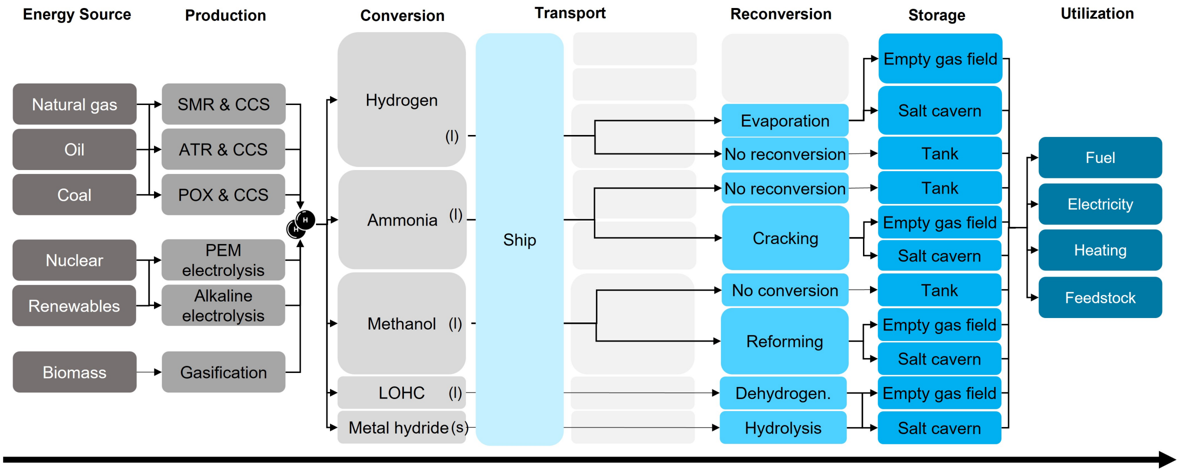
In this interview different domestic and global H_2 supply chains with defined alternatives are presented as possible solutions for the Netherlands in 2030 (see below). The supply chains defined for this study consist of the following seven components: Energy source, production, conversion, transport, reconversion, storage, and utilization. Many H_2 supply chains in other configurations are also currently being discussed in academia and industry, but these will not be discussed further in this interview.

Questions

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today and how will it change in the future?
2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?
3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?
4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?
5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?
6. When assessing H_2 supply chains, what are the most important criteria to consider?

Hydrogen supply chains




Energy Source
Production
Conversion
Transport
Reconversion
Storage
Utilization
Natural gas
Oil
Coal
Nuclear
Renewables
Biomass
SMR & CCS
ATR & CCS
POX & CCS
PEM electrolysis
Alkaline electrolysis
Gasification
H
Hydrogen
(l)
Ammonia
(l)
Methanol
(l)
LOHC
(l)
Metal hydride
(s)
Ship
Evaporation
No reconversion
No reconversion
Cracking
No conversion
Reforming
Dehydrogen.
Hydrolysis
Empty gas field
Salt cavern
Tank
Tank
Empty gas field
Salt cavern
Tank
Empty gas field
Salt cavern
Empty gas field
Salt cavern
Fuel
Electricity
Heating
Feedstock

C

Appendix: Interview summaries

Interview 1

Interviewer	Maleen Hiestermann
Interviewee	Energy producer
Job description	Business Developer
Date	20.05.2022
Duration	35 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

Currently, our company develops an offshore wind electrolysis project for low-carbon H_2 in the Netherlands. We need to make sure we reach customers with a product at a price that meets their needs. We are still building our H_2 business and are not selling H_2 to customers today. However, some of our assets produce H_2 for our needs.

Our goal is to play a role in the entire H_2 supply chain. We want to produce H_2 and provide the production energy required. We also want to be involved all the way up to the customers who uses H_2. We do not want to own everything in the supply chain but we would like to control it. We want to operate the regional and national Dutch market to leverage existing assets such as electrolyzers or import terminals to supply our customers with the H_2 they need.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

For the primary energy source and domestic production in the Netherlands, we focus on renewable H_2 production using offshore wind energy and electrolysis. We could supplement wind with solar energy to achieve an additional load factor of 5%. Low-carbon H_2 is distinguished between recovered H_2 from processed gases in refineries and chemical plants and specifically produced H_2 with SMR and CCS. We are not actively pursuing stand-alone investments in SMR and CCS. We may consider upgrading H_2 as a byproduct if we want to balance the intermittent renewable H_2 supply. Currently, there is a demand for 1.5 million tons of H_2 in the Netherlands, of which 600,000-700,000 tons are produced as a byproduct, and the rest by SMR. If we replace low-carbon with renewable H_2 production, this means that SMR capacity will not be fully utilized. What will those assets then be used for? As a balancing option for renewable H_2?

In terms of imports, we look mainly at renewable and low-carbon ammonia and liquefied H_2 as energy carriers. We have projects that are well advanced under our control. At the same time, we look at other technologies as we have not made a final investment decision on any import project or carrier yet.

In terms of utilization, industrial customers using grey H_2 as feedstock will be under particular pressure to convert it to renewable or low-carbon H_2. Replacing natural gas with H_2 and using it as a fuel for high-temperature heating could probably make a more significant contribution. That is the difference between 2030 when more attention is paid to feedstock replacement, and 2050, when H_2 is also used as a fuel for high-temperature heating and electricity.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

Above all, we need governmental support in H_2 supply chains to get it going. Currently, there is a gap between the willingness to pay and the actual cost of the product in all use cases. There is additional value if there is a premium, such as using H_2 in the refinery. Current policies are however insufficient to fully address the transition to a H_2 economy. So where and how will this support come about?

Companies using H_2 as a feedstock need a very reliable base load and high-purity H_2. Currently, renewable H_2 cannot provide that on its own because there are no imports and no storage yet. There is visibility to store H_2 in the H_2 backbone, but that needs to be defined more precisely. So, if a customer wants to decarbonize their H_2 consumption in the short term, low-carbon or a mix of low-carbon and renewable energy is an option as it is less expensive. Suppose a company is thinking about its future from 2030 onward, it should only use renewables.

In the end, our customers are primarily concerned with the carbon intensity of the H_2 they use and the price. They want to comply with legislation, so if there is a mandate from the Dutch government or the EU to use 50% renewable H_2 at their site, they know that they have to adhere to it.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

We know what it costs to produce H_2 using offshore wind turbines. The price of electrolyzers may come down over time. Pricing is essential for primary energy source selection and production to compete with imports in the long run. It is good that there is an existing import structure regarding ammonia import. However, there are concerns about the health and safety of ammonia and nitrogen emissions from cracking. We find liquid H_2 more attractive from a technology perspective because we are familiar with the liquid natural gas business. However, there are no ships for global transport yet, apart from the test ship between Japan and Australia. For both ammonia and liquefied H_2, the efficiency is questionable when you look at converting and reconverting H_2. If one of the two carriers is preferred worldwide and there are no fundamental differences between them, that will also influence our decision.

For the end customer, however, it does not matter which energy carrier is used. If the final product meets the requirements (purity and base load), they will use it. Especially in light of the current war in the Ukraine, it is important to complement some of the domestic production with imports from a diverse set of countries similar to our natural gas approach.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

The Netherlands provides subsidies for CCS to produce H_2, which is relevant because you can then build a future low-carbon supply chain for H_2. EU measures also require retailers of gas and diesel to meet a blending target for transport or use H_2 as part of their refining process. They receive Renewable Energy Directive II credits in doing so. These are reasonable measures, but they are not enough. What we need is a carbon contract for differences on the customer side. For example, if you are a chemical company and you want to use renewable H_2, then the amount of CO_2 saved by buying renewable H_2 should be taken into account. You should be compensated for using renewable H_2 so that you can pay the H_2 producer and still make a business case.

6. When assessing H_2 supply chains, what are the most important criteria to consider?

Affordability for the end user is essential. Otherwise, companies producing or consuming H_2 will not necessarily stay in the Netherlands. This is an uncertainty in the long run: How will the scenarios develop, and how much industry will stay in the Netherlands or Europe? The current geopolitical situation makes us want to keep the industry from a strategic point of view. At the same time, we want to convert this industry with a higher-priced feedstock for raw materials or heating fuels. It may not be sustainable for society to bear the different costs to keep the industry here or for the industry to stay here but then lose export markets it supplies because it is too expensive.

Aside from the industry potentially leaving Europe, there is the impact of other H_2 off-take markets such as Japan or South Korea. Suppose other markets move much more aggressively than we are to low-carbon technologies. In that case, it may be that, similar to natural gas, ammonia or liquefied H_2 will not be as widely available as we think.

