The exploration and evaluation of the hydrogen infrastructure value chain for the heavy-duty truck sector in the Netherlands.

An investigation into the current state of the hydrogen infrastructure value chain for heavy-duty freight road transport in the Netherlands, gaining insights into its feasibility for successful implementation.

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Tjerk Willinge Gratama
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Summary

As the Netherlands is willing to transition to sustainable heavy-duty (HD) freight transportation, which is important for meeting EU's CO_2 neutrality targets by 2050, a necessity arises to explore alternative clean energy options. This study delves into the integration of green hydrogen within the heavy-duty truck (HDT) sector in the Netherlands. Establishing a robust hydrogen infrastructure is essential for green hydrogen to emerge as a viable fuel in this sector. However, the current trajectory of this infrastructure development is uncertain, warranting a closer examination of the transition's progress.

The objective of this research is to investigate the current progress of the hydrogen infrastructure value chain for the HDT sector in the Netherlands (i.e., green hydrogen supply (domestic production + import), storage, transportation, refuelling stations, and hydrogen-powered trucks) and gain insights for future sustainability initiatives in this domain to increase the likelihood of realizing heavy-duty trucks (HDTs) on green hydrogen. A comprehensive understanding of the socio-technical system (STS) of the Dutch hydrogen infrastructure is important as it illuminates the complex interplay between human behaviour, technological factors, and organizational structures, crucial for determining the feasibility and effectiveness of green hydrogen adoption in this context. This study leverages qualitative research approaches, constituting desk research and semi-structured expert interviews. This methodology allows to examine the current progress of the infrastructure thoroughly based on existing articles and data files, while expert interviews offer deeper insights into the system's performance. By combining these approaches, a thorough qualitative analysis of the hydrogen infrastructure value chain is conducted, facilitating the integration of green hydrogen into the HDT sector in the Netherlands.

The initial phase of this study involved conducting a thorough literature review to assess the existing research landscape pertaining to the progress of the hydrogen infrastructure value chain. Analysis of academic and grey literature articles highlighted various challenges across technological, institutional, and stakeholder domains, contributing to uncertainty surrounding the trajectory of hydrogen technology within its institutional and stakeholder contexts. This review revealed a notable gap in the literature concerning the current state of technology, institutions, and stakeholder processes driving the transition towards a sustainable HDT sector. To address this gap, the study employed the TIP (Technology, Institutions, Process) framework to explore and evaluate the current progress of the physical infrastructure within its institutional and stakeholder contexts. The analysis began with examining the development of the physical infrastructure of the entire value chain, primarily using desk research. Additionally, institutional initiatives supporting infrastructure development and prevailing collective stakeholder strategies were explored. Following this, the study mainly used conducted semi-structured expert interviews (totalling 6) to evaluate the performance of the TIP aspects and illuminate the dynamics between technological advancements, institutional support, and stakeholder engagement in facilitating the transition towards sustainable heavy-duty trucks.

Illustrated in Figure 1, which depicts the interrelations among the TIP aspects, the analysis indicates promising advancements in the supply side of the hydrogen infrastructure value chain, essential for delivering green hydrogen to heavy-duty trucks. Numerous policy initiatives are bolstering the physical infrastructure construction, complemented by the entrepreneurial spirit amongst hydrogen infrastructure developers, which encourages contributions to infrastructure projects. Nevertheless, uncertainties persist in the practical implementation of the technology, leading to hesitancy among hydrogen stakeholders throughout the value chain. The primary challenge regarding the functioning of this socio-

technical system lies in stimulating the demand side of the hydrogen infrastructure value chain for the HDT sector in the Netherlands, specifically in realizing and adopting hydrogen-powered trucks. Currently, transport companies lack sufficient incentives to transit towards hydrogen-powered trucks.

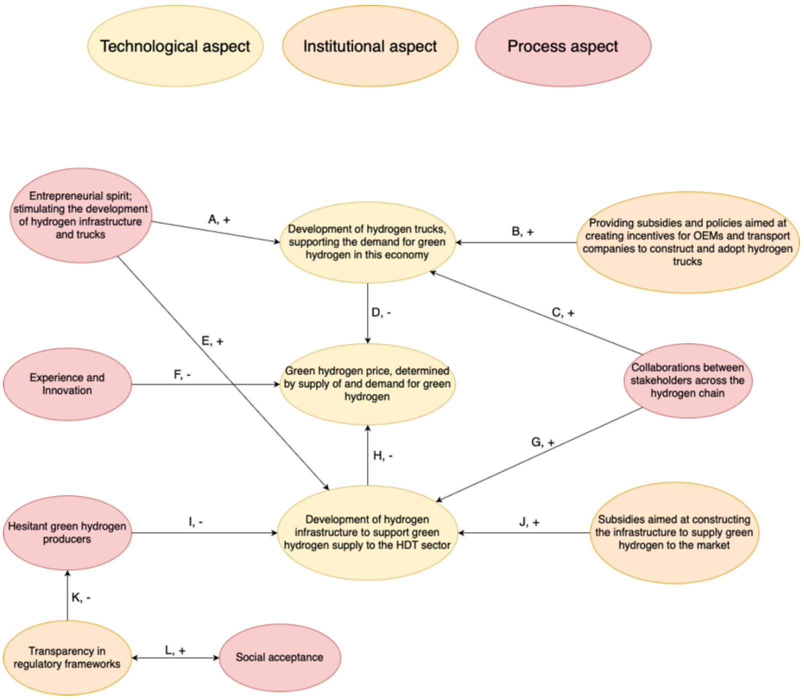

Figure 1: Visualization of relations between TIP aspects.

To pave the way for green hydrogen to serve as a prominent fuel for the HDT sector in the Netherlands, several recommendations emerge. Recommendations concerning the supply side aim to address uncertainties surrounding green hydrogen technology, while those pertaining to the demand side focus on incentivizing and supporting heavy-duty transport companies in transitioning to hydrogen-powered trucks. Ultimately, if both supply and demand for green hydrogen progress simultaneously, which hinges on the development of the necessary hydrogen infrastructure within The Netherlands, this energy carrier could emerge as a sustainable solution for fuelling the HDT sector in the country.

The principal limitations of this study lie in its qualitative methodology and its narrow focus solely on the Netherlands. Given the qualitative nature of this research, future investigations could benefit from integrating quantitative data for a more comprehensive analysis. Quantitative analyses could encompass evaluating investment trends, conducting cost-benefit assessments of hydrogen infrastructure projects, and monitoring the uptake rates of hydrogen-powered trucks. Additionally, while this study primarily examines the Dutch context, expanding the scope to include comparative analyses with countries at various stages of hydrogen infrastructure development could offer valuable insights. Such comparisons could unveil global best practices and lessons learned, facilitating a more globally informed approach to hydrogen infrastructure development.

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List of abbreviations

AFIR	Alternative Fuels Infrastructure Regulation
CAPEX	Capital Expenses
CCS	Carbon Capture and Storage
CEF	Connecting European Facility
CO_2	Carbon Dioxide
COSEM	Complex Systems Engineering and Management
DEI	Demonstratie Energie- en Klimaatinnovatie
EI	Expert Interviews
EIA	Energy Investment Allowance
ETD	Energy Taxation Directive
EU	European Union
EZK	Economische Zaken en Klimaat
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell Hydrogen
FID	Final Investment Decision
GW	Giga Watt
H_2ICE	Hydrogen Internal Combustion Engine
HD	Heavy-Duty
HDT	Heavy-Duty Truck
IAD	Institutional Analysis and Development
IPCEI	Important Projects of Common European Interest
LNG	Liquid Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
MW	Mega Watt
NL	Netherlands
NWP	Nationaal Waterstof Programma
OEMs	Original Equipment Manufacturers
OPEX	Operational Expenditures
RED	Renewable Energy Directive
RES	Regional Energy Strategies
RFUs	Renewable Fuel Units
RQ	Research Question
SDE	Stimulering Duurzame Energieproductie en Klimaattransitie
SQ	Sub-Questions
STS	Socio-Technical System
TTW	Tank-To-Wheel
TCO	Total Cost of Ownership
TIP	Technology, Institutions, Process

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1. Introduction

1.1 Unsustainable heavy-duty truck (HDT) sector

Our world remains heavily reliant on fossil fuels, which are major contributors to global climate change, responsible for over 75% of worldwide greenhouse gas emissions, predominantly CO_2 (United Nations, n.d.). These emissions exacerbate global warming, posing significant threats to future generations (EPA, n.d.).

Transportation sector

The transportation sector has historically posed a significant challenge in terms of reducing greenhouse gas emissions, prompting considerable effort to address this issue effectively. In recent years, however, with the Sustainable Development Goals and the Paris Climate Agreement, adaptation of transport to the future climate, once a poor relation in terms of climate change response, is increasingly being recognized as vital to the continued success of mobility and global trade and development (UNCTAD, 2019). In Europe, the European Commission aims to reduce the total amount of emitted greenhouse gases to zero by 2050 as outlined in the European Green Deal (European Commission, n.d.-c). However, major reasons like the increasing kilometres travelled, the continued dominance of fossil fuels in transport, and high average vehicular CO_2 emissions make it particularly challenging to mitigate the emissions from the transportation sector (Weger et al., 2021). The European Environment Agency reports that the transportation and mobility sector, including automotive, is responsible for 25% of all greenhouse gas emissions, highlighting the need for decarbonization in this area.

Heavy-duty (HD) freight road transportation

Notably, heavy-duty trucks (HDTs), which make up just 2% of the EU's total vehicle fleet, account for 20% of these emissions. The European Commission has set a target to cut emissions from the transportation and mobility sector by 15% by 2030 and 90% by 2050, compared to levels in 1990. To align with these reduction targets, it's projected that the EU will need to switch out 280,000 diesel heavy-duty trucks for zero-emission alternatives by 2030 and increase this number to 1.5 million by 2050 (Serrano & Ruiz, 2023).

Within the Netherlands the mobility sector is accountable for 18.5 percent of their total greenhouse gas emissions. At present, HDTs are responsible for nearly one-third of the total CO_2 emissions from the mobility sector (CBS, n.d.). The distribution of CO_2 emissions across different mobility segments in the Netherlands, including the HDT sector, is visualized in Figure 2 below.

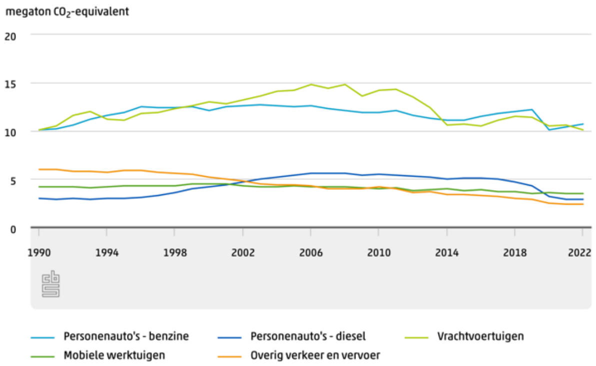

Figure 2: Distribution of CO_2-emissions across different mobility segments in the Netherlands (CBS, n.d.).

1.2 Hydrogen as a potential solution

Currently, our society is actively exploring energy carriers that have net-zero CO_2 emissions throughout their operational lifecycle. Hydrogen might be an alternative fuel to reduce the amount of emitted CO_2 from the HDT sector. It can be used for powering transportation. This energy carrier has many advantages as it has abundant sources, a high calorific value of combustion, the ability to be an energy storage medium, and clean and pollution-free usage (Zou et al., 2022). Therefore, hydrogen technologies are nowadays being matured and gradually industrialized. Furthermore, the world is currently facing increasing pressures that are aimed at climate change and the prevention of natural disasters. To conclude, hydrogen has attracted much attention and has become a strategic choice for the energy transformation of many countries (Zou et al., 2022).

Hydrogen that is produced from sustainable energy sources like wind, solar, or hydropower is called green hydrogen. Through electrolysis, water is split into hydrogen and oxygen using electricity in an electrochemical cell. This process emits no CO_2 and is therefore fully sustainable. However, currently, almost all hydrogen produced in the Netherlands is grey which means that CO_2 is released in the atmosphere during its production. It is made using fossil fuels. If the CO_2 released in the production of grey hydrogen does not enter the air but is stored or used, we speak of blue hydrogen. For example, CO_2 can be stored in an empty gas field. Because the CO_2 does not enter the atmosphere, it does not contribute to global warming (Milieucentraal, n.d.).

While electric trucks present a potential solution as well, their larger size and weight necessitate significantly larger batteries compared to passenger cars. This poses challenges, especially in the transportation sector, where long distances are common. To cover the extensive distances travelled by trucks solely with batteries, a disproportionately large and heavy battery would be required, rendering it economically impractical. Hydrogen is then a suitable alternative (Milieucentraal, n.d.).

1.3 Lacking hydrogen infrastructure development

With the introduction of green hydrogen and the evidence that it has the potential to make transport systems fully sustainable, we should think about how our society could realize an appropriate infrastructure that is indispensable to supply the hydrogen produced from renewable energy sources to hydrogen-powered trucks. Worldwide, a common approach to introducing green hydrogen to the market is still lacking. It seems that it will take time to realize an appropriate infrastructure. The introduction of alternative fuels will require long-term investments for setting up and expanding infrastructures which are especially true in the case of a hydrogen economy based on renewables (Ramesohl & Merten, 2006). The exorbitant costs associated with green hydrogen and the development of the additional infrastructure render this energy carrier a more expensive alternative when compared to conventional energy sources as natural gas or coal. Additionally, green hydrogen production processes face still low energy efficiency issues. In the end, such challenges deter infrastructure development (Arup, 2023).

1.4 State-of-the-art knowledge

In this section, we delve into the existing literature on the topic. It's crucial to explore the expanding body of literature and reports from prominent consultancies and international agencies to thoroughly comprehend the available knowledge regarding hydrogen infrastructure development. In addition, grey literature has supplemented the state-of-the-art academic knowledge to create a specific knowledge gap in the subsequent subsection. An overview of the examined literature is presented in Appendix A.

Need for hydrogen infrastructure development

Faye et al. (2022) have enunciated that the foundational elements for realizing a sustainable hydrogen economy reside in the earnest consideration of hydrogen production, storage, and transportation. The writers are pointing at further research into modern hydrogen infrastructure to identify the most promising areas for future developments in these important domains. Rasul et al. (2022) argue that the capability of hydrogen production, storage, and supply is worldwide far less than what will be needed in the future. They mention that hydrogen infrastructure including, production, storage, and transportation to end users must be developed to embrace hydrogen's full potential. The infrastructure for hydrogen transport and storage is not fully developed anywhere in the world to cope with the demand that will arise when vehicles will progressively be converted to hydrogen powered fuel or fuel cells.

In the context of HD freight road transportation in the Netherlands, Rijksoverheid (2022) reports the government's commitment to expediting the use of hydrogen in trucks and other substantial modalities. A requisite component for the actualization of this endeavour involves the establishment of a robust and reliable infrastructure. This infrastructure is imperative to reach the outlined objective for 2050, wherein all HD vehicles, including trucks, in the Netherlands are mandated to operate entirely sustainable.

Technological challenges

Le et al. (2023) pays attention to the main challenges concerning hydrogen introduction, particularly the high costs associated with the production and storage of (green) hydrogen. These costs surpass those of the conventional fossil fuels. In addition, the writers note the scarcity of hydrogen infrastructure, including storage facilitates and refuelling stations. Nauta & Geilenkirchen (2021) adds the formidable challenge in the widespread adoption of hydrogen, notably citing a suboptimal Well-to-Wheel efficiency (which refers to the overall efficiency of hydrogen production, distribution, and utilization in vehicles). The dynamic landscape of developments concerning charging and refuelling infrastructure, system degradation, and safety issues further compounds the insecurities surrounding the viability of hydrogen.

Particularly in the context of HD freight road transport, the precise trajectory and ultimate configuration of the hydrogen landscape remains undetermined. The article written by Litvinenko et al. (2020) assert that the hydrogen economy does not have the necessary foundation in terms of physical infrastructure; there is a lack of technological possibilities to construct large-scale and geographically distributed infrastructure. According to NWP (2022), this is true for the hydrogen infrastructure in the Netherlands. They argue that the challenge is clear; with a poor supply of renewable and low-carbon hydrogen it is imperative to scale up the entire chain significantly – production, import, transport, distribution, and use. To fully and timely utilize the potential of hydrogen, a significant scale-up is required in the field of hydrogen production, the roll-out of transport and distribution infrastructure and the development of hydrogen vehicles, including trucks, and filling stations.

Institutional challenges

Van der Spek et al. (2022) mention that the realization of a hydrogen economy is contingent upon an unwavering political support. These writers do point at several challenges that need to be addressed simultaneously, including technological advancements in hydrogen production, infrastructure development, market structuration, policy formulation, and the design of cogent business models. Legislators and regulators face the critical task of creating and enabling a consistent legal framework for the hydrogen infrastructure and market. This framework must balance climate goals, cost-effectiveness, security, flexibility, safety, and fairness to the end consumers. The authors argue that the barriers to invest in hydrogen infrastructure in Europe is nested in the intersection between commercial, financial, legal, and policy constraints. Sharma et al. (2023) adds that the production of hydrogen requires policy development and implementation. According to them, an efficient policy development structure will not only support the sustainable production of hydrogen but also stimulate hydrogen distribution and storage development.

Nauta & Geilenkirchen (2021) assert that the discourse surrounding the utilization of hydrogen in the transportation sector in the Netherlands remains ongoing. Nevertheless, current policy is till now merely focused on the energy carrier's utilization in the mobility sector, resulting in a restricted application in this domain. Given the limited advancements so far and the substantial challenge of achieving a climate-neutral mobility system, a necessity arises to formulate more concrete policies governing the deployment of the energy carrier in mobility. Ekinetix (2021) further emphasizes that expeditious development of the hydrogen ecosystem in the Netherlands requires robust and incentivizing policies. The current juncture calls for a transition from a singular, technically oriented innovation policy to the pragmatic scaling up of infrastructure and associated fleets, under the adage "from testing ground to sustainable ecosystem".

Process (stakeholder) challenges

Schönauer & Glanz (2021) try to elaborate on previous studies on the social acceptance of large-scale hydrogen infrastructure projects. They observe a cognitive dissonance, whereby individuals, while generally embracing the conceptual framework of a hydrogen economy, prove a less sanguine attitude when they are confronted with the infrastructural implementation of the technology. They mention that trust in the stakeholders is a critical underpinning of this transformation in disposition. Emodi et al. (2021) elaborate on this as they elucidate that there is little attention given in earlier studies toward the social impact of hydrogen infrastructures on local communities and indigenous groups. Local authorities must be engaged into the hydrogen economy according to them. In addition, Le et al. (2023) stress that to achieve the realization of the hydrogen infrastructure, public education and heightened awareness could play important roles in promoting the acceptance and use of the technology. The discourse of Le et al. (2023) further underscores the necessity to tackle multiple challenges related to production, storage, transportation, and the intrinsic low energy density of hydrogen. They posit that to solve these multifaceted challenges requires a concerted effort encompassing the collective agency of industry leaders, scholars, legislators, and the public. Germscheidt et al. (2021) agrees upon the realization of such coalitions to achieve green and cost-effective hydrogen production.

With the focus on the hydrogen infrastructure within the Netherlands, NWP (2022) argues that challenges persist in fostering collaboration between the government and the private sector to catalyse opportunities for the utilization of hydrogen in the transportation sector. Anticipating substantial development in the vehicle market, there is an expectation that a comprehensive network of hydrogen filling stations catering to multiple modalities, including HD trucks, can be established nationwide by 2030. The writers further expand upon the fact that the social acceptance of the technology within this domain should be given more attention to enhance the likelihood of successful integration into society.

1.5 Unclear vision on hydrogen infrastructure development

The current state of the literature underscores the necessity for further exploration of modern hydrogen infrastructure to pinpoint areas ripe for future advancements in these critical domains. Specifically, within the Netherlands, the government is actively pushing for the adoption of hydrogen in heavy-duty trucks, recognizing the indispensable role of infrastructure in realizing this ambition. However, literature emphasizes a range of technological, institutional, and process-related challenges that hinder the development of such infrastructure.

The trajectory of physical hydrogen infrastructure construction, especially for HD freight road transportation in the Netherlands, appears ambiguous. For green hydrogen to establish itself as a viable alternative fuel for the HDT sector, a comprehensive and robust infrastructure is imperative. Furthermore, there is a noticeable gap in understanding the institutional support required for these infrastructures. The literature indicates a lack of clear policy focus in the country regarding the utilization of hydrogen as an energy carrier, particularly for the HDT sector. Establishing a robust institutional framework, inclusive of legislation and regulations, is crucial to provide a solid legal foundation for hydrogen infrastructure and market operations. Finally, the extent of concerted efforts among existing stakeholders to drive the development of resilient hydrogen infrastructures remains uncertain. Additionally, the perceived significance of social acceptance of the technology underscores the need for effective strategies to manage it, ensuring the success of hydrogen infrastructure implementation.

The state-of-the-art literature falls short in depicting the ongoing progress of the hydrogen infrastructure value chain for the HDT sector in the Netherlands and how technology, institutions, and stakeholder processes are shaping this transition.

1.6 Understanding the socio-technical system

This research aims to delve into the deficiency within the hydrogen infrastructure for HD freight road transport in the Netherlands, which still hinders green hydrogen from becoming a potential energy carrier in this domain. To address this challenge, we undertake exploration and evaluation of this specific infrastructure. A comprehensive understanding of the socio-technical system (STS) of the Dutch hydrogen infrastructure is important. Understanding the socio-technical system of the Dutch hydrogen infrastructure is essential as it illuminates the complex interplay between human behaviour, technological factors, and organizational structures, crucial for determining the feasibility and effectiveness of green hydrogen adoption in this context.

Ultimately, the objective is to ascertain the status of the transition, evaluating the integration of green hydrogen and its accompanying infrastructure into our societal framework. This examination considers institutional considerations and the engagement of significant stakeholders in the process. The analysis reveals that this socio-technical system is nowadays subject to unstable requirements and constraints based upon an ill-defined environmental context. This fact will guide us toward the choice for a specific research approach in the following section.

1.7 A design-science approach; the TIP framework

To address the research objective described above, the study has analysed three main aspects of the system: technology, institutions, and process, along with examining the relationships between them. From a technological standpoint, the analysis will encompass green hydrogen supply, storage, transportation, and the establishment of refuelling stations and trucks, constituting the hydrogen infrastructure value chain. Meanwhile, an investigation into institutional initiatives implemented by regulatory bodies at both European and national levels will shed light on their influence on the infrastructure development. Furthermore, the collective strategy of stakeholders in the socio-technical system will be analysed to understand their specific interests and interactions, contributing to the process aspect of the system. Ultimately, the analysis will delve into the relationships among the TIP (Technology, Institutions, Process) aspects, shedding light on the interplay between technological progress, institutional backing, and stakeholder involvement in driving the shift towards sustainable heavy-duty trucks.

Employing a design science approach, particularly the TIP framework, the research aims to explore and evaluate the hydrogen infrastructure for HD freight road transport in the Netherlands. Insights derived from this research may pave the way for successful implementation of the hydrogen infrastructure in the future.

1.8 Research questions

This research is aimed at exploring the current state of hydrogen infrastructure development specifically tailored for HD freight road transportation in the Netherlands and provide insights about this development to determine if green hydrogen has the potential to become a viable substitute for the use of diesel in trucks in the future.

The main research question (RQ) is as follows:

How promising is the current development of hydrogen infrastructure in the Netherlands to support the integration of green hydrogen as a fuel for the heavy-duty truck (HDT) sector?

To answer the main RQ, four sub-questions will be formulated and answered during the research process to guide the investigation properly. The following sub-questions (SQ) will be investigated:

SQ1: What is the current technological status of the physical hydrogen infrastructure for heavy-duty freight road transportation in the Netherlands?

Answering this question is a priority because it is essential to understand the composition of the physical artifact and the technologies necessary to facilitate hydrogen-powered heavy-duty trucks in the Netherlands. By examining ongoing projects aimed at developing this infrastructure, we can gain a more comprehensive understanding of the current development of this aspect. From there, an examination can be done on its institutional environment wherein the infrastructure needs to operate. Without favourable policies, no technology would be able to penetrate the existing regime of fossil fuelled mobility. It will be imperative to investigate the institutional context. Therefore, the second sub-question will look as follows:

SQ2: How is the institutional context shaping the development of the physical infrastructure within the Netherlands?

This question will initiate an investigation into the present institutions and regulations for hydrogen infrastructure implementation and how they influence the realization of the infrastructure. The third sub-question is about the relevant stakeholders and their strategies to properly coordinate the transactions needed to construct the technological artefact:

SQ3: Who are the common stakeholders within this socio-technical system, and how do they collectively coordinate the realization of the hydrogen infrastructure?

Finally, the performance of the TIP aspects is evaluated and interactions between the aspects are explored to determine how they collectively influence the development of the system. The fourth sub-question is as follows:

SQ4: How are the TIP aspects performing and to what extent are they aligned in the development of the hydrogen infrastructure?

Responses to the above-mentioned sub-questions have steered the research process towards resolving the main research question, assessing the progress of Dutch society in establishing the hydrogen infrastructure for the integration of green hydrogen into the HDT sector, and identifying insights for future sustainability efforts in this area.