Interview 2

Interviewer	Maleen Hiestermann
Interviewee	Hydrogen producer
Job description	Business Developer
Date	03.06.2022
Duration	45 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

Our company has been selling H_2 in traditional means of transportation (cylinders, cylinder bundles, and tube trailers by truck) for many years. We also offer ”build-and-operate” systems for on-site electrolysis or SMR. This means that we install, operate and maintain a H_2 production facility for industrial customers with a high continuous demand for H_2. We thus provide H_2 in two ways: (1) We produce and supply H_2 directly for small to medium-sized customers. (2) We install and operate H_2 plants for larger industrial customers on site. We have the knowledge and technology to handle all supply chain elements, from production over storage in salt caverns to the last mile delivery. We produce what our customers demand based on their available resources.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

In the Netherlands, SMR with CCS is already and will be the primary driver of industrial H_2 by 2030, simply because the technology of large-scale plants will be available in time. The target for 2050 is a large share of electrolysis using wind and solar power. However, imported renewable H_2 produced in countries with better climates will account for at least an equal share of Dutch consumption.

We also work on two projects where H_2 is the end product of biomass gasification (wood chips). However, there is always the question of feedstock availability, and even if the availability is there, one can immediately think about the environmental footprint of transporting the feedstock to the gasification plant. We see that gasification projects are postponed in the Netherlands because it has been recognized that importing trees from Canada is not good for the environment. Some smaller projects still have a genuine business case but will not play a big role. H_2 as a byproduct, will also contribute to a small part of the total H_2 supply in the Netherlands.

As for import, each carrier or form of transport has its benefits. In the short term, we see a mix of blending H_2 into existing natural gas pipelines and then recovering it from the pipelines at our customers' sites. The absolute efficiency of liquid H_2 transportation is questionable due to the energy required to keep it at a specific temperature and the CO_2 emissions caused by the ship. This already invalidates the idea of low-carbon transportation. However, we consider using liquid H_2 on a larger scale for inland transport. In Europe, we are not yet as advanced as in the USA as we have only three liquefaction plants. The market is expanding, but these are large-scale projects with high H_2 demand. Ammonia and methanol are interesting for direct use as we are already familiar with their transport from our traditional business. We investigate them for direct use with our customers. We also follow the development of LOHCs closely but do not interfere too much.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

The biggest challenge I see on the production side is the availability of the technology, i.e., the scale of reliable electrolyzers by 2030. The other challenge is the financial side. Everyone wants to be the first, but no one wants to take the risk. A clear subsidy system needs to be implemented to create a level playing field for all industrial users so that no one doubts their competitiveness if they are the first to switch to renewable H_2. However, I see the difficulty in limiting the plant capacity to 50-100 MW in the subsidy scheme, as this invites smaller companies with no knowledge or experience in manufacturing and operating a H_2 plant. In these business cases, many economic and safety issues are ignored to get the project off the ground and eligible for the subsidy program. In the long run, this could lead to many low-quality projects or projects that do not have strict safety or production quality policies. If you subsidize too quickly, you could end up subsidizing the wrong project.

In addition to the financial factors and the availability of the technology, the maturity of the technology is an issue that is often discussed. We have been working with electrolyzers for years, but these are all small plants of 5-8 MW, while current discussions always talk about large plants, i.e. 50-100 MW, which have never been built. Talking to customers is a 20-30 year investment, so these factors play an important role.

When looking at the market, there is a split between the traditional industries that need high-quality H_2 as a fuel or feedstock and the future industries that use H_2 for electricity generation and heating their homes. I worry about how the different quality types of H_2 can be mixed in the backbone when we all use it for different purposes. We see the benefits of a common carrier system, but as an industrial H_2 producer, we are used to contracts between two companies. We do not know how it will work regarding governance, responsibility, and quality obligations, which are entirely different in a consumer market than between a gas producer and a gas buyer.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

The maturity and capacity of the technology are important. In addition, customers also pay attention to their brand image/reputation. So it is not only an economic or technical decision but also about showing their surroundings that they are reducing their environmental footprint. However, technical and economic criteria are the main factors. For the economic criteria, taxes on GHG emissions and their development are important to consider. They will become more expensive, but no one knows precisely by how much. This makes future investments difficult for our customers.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

At the moment, the governmental support is minimal. In the last two years, the subsidy programs have focused much on CCS. This is good for us as a company. However, when talking about the strategic goals of the Netherlands compared to the neighboring countries, more support and budget should be allocated to electrolysis projects. There are many announcements of intentions or collaborations, but ultimately companies wait for the final investment decision based on a subsidy program. This slows down the transition, which will also lead to frustrations in the long run. If we wait too long, it could scare off potential investors. It is always easy to point to Germany, but they have had larger budgets for H_2 for a longer time as CCS is not an option for them. Because of the geographic location of the Netherlands and their connection to gas fields, CCS was more a priority for us.

Overall, everyone is looking at politics right now to establish the systems in terms of subsidies, qualifications, quality control and trading places. That is 100% the key to getting things going, and we need a European-structured system rather than each country doing its policy.

Interview 3

Interviewer	Maleen Hiestermann
Interviewee	Transport and storage operator
Job description	Advisor
Date	20.05.2022
Duration	35 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

Our goal is to create a national H_2 transmission system. We also try to get a complete overview of the development of supply and demand, but we do not see our role in developing supply and demand. Our role is to store H_2, mainly in salt caverns, and transporting it. Currently, we have a pipeline in Zeeland that transports H_2. Then there are numerous investment decisions for several other pipelines and the H_2 backbone, which from 2027 will connect the big industrial clusters in the Netherlands with Germany and Belgium. The future H_2 backbone will be based on 85-90% of existing pipelines used to transport natural gas. A number of these pipelines will be freed up by the termination of the Groningen field operations. We also look at the conversion of H_2 to natural gas for households. Households are mainly supplied with natural gas and using H_2 instead requires a conversion of the heating systems, which could be very expensive.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

In the first few years, H_2 will be used primarily as a feedstock in industry, then as a heating fuel in industrial processes, and later as a fuel in heavy mobility. Electricity will be added later, perhaps after 2030.

For production, the focus is on electrolysis with renewable electricity. The official Dutch position is that low-carbon H_2 is used as a starter solution. The new EU guidelines state that as early as 2030, at least 50% of all industrial H_2 should come from renewable sources. By 2030, there will be about 4-6 GW of electrolysis in the Netherlands, which is still not enough. The share of SMR will be higher than electrolysis but that will change by 2050. By 2026/2027, there will be a H_2 import terminal in Rotterdam, through which, e.g. ammonia could be delivered directly to fertilizer factories.

The H_2 backbone will be used to transport high-quality H_2 between large industrial clusters that use it as a feedstock or for high-temperature heating. The backbone will connect to salt cavern storage facilities and countries such as Germany and Belgium. The system thus has two characteristics: (1) Transport between industrial clusters and import terminals and (2) transit between the Netherlands, Germany and Belgium for H_2 mainly produced in the North Sea by electrolysis. The pipelines will use H_2 as a gas. Otherwise, ammonia will probably be imported and transported directly to the industry. We also consider import terminals converting ammonia to H_2 and transporting it as gas, but this requires a good business case.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

The most critical part will be to create enough demand in the industry to make the system work properly. Part of the industry is still hesitant to make or prepare for a switch from natural gas to H_2 because it is too expensive.

Converting the transport system should not pose significant technical difficulties. We have already investigated the possibility of converting the natural gas pipelines in the Netherlands to transport H_2, and it is feasible for 99% of all pipelines in our system. The only thing that needs to be done is to inspect, clean and possibly replace certain parts, which involves little investment. However, the critical question is whether enough pipelines will be available for reuse in the coming years to make the H_2 backbone a reality. This is mainly a consequence of the recent gas crisis, which has changed the supply situation, as much liquefied natural gas must be transported to the Netherlands to compensate for the loss of Russian gas supplies.

Another critical point is the uncertainty about standards for the maximum percentage of mixing H_2 and natural gas, as well as the lack of guidelines for safety standards. A typical pipeline for gas distribution in the Netherlands needs four meters on both sides for safety measures, but this has not been defined yet for H_2. They probably need more space. This is not a problem for larger pipelines, as many pipelines in the Netherlands run in wide corridors and can easily be extended with pipelines for other gases. However, it will be complicated for new distribution pipelines.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

An important factor is the availability of space, as the Netherlands is a densely populated country with little room for new developments. For example, where can we find enough space for a new type of storage or large-scale electrolyzer? Another factor is the availability of people who can implement the new developments.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

The Dutch government has a good idea of the role we should play in the energy system, namely transport and storage. The government watches closely what we are doing and supports us in developing the H_2 backbone. It supports us financially and in finding enough space for new pipelines or in legal matters. We receive sufficient support of around 750 million euros to realize the H_2 backbone, making it easier to complete it in time.