1.9 Link to COSEM – Transport & Logistics

The research fits into the COSEM master track as this thesis ensures a well-defined learning process about the design of a transport and infrastructure system from an integrated transport, economic, environmental, and spatial perspective. An alternative is explored and evaluated for the design of improved ways of fuelling transportation to gain insight into the hydrogen infrastructure processes from a multi-actor perspective. Eventually, the exploration and evaluation of this complex socio-technical system might guide green hydrogen to becoming a more compatible option for fuelling HD freight road transportation within the Netherlands.

1.10 Report structure

The structure for the rest of this report is organized as follows: Chapter 2 details the methodology applied to tackle the research questions. Chapter 3 provides an in-depth look at the system's technological advancements, while Chapter 4 discusses how the institutional framework operates. Chapter 5 sheds light on stakeholder initiatives. Moving forward, Chapter 6 assesses the efficacy of each element and their interplay. The discussion is presented in Chapter 7, leading to the conclusion in Chapter 8. Additional information is presented in the appendices at the end of the report. Appendix A presents the reviewed literature, Appendix B the development of the hydrogen backbone, Appendix C a broad description of policy initiatives, Appendix D policy objective trees, Appendix E a general description of European and national coalitions, and Appendix F summarizes the interview outputs.

2. Research methodology

This chapter outlines the research methodology of this study to develop answers on the sub-questions and main research question. Section 2.1 describes the research design. Subsequently, selected data collection methods are elucidated. Finally, the used theoretical framework is described that is applied to analyze the complex socio-technical system.

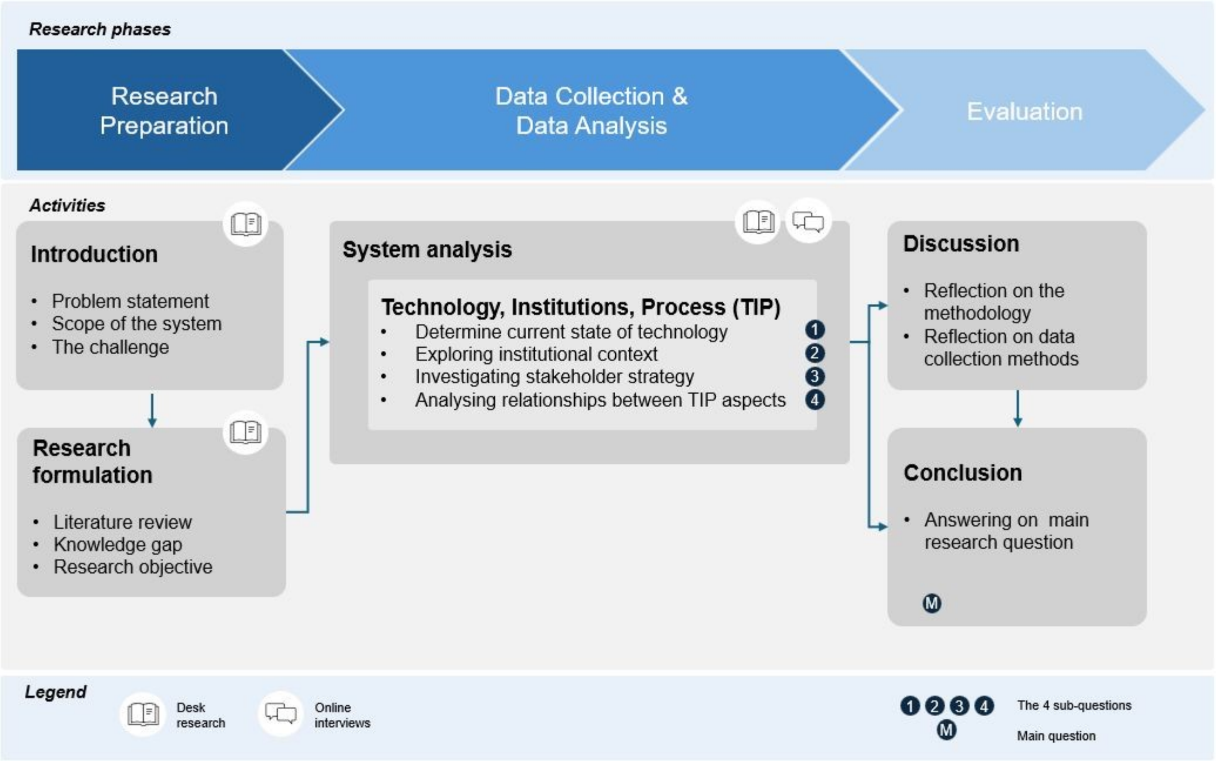

Figure 3: Research flow diagram.

2.1 Research design

The research flow is illustrated in Figure 3 above. The initial phase of this study involves thorough exploration of online data resources, scoping the problem, and identifying the knowledge gap. Subsequently, in the second phase, a research framework, the TIP, is employed to address the research questions through a combination of desk research and expert interviews. The final phase entails a comprehensive discussion on data collection, research frameworks, and ends with drawing conclusions.

2.2 Data collection

This section details how data was collected for this study to address the research questions. To understand the current development of physical hydrogen infrastructure, as well as its institutional context and stakeholder strategies, initial insights were gained through desk research. Interviews with experts in the field were then conducted to supplement and validate these findings. Additionally, a qualitative data analysis tool, ChatGPT, was utilized to organize and structure the collected data. Finally, a data management section is formulated to ensure the proper handling of data, aligning with the ethical standards of Delft University of Technology and the guidelines of the Human Research Ethics Committee. These standards prioritize ethically sourced data and compliance with the general data protection regulation.

2.2.1 Desk research

For the state-of-the-art literature review and further data collection throughout the study various articles from both contemporary academic and grey literature are examined.

To identify pertinent scientific and grey literature articles, several iterative search queries were executed on the platforms Google (Scholar) and Scopus. The search queries were refined from broad descriptions to more detailed ones to comprehensively explore the entire hydrogen ecosystem. Table 1 provides an overview of how this refinement process was carried out and lists the specific search queries used.

Table 1: Search queries on Google (Scholar) and Scopus.

Search Query	**Search terms**
1	“Hydrogen” AND “Production” OR “Storage” OR “Transportation”
2	“Hydrogen production” AND “Hydrogen storage” OR “Hydrogen transportation”
3	“Hydrogen production” AND “Hydrogen storage” AND “Hydrogen Transportation”
4	“Hydrogen infrastructure” AND “Technological problems” OR “Institutional problems” OR “Stakeholder problems”
5	“Hydrogen production” OR “Hydrogen storage” OR “Hydrogen transportation” AND “Technological problems” OR “Institutional problems” OR “Stakeholder problems”
6	“Hydrogen production” OR “Hydrogen storage” OR “Hydrogen transportation” AND “Technological challenges” OR “Institutional challenges” OR “Stakeholder challenges”
7	“Hydrogen infrastructure” AND “Heavyweight” AND/OR “Road transportation” AND/OR “Netherlands”
8	“Hydrogen infrastructure” AND “Heavy-duty” OR “Heavyweight” AND/OR “Freight” AND/OR “Road transportation” AND/OR “Netherlands”

For the academic literature review, existing literature from 2019 onwards was investigated as the introduction of hydrogen with its additional infrastructure is nowadays an ongoing discussion. Moreover, a snowballing technique was used to extend the review process, yielding additional insights that proved to be valuable for the exploration of the knowledge gap.

To comprehensively address the broader issue surrounding hydrogen infrastructure (encompassing rows 1-6 in Table 1), scientific literature was consulted. The selected articles do primarily focus on the production, storage, and transportation of hydrogen, along with the attendant challenges associated with these processes. These challenges are systematically examined form a technical, institutional, and stakeholder perspective within the context of hydrogen infrastructures.

During the literature search into the hydrogen infrastructure for HD freight road transport in the Netherlands, it became evident that there is a notably scarcity of scientific literature addressing this specific topic. Consequently, recourse to grey literature articles was undertaken to develop the precise knowledge gap pertinent to this research. The search terms delineated in row 8 of Table 1 did yield multiple articles retrievable via Google.

2.2.2 Expert interviews

To enhance and expand upon the insights derived from desk research, extant data is gathered through expert interviews. The main aim of the interviews is to acquire diverse perspectives and deeper understanding concerning the creation of a comprehensive hydrogen infrastructure and the limitations that must be considered in these developments.

The interviews were semi-structured initially following a structured format but later evolving into in-depth discussions. As elucidated by Bryman (2016), the approach of conducting semi-structured interviews enabled us to delve deeper into the queries posed to the respondents, giving the opportunity to develop a meticulous account of their responses. In addition to the general inquiries concerning the intricate STS of hydrogen infrastructure, all interviewees were subjected to a set of interdisciplinary questions specific to their roles within the system. The choice for Bryman’s semi-structured interviews method is intentional, as it offers flexibility and depth necessary for the interview process. This approach allowed us to pose supplementary questions during the interview, which have led to unexplored avenues of discussion related to the development of the socio-technical system. The qualitative outcomes obtained from these interviews have bridged the gaps in knowledge that desk research alone cannot address. Eventually, this systematic approach eased a comprehensive analysis of the system, and led to additional insights that were needed to formulate a robust response to the main research question.

To identify interviewees and collect additional crucial data, participation in the "National Hydrogen Congress" (Utrecht, Netherlands) was undertaken. This event covered various aspects of hydrogen application within society, notably its utilization in heavy-duty trucks. Connections made at this congress facilitated the scheduling of several interviews. Furthermore, additional interviewees were identified through online searches. A snowball sampling technique was utilized as well, where interviewed individuals recommended other relevant respondents, effectively broadening the pool of participants for the study.

A total of six interviews were conducted, involving 8 respondents (Table 2). The data collection process continued until reaching data saturation, indicated by the observation that little additional data emerged from the interviews beyond what had already been gathered. An overview of the summarized output of the interviews is presented in Appendix F.

Table 2: Overview of conducted interviews.

Function	Code in text	Date	Duration
Hydrogen refuelling station developer	EI-1	19-01-2024	60 min
Green hydrogen production company	EI-2	30-01-2024	60 min
Hydrogen transportation + refuelling station developer	EI-3	31-01-2024	45 min
Hydrogen storage + transportation developer	EI-4	21-02-2024	45 min
Legislative authority	EI-5	20-03-2024	45 min
A consortium, realizing hydrogen trucks	EI-6	02-04-2024	45 min

2.2.3 Qualitative data analysis tool; ChatGPT

ChatGPT, which is an artificial intelligence language model developed by OpenAI, is utilized as a software tool in this study. It has played a significant role in organizing and summarizing the outputs of interviews, thereby saving considerable time. Additionally, the software has been used to elucidate connections within the study, enabling clearer and more coherent communication of relationships and patterns identified in the data.

2.2.4 Data management

As this research contains several interviews with different stakeholders in this socio-technical system, the guidelines of the Human Research Ethics Committee of the TU Delft are maintained. Prior to the commencement of the interviews, the prospective interviewees are duly consulted to ensure their willingness to participate. Subsequently, as the interviews had proceeded, the content and scope of the discussion to which the interviewees had granted permission was explained in detail. Following the interviews, summarized reports were sent to the interviewees to ascertain their concurrence with the findings. The interviewees have had the opportunity to review and request revisions to specific statements if deemed necessary. Ultimately, the master thesis including the interviews will be made publicly accessible.

2.3 Design-science approach; the TIP framework.

A design science approach aims to identify a void in the functioning of a socio-technical system. As is illustrated in Figure 4, a general loop exists between the generation and design of alternatives, and the testing of the alternatives against certain requirements and constraints. In this case green hydrogen, with its infrastructure, is regarded as a design alternative for powering HD freight road transportation. The requirements and constraints are, in a more general sense, created from three different aspects of a socio-technical system namely technology, institutions, and process, structured within a TIP framework, which is elaborated on later in this section.

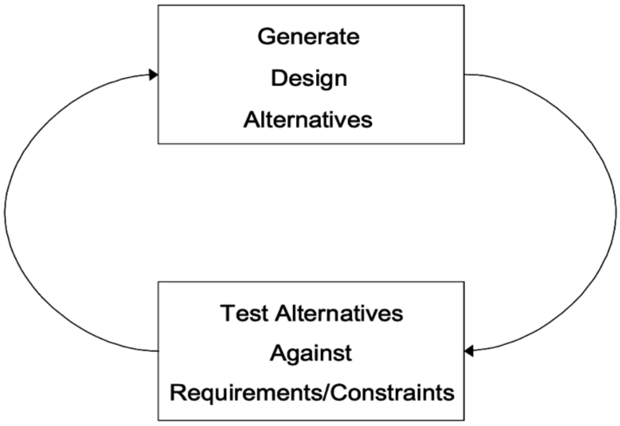

Figure 4: The generate/test cycle (Hevner et al., 2004).

Hevner (2007) explores the generate/test cycle in design science research, outlining three interconnected domains as depicted in Figure 5. The Relevance Cycle links the research project's contextual environment with design activities, focusing on identifying opportunities and challenges within a specific application domain comprising people, organizational systems, and technological systems aimed at a common goal. This cycle initiates design science research with a framework that sets constraints and evaluation criteria for the research outcomes.

The Rigor Cycle connects design science activities to the existing body of scientific knowledge, using past experiences and expertise to ensure innovation. It involves selecting and applying theories and methods for both creating and evaluating the artifact, contributing to the knowledge base through enhancements, extensions, and the experiences gained from research and real-world testing.

At the heart of design science research is the internal Design Cycle, which revolves around continuously generating and evaluating design alternatives based on set requirements until a satisfactory solution is found. The requirements stem from the Relevance Cycle, and the design theories and methodologies are drawn from the Rigor Cycle. Maintaining a balance between constructing and evaluating the evolving design artifact is crucial throughout this cycle.

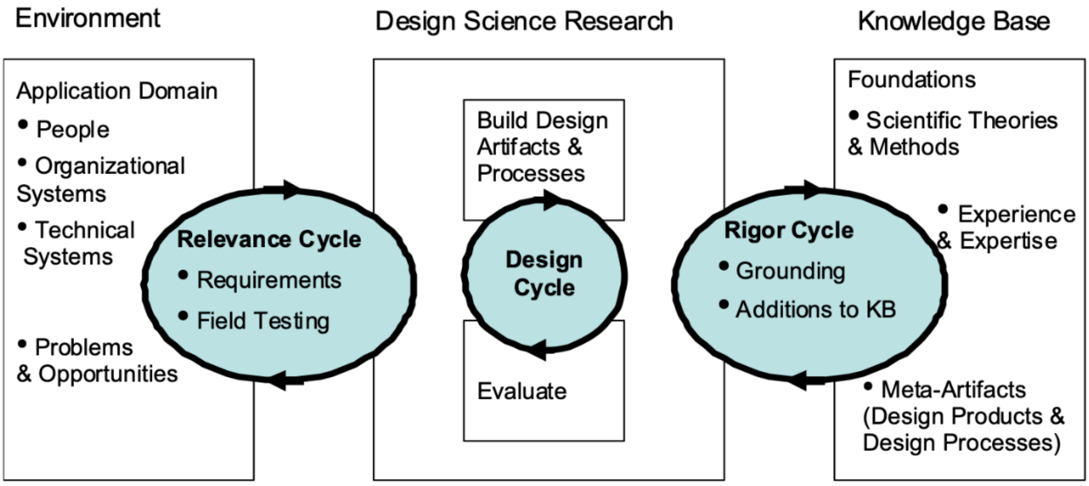

Figure 5: Design Science Research Cycles (Hevner, 2007).

This conceptual research approach is used to evaluate how our society is currently developing the hydrogen infrastructure that is required for the adoption of green hydrogen-powered trucks within the Netherlands. This has manifested as follows:

- Design cycle: this domain involves the evaluation of the hydrogen infrastructure for the HDT sector by our society. This consists of the supply, storage, and transportation of green hydrogen, and the development of refuelling stations and hydrogen-powered trucks. Next to that, the institutional and stakeholder environments of the infrastructure are evaluated in this theoretical cycle.
- Relevance cycle: this iterative cycle serves as the foundational basis for establishing evaluative criteria, facilitating the assessment of the performance of the current hydrogen infrastructure value chain for the HDT sector within the Netherlands in the Design Cycle.
- Rigor cycle: building upon existing knowledge about the physical hydrogen infrastructures and their institutional and process context. Output of the Design Cycle serves as new theoretical regimes for the Rigor Cycle.

The TIP framework

The TIP framework can be used to transform the design-science approach into a tangible analysis of the system. The convergence of the three pivotal aspects in intervention design, namely technology, institutions, and process, constitutes an essential foundation for the comprehensive evaluation of the current performance of hydrogen infrastructure for HD freight road transportation in the Netherlands. While each of these facets maintains its specific focus, they are interconnected, mutually influencing each other, thus coalescing to configure the implementation processes, as is visualized in Figure 6 below.

The "Technology" aspect refers to the physical artifacts, infrastructures, and technical systems that constitute the material basis of innovation within a socio-technical system. This aspect encompasses the design, development, and deployment of technologies, including hardware, software, and engineering solutions, aimed at addressing societal needs or challenges. The technology aspect involves understanding the state-of-the-art in relevant fields, assessing the technical feasibility and performance of innovations, and evaluating their potential impacts on society, economy, and the environment.

The "Institutions" aspect pertains to the formal and informal rules, norms, and organizational structures that govern the behavior of actors within a socio-technical system. This aspect focuses on the regulatory frameworks, policy initiatives, legal arrangements, and industry standards that shape the development, deployment, and diffusion of technologies.

Finally, the "Process" aspect refers to the dynamic interactions and collective actions of stakeholders involved in driving innovation and change within a socio-technical system. This aspect emphasizes the procedural aspects of innovation, focusing on how various actors, such as government agencies, industry players, and civil society organizations, collaborate, negotiate, and coordinate their efforts to advance technological developments and institutional arrangements.

As a result, the development and evaluation of the hydrogen infrastructure regarding its technology, institutions, and process aspects can be envisaged. This assessment will materialize as a product from the examinations within the three facets and between them, which will elucidate the requirements and constraints that, in turn, will serve as the criteria for the evaluation of the infrastructure.

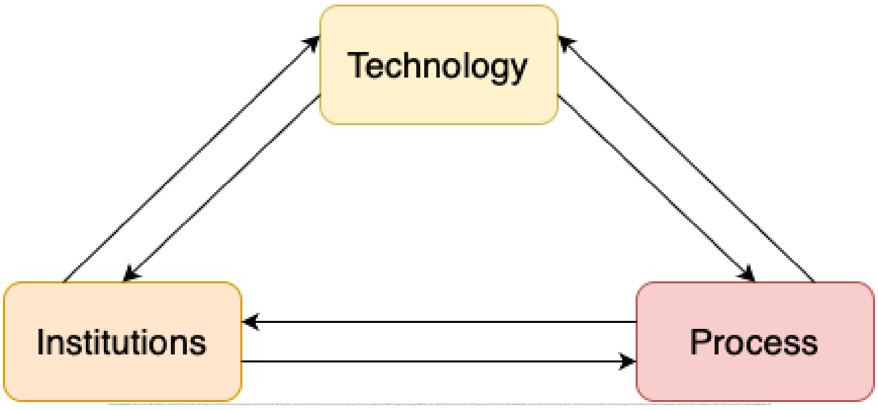

Figure 6: Simple visualization of the TIP framework.

3. Technology

This chapter provides an overview of current developments in realizing the physical infrastructure for the operation of HD vehicles powered by renewable hydrogen in the Netherlands. Section 3.1 constitutes the supply of green hydrogen encompassing domestic production and import from other regions. In section 3.2, hydrogen storage and transportation methods and ongoing projects are presented. Section 3.3 visualizes realized hydrogen refuelling stations and the construction of hydrogen-powered trucks. The last sub-section summarizes the current progress of the technological aspect. By examining current technological advancements and initiatives, we aim to shed light on the progress being made in the development of hydrogen infrastructure to facilitate the transition to sustainable transportation solutions. The entire hydrogen infrastructure value chain for the HDT sector is visualized in Figure 7. This chapter will answer SQ1: *What is the current technological status of the physical hydrogen infrastructure for heavy-duty freight road transportation in the Netherlands?*

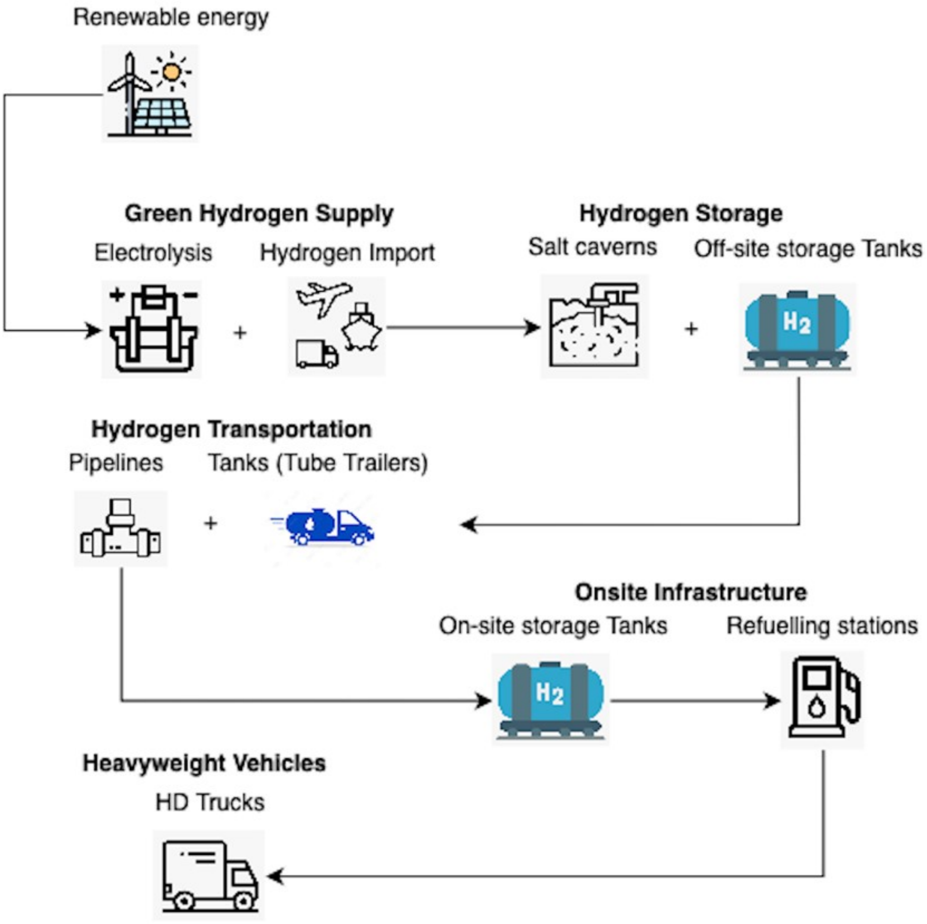

Figure 7: Value chain of the hydrogen infrastructure for HD freight road transport.

3.1 Green hydrogen supply

Currently, the Netherlands holds a significant position in hydrogen production and is considered a crucial player in this field (RVO, 2022a). As the second-largest hydrogen producer in Europe, the country generates approximately 9 million m3 of (fossil-based) hydrogen annually. In pursuit of extensive generation of carbon-neutral (green) hydrogen, the Dutch objective is to achieve 4 GW of installed electrolyzer capacity by 2030 (RVO, 2022a). This section aims to highlight the technological progress of green hydrogen supply in the Netherlands for supporting HD freight road transportation.

Several green hydrogen production projects in the Netherlands will first be analyzed. In conjunction with domestic hydrogen production, it is crucial to explore the import of green hydrogen from other countries. Green hydrogen import will supplement production in the Netherlands.

3.1.1 Green hydrogen production development

This segment seeks to delineate the current green hydrogen production initiatives and plans going on in the Netherlands. Its objective is to scrutinize their status and advancement, particularly concerning their potential to supply the heavy-duty freight road transportation sector with renewable hydrogen. Currently, there are numerous green hydrogen production projects in various stages of design and execution. Some important green hydrogen production projects and their state of progress are described in Table 3 below.

Table 3: Electrolyzer plants for powering HD freight road transport in NL.

Green hydrogen production projects for HD freight road transportation		
Project name	**Description + Current Status**	**Capacity**
H2ermes	In the Amsterdam Metropolitan Area of the Netherlands, the construction of the green hydrogen factory H2ermes, initiated by HyCC, has completed its feasibility study in 2022 with the aim of making its Final Investment Decision in 2023. The first green hydrogen is expected to be produced in 2025/2026. This project aims to play a significant role in the region's decarbonization efforts across industry and transportation (H2ermes, n.d.)	100 MW
Holland Hydrogen I	This green hydrogen plant will initially be used at the Shell refinery in Pernis on the Tweede Maasvlakte to partially decarbonize the production of fossil fuels. This saves a minimum of 200.000 tons of CO2 per year. The hydrogen will later also be used to decarbonize trucks in the transport sector. The factory will produce hydrogen using the wind energy from the Hollandse Kust Noord wind farm. Currently, the FID has been made and the project finds itself in the execution phase (building). Production is set to begin in 2025 (Shell, 2022).	200 MW
Djewels	HyCC and Gasunie have forged a partnership to establish a hydrogen plant at Chemiepark Delfzijl. Through this collaboration, HyCC and Gasunie seek to cultivate expertise in converting sustainable electricity into hydrogen via water electrolysis. According to the current planning, the installation will be operational in 2024 (Gasunie, 2024a).	20-30 MW
H2-Fifty	Bp is together with HyCC engaging in realizing a green hydrogen plant at the Second Maasvlakte in the Port of Rotterdam. The required electricity will be provided by wind turbines in the North Sea. Initially, the hydrogen will be used for desulphurizing Bp's refinery, but as later also for powering HD road transportation in the country. The FID was taken in 2022. The goal is to be operational before 2025 (H2Fifty, n.d.).	250 MW
ELYgator	This electrolyzer will be built in Terneuzen, which will produce hydrogen for the industry and mobility sector in the Netherlands and surrounding countries. ELYgator is a new step in Air Liquide's roadmap to contribute to the European Green	200 MW

	Deal. At the end of 2024, it is expected that the Final Investment Decision will be made. The plant will be operational in 2026/27 (AirLiquide, 2024).	