6. When assessing H_2 supply chains, what are the most important criteria to consider?

The H_2 system will not exist and be developed by itself. It will depend on other systems, such as the electricity system, as it is a solution to balance the electricity supply and demand. Therefore, dependence on other systems is essential for evaluation. Another problem of balancing supply and demand links to flexibility. Sufficient transmission capabilities could impact the need for power plants, electrolysis, and storage facilities. If there are sufficient transmission options, there may be less need for electrolysis, which affects H_2 production. So there is a dependency between transportation and flexibility.

Interview 4

Interviewer	Maleen Hiestermann
Interviewee	Built environment
Job description	Consultant
Date	25.05.2022
Duration	40 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

Our company is involved in many H_2 projects in the Netherlands. On the one hand, we work for the Dutch government to provide them with knowledge for their subsidy programs. On the other hand, we also work with the industry in the Netherlands to advise them on issues related to infrastructure and technology, but also the economic viability and social acceptance of H_2 projects. Finally, we also take care of permit applications for H_2 production projects.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

Depending on how quickly projects develop abroad, the import of H_2 will be greater than local production in 2030, but definitely in 2050. First, we will import ammonia for direct use because at least an existing production infrastructure is in place. In the long term, large-scale cracking of ammonia to H_2 could be added, which has not been done before but can be developed relatively quickly. However, you need much energy which increases the costs of the imported H_2. Liquid H_2 will also play a significant role because it is much easier to convert back to H_2. Compared to ammonia, liquid H_2 might become cheaper in the long run. However, I do not think that there will be a single winner. In the short term, methanol and LOHC will also play a role. LOHC can be used for shorter distances because many existing processes and facilities at ports are already in place. However, they become expensive at longer distances because you have to ship LOHC back and forth. At a certain distance, pipelines will then have to be considered instead of ships. H_2 gas will have the highest share, mainly if we use pipelines with H_2 gas, but it will be important for ports to be flexible and prepare for a mix to be future-proof.

The use of low-carbon H_2 depends on current research but also on EU policy, which is leaning towards renewable H_2. It makes sense to work on low-carbon H_2 in parallel because renewable H_2 requires much renewable energy, and there is much resistance to the production size of solar and wind farms. I studied the import of H_2 in over 25 countries, and the only country that worked on low carbon H_2 was Australia. Well, those 25 countries were all countries that had perfect conditions for solar, wind or hydropower, which is why they chose to produce renewable H_2. Still, I see importing renewable H_2 as more likely than low-carbon.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

One of the most significant uncertainties is that there is not enough infrastructure and human resources to build it.

The nitrogen crisis also tempts many projects around H_2 or CCS to stagnate. After all, you cannot receive building permits because of the nitrogen that pollutes the air and natural habitats.

Going further, H_2 is still too expensive. Many companies are already doing some matchmaking to link the off-taker with the developer on the production side. They agree on contracts to produce a certain amount which will then be consumed for the next ten years. The German government is trying to solve this chicken-and-egg problem by calling for tenders for renewable H_2 projects. The bids will be matched with what the industry is willing to pay. It will help to accelerate the energy transition because H_2 prices are 4-8 times higher than natural gas.

Another critical issue is demand. If you look at business scenarios, H_2 is often not preferred by the industry because it is too expensive compared to CCS or electrification. The government wants the industry to go hybrid to be able to switch between electricity and H_2 to make the best use of available energy. However, for cost reasons, that is not attractive to the industry.

Another problem is space constraints, especially in ports, because they have limited space available.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

The most important factors are the costs and the existing infrastructure. The costs are the free onboard costs, i.e., the costs for producing H_2 and converting and delivering it to the ports. They do not include infrastructure costs needed in the Dutch ports for the supply chain or reconversion costs. Considering the reconversion costs, you need a lot of energy, which we do not have in the first place as we already import energy.

On the environmental side, the spatial impact and water requirements are important factors, as H_2 production often takes place in countries where water is scarce, which is a significant problem.

As for the technical side, efficiency is not so important, as it all comes down to price. When electricity is abundant and available at a low price, efficiency is unimportant.

Finally, it is important to include ethics in the social assessment because most H_2 production will take place in countries where electricity production for H_2 is perhaps ten times the total electricity demand of the country. The investment figures could be twice the country's GDP. Countries will be flooded with money from international project developers without knowing if the business is worthwhile or if they will be exploited.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

The EU is a crucial factor when it comes to H_2 supply chains because if they aim for renewable H_2 with their policy, that influences the amount of H_2 we import. If we go for low-carbon H_2 first, we can produce it quite well in the Netherlands. Renewable H_2 will be more difficult to produce. The EU is going to set up a H_2 scheme where it will set the requirements for renewable H_2, and one of the requirements is that if you import H_2 from a country, that country must also make an effort to decarbonize itself. That could affect how much H_2 we will import and the countries we import it from.

On the import side, the Netherlands does not specify anything, but within the country, it does. Especially ports like the Port of Rotterdam are approaching all countries that are likely to be able to produce renewable H_2 and asking them to export it to the Netherlands. In return, they offer to provide their knowledge to help them build the H_2 supply chain. They know that many industries in Northwest Europe obtain a lot of energy and resources through the ports. If they do not provide energy in the future, all these industries will disappear.

Overall, many things are well in place in the Netherlands. For example, the industry knows that there is an emission trading system, and they know what to expect, even if energy prices rise and fall these days. However, the industry needs more subsidies for H_2 because it is not explicitly included in the SDE scheme.

Interview 5

Interviewer	Maleen Hiestermann
Interviewee	Industrial sector
Job description	Consultant
Date	17.05.2022
Duration	38 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

Our company assists in the planning and permitting of H_2 production facilities. We had the first two permits for large-scale H_2 production in the Benelux. Most of our customers are project developers and sell H_2. Currently, we are working with companies designing and permitting offshore wind plants for producing H_2.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

Today, our production projects are mainly based on offshore wind turbines contractually linked to onshore electrolyzers. According to the EU's Renewable Energy Directive II, the wind profile must match the H_2 production profile to ensure that the produced H_2 is renewable. That will be the default H_2 production option in the Netherlands. Studies show that most H_2 will be imported through our ports by 2050. The primary energy source will be a combination of wind and solar energy, coming from places with enough wind and good solar conditions. By 2030, low-carbon H_2 based on SMR will still account for the highest share of total production. For new markets, we will partially switch to electrolyzers. Current production through SMR will be adjusted with CCS to achieve sufficient emission reductions in the short term. However, by 2050, I expect this production method to account for only a tiny share as we aim to reduce total natural gas production in the Netherlands.

For conversion, everything is transported as H_2 and not yet as LOHC or ammonia. There are many studies about what should be the right energy carrier, especially for imports. The initial transportation plans are based on trucking. However, once production is up and running, almost all H_2 will be transported by pipeline to industrial users as gas. This will account for 90-95% of the H_2 market. Liquid H_2 is only interesting for transportation by ship over long distances because we have a large pipeline volume in the Netherlands, and much energy is needed to cool or liquefy H_2.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

The most important problem is that we do not have enough renewable energy for producing H_2. Secondly, we do not have the infrastructure yet. We barely have enough capacity to get electricity and H_2 to the right places. The H_2 backbone will be an essential requirement for H_2 transport and storage, but it is still uncertain how it will be rolled out. We still need a place to store H_2 because one of the biggest problems in the future will be that most industrial users need a constant base load. We need large-scale storage to fill the gap of a few thousand hours when there is no wind. Large salt caverns or other large-scale storage options will be essential but also expensive. Thirdly, the business case for H_2 production is not yet very promising. The subsidy mechanisms do not support H_2 production very well. There are many projects on paper, but few projects have permits. Hardly any project has a financial deal with investors willing to invest in H_2 production, as the subsidy schemes are not yet interesting enough to close the gap between low-carbon and renewable H_2. Lastly, creating the supply chain for importing H_2 is crucial. This is not easy because you need stable regions for production and a way to transport large quantities of H_2 over a very long distance.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

First of all, the industry wants to achieve as many production hours as possible, but the supply of renewable energy is not constant, so a combination of wind and solar is needed.

Another factor in the choice of technology for H_2 production is maturity. Currently, alkaline electrolysis is chosen for almost all projects because it has been proven on a large scale. Current projects also look at PEM electrolyzers, which is slightly more expensive and uses scarce materials with increasing prices. If we want to use PEM electrolyzers on a large scale, we already see that there is probably not enough material to scale it up.

Next, European legislation requires an increased percentage of renewable fuels and the use of H_2 in refineries. Large H_2 production plants can receive credits for CO_2 emissions under the European trading scheme. This is interesting for project developers, as an increase in the value of renewable H_2 can be expected. Companies already using H_2 can more easily introduce it if they are gas-based. If they need to convert their processes to H_2, this will probably happen in the long term as it requires large, difficult investments under high-cost uncertainties.