The Netherlands is an emerging player in the green hydrogen sector, with projects as Holland Hydrogen I, North-H2 and ELYgator demonstrating significant capacities aimed at meeting the demands of both industrial applications and HD freight road transportation. The strategic focus on scalable, renewable energy sources for hydrogen production positions these initiatives as critical to the decarbonization of freight road transport.

The electrolyzer projects Djewels and H2-Fifty, while primarily targeting industrial uses, contribute to a growing ecosystem of green hydrogen that could support transportation needs as well. Their production capacities, though not allocated to the HDT sector in the first place, bolster the overall supply of green hydrogen, potentially earmarking portions for HD freight road transportation as the market demand and infrastructure development continue to evolve.

Coastal electrolyzers utilizing wind energy

The hydrogen production projects listed in Table 3 are situated near the Dutch coastline. This strategic location is primarily attributed to their proximity to offshore wind farms. These wind farms can generate substantial amounts of electricity, which in turn can power the operations of large-scale electrolyzers utilized in hydrogen production (EI-6). The capacities and efficiencies of these coastal electrolyzers far surpass those of their onshore counterparts, which typically rely on electricity from inland wind turbines or solar panels. For instance, consider the H2Hollandia electrolyzer project, which leverages one of the largest solar panel arrays in the Netherlands to operate a 5 MW electrolyzer (TKI Nieuw Gas, 2020). However, such minor capacities may be less appealing for meeting the demand for green hydrogen in heavy-duty freight road transportation once the market is established. Moreover, solar energy is not considered a sufficient energy source in the Netherlands due to inadequate sunlight (EI-6).

The biggest electrolyzer is planned to be built above the Dutch wadden islands. This plant has a target operational date of 2031. Minister Jetten for Climate and Energy lends support to this initiative in the battle against climate change, underscoring the emission-free nature of green hydrogen production. Previous announcements disclosed plans for two North Sea wind parks above the Wadden region – one dedicated to electricity generation and the other specifically designed for hydrogen production. The wind park near the hydrogen plant is stated to supply 500 MW to the facility. It has the advantage of utilizing the pre-existing natural gas pipelines for transporting hydrogen to the rest of the Netherlands to eventually supply the hydrogen for amongst others HD vehicles. This endeavor will result in a well-connected hydrogen network (Rijksoverheid, 2023).

3.1.2 Green hydrogen production goals

Setting clear production goals for the future is essential to ensure the development of a robust hydrogen infrastructure capable of meeting the demands of amongst others the HD freight road transportation sector. The existing technological goals outlined in Table 4 below provide a roadmap for the evolution of green hydrogen production and its contribution to the overall hydrogen supply infrastructure. These goals serve as guiding principles for the development and implementation of green hydrogen production projects, playing an important role in establishing the supply side of the hydrogen infrastructure value chain.

Table 4: Overview of existing goals for the future regarding hydrogen production in the Netherlands, derived from (NWP, 2022).

2022-2025	- 600 MW electrolysis capacity implemented linked to renewable sources. - Realization of 10 electrolysis projects of various scales; both <20 MW and >100 MW for diverse applications in different regions. - Investment decisions made for 2000 MW electrolysis capacity.
2025-2030	- 80 PJ hydrogen production from renewable energy sources. Scaling up both centralized (domestic platforms) and decentralized electrolysis (in turbines) at sea. - No operational support is required for renewable hydrogen production after 2030, as successful policies have led to a robust demand for renewable hydrogen.
After 2030	- A transition to market-driven hydrogen supply; shift from a government-driven to a market-driven hydrogen supply in which supply follows demand based on standardization and pricing. New electrolysis projects will be economically viable without operational expenditures support (OPEX), only CAPEX-support will be needed for specific installations. - There is a certainty in market demand for renewable hydrogen in the Netherlands by 2030, facilitated by clear hydrogen goals in Europe and corresponding policies. - Exponential growth in renewable electricity production: foster exponential growth in the production of renewable electricity, particularly from offshore wind, aiming for an expansion to 50 GW by 2040 and 70 GW by 2050. - Inevitable growth in electrolysis capacity: acknowledge the inevitable growth in electrolysis capacity on land or at sea beyond 2030 to accommodate the rising demand for hydrogen.

3.1.3 Green hydrogen import

The anticipation is that there will be a need for green hydrogen import in addition to domestic production, given the substantial demand in the industrial and transportation sectors (NWP, 2022).The future landscape of international hydrogen trade reveals a diverse scenario: a considerable number of countries with the potential to export, multiple methods for hydrogen transport and storage, and a range of applications for hydrogen. Some nations will center their efforts on exporting hydrogen, particularly those with advantageous conditions for production, such as sunny countries or regions with strong winds. These regions include the Middle East, where abundant solar and wind resources offer favorable conditions for hydrogen production. There, solar and wind power yields significantly more electricity than in the Netherlands, substantially reducing the production costs of green hydrogen (EI-1). Additionally, North Africa, including countries like Morocco, Algeria, and Egypt, boasts similar renewable energy potential. Other regions of interest for hydrogen production include Namibia, Chile, Brazil, the United States, and Australia, all characterized by ample sunlight and wind. As the Netherlands seeks to transition to cleaner energy sources, exploring partnerships and import opportunities with hydrogen-rich regions worldwide could play a crucial role in ensuring a sustainable and reliable hydrogen supply chain (EI-2).

Although it still needs to be transported to Europe, this proves to be financially feasible. The flexibility in the supply chain is emphasized, acknowledging that ships will traverse the globe to transport hydrogen from point A to B. This is further supported by the construction of import facilities, albeit still in development (such as the ACE terminal in the port of Rotterdam (ACE Terminal, 2024)). It is a long-term option being considered to balance the green hydrogen ecosystem. Although not fully realized yet, it is seen as a forward-thinking approach (EI-1).

The demand for renewable hydrogen in industry and mobility is estimated to be between 60 and 100 PJ in 2030 by CE Delft and TNO. It is expected that the commencement of substantial hydrogen imports will take place around 2025-2026, with a more extensive scale set to unfold towards 2030.

By engaging in the import and transit of hydrogen, the Netherlands can uphold and enhance its existing status as an energy hub in Northwestern Europe. The analysis of hydrogen imports will encompass various products and fuels derived from hydrogen, including ammonia, methanol, and liquid organic hydrogen carriers (LOHC). In fact, identifying these streams is currently a complex task (NWP, 2022).

3.2 Hydrogen storage and transportation

To facilitate HD freight road transport and various other applications, it is essential to balance hydrogen supply and demand using storage techniques. This ensures that excess hydrogen supplied can be stored for times when supply will be lower, allowing society to continue utilizing this clean energy carrier. Additionally, the hydrogen must be transported to various locations within the country to supply nationally distributed refuelling stations. Hydrogen storage and transportation ensure the continuous alignment of hydrogen supply and demand. This section provides an overview of current endeavors employed for storing and transporting hydrogen within the Netherlands, and presents established goals related to this domain for the periods 2022-2025, 2035-2030, and after 2030.

3.2.1 Hydrogen storage

Currently, there are two primary methods for hydrogen storage in the Netherlands. The first approach involves utilizing salt caverns, while the second entails storage in specific hydrogen tanks. The following outlines both options and presents how both initiatives are realized within the Dutch society.

Salt caverns

Salt caverns are underground spaces suitable for hydrogen storage. It is acknowledged that the vast volumes of these caverns can accommodate significant amounts of hydrogen, presenting a promising prospect, especially for locally produced gaseous hydrogen (EI-1). The storage of hydrogen in such caverns, at depths ranging from approximately 1 to 3 kilometers, mirrors the existing practices with natural gas. This underground hydrogen storage, in its gaseous state, serves three primary functions (Gasunie, 2024c):

- Short-cycle storage to address temporary imbalances in demand or supply, spanning hours to two weeks.
- Seasonal storage to manage fluctuations in demand and supply over seasons, ranging from weeks to months.
- Long-cycle storage to ensure a secure supply in case of emergencies.

For over 10 years, Gasunie's subsidiary, EnergyStock, has been safely storing natural gas in these cavities near Zuidwending. Another subsidiary of Gasunie, HyStock, has successfully conducted a pilot for hydrogen storage in collaboration with TNO. The results indicate that the current method of safely storing natural gas is also suitable for hydrogen storage. Additionally, hydrogen can be stored in salt caverns in a manageable way concerning technical integrity, geological density, and stability. At the Zuidwending location, plans are currently being developed to create four new salt caverns for hydrogen storage. Deep in the ground at this location, there is a salt layer. By dissolving the salt in this layer with water and pumping the salty water to the surface, caverns or voids in the ground are created. The first salt cavern is expected to be operational in 2026 (Allesoverwaterstof, n.d.). Furthermore, the existing six salt caverns used for natural gas storage at this location could also potentially be repurposed for hydrogen storage (Gasunie, 2024c).

Next to that, Gasunie and Patrizia/storag Etzel are planning to develop hydrogen storage caverns in the Etzel salt dome in the German state of Lower Saxony. The goal is to develop and manage a storage facility for multiple caverns with a total capacity of up to 1 TWh of hydrogen, following a feasibility study. The location of the storage caverns in Etzel is strategically positioned with perfect access to both the German and Dutch hydrogen markets. This project is recently announced, which means that it is still in the concept stage (Gasunie, 2024b).

Hydrogen storage in tanks

In addition to the storage method involving salt caverns, hydrogen can also be stored in specific hydrogen tanks. This can be achieved through three approaches: compressed hydrogen, liquefied hydrogen, or materials-based storage (WaterstofNet, n.d.-b). Nowadays, smaller-scale hydrogen storage is almost exclusively done using hydrogen tanks (Waterstofguide, 2023). These tanks can be either off-site or on-site. Off-site storage tanks, situated at production or central distribution facilities, store hydrogen in large quantities before it is transported. On-site storage tanks, located near refueling stations, directly supply hydrogen to these stations, ensuring immediate availability.

Compressed hydrogen

As mentioned earlier, the volume occupied by hydrogen is considerably larger than that of other hydrocarbons, nearly four times that of natural gas. To make hydrogen practical for various applications, including heavy transport, compression becomes necessary. The challenges lie in hydrogen's low energy density, expansive volume, and the requirement for cryogenic storage, posing significant barriers to its widespread adoption. These challenges, particularly relevant in mobility applications like heavy transport, may significantly limit cargo space due to the space and other necessities for hydrogen storage. While this may not be a concern for hydrogen storage in general, it does underscore the importance of considering the specific requirements for supplying hydrogen to HD vehicles (Willige, 2022).

Liquefied Hydrogen

The process of storing hydrogen in a liquid form is technically intricate and has historically incurred significant costs. To achieve this, hydrogen needs to be cooled to a temperature as low as minus 253 degrees Celsius and then stored in well-insulated tanks to sustain this low temperature and minimize evaporation. This necessitates the use of a complex storage tank. As a result, the adoption of liquefied hydrogen has been limited thus far. On the other side, liquefied hydrogen boasts a higher energy density compared to gaseous and compressed hydrogen, which serves as a significant advantage. As the production and demand for renewable hydrogen increase, the potential for greater economies of scale could render liquefaction a more feasible option for storage and transportation (Willige, 2022).

Materials-based hydrogen

An alternative to compressed and liquefied hydrogen is materials-based storage, where solids and liquids capable of chemically absorbing or reacting with hydrogen are employed to bind it. Utilizing ammonia, a compound composed of hydrogen and nitrogen, as a carrier for hydrogen is arguably the option with the most potential. It is considered as an efficient approach. Its energy density by volume is nearly double that of liquefied hydrogen, making it considerably easier to store and transport. This entails converting hydrogen to ammonia, transporting it to its end-destination, and then cracking it to release the hydrogen at its point of use. However, it's important to note that ammonia cracking is still in the early development stage, and conversion rates remain relatively low, around a third at best (Willige, 2022). Several Dutch companies that try to develop tanks for hydrogen storage are listed in Table 5 below.

Table 5: Overview of Dutch initiatives for hydrogen storage in tanks.

Compressed hydrogen storage	
H2Storage	H2Storage is a company dedicated to developing compressed hydrogen tanks. Its objective is to create an innovative lightweight composite hydrogen storage tank suitable for both mobile and stationary storage under high pressure. These tanks play a vital role in enabling emissions-free heavy road transport, facilitating seasonal storage of renewable energy in urban settings, and supporting large-scale storage of energy from sustainable sources such as wind and solar farms. Additionally, the project aims to establish a production facility for (semi) automated series production of these tanks, with an annual production target ranging from 10,000 to 60,000 units (RVO, n.d.).
NPROXX	NPROXX provides multiple element gas containers, trailers, and bundles different pressure levels and storage capacity based on their technology. They are further recognized for designing, producing, and manufacturing pressure vessels for high-pressure hydrogen storage. High-strength lightweight composite pressure vessels are integrated in standard containers for use at H2 refuelling stations (NPROXX, 2024).
Liquefied hydrogen storage	
Air Products Nederland	The company Air Products Nederland possesses the technology required to store and transport hydrogen in both liquid and gaseous forms within the Netherlands. Having the capability to handle both forms of hydrogen storage enables Air Products to meet diverse needs of its customers and support the growing of the hydrogen economy in the country (Air Products, 2024).
Toray Advanced Composites	Toray Advanced Composites focuses on developing liquid hydrogen composite tanks. This is a research program directed at creating lightweight composite tanks capable of withstanding extreme low temperatures associated with liquid hydrogen. For HD road transportation in the Netherlands, the applicability of this technology would depend on the adaptation and scalability of liquid hydrogen storage solutions to meet the requirements of the road vehicles. While the primary focus of the company is on aviation, the advancements in their liquid hydrogen storage technology could certainly have implications for other sectors like the HD road transportation sector (Toray Advanced Composites, 2021).
Materials-based hydrogen storage	
Power-to-Ammonia	In the Netherlands, there is a project called Power-to-Ammonia, which aims to convert renewable electricity into ammonia and store it in liquid form at -33 degrees Celsius and atmospheric pressure. This initiative is still in early development stages (te Roller, n.d.).

3.2.2 Hydrogen transportation

Currently, pipelines are the most efficient means of satisfying domestic hydrogen demand due to their cost-effectiveness relative to alternative options (EI-5). Alongside pipeline transport, hydrogen can be conveyed using tanks in various forms beyond its gaseous state, including liquefied or compressed hydrogen, and packaged carriers or compound forms like ammonia.

Pipeline transport

The Hydrogen Backbone (Figure 8), a national primary network for hydrogen connecting industry, storage, production, and surrounding countries, aims to contribute to this initiative. An advantage is that the existing natural gas network can largely be repurposed for this purpose. Moreover, the Netherlands possesses additional favorable conditions that can enhance the robustness of the hydrogen chain: its location along the North Sea, where wind farms can supply electricity for green hydrogen; extensive experience with carbon capture and storage (CCS); and the availability of depleted gas fields and salt caverns for hydrogen storage (Pont klimaat, 2021).

Gasunie aims to connect all five industrial clusters in the Netherlands in the future, incorporating hydrogen storage facilities, production sites, and hydrogen infrastructure in surrounding countries. The national hydrogen network will be largely established using existing infrastructure (HyWay 27) and, to a lesser extent, with newly constructed pipelines. Gasunie is in discussions with the Dutch industry to assess the demand for sustainable hydrogen.

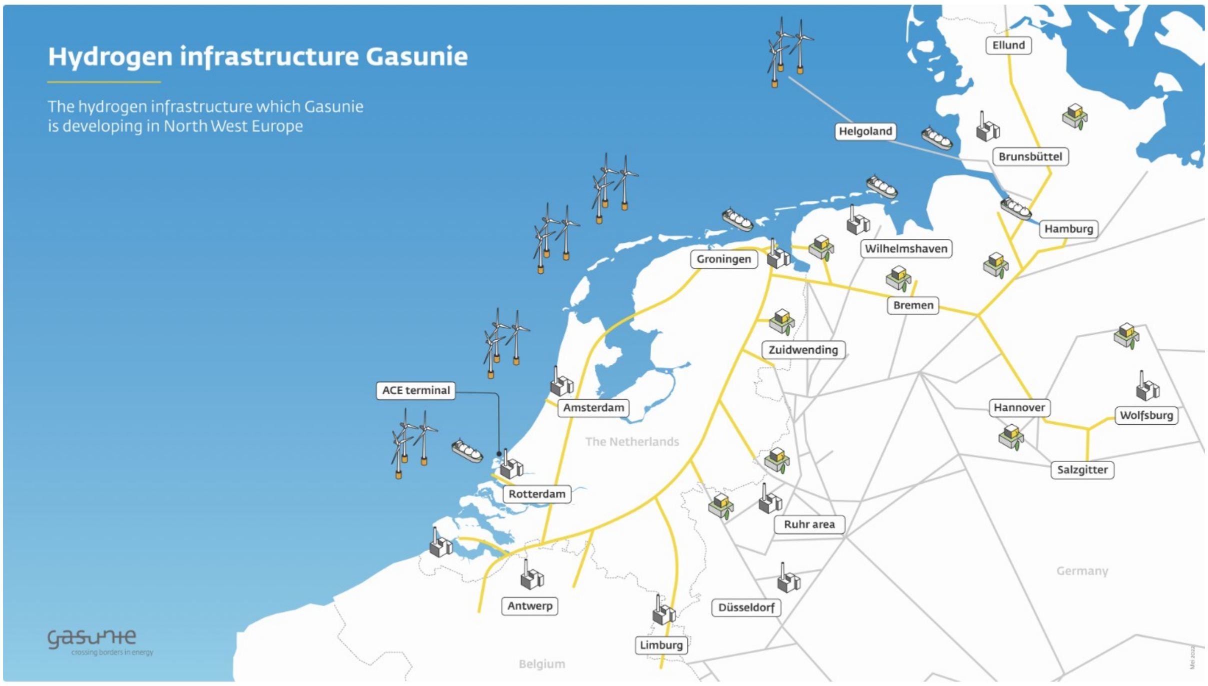

Figure 8: Hydrogen infrastructure (Hydrogen Backbone) (Gasunie, 2024d).

The development of the transport network has commenced in 2023. On October 27 that year, His Majesty the King conducted the inaugural ceremony marking the commencement of the national hydrogen network's construction in the Netherlands. King Willem-Alexander led the event at the construction site of Hynetwork, another Gasunie subsidiary, located in the Rotterdam harbor, where the initial segment of the nationwide network is being established

(Gasunie, 2023). By 2030, a transport network will be in place, extending in the major industrial clusters. It interconnects these clusters, provides access to storage facilities, and links the Netherlands with its neighboring countries, as depicted above. The three specific phases with their corresponding developments can be found in Appendix B.

In the realm of mobility, especially with an increasing focus on heavy-duty transport, the transportation of hydrogen to fuel stations is facing constraints within the limits of road transport. To avoid potential setbacks in the shift toward emission-free mobility, it is crucial to proactively develop a distribution infrastructure. In the Minister's communication on the 'Advancement of the hydrogen transport network' on June 29, 2022, there is an indication of an upcoming investigation into the establishment of hydrogen distribution networks. It mentions that it is imperative to achieve clarity in the upcoming years regarding the possible evolution of infrastructure in regional domains that not only caters to market demands but is also technically feasible. This research has engaged stakeholders from the mobility sector and Cluster 6 industry (other than the five connected industry clusters). In the end, the goal is to provide all refuelling stations in the Netherlands with hydrogen. This means that there is a need to explore how the hydrogen can be supplied to refuelling stations and cluster 6 that are not directly connected to the backbone (NWP, 2022).

In addition to the hydrogen backbone, entrepreneurial firms as Air Liquide have developed own pipelines to transport their hydrogen. For over 40 years, Air Liquide has developed unique expertise in mastering the entire hydrogen chain (production, storage, and distribution) in the Benelux. Air Liquide contributes to the widespread use of hydrogen in the transportation sector, including supporting the global deployment of necessary refuelling stations. Their network has a length of 2.225 km in Belgium and the Netherlands, in which a hydrogen network (WaterstofNet, n.d.-a).

Transportation with hydrogen tanks

Transporting hydrogen in the Netherlands over the road follows the same principles outlined in the section on "Hydrogen Storage in Tanks." The hydrogen stored in these tanks can be transported accordingly to the end destinations (NL Hydrogen, 2023). The advantage of these hydrogen tanks is that they can be easily transported on, for example, trucks using tube trailers making it a flexible task. However, it is not the most cost-efficient way to transport hydrogen.

3.2.3 Hydrogen storage and transportation goals

For the realization of the hydrogen storage and transportation projects in the Netherlands, the country elaborates on specific targets to bolster the construction of such projects, presented in Table 6. In this respect, the establishment of such goals is imperative for the realization of a robust and resilient storage and transportation infrastructure.

Table 6: Overview of predefined goals for hydrogen storage and transportation, derived from (NWP, 2022).

2022-2025	- The initial segments of the transport network are undergoing development (Appendix B). - Projections indicate the initiation of the first import flows and transit to Germany by the end of this phase (2025-2026) (section 5.1.3). - Additionally, a storage cavern is set to be completed and integrated into the transport network by 2025-2026. Furthermore, the initiation of the development of three additional storage caverns is planned.
2025-2030	- In the period from 2025 to 2030, the second phase of the rollout plan of the hydrogen backbone is in progress (Appendix B). The demand from various regions, including the Chemelot industrial cluster in Limburg and dispersed industrial entities across the country (Cluster 6), as well as the demand from the tank infrastructure for the transport and mobility sector, needs to be addressed from the coastal clusters. - By the end of the second phase, all industrial clusters could be linked to the transport network, and connections with neighboring countries established. - The initial 3 to 4 onshore salt caverns must be fully operational and implemented by 2030. The subsequent sites for additional salt caverns or storage fields are identified, and plans are formulated for their comprehensive development, both onshore, offshore, and internationally. Additionally, in this phase, the first storage locations for aboveground hydrogen carriers (at least for ammonia and liquid hydrogen) are being developed.
After 2030	- The completion of the third phase of the rollout plan is anticipated by 2030 (Appendix B). It is currently expected that a pipeline in the gas network will be repurposed for use along the route from Zeeland to Chemelot by 2030. This not only enhances supply reliability within the Netherlands but also expands the capacity for transporting hydrogen to Germany. - To support the large-scale deployment of hydrogen production at sea after 2030, a hydrogen infrastructure for transporting and storing offshore-produced hydrogen is deemed necessary.

3.3 Hydrogen refuelling stations and trucks

The final segment of the hydrogen infrastructure value chain encompasses hydrogen refuelling stations and the heavy-duty trucks. Ensuring an adequate number of hydrogen trucks requires simultaneous development of hydrogen refuelling stations, presenting a chicken-and-egg scenario which is elaborated on below. Subsequently, we delve into an analysis of the current development of hydrogen refuelling stations and trucks in the Netherlands, and highlight goals set to advance this last component of the hydrogen infrastructure value chain.

3.3.1 Chicken-and-egg dilemma

For the realization of hydrogen refuelling stations and trucks, a comparison to the chicken-and-egg dilemma is appropriate. This dilemma visualizes a clear picture of the pressing need for simultaneous progress in developing both hydrogen-powered HD trucks and the required refuelling infrastructure. It underlines the fact that these two aspects are interdependent. On the one hand, transport companies hesitate to invest in hydrogen trucks, and therefore restraining original equipment manufacturers (OEMs) from building these trucks, due to a lack of certainty regarding the development of refuelling infrastructure, while on the other hand, the development of refuelling stations is stalled by concerns over insufficient hydrogen purchase from transport companies using hydrogen-powered HD trucks. This situation leads to a standoff where neither transport companies and OEMs nor refuelling station developers make the first move; transport companies and OEMs are waiting for more refuelling stations to commit to hydrogen trucks, while refuelling station developers want assurance of truck adoption to justify building these stations (Nauta & Geilenkirchen, 2021).

It's crucial to recognize that the chicken-and-egg dilemma extends across the entire value chain of hydrogen infrastructure. The lack of green hydrogen supply impedes cost reduction for the energy carrier, posing challenges for transport companies in utilizing hydrogen trucks. Similarly, without sufficient demand from the freight transportation sector, hydrogen producers may not find it profitable to supply hydrogen to HD trucks.

3.3.2 Current development of refuelling stations and trucks

In the realm of heavy-duty transportation, various European projects are currently underway to introduce hydrogen refuelling stations and hydrogen-powered trucks. These initiatives, exemplified by projects like HyTrucks, PinkCamel, and H2 Accelerate, are aimed at revolutionizing the transportation sector. However, the successful deployment of these trucks and the corresponding establishment of large-scale refuelling stations require careful planning and consideration of lead times. Typically, scaling up truck production and setting up refuelling stations entail a lead time of approximately 2 to 3 years. Therefore, it is imperative to timely establish sufficient refuelling station capacity, ensuring both geographic coverage and adequate fuelling capacity per station to accommodate the widespread adoption of hydrogen-powered trucks (NWP, 2022).