Lastly, the connection to pipelines, i.e. between industrial sites, import terminals and production sites, will also become very important in investment decisions. Will you electrify your process if you cannot connect to the H_2 infrastructure? If there is no infrastructure for that either, will you move your process to another country with enough sustainable energy?

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

The main support at the moment is the development of the H_2 backbone. The only other support scheme is the SDE scheme, which is not made for H_2 production. The problem is that H_2 production is more expensive per ton of CO_2 than e.g. CCS projects as it requires high capital and maintenance costs. The SDE scheme promotes the most cost-effective ways to reduce CO_2 emissions, which is a good thing, but it means that new technologies that need more subsidies never get them because they are not as profitable.

There are not yet many standards or legislation for H_2 production. When we apply for a permit, there are no European standards, so we have to do it ourselves, based on e.g. US standards. The authorities that issue the permits do not always know how to make the right decisions, making it even more challenging to get the funding to complete the procedures promptly.

Procedures are also constantly under pressure due to a lack of staff capacity. Permitting procedures will be a problem in the future because of the time it takes. For example, getting a power grid connection can take 7-8 years. If governments say they want 4 GW by 2030, these projects must be approved now. However, when I look at the current permits, we do not have that many yet. We need a lot of large connections, which is causing problems for the high-voltage grid operators. They cannot expand their capacities fast enough, and the regional planning procedures are not helpful either.

Interview 6

Interviewer	Maleen Hiestermann
Interviewee	Transport sector
Job description	Business Developer
Date	20.05.2022
Duration	35 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

In the port of Rotterdam, there are numerous projects on H_2 in production, infrastructure, import, export, and utilization. The heart of the H_2 economy in the port area will be the H_2 backbone. This openly accessible H_2 pipeline connects producers and consumers in the port area. We also work on a pipeline to Germany. In addition, we also work on imports, as we see that the application for H_2 will be quite broad in the future.

Our company has two main tasks: (1) As a landlord, we own the land and lease it to our customers. We, therefore, ensure the safe and efficient handling of ship movements in the area. (2) As port developers, we facilitate, coordinate or incentivize specific directions and developments. We provide the basic infrastructure that everyone can use. It is more efficient for us because we do not have to provide much space for other infrastructures. For our customers, it also means they have all the resources they need to operate sustainably and economically. Developing and investing in H_2 production or conversion is something that companies do themselves. We do not own any production plants.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

In the Netherlands, we need a lot of H_2. At the moment, we are the energy hub in Europe and we want to maintain this function. One study estimated that if you switch the current demand from fossil fuels to H_2, 20 million tons of H_2 will flow through the port in 2050. From today's perspective, that is very low, as many new sectors are now also looking at H_2. There is already a large H_2 cluster with 0.5 million tons of H_2, but that is grey H_2 used in chemical processes and refineries. If we plan on 20 million tons of H_2, that means we need 200 GW of wind energy, but our North Sea only offers 75 GW, and that is for the whole country. Not all of it will be used for H_2 production, so a lot needs to be imported. We have estimated that we can produce about 10%, or 2 million tons of H_2, on-site in Rotterdam. Thus, 90% will have to be imported. We are therefore looking around the world to see where there are favorable conditions in terms of sun and wind to generate enough renewable electricity at quite favorable prices for H_2 production.

Low-carbon H_2 produced with SMR and CCS offers a start. The port is already producing and using 0.5 million tons of H_2. We are working on CCS projects like Porthos so that the current grey H_2 becomes low carbon. Another project, H-Vision, reuses refinery waste gases to produce low-carbon H_2. However, the focus is on renewable H_2. Regulations force us to switch to renewable solutions as soon as possible. Low-carbon H_2 will play an important role in the coming years to bring H_2 to the market as quickly as possible. However, European legislation makes it very difficult to import non-renewable sources. They clearly state that the focus is on renewable H_2. Biomass is quite limited in the Netherlands, so the focus is on wind and solar energy as a primary nergy source.

When we look at our import and export projects, we see that 80% of the supply chains will use ammonia as a carrier. However, the question is whether we should use ammonia directly as fuel for shipping, heat source, fertilizer or convert it to H_2, which requires more energy. Methanol and LOHC are also mentioned, but ammonia is the first promising carrier for import. The H_2 backbone in our port is for H_2 gas, and the pipelines to Germany could include an ammonia pipeline in addition to a H_2 pipeline in the future.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

A critical point is the limited wind and solar energy in the Netherlands, so local H_2 production will be limited. At the same time, we have centers with high demand, as we have one of the largest industrial clusters in northwestern Europe. Imports will therefore be essential and thus dependent on other countries.

Also critical in my view is that many projects will have to be carried out simultaneously to get off the ground. Infrastructure, including transportation and storage of, e.g. ammonia and methanol, and safety precautions must be taken to use the material properly. There are many different schedules and projects that are often not very well aligned, which causes problems. There is also the uncertainty of which H_2 carrier to choose. Do we want to organize this centrally, or should we let everyone do it themselves? These questions and uncertainties make it hard to start implementing supply chains. The regulation also makes it challenging to import H_2 as a renewable energy source.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

As for the technology, we let the parties decide for themselves what is best for them. We want to use the most space-efficient technologies because we have limited space in the port. However, there are many projects and significant differences in new technologies and their systems. Right now, we use alkaline electrolysis, but we are also investigating PEM electrolysis. We also have high-temperature electrolysis, which is still in its early stages.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

We work closely with the Dutch government to ensure that import and production can be accelerated in the Netherlands. We are now starting to figure out what we need and translate it into regulations, which takes time. Overall, the government seems to be a big supporter of the H_2 economy. There is also much support from the EU, and they work closely with the Dutch government. H_2 has been an ambitious target since the crisis in the Ukraine. We have more than doubled our targets for renewable H_2 from 5 to 20 million tons in 2030.

6. When assessing H_2 supply chains, what are the most important criteria to consider?

For the technical assessment, the capacity and availability of resources and material is important, for example, to build electrolyzers. For the economic assessment, conversion costs are essential. For the social assessment, the impact on job creation should be considered. In addition, space efficiency is important.

Interview 7

Interviewer	Maleen Hiestermann
Interviewee	Local government
Job description	Advisor
Date	17.05.2022
Duration	35 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

As a city, we are primarily involved in local H_2 production. We subsidize and enable projects in our region or ensure that the spatial planning requirements are met. In terms of subsidies, we play a minor role because we do not have the same financial resources and instruments as the national government or the EU. However, we can support innovation and research by acting as a field laboratory. For large projects, we are involved in land use planning, permitting, environmental impact assessment, regulatory compliance, stakeholder management, and being a facilitator to communicate opportunities for businesses and policies in our municipality. In the future, our role may change. As H_2 supply increases, the use of H_2 in the built environment could become interesting. In that case, we will play a more significant role because we have a coordinating role in the energy transition in the built environment.

For the future, it is very important to stay in conversation with companies, technology providers, other countries, and our port authority to ensure that we develop our policies in line with the technologies. However, most projects we are currently pursuing are business-related, i.e., with industrial, trucking or shipping companies and not with citizens. Citizens come into play exactly when projects are developed near them or directly using H_2. Then we will communicate more with citizens, but at the moment, that is not quite the case.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

For local production, there will most likely be a balance between low-carbon and renewable H_2. Low-carbon H_2 is easier to produce on a larger scale, but renewable H_2 is what we are aiming for. In importing H_2, different forms will emerge in the second half of this decade. Import will play a more significant role than local production. When we looked at the H_2 economy, we first thought we would use low-carbon and some renewable H_2. Then, we realized that renewable H_2 could be developed in parallel with low-carbon H_2. Now, developments with H_2-based feedstocks are moving so fast that import will be the most crucial flow.

For utilization, our regional vision is to use H_2 as a fuel for heavy-duty transportation, for process industries, or as a feedstock for industry. We do not see it for passenger vehicles or residential heating, but that may change in the future if the import flow of H_2 increases as we envision it. Right now, there is a large amount of waste heat in the industry that we think should be used first. However, after 2030, we can re-evaluate the situation. We also see using H_2 for load balancing.

For local production, we will use H_2 directly as a gas. We are looking at several routes by ship rather than pipelines for import. For methanol or ammonia, industries that use it should import it directly rather than H_2. We also need to determine the efficiency of cracking ammonia versus using LOHC or liquid H_2. Liquid H_2 seems to have the highest efficiency in theory if you want to use actual H_2. However, it requires small fine-tuning given the energy needed to bring it down in temperature and the losses during transportation. We do not have a preferred technology option yet because they are all still in the development phase regarding commercial deployment and policy requirements.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

For local production, ensuring renewable electricity is a critical point. This is done in particular through offshore wind farms, which will be the primary energy source in the Netherlands. We need to make sure that there is enough wind energy available and that, both technically and politically, the connection between wind farms and electrolyzers is validated. That should be a priority for the national government in particular.