At present, there are twenty-two operational hydrogen refuelling stations, with plans for an additional four stations in the pipeline. However, the majority of these refuelling stations are not suitable for heavy-duty trucks. These stations require larger infrastructure, commonly referred to as XL stations. Currently, three notable stations are under construction, including the station in Botlek, the Total station in Utrecht, and the XL station in Groningen operated by Holthausen (EI-6).

A recent gathering focused on 'Heavy Transport on Hydrogen' highlighted the significant progress made by major and smaller truck manufacturers alike. Key industry players such as VOLVO Group, DAF Trucks NV, Iveco Group, Daimler Truck AG, Mercedes Benz Trucks, TEVVA Hydrogen Electric Trucks, and others showcased their developments in hydrogen truck technology. This collective effort signifies a promising future for hydrogen-powered transportation in Europe and beyond, paving the way for a sustainable and environmentally friendly transport sector (Life New Hyts, 2024).

As of February 2023, there were 27 hydrogen trucks operational in the Netherlands, although their current number in 2024 remains unknown (de Ondernemer, 2023). Given that hydrogen technology is still in its early stages, there is a noticeable limited supply of hydrogen trucks available from OEMs. These OEMs develop hydrogen-powered trucks in two ways: with an implemented fuel cell (FCEV) or an internal combustion engine (H_2ICE). A fuel cell electric vehicle employs a propulsion system like electric vehicles, converting energy stored in hydrogen into electricity through the fuel cell (US Department of Energy, n.d.). A hydrogen internal combustion engine operates similarly to a traditional combustion engine but utilizes hydrogen as fuel, resulting in near-zero emissions (Garrett, n.d.). The realized trucks in the Netherlands are all FCEVs. H_2ICEs are still in the conceptual stage (EI-6).

3.3.3 Goals for establishing hydrogen refuelling stations and trucks

The establishment of hydrogen refuelling stations and the deployment of hydrogen-powered trucks must occur concurrently. In Table 7, goals and initiatives aimed at constructing these stations and trucks are outlined, advancing the adoption of zero-emission hydrogen-powered HDTs, with the ultimate objective of achieving carbon neutrality by 2050.

Table 7: Overview of goals regarding the establishment of hydrogen trucks and refuelling stations, derived from (NWP, 2022).

2022-2025	- Minimum of 10 Extra-Large (XL) hydrogen refuelling stations designed for heavy-duty transport. - Having adequate vehicles deployed per station, during this period the focus will be on hydrogen trucks utilizing fuel cell technology (FCEV) or internal combustion engine technology (H_2ICE). - For XL stations, this means catering to between 25 and 50 heavy-duty transport vehicles within 1 to 5 years of realization. By 2025, the plan is to have at least 4 XL stations under construction, each with the capacity to serve between 150 and 200 heavy-duty transport trucks by 2027. The targeted consumption of approximately 8 million kilograms (1 PJ) of hydrogen in road mobility is expected by 2025. - 3,000 hydrogen-powered HD trucks realized.
2025-2030	- A nation-wide network of hydrogen refuelling stations (at 350 and 700 bar), ensuring sufficient coverage in service areas, allowing users to refuel within a reasonable time and distance. - Collaborative efforts from both the government and the private sector are directed towards creating an appealing Dutch market, offering a diverse range of hydrogen electric vehicles (FCEVs), and vehicles equipped with a hydrogen internal combustion engine (H_2ICE). This includes establishing an extensive network of refuelling stations and providing supportive subsidies for both refuelling stations and vehicles. The Total Cost of Ownership (TCO) for FCEVs in relevant segments such as public transport, distribution (LCVs), and heavy transport is becoming increasingly competitive. Negotiations are underway for the use of renewable hydrogen in mobility in 2030.
After 2030	- Hydrogen stands as a complete emission-free choice in the mobility sector. Secondly, the market can smoothly operate without the need for ongoing support. And finally, a diverse and competitive range of vehicles is available.

3.4 Current progress of technological aspect

Currently, several initiatives in the Netherlands are underway to advance the implementation of trucks powered by green hydrogen. While many electrolyzer projects are still in the pre-construction phase, notable exceptions include the Holland Hydrogen I project, which is currently under construction and stands as the largest and most pivotal endeavor in this domain. These electrolyzers play a crucial role in generating green hydrogen for the HDT sector in the Netherlands. To facilitate the importation of green hydrogen, several import terminals are in the development stages, including the ACE terminal in Rotterdam. Imported green hydrogen complements domestic production in meeting the demand for this energy carrier. Hydrogen will be stored in salt caverns, currently under development in Groningen and Germany near the border, as well as in storage tanks, which are also in the early stages of development, until needed at on-site refuelling stations. The construction of an underground “Hydrogen Backbone” is in progress to transport hydrogen to these stations, with an expected completion date around 2030, effectively connecting the five main industry clusters. Tube trailers are already operational for transporting hydrogen to refuelling stations not directly linked to these clusters. The construction is underway for three XL-refuelling stations in Botlek, Utrecht, and Groningen, specifically designed to cater to hydrogen-powered trucks. Multiple OEMs are actively involved in the production of hydrogen-powered trucks. As of February 2023, there were only 27 operational hydrogen trucks in the Netherlands, though the current number in 2024 remains undisclosed.

4. Institutions

This segment outlines the strategic approach of institutions towards building the hydrogen infrastructure for heavy-duty freight transportation in the Netherlands. Section 4.1 reviews and assesses the supportive policy measures initiated by regulatory entities at the European level. Section 4.2 analyses current policy initiatives in the Netherlands, aimed at facilitating the energy transition from the use of fossil fuels towards green hydrogen in this sector. Section 4.3 briefly discusses the current progress of the institutional aspect. This chapter answers SQ2: *How is the institutional context shaping the development of the physical infrastructure within the Netherlands?*

4.1 EU policy initiatives for hydrogen implementation and infrastructure development

The development of the Netherlands' hydrogen market crucially depends on both European and national policy frameworks (NWP, 2022). Section 4.1 will outline the EU's strategic approach to implement hydrogen, followed by an exploration of significant European policy initiatives designed to bolster this strategy.

4.1.1 European institutional hydrogen strategy

To align with the European Green Deal of achieving zero-emissions in 2050, the European Commission has introduced certain policy frameworks. First, the European Commission presented a comprehensive package of legislative proposals in July 2021, known as the Fit-for-55 package. It commits to the EU's objective of reducing net greenhouse gas emissions by a minimum of 55% by 2030 compared to 1990 levels. The proposed package seeks to align EU legislation with the 2030 goal. This collection of proposals is aimed at revising and updating existing EU legislation while introducing new initiatives. The goal is to ensure that EU policies align with the climate objectives set by the council and the European Parliament. The package strives to establish a cohesive and fair framework for achieving the EU's climate goals. It emphasizes a social transition, the preservation and enhancement of innovation and competitiveness in the EU industry and strengthening the EU's leadership in the global fight against climate change (European Council, n.d.). Additionally, in 2022, the European Commission presented the REPowerEU plan. This plan builds upon the implementation of the Fit-For-55 package. REPowerEU is a plan aimed at saving energy, enhancing energy efficiency, diversifying the energy supply, and accelerating the transition to clean energy (Europese Raad, n.d.). Together, these strategies represent a comprehensive approach to fostering a sustainable, low-carbon future for the HD freight road sector and beyond, embodying the EU's commitment to innovation, competitiveness, and global climate leadership.

The European Union actively promotes and incentivizes the adoption of hydrogen in the transportation sector through various policies and tools which will be analyzed in the section below. The goal of the EU for HD road transport is to mandate a reduction of 15% in CO_2 emissions by 2025 and even more ambitious target of 30% by 2030 (European Commission, n.d.-g).

4.1.2 Current EU policy initiatives

To fulfill the objectives of the European Green Deal by 2050, as well as the ambitions laid out in Fit-For-55 and REPowerEU, it is important for the EU to transform these ambitions into specific regulations and legislations. The construction of the hydrogen infrastructure for heavy-duty freight road transport in the Netherlands is significantly influenced by a series of interconnected policy measures from the European Union. Although these initiatives differ in their specific focuses and goals, together they create a cohesive strategy aimed at accelerating the transition towards a sustainable hydrogen-powered future. Table 8 outlines relevant policy initiatives implemented by the European Commission to promote the expansion of hydrogen infrastructure projects across Europe (broad description of the initiatives is provided in Appendix C1). Subsequently, an analysis of these measures and their significance in directing the EU's shift towards a hydrogen-fuelled economy is provided, encompassing the necessary infrastructure development. This analysis delves into the combined effects of these policies, underscoring their collaborative role in supporting the establishment of the hydrogen infrastructure needed to integrate green hydrogen into the HDT sector in amongst others the Netherlands.

Table 8: Overview of EU policy initiatives for hydrogen infrastructure development for HD freight road transportation in the Netherlands.

Domain	**Policy initiative**	**Brief description**
Initiatives for hydrogen implementation	Renewable Energy Directive	The RED series progressively escalates the EU's commitment to renewable energy. Initiated in 2009 with RED I, because of the Fit-for-55 package, the RED III aims for 42.5 % renewable energy share and 60% CO_2 reduction in 2030 compared to 1990 levels to achieve zero emissions by 2050 (van Ahnee, 2023).
	Gas and Hydrogen Decarbonization Package	The Gas and Hydrogen Decarbonization Package, released in December 2021, updates the EU's Gas Directive and Regulation to accelerate the decarbonization of gas markets. It aims to streamline the development of dedicated infrastructure and improve market conditions for hydrogen, removing barriers to create a competitive hydrogen economy (European Commission, n.d.-f).
	EU Taxonomy	The EU Taxonomy, a key element of the EU's sustainable finance framework, aims to enhance market transparency by directing investments into activities crucial for an eco-friendly transition aligned with the European Green Deal. It establishes a classification system identifying activities contributing to a net-zero goal by 2050 and broader environmental objectives (European Commission, n.d.-b).
	Energy Taxation Directive	The Energy Taxation Directive (ETD) is instrumental at both EU and member state levels in promoting the transition to cleaner energy sources, supporting sustainable industry practices, and encouraging eco-friendly decisions, all within a framework aiming for social fairness in the green transition. It sets the EU's standard for energy taxation, influencing the shift towards sustainable practices by aligning taxes with environmental and public health impacts (European Commission, n.d.-h).
Initiatives for assignment of subsidies	Important Projects of Common European Interest (IPCEI)	The IPCEI Hydrogen instrument supports significant hydrogen projects across the EU with government funding, allowing for substantial subsidies (RVO, 2022c).
	Horizon Europe	Horizon Europe is the EU's foremost funding program for research and innovation, designed to tackle climate change and boost competitiveness and growth. Special emphasis is placed on developing low-carbon industrial applications and pioneering technologies, particularly in the field of hydrogen, underlining the program's commitment to driving Europe towards a green, healthy, and resilient future (European Commission, n.d.-d).
	Connecting European Facility	The Connecting European Facility (CEF) is an essential funding instrument for the European Green Deal. Specifically, the CEF for transport financially supports the European transport infrastructure policy by funding the construction of new and the upgrading of existing transport infrastructure, including those for hydrogen (European Commission, n.d.-a)

Initiative specifically for hydrogen implementation in road mobility	Alternative Fuels Infrastructure Regulation (AFIR)	The updated AFIR regulation mandates the deployment of electric and hydrogen refuelling stations across the EU by 2030. A strategic deployment of hydrogen stations is required at every 200 km along the TEN-T core network and in all urban nodes, facilitating EU-wide hydrogen vehicle mobility (Europese Raad, 2023)

Energy transition framework

The EU's energy transition strategy, underpinned by a series of policy frameworks, has paved the way for substantial developments in renewable energy infrastructure, crucial for incorporating green hydrogen into the HDT sector. This holistic approach combines setting ambitious environmental goals with practical measures for infrastructure development, facilitating the transition to green hydrogen as a viable fuel alternative (Nauta & Geilenkirchen, 2021). It emphasizes optimizing existing infrastructure alongside new developments, aiming to establish a competitive hydrogen market. This strategy not only aligns with the EU's broader environmental objectives but also positions member states for a smoother transition to a green economy, exemplifying a comprehensive method that bridges policy goals with real-world applications.

Enriching the ecosystem with strategic subsidies

The overall goal of incorporating subsidies like those mentioned in the strategic framework (Table 8) is to significantly boost EU's efforts in realizing a hydrogen infrastructure vision (EI-1). These subsidies aim to provide essential financial support and foster innovation necessary for the advancement and widespread deployment of hydrogen technologies and infrastructure across member states. By addressing financial barriers, promoting research and development, and incentivizing infrastructure investments, these subsidies facilitate the establishment of a robust hydrogen economy, including for heavy-duty freight road transport (EI-1). Ultimately, they aim to overcome obstacles associated with developing hydrogen infrastructure, stimulate innovation, and promote cross-border cooperation, thereby contributing to infrastructure expansion and the adoption of hydrogen-powered HDTs throughout Europe (European Commission, n.d.-a).