Another critical issue is ensuring sufficient demand from the industry and they have access to accommodate the renewable H_2. This means having the infrastructure in place not only within the port but also in the hinterland.

Another critical issue is competitiveness. The potential of H_2 and the supply chains associated with it are growing, so we as a region need to keep up. We need to ensure that the strategy we pursue and the policies that support it keep pace with the potential of the technology. H_2 holds great potential for a more sustainable economy.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

Technical feasibility, the overall sustainability of the supply chain, and costs are important. Costs are something that we as a city cannot control or manage per se. It is decided by the market. If the costs determined by the market do not reflect the actual costs and benefits to society, either the national government or the EU can make adjustments, e.g., with the emission trading system of the EU.

Safety is another factor and concern. Some of these carriers, particularly ammonia, carry a risk that we have already dealt with in the port over the last 50 years. That said, H_2 is a new technology, and we must ensure it is appropriately handled. We have a responsibility to take care of our citizens. Although some cities like Tokyo have H_2 refueling stations right in the city center, H_2 is still considered unsafe and explosive in this country. People still think of H_2 bombs or the Hindenburg. However, these technologies have nothing to do with our current technology.

Lastly, the availability of space is a problem. Rotterdam is a busy city, and the port is one of the world's most intensively used industrial areas. Space is always in short supply, and I can imagine the development of different H_2 supply chains competing with each other. That is fine to a certain point, but as they mature, there may be a greater spatial demand on all these pipelines. We are still in the innovation and development phase, but we will have to consider the spatial implications more.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

Currently, the Netherlands is pursuing all supply chains simultaneously, which is a wise decision because the technologies are still developing. We do not know how significant their potential can be. Investing in them ensures that we obtain a stable amount of H_2 and reduce our national emissions in the short term. We need to ensure that the policies support the development of all supply chains. For example, subsidizing low-carbon H_2 production from process waste/externalities when there are no more refinery emissions while also ensuring that the entire supply chain for local production of renewable H_2 is established. Several instruments are already in place, but some still need attention, such as linking wind energy and H_2 production and subsidizing the early operating phase. To begin with, electrolyzers are not yet competitive enough to be included in the SDE scheme. The national government will design a new instrument through the Climate Fund, but details are not yet available. There is only a reservation of 15 billion euros for the next ten years.

Interview 8

Interviewer	Maleen Hiestermann
Interviewee	National government
Job description	Program manager
Date	16.05.2022
Duration	35 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

H_2 has the potential to play an important role in the energy transition as it can be used almost everywhere and can be a solution to many problems. H_2 could create a more efficient energy system, but many things are still uncertain, so it could also be a failure. How quickly H_2 can eventually play its role depends on the cooperation we create between sectors, neighboring countries, and internationally.

As the national government, we guide all stakeholders, provide clarity for those who want to invest in H_2, and talk to the EU to make the right policies. We need to make optimal decisions by listening to everyone in the industry and abstracting what is true and what is not and what is consistent with the decisions we have already made. We create certainty in investment decisions because, for example, the first offshore wind farms that produce H_2 will be more expensive than those that follow years later.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

In the Netherlands, we mainly aim at renewable H_2, which is produced from wind and solar energy using alkaline or/and PEM electrolyzer. Currently, a lot of H_2 is produced from natural gas, but we know that this will come to an end, so we try to end it as soon as possible. Biomass as a primary energy source for H_2 production is a sensitive topic in the Netherlands. Biomass was part of the Climate Agreement in 2019, but politicians agreed not to pursue it due to low public acceptance. Projects have been stopped or put on hold and will not be resumed anytime soon.

Low-carbon H_2 is a complicated topic. We are still undecided as there are different types of low carbon initiatives such as H_2 Gateway and H-Vision. We support H-Vision because it reuses process waste or externalities to create new value (like H_2), making the process more circular. However, we are not sure about H_2 Gateway because it is a H_2 production factory that uses natural gas. At the end of the day, we do not want CO_2 emissions. If we use CCS, it might be better to use it in industrial processes that use grey H_2, rather than producing low-carbon H_2 with CCS. The purity of low-carbon H_2 is also not as high as that of renewable H_2. Thus, the questions arises, how can we mix the two types of H_2? Will it not cost us too much to mix them?

Overall, we would rather import renewable H_2 than build our own low-carbon factories. However, we are still investigating this case.

Import will play an important role in the Netherlands, as we are a country with high energy demand and limited space. Fortunately, the Port of Rotterdam is already very active and will play an essential role in the import and export of H_2 to our neighboring countries. Many memorandum of understandings have already been signed with other countries to see how we can work together in the future. However, many countries are also interested in renewable H_2. Mainly because of the war between Russia and Ukraine, we believe that the Netherlands should generate as much H_2 as possible to reduce our dependence on other countries. We are currently studying our demands, the timeline, how we can meet them, and how we can remain independent from countries that could harm us. However, because of the dynamics around H_2, there are many assumptions to be made, so we need to be adaptable in our outlook.

Ammonia is often mentioned as an energy carrier for H_2 for import. We could buy ammonia, convert it into renewable H_2 gas, and use the H_2 backbone to transport it. Thus, the leading carrier for H_2 will be H_2 gas because that is what the H_2 backbone will be built for. However that could change after 2030. There could be ammonia pipelines from the Middle East to Europe, but we do not know how things will develop. For storage, we consider salt caverns.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

The current critical point is the high price of renewable H_2 and the uncertainty of whether upscaling the production will lower the price enough. The biggest challenge is creating a market that matches supply and demand so that people have enough confidence to decide to switch to cleaner energy. On the supply side, they need demand to make investment decisions. On the demand side, they want to use renewable H_2 but are unsure if enough can be produced to transition from their current energy source to renewable H_2.

After addressing this problem, other issues will come into focus, such as whether enough raw materials are available, the environment is sufficiently protected, the H_2 economy is of benefit for everyone or people are treated properly.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

Innovation is very important because the technology we will use depends on its development. For example, offshore wind power is an essential energy source for us, which is why we expect H_2 to be produced initially onshore near the point where the cables from offshore wind farms enter the Netherlands. However, for space reasons, we will try to produce H_2 offshore, but we need innovation. We do not yet know what kind of technology is best and most efficient and how we can organize it better legally. The EU plays a considerable role in this because they define how we have to work. So as a Dutch government, we need to figure out how to organize these decisions, for example, whether we need additional roles such as an offshore grid developer for H_2.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

Society, in general, does not know much about H_2 to have a clear opinion. They know that H_2 can be used in cars or for residential heating, which both will only be used to a small extent by 2030. Sometimes communities want to use H_2, but they do not want wind or solar farms, which are necessary to produce it. In the Netherlands, fortunately, a program creates the national energy system plan. It involves a group of experts who try to make decisions for the energy system. There are many international connections for the energy system as a whole. The EU defines certain goals and policies, but the Netherlands often acts as a thought leader. So instead of waiting for the EU to tell us what to do, we often do things first.

Currently, there is a climate agreement that calls for 500 MW in 2025 and 3-4 GW in 2030. In a recent debate with the parliament, a new plan called for 8 GW in 2030 as offshore wind will be scaled up. A more specific roadmap is planned for the end of September that translates climate initiatives and energy programs involving H_2 to sectors, infrastructure and storage. This roadmap considers laws, regulations, health and safety. We need to connect energy projects that include H_2 to ensure that if they make decisions, we know their impact on the entire supply chain. That way, we can shape policies. In the H_2 sector, we know so little on one side but so much on the other. We therefore need to put our thoughts together about what is needed and what path we need to take to achieve our goals.

The delegated act as part of the Renewable Energy Directive II defines when we can call something renewable H_2. That is important because we cannot publish a subsidy instrument if we do not know what to stimulate. Now, we can finally introduce the H_2 subsidy program to ensure that the first projects can build and realize their business cases. The subsidy is for production projects of 50-100 MW. The SDE scheme is very competitive. Getting subsidies for costly technologies, such as electrolyzers, is usually challenging. Therefore, we have created a separate instrument for them.

Interview 9

Interviewer	Maleen Hiestermann
Interviewee	Research and Development
Job description	Researcher
Date	19.05.2022
Duration	50 min

1. What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?

As a research university, we work together with the industry to analyze e.g. which empty gas fields are feasible for storing H_2 in the North sea. We are also involved in discussions with the national government to use a H_2 pipeline between the Netherlands and Saudi Arabia.

2. Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?

H_2 production with natural gas will be a solution for the transition to 2040 because you can build it now and operate it for about 20 years. Existing SMR plants in the port of Rotterdam will be equipped with CCS. However, if one builds new H_2 production plants that run solely on natural gas, then ATR with CCS is used, as it captures up to 90% H_2 instead of 60% with SMR. Methane pyrolysis is also a fast-growing solution worldwide to lower the price of H_2 and avoid CO_2 emissions.

For renewable H_2 production, the only viable option for the Netherlands is converting offshore wind to H_2 directly on the platform or in the turbine. Then, the existing natural gas pipelines are used to bring H_2 onshore. Studies show that we have the potential to develop about 72 GW of offshore wind power in our part of the North Sea, and there is an additional 30 GW of power near the coast. About 40-50 GW could be used for H_2, which leads to 4-5 million tons of H_2. The rest will be imported. Another emerging technology is converting biogas to H_2 and CO_2 with SMR and capturing the CO_2. It leads to negative emissions but will only play a minor role.

The main H_2 carrier is gaseous, compressed H_2. However, ammonia is the most interesting energy carrier for direct use because the infrastructure is already in place. Ammonia can be used as fertilizer and directly in diesel engines or gas turbines. The main advantage of LOHC is that you can use the standard oil tankers and oil tanks for storage. However, they have to be dehydrated, which costs a lot of high-temperature heat. Thus, LOHC make sense in the chemical industry, where waste heat is generated. Liquid H_2 is very interesting as an energy carrier for transportation by truck to refueling stations over longer distances because you can transport a lot more than with compressed H_2. Thus, each carrier and supply chain depends on the utilization of H_2.

Shipping is more expensive than transporting H_2 by pipeline, even if it comes from North Africa, the Middle East, or Iceland. Therefore, pipelines will account for most imports to supply the industry, as they need cheap H_2. There is an agreement with Gasunie on the European H_2 backbone, which includes 85% converted natural gas pipelines and 15% new pipelines. In 2027, the system should be in place. It includes storage capacity and can provide the base load. In addition, other storage options such as salt caverns will be used. They can store a huge amount of energy compared to batteries, but empty gas fields can store even more. However, salt caverns are better for daily and weekly fluctuations, while gas fields can be used for seasonal or strategic reserves. A mix of salt caverns and empty gas fields is therefore necessary to store H_2 in the energy system in the future.

3. What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?

In addition to the international pipeline system and the creation of standards, one of the critical issues is energy storage to combat energy security and disruptions. We experienced this in high prices during the war in the Ukraine. In the Netherlands, we import gas on a base load basis, which means we import too much in the summer and store it for the use in winter. The storage capacity of gas is about 100 kWh, almost the total electricity consumption in the Netherlands. With battery storage, we will never reach that. Due to seasonal demand patterns, we use about ten times as much gas in winter as in summer. Therefore, we need extensive seasonal storage facilities with H_2 to solve the problem of matching supply and demand.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

There is a growing awareness, especially among the industry and energy companies, that H_2 is a low-carbon/carbon-free energy carrier that can be transported around the world and solve many problems, such as the fluctuations in renewable energy. As a result, the EU has included H_2 in their targets and set 40 GW, or 5.6 million tons, to be produced in 2030. However, the war in the Ukraine has made the EU realize that it needs to be less or completely independent of gas imports from Russia. As a result, among other things, the target for H_2 has been increased to 20 million tons in 2030 (10 million tons imported outside the EU and 10 million tons produced in the EU). In general, there will be more production in places where a lot of hydropower, wind or solar power is available. For this, we need an infrastructure consisting of about 75% pipelines and 25% ships to be less dependent on the inflexible pipeline transport.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

I am very glad that we have the EU. The Netherlands is very inactive, and they have to follow the EU agenda at a certain point. For example, our initial target was 3-4 GW of electrolyzer capacity in 2030, with a production of 400,000 tons. However, the EU is more ambitious and specific in its ”Fit for 55 program”: 5.6 million tons, 50% of industrial demand must be renewable in 2030, and 2.6% of transport fuels must be renewable H_2. The Netherlands adapted its targets increasing the electrolyzer capacity to 8 GW. However, looking at the EU targets, the Netherlands needs at least 1 million tons, i.e. 10 GW of local offshore production and at least 1 million tons of H_2 import in 2030.

In the Netherlands, there are not many subsidies. The governing parties have agreed on H_2 and support it. However, if you look at the financial figures, they have agreed on 5 to 10 billion euros for H_2, without naming specific measures. In Germany, for example, there are many specific measures to introduce H_2, such as tenders to buy and sell H_2 abroad at lower prices for the industry. In the Netherlands, we do not have such an instrument. We only have bilateral memorandum of understandings.

The Netherlands has already lost the pole position to Germany, France and the UK. Our industry was built on cheap gas, which is why we have a large chemical and metal industry and are the second largest producer and consumer of H_2 after Germany. However, due to high energy prices, ammonia production has already decreased in the Netherlands. Certain parts of the industry will move to where the cost of renewable energy and H_2 is cheapest. The aluminum industry, for example, moved to Iceland because of the availability of cheap hydropower and geothermal electricity. Each country and Europe itself should thus pay attention to how competitive they are. In the Netherlands, we need to expand our offshore wind much faster and add another 10 GW for H_2 generation by 2030, or we will lose a large part of the industry.

6. When assessing H_2 supply chains, what are the most important criteria to consider?

Safety is undoubtedly an important criterion. In addition to GHG emissions, the impact on the natural habitat and other emissions, such as nitrogen, are also important to assess. So, when assessing supply chains it is not about energy consumption but the resulting emissions and costs.

Technically, we do not have much of a problem because the technologies have been around for decades, and the costs will come down as we scale up. Also, efficiency is not necessary to assess because what matters are costs, such as electricity costs but also investment costs. Finally, scalability must be considered as well.

Interview 10

Interviewer	Maleen Hiestermann
Interviewee	Research and Development
Job description	Researcher
Date	19.05.2022
Duration	40 min

1. **What role do H_2 supply chains play in your company? How are you involved in H_2 supply chains today, and how will it change in the future?**

As researchers, we analyse financial and safety aspects, design the overall sustainable energy production and calculate the size of the required storage and electrolyzer based on the demand profiles of customers using H_2 and the available renewable energy. In some projects, we are also involved in setting up electrolyzer systems for small-scale local production.

For H_2 supply chains, more detailed knowledge of how the different supply chains systems work together is needed. The models we currently use in research are simplified regarding how electricity is converted to H_2 or how losses occur during storage or compression. The information is probably there, but it needs to be integrated into the models.

Smart control of power systems is another issue that plays a significant role in good system integration. Control is about regulating supply and demand, but also about different energy carriers and intelligently converting one into the other. This is where we, as researchers, see our role in helping the industry.

2. **Which (parts) of the presented H_2 supply chains are your company currently using, investigating, or/and strategically pursuing in the Netherlands in the future? Why?**

Large-scale production of renewable H_2 will take some time, as it requires significant renewable electricity generation capacity. In the meantime, if we want to start building an entire supply chain, we will work with low-carbon H_2. If there is a severe replacement of natural gas with H_2, we will not be able to produce the required H_2 all ourselves. We do not have much space in the Netherlands, and we do not have much renewable energy. Therefore, imports from countries with a lot of wind, sun, and space will be important. The difference between the expected prices for renewable H_2 produced in different parts of the world will lead to a high share of global instead of local H_2 production.

At the local level, H_2 will be used as a storage medium for intermittent renewable power. This can be cost-effective because you save on investment costs for grid extension or transport, and you can use the stored H_2 directly in local businesses. I am not sure if we will use biomass in the Netherlands. It could replace some natural gas consumption but will not be used to produce H_2.

In our view, H_2 will mainly be used and transported as a gas, but that is also because we are involved in local storage and utilization. If you import energy from overseas, it might be a good idea to convert H_2 to e.g. ammonia so it can be transported more easily by ship. Depending on how much H_2 is consumed in the Netherlands and whether the demand is continuous or intermittent, pipelines or trucks might be an option for local distribution. Pipelines, if you want to replace natural gas completely with H_2, but in most cases by truck, at least in the early stages.

3. **What are the critical points in H_2 supply chains regarding their implementation and upscaling in the Netherlands? Why? Would this be different in the future?**

Designing a system is not easy, but it is doable. The difficult part is to achieve a positive business case with sufficient demand. Many stakeholders are interested in H_2. However, committing to buy it within five years is difficult due to the availability and price uncertainty in H_2 and other energy prices. It creates an uncertain business case. There was a huge price difference between natural gas and renewable H_2. Now it is lower, but no one knows how long or how high it will evolve.

Current subsidies mainly focus on the production of H_2 and not so much on the utilization. The financial risk associated with transitioning to renewable H_2 is not helping companies get started in the short term. We need to overcome this hurdle before companies start using H_2.