Regulatory support and fiscal incentives

This cohesive strategy also involves regulatory and fiscal structures to incentivize investments and facilitate the transition towards sustainable energy sources in heavy-duty freight road transportation. The regulatory aspect focuses on creating a clear and supportive environment for hydrogen-related projects. By offering clarity on what qualifies as sustainable investments, regulatory frameworks guide investments towards initiatives that support environmental objectives and accelerate infrastructure expansion (European Commission, n.d.-b). On the fiscal side, the aim is to make cleaner energy forms, like green hydrogen, more economically attractive. This involves adjusting tax policies to favor lower-emission alternatives and encourage the adoption of green hydrogen in heavy-duty freight road transportation. However, current fiscal measures may not fully reflect the benefits of green hydrogen, potentially hindering its adoption and infrastructure development (European Commission, n.d.-h). The synergy between financial incentives and regulatory frameworks exemplifies the EU's comprehensive approach to stimulate the development of the hydrogen infrastructure. By providing clarity for investments and improving the attractiveness of green hydrogen as a sustainable energy option, the EU aims to create a conducive environment for the expansion of the hydrogen economy.

Ensuring accessibility and adoption

Finally, this strategy tries to improve the accessibility of hydrogen refuelling stations and as a result the adoption of hydrogen-powered HD trucks with the help of specific initiatives such as the AFIR. By mandating the creation of a supportive network for heavy-duty vehicles and others by 2030, the initiative ensures widespread availability of hydrogen fuel along key transport corridors. This addresses concerns about fuel access during long-distance trips and motivates the initial shift towards hydrogen-fuelled vehicles. Additionally, the initiative underscores the practicality of using such vehicles throughout the EU and paves the way for the integration of zero-emission heavy-duty trucks into transportation systems (Europese Raad, 2023).

4.1.3 Implications of EU policy initiatives on policy development in the Netherlands

The collaborative efforts of these initiatives highlight a comprehensive strategy aimed at fostering hydrogen infrastructure crucial for making HD freight road transportation in the Netherlands sustainable. These policies not only seek to increase the share of renewable energy and reduce CO_2 emissions but also address the specific infrastructure and market needs for hydrogen's role in the transportation sector. By combining strategic subsidies, financial incentives for investors, regulatory frameworks, and technology accessibility, these initiatives try to create a favourable environment for the adoption of hydrogen-powered heavy-duty vehicles.

Directives and regulations set at the EU level directly impact Dutch policies, as adherence to these directives is mandatory. Also, the Netherlands can utilize subsidies provided by the EU to support various initiatives, including the development of hydrogen infrastructure. To align with European regulations and directives, the Dutch government engages in national policy development. In response to EU directives promoting renewable energy and sustainability, the Netherlands actively participates in developing policies that facilitate the development of hydrogen infrastructure domestically, which will be elucidated in the segment below. This entails strategic planning, investment, and regulatory frameworks aimed at supporting the growth of hydrogen technology and its integration into the Dutch energy landscape.

4.2 Dutch policy initiatives regarding hydrogen implementation and infrastructure development

The Netherlands is pursuing various policy initiatives aimed at realizing a hydrogen economy, focusing amongst others on the integration of green hydrogen as a fuel for HD freight road transportation. Table 9 below illustrates important policy initiatives, which will subsequently be analyzed to explore their role in stimulating the development of the infrastructure (broad descriptions of the initiatives can be found in Appendix C2).

Table 9: Overview of Dutch policy initiatives.

Policy initiatives in NL for hydrogen infrastructure development	**Brief description**
Dutch Climate Agreement	The Dutch government aims to scale hydrogen production to 3-4 GW by 2030, focusing on both green and blue hydrogen development to contribute optimally to the broader hydrogen system, with specific targets set in the Dutch Climate Agreement for hydrogen consumption in the mobility sector, including establishing 50 hydrogen refuelling stations by 2025, supporting 18,000 vehicles (Rijksoverheid, n.d.).
SDE ++ subsidy	A subsidy instrument for large-scale production of sustainable (renewable) energy and technologies that reduce CO_2 emissions (RVO, 2023b).
"Hydrogen in Mobility" subsidy	The Ministry of Infrastructure and Water Management introduces a subsidy scheme with a 22 million euro budget targeting heavy road transport to overcome the 'chicken and egg' dilemma in hydrogen mobility by promoting consortia of infrastructure operators, transport companies, and shippers for simultaneous vehicle and fuel infrastructure development, aiming to set up stations and trucks in 5 to 10 locations nationwide to scale green hydrogen production and ensure a balanced refuelling network, while recognizing the need for further action to meet climate goals and encouraging clean truck transitions by 2040 (EGEN, 2023).
Temporary scaling instrument	A scaling instrument for small electrolysis projects (0.5 – 50 MW), with the goal to offer valuable insights to other stakeholders (NWP, 2022).
The National Growth Fund -> DEI+ subsidy	The National Growth Fund, initiated by the Ministry of Economic Affairs and Climate and Finance with a 20 billion euro allocation for 2021-2025, focuses on boosting the Dutch economy through projects in Knowledge Development, Research and Development, & Innovation, supported by DEI+ subsidies to significantly cut CO2 emissions within a decade through pilot and demonstration projects and the development of water electrolysis, electrochemistry, and the transportation, storage, and application of green hydrogen (RVO, 2023a).
The Energy Investment allowance (EIA)	A fiscal arrangement for entrepreneurs that allows businesses to deduct 45.5% of the investment costs for an initiative resulting in CO_2 reduction from their profits (NWP, 2022).
Zero-emission zones	Starting in 2028, the Netherlands will enforce 'zero emission zones' in cities, effectively banning diesel vehicles from at least 29 urban areas, thereby significantly ramping up the pressure on the transport sector to transition to zero-emission vehicles (milieuzones, n.d.).
CO_2-emission restrictions	CO_2-emission restrictions (mandatory legislation) to accelerate the transition to hydrogen vehicles. This could involve legally requiring OEMs to produce trucks that collectively no more than a certain amount of CO_2, thereby forcing them to transition to sustainable vehicles. Emission reduction goals for trucks, aiming for a 45-65% reduction in emissions by 2030-2035, is subject to substantial fines (EI-3).

Truck toll	In 2022, the Dutch Parliament endorsed the legislation for initiating a truck levy. From 2026 onwards, a toll based on the distance traveled will be applied to trucks on Dutch highways (RailGood, 2022). Trucks that are not environmentally friendly will incur higher per-kilometer toll charges compared to their sustainable counterparts. Via this way the government is trying to drive back the use of diesel trucks by transport companies (EI-5). A portion of the proceeds will be allocated back to the transportation industry to fund investments in environmentally friendly trucks.
HBE-regulation	The HBE-regulation mandates that energy suppliers to the transportation sector meet an annual minimum of sustainably generated energy, monitored through tradable Renewable Fuel Units (RFUs), to ensure a growing share of renewable energy in the sector's total consumption (Koolen Industries, 2023).

Developing a robust hydrogen infrastructure supply chain for green hydrogen in HD freight road transport

The Dutch government is focusing on enhancing hydrogen infrastructure for the HDT sector, highlighting a strategic dedication to reduce carbon emissions, and embracing sustainable energy practices. With a strong push towards expanding hydrogen production, particularly from renewable sources, there's a plan to create a comprehensive hydrogen fuel supply chain (Rijksoverheid, n.d.). This involves the installation of hydrogen refuelling stations to serve heavier vehicles like trucks, aiming to significantly cut CO_2 emissions in the transportation sector by fostering the adoption of hydrogen-powered trucks and related infrastructure, illustrating a comprehensive strategy to promote hydrogen as a clean alternative fuel.

This approach is part of a larger vision to ensure that all new trucks in the Netherlands will operate without exhaust emissions by 2040 (Ecotips, 2024). Ultimately, the comprehensive strategy aims to accelerate progress towards meeting climate targets while supporting the adoption of hydrogen in HD freight road transportation and beyond.

Market stimulation through national subsidies

This strategy, supported by an array of government subsidies and funding programs, seeks to overcome the challenges faced in the early market development stages for hydrogen-powered trucks and the necessary supporting infrastructure. Central to these efforts is the aim to facilitate the transition towards clean energy, closely aligned with the country's long-term climate goals.

For this transition the promotion of large-scale sustainable energy production is important, notably through the creation of green hydrogen. This is achieved by deploying advanced electrolyzer technology, which is part of building an extensive network of hydrogen infrastructure. The construction of the electrolyzers is supported by significant subsidy amounts (RVO, 2023b). Such infrastructure is key to the widespread use of green hydrogen in heavy road transport, ensuring that hydrogen-powered trucks have the necessary fuel supply. This move towards green hydrogen not only supports the operation of these vehicles but also addresses the initial challenges of matching supply with demand in the emerging hydrogen market.

In addition to stimulating the supply side of the hydrogen market, the Dutch government has implemented targeted subsidy schemes designed to boost investment across the entire hydrogen value chain. This includes the construction of hydrogen refuelling stations and the rollout of hydrogen-powered trucks. These subsidy schemes are particularly focused on promoting collaboration among a wide range of stakeholders, including infrastructure operators, transport companies, and shippers. The goal is to create a stable demand for hydrogen, thereby improving the scalability and economic viability of hydrogen fuel (EGEN, 2023).

Innovation and entrepreneurial incentives

Technological innovation is recognized as crucial, leading to significant investments dedicated to advancing hydrogen production technologies. By allocating substantial resources to enhance the capacity of electrolyzers, this strategy effectively supports the production of the necessary green hydrogen for the future. The aim is to create a robust hydrogen infrastructure, prioritizing projects that are both scalable and feasible for execution. These initiatives are intended not just to increase capacity but also to gather valuable insights and establish best practices that can inform future expansion efforts (NWP, 2022).

Additionally, there's a concerted effort to promote technological progress through the funding of pilot and demonstration projects focused on reducing CO_2 emissions. This includes a strong emphasis on research, development, and innovation within the realm of sustainable energy (RVO, 2023a). Such dedication to driving technological development is critical for facilitating the broader integration of green hydrogen.

Entrepreneurial incentives are strategically crafted to encourage business investments in the development of hydrogen infrastructure suitable for HD freight road transportation. Through specific financial incentives, businesses are motivated to invest in projects that reduce CO_2 emissions, including the establishment of hydrogen refuelling stations, the introduction of hydrogen-powered vehicles, and the enhancement of distribution networks. These incentives offer significant financial benefits, reducing the fiscal burden on companies engaging in such projects. The aim is to stimulate private sector participation in expanding the hydrogen infrastructure, thereby accelerating the transition towards more sustainable transportation solutions. Investments that align with critical areas of hydrogen use, storage, and distribution are particularly encouraged, highlighting the government's intent to facilitate innovation and technological progress in the hydrogen sector (NWP, 2022).

Regulatory support and compliance pressures

By implementing restrictions on the use of non-renewable energy, the use of green hydrogen could pave its way into the current regime where fossil fuels are dominant. Banning diesel vehicles on the Dutch roads from 2040 onwards is an important guideline of this strategy, with a clear emphasis on transition to alternative fuels. This approach reflects a broader commitment to reducing pollution and achieving climate goals, positioning hydrogen vehicles alongside electric vehicles as viable alternatives. The establishment of zones in the Netherlands that prohibit polluting emissions in urban areas accelerates this shift by compelling the transport sector to adopt zero-emission vehicles, including hydrogen-powered options, to meet new environmental standards (milieuzones, n.d.).

Regulatory measures that limit the CO_2 emissions within the transportation sector effectively mandate the adoption of sustainable vehicles by setting legal limits on CO_2 emissions for OEMs. With ambitious targets for emission reduction in the coming years, there is a strong push for the sector to transition towards vehicles powered by clean energy sources, such as hydrogen. The potential for fines for non-compliance adds a layer of urgency to this transition, making hydrogen vehicles an increasingly attractive option for those seeking to meet regulatory standards and avoid penalties (EI-3). In addition, the use of truck tolls might stimulate the adoption of hydrogen-powered trucks as transport companies face higher variable costs when using fossil-fuelled trucks (RailGood, 2022).

Finally, it will become necessary for transport companies to use a certain amount of renewable energy as green hydrogen into their operations according to the Dutch institutional hydrogen strategy (Koolen Industries, 2023). The encouragement of renewable energy integration within the transport sector, through requirements for energy suppliers to include a minimum share of sustainable energy in their offerings, incentivizes the production and use of green hydrogen. By mandating a quota of sustainably generated energy, signified through a system of tradable units, this approach fosters the development and utilization of green hydrogen infrastructure. It ensures that renewable energy, including green hydrogen, accounts for an increasing portion of the energy