4. Which factors influence your decision on a H_2 supply chain? How do they influence it? Would this be different in the future?

In addition to cost, safety and sustainability factors, the effort required to transition is also important. If the industry wants to switch from a mixture of H_2 and natural gas to only H_2, it has to convert its plants which requires investment. The investment depends on what kind of plants companies have and how old they are. Companies often do not know what they need to do. I am involved in a learning community with companies to discuss what converting to H_2 means in terms of safety, installation costs, the differences between H_2 and natural gas and its implications. There is not a lot of expertise and experience, especially on the practical side.

5. How does the Netherlands (policy, resources, society) influence your choice of H_2 supply chains? Would this be different in the future?

There are quite a few subsidies from the government for research programs, especially for large electrolyzer projects, but that is all on the supply side. On the demand side, there is the planned H_2 backbone, but it is uncertain where it will go and which region will be supplied in the short and long term.

For smaller local H_2 facilities, the safety regulations for the production, use and storage of H_2 are not clear yet. Many municipalities do not know how to handle H_2 production and storage to replace natural gas as they have worked with natural gas for many years. As no specific H_2 rules exists yet, municipalities have to figure this out on their own. They set their own rules, which takes much time. Besides the rules, the social acceptance and safety of people living near the H_2 plants are also important. However, this is still unexplored, as experiments are mainly carried out in industrial areas which are far away from residential areas.

6. When assessing H_2 supply chains, what are the most important criteria to consider?

When planning the transition to H_2, it is important to have a long-term vision of where you want to go. Companies could easily start by blending up to 10-15% H_2 into their natural gas. At some point, however, they must convert their plants keeping the end goal in mind. What I see in the discussions in the H_2 learning community is to make the process more efficient, i.e., reduce and reuse the energy waste first to reduce the need for primary energy. CO_2 pricing and its development also play an essential role in the policy assessment. The material used for the technology and its availability are also important, especially concerning the scarce materials used in electrolyzers.

D

Appendix: performance analysis

D.1. Techno-economic data

Economic performance

To compare the economic performance of H_2 supply chains, $CAPEX$, $OPEX_{fix}$, and $OPEX_{var}$ are estimated per supply chain component.

Tables D.1 and D.2 show the selected import countries, transport distance and the price data used. Tables D.3 to D.8 contain the specific techno-economic data per selected supply chain component.

Table D.1: Distance from each selected import country to the Netherlands

Country	**Export**	**Import**	**Distance*** (nm)	**Reference**
United Arab Emirates	Port of Jebel Ali	Port of Rotterdam	7029	(Government UAE, 2022)
United States	Port of Corpus Christi	Port of Rotterdam	6139	(Port Corpus Christi, 2022)

*Based on (Shiptraffic, n.d.)

Table D.2: Price data

	Unit	**Value**	**Reference**
Exchange rate	€/USD	0.95	Based on June 2022
Heavy fuel oil	€/t	874	Based on June 2022 (Ship & Bunker, n.d.)
CO_2 emission cost	€/tCO_2	100	(Brändle et al., 2021)
NG (Netherlands)	€/kWh	0.128	Based on June 2022 (EEX, n.d.)
NG (United States)		0.018	Based on June 2022 (EIA, 2022a)
Electricity offshore wind (Netherlands)		0.065	(PBL, 2021)
Electricity solar PV (United Arab Emirates)		0.048	(IRENA, 2022)
Electricity grid (Netherlands)		0.284	Based on June 2022 (EPEX, n.d.)
Electricity grid (United States)		0.086	Based on June 2022 (EIA, 2022a)

Table D.3: Techno-economic data on H_2 production

	Unit	**PEM electrolysis**	**SMR with CCS**
		(Reuß et al., 2017)	(Kim et al., 2021)
Lifetime	year	10	20
$Invest_{total}$	M€	500	237
$throughput$	MtH_2/year	100	78
OM	% of CAPEX/year	3	13
Electricity consumption	kWh/kgH_2	48	7.87
NG consumption	MW/year	–	434
CO_2 capture rate	%	–	90
Full load hours	h/year	5300	8000

Table D.4: Techno-economic data on NH_3 conversion and reconversion

	Unit	**Pump**	**Air separation**	**Haber-Bosch**	**Cracking**
		NH_3	N_2	NH_3	NH_3
		(Nayak-Luke et al., 2021)	(Kim et al., 2021)	(Kim et al., 2021)	(Kim et al., 2021)
Lifetime	year	25	20	25	20
$Invest_{total}$	M€	1.2	46	1308	398
$throughput_{base}$	tH_2eq/day	2.8	301	390	500
OM	% of CAPEX/year	4	8	3	3
Full load hours	h/year	8000*	8000*	8000*	8000*
Electricity consumption	kWh/kgH_2	0.2	0.57	3.4	–
NG consumption	kWh/kgH_2	–	–	–	4.2**
Capacity	GW	0.007	–	–	–
(Boil-off) Losses	%/year	–	–	–	–

*Assumption

**Andersson and Grönkvist (2019)

Table D.5: Techno-economic data on H_2 conversion and reconversion

	Unit	**Compressor**	**Liquefaction**	**Evaporation**
		H_2	LH_2	LH_2
		(Reuß et al., 2017)	(Reuß et al., 2017)	(Reuß et al., 2017)
Lifetime	year	15	25	10
$Invest_{total}$	M€	0.004	1844	0.006
$throughput_{base}$	tH_2eq/day	0.001	500	1
OM	% of CAPEX/year	4	8	3
Full load hours	h/year	8000*	8000*	8000*
Electricity consumption	kWh/kgH_2	1	6.78	0.6
Capacity	GW	< 0.0001	–	–
(Boil-off) Losses	%/year	0.5	1.65	–

*Assumption

Table D.6: Techno-economic data on LH_2 and NH_3 shipping

	Unit	**Shipping**	**Shipping**
		LH_2	NH_3
		(Kim et al., 2021)	(Kim et al., 2021)
Lifetime	year	20	20
$Invest_{total}$	M€	154	76
OM	% of CAPEX/day	0.01	0.01
Ship max loading	t/ship	10 840	50 400
Fuel consumption	t/day	23	29
(Boil-off) Losses	%/day	0.3	0.025
Distance*	nm	6500*	6500*
Average speed	knots	10	10

*Average distance from selected import countries to the Netherlands

Table D.7: Techno-economic data on H_2 and NH_3 pipelines

	Unit	**Pipeline** H_2 (g) (Reuß et al., 2017)	**Pipeline** NH_3 (l) (Nayak-Luke et al., 2021)
Lifetime	year	40	25
$Invest_{base}$	€/m	see EQ 11	1396
$throughput$	MtH_2/year	2*	2*
OM	% of CAPEX/year	4	0.03
Diameter pipeline	m	0.91**	0.25
Pipeline distance	km	1400**	1400**
Losses	%/year	0.5	0

*Based on HyChain (2022) supply chain tool

**Based on planned H_2 backbone (RVO et al., 2021)

Table D.8: Techno-economic data on H_2 and NH_3 storage

	Unit	**Salt cavern** H_2 (g) (Reuß et al., 2017)	**Tank** NH_3 (l) (Nayak-Luke et al., 2021)
Lifetime	year	30	25
$Invest_{base}$	M€	81	26
$Invest_{scale}$	–	0.28	1
$volume_{compare}$	m^3	500 000	25 000
OM	% of CAPEX/year	2	3
Electricity consumption	kWh/kgH_2	0.1	0.21
Losses	%/year	0	0

Environmental performance

To compare the environmental performance of H_2 supply chains, CO_2 emissions, NOx emissions, and the land requirement are estimated per supply chain component.

Tables D.9 shows the specific CO_2 emissions, NOx emissions and land requirement per energy source and Tables D.3-D.8 contain the energy consumption per supply chain component.

Table D.9: CO_2 emission, NOx emissions and land requirement per energy source

Energy source	**Unit**	**Value**	**Reference**
Electricity renewables		0	Assumption
Electricity grid (Netherlands)		0.453	(Scarlat et al., 2022)
Electricity grid (United States)	$kgCO_2$/kWh	0.392	(Ahn et al., 2022)
NG		0.238	(Reuß et al., 2017)
Heavy fuel oil		0.600	(Lindstad et al., 2015)
Electricity renewables		0	Assumption
Electricity grid (Netherlands)		0.241	Based on NOx:CO_2 proportion in United states
Electricity grid (United States)	gNOx/kWh	0.208	(Ahn et al., 2022)
NG		0.028	(Babaee et al., 2020)
Heavy fuel oil		2.50	(Lindstad et al., 2015)
Electricity offshore wind		2.33	(Cheng & Hammond, 2016)
Electricity solar PV		13.5	(Cheng & Hammond, 2016)
Electricity grid (Netherlands)	km^2/TWh	2.67	Based on fossil:renewables in electricity grid
Electricity grid (United States)		1.66	Based on fossil:renewables in electricity grid
NG		0.09	(Cheng & Hammond, 2016)

D.2. Detailed results

Table D.10: Detailed techno-economic results per supply chain

	Objective	Criteria	PEM electrolysis	-	-	-	-	Compressor	Pipeline	Salt cavern
D1	Affordability	CAPEX [€/kgH$_2$eq]	0.67	-	-	-	-	0.00	0.17	0.01
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.16	-	-	-	-	0.00	0.08	0.00
		OPEX$_{var}$ [€/kgH$_2$eq]	3.09	-	-	-	-	0.33	-	0.03
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.00	-	-	-	-	0.45	-	0.05
		NOx emissions [gNOx/kgH$_2$eq]	0.00	-	-	-	-	0.24	-	0.02
		Spatial footprint [km^2/kgH$_2$eq]	1E-07	-	-	-	-	3E-09	-	3E-10

	Objective	Criteria	SMR with CCS	-	-	-	-	Compressor	Pipeline	Salt cavern
D2	Affordability	CAPEX [€/kgH$_2$eq]	0.31	-	-	-	-	0.00	0.17	0.01
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.40	-	-	-	-	0.00	0.08	0.00
		OPEX$_{var}$ [€/kgH$_2$eq]	2.51	-	-	-	-	0.33	-	0.03
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.40	-	-	-	-	0.45	-	0.05
		NOx emissions [gNOx/kgH$_2$eq]	1.97	-	-	-	-	0.24	-	0.02
		Spatial footprint [km^2/kgH$_2$eq]	2E-08	-	-	-	-	3E-09	-	3E-10

	Objective	Criteria	PEM electrolysis	-	Liquefaction	Shipping	Evaporation	Compressor	Pipeline	Salt cavern
G1	Affordability	CAPEX [€/kgH$_2$eq]	0.67	-	1.02	0.23	0.00	0.00	0.17	0.01
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.13	-	0.87	0.08	0.00	0.00	0.08	0.00
		OPEX$_{var}$ [€/kgH$_2$eq]	2.28	-	0.33	0.17	0.20	0.33	-	0.03
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.00	-	0.00	0.67	0.27	0.45	-	0.05
		NOx emissions [gNOx/kgH$_2$eq]	0.00	-	0.00	2.81	0.14	0.24	-	0.02
		Spatial footprint [km^2/kgH$_2$eq]	6E-07	-	9E-08	-	2E-09	3E-09	-	3E-10

	Objective	Criteria	PEM electrolysis	Air separation	Haber-Bosch	Shipping	Cracking	Compressor	Pipeline	Salt cavern
G2	Affordability	CAPEX [€/kgH$_2$eq]	0.67	0.05	0.94	0.13	0.24	0.00	0.17	0.01
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.13	0.01	0.30	0.05	0.07	0.00	0.08	0.00
		OPEX$_{var}$ [€/kgH$_2$eq]	2.28	0.03	0.16	0.26	0.64	0.33	-	0.03
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.00	0.00	0.00	1.05	1.00	0.45	-	0.05
		NOx emissions [gNOx/kgH$_2$eq]	0.00	0.00	0.00	4.39	0.12	0.24	-	0.02
		Spatial footprint [km^2/kgH$_2$eq]	6E-07	8E-09	5E-08	-	4E-10	3E-09	-	3E-10

	Objective	Criteria	PEM electrolysis	-	Liquefaction	Shipping	Evaporation	Compressor	Pipeline	Salt cavern
G3	Affordability	CAPEX [€/kgH$_2$eq]	0.31	-	1.02	0.23	0.00	0.00	0.17	0.01
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.40	-	0.87	0.08	0.00	0.00	0.08	0.00
		OPEX$_{var}$ [€/kgH$_2$eq]	0.75	-	0.61	0.17	0.20	0.33	-	0.03
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.35	-	0.27	0.67	0.27	0.45	-	0.05
		NOx emissions [gNOx/kgH$_2$eq]	1.71	-	1.41	2.81	0.14	0.24	-	0.02
		Spatial footprint [km^2/kgH$_2$eq]	2E-08	-	2E-08	-	2E-09	3E-09	-	3E-10

	Objective	Criteria	PEM electrolysis	Air separation	Haber-Bosch	Shipping	Cracking	Compressor	Pipeline	Salt cavern
G4	Affordability	CAPEX [€/kgH$_2$eq]	0.31	0.05	0.94	0.13	0.24	0.00	0.17	0.01
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.40	0.01	0.30	0.05	0.07	0.00	0.08	0.00
		OPEX$_{var}$ [€/kgH$_2$eq]	0.75	0.11	0.63	0.26	0.64	0.33	-	0.03
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.35	0.22	0.13	1.05	1.00	0.45	-	0.05
		NOx emissions [gNOx/kgH$_2$eq]	1.71	0.12	0.71	4.39	0.12	0.24	-	0.02
		Spatial footprint [km^2/kgH$_2$eq]	2E-08	2E-09	9E-09	-	4E-10	3E-09	-	3E-10

	Objective	Criteria	PEM electrolysis	Air separation	Haber Bosch	Shipping	-	Pumps	Pipeline	Tank
G5	Affordability	CAPEX [€/kgH$_2$eq]	0.67	0.05	0.94	0.13	-	0.00	0.09	0.07
		OPEX$_{fix}$ [€/kgH$_2$eq]	0.13	0.01	0.30	0.05	-	0.00	0.00	0.02
		OPEX$_{var}$ [€/kgH$_2$eq]	2.28	0.03	0.16	0.26	-	0.07	-	0.07
	Sustainability	CO$_2$ emissions [kgCO$_2$/kgH$_2$eq]	0.00	0.00	0.00	1.05	-	0.09	-	0.10
		NOx emissions [gNOx/kgH$_2$eq]	0.00	0.00	0.00	4.39	-	0.05	-	0.05
		Spatial footprint [km^2/kgH$_2$eq]	6E-07	8E-09	5E-08	-	-	5E-10	-	6E-10

Table D.11: Detailed techno-economic results per performance criteria

	Production	Conversion	Transport (Shipping)	Reconversion	Storage	Transport (Pipeline)	Total
H_2 costs [€/kgH_2eq]							
D1	3.90	0.33	-	-	0.04	0.25	4.52
D2	3.21	0.33	-	-	0.04	0.25	3.83
G1	3.09	2.22	0.49	0.53	0.04	0.25	6.61
G2	3.09	1.49	0.44	1.28	0.04	0.25	6.59
G3	1.46	2.50	0.49	0.53	0.04	0.25	5.27
G4	1.46	2.04	0.44	1.28	0.04	0.25	5.50
G5	3.09	1.49	0.44	0.07	0.16	0.09	5.34
CO_2 emissions [kgCO_2/kgH_2eq]							
D2	0.00	0.45	-	-	0.05	-	0.50
D2	0.40	0.45	-	-	0.05	-	0.90
G1	0.00	0.00	0.67	0.72	0.05	-	1.45
G2	0.00	0.00	1.05	1.45	0.05	-	2.55
G3	0.35	0.27	0.67	0.72	0.05	-	2.06
G4	0.35	0.36	1.05	1.45	0.05	-	3.26
G5	0.00	0.00	1.05	0.09	0.10	-	1.24
NOx emissions [gNOx/kgH_2eq]							
D1	0.00	0.24	-	-	0.02	-	0.27
D2	1.97	0.24	-	-	0.02	-	2.23
G1	0.00	0.00	2.81	0.39	0.02	-	3.22
G2	0.00	0.00	4.39	0.36	0.02	-	4.77
G3	1.71	1.41	2.81	0.39	0.02	-	6.34
G4	1.71	0.83	4.39	0.36	0.02	-	7.30
G5	0.00	0.00	4.39	0.05	0.05	-	4.48
Spatial footprint [km^2/kgH_2eq]							
D1	1.1E-07	2.7E-09	-	-	2.7E-10	-	1.1E-07
D2	2.2E-08	2.7E-09	-	-	2.7E-10	-	2.4E-08
G1	6.4E-07	9.2E-08	-	4.3E-09	2.7E-10	-	7.4E-07
G2	6.4E-07	5.4E-08	-	3.1E-09	2.7E-10	-	7.0E-07
G3	2.2E-08	1.8E-08	-	4.3E-09	2.7E-10	-	4.4E-08
G4	2.2E-08	1.1E-08	-	3.1E-09	2.7E-10	-	3.5E-08
G5	6.4E-07	5.4E-08	-	5.3E-10	5.7E-10	-	7.0E-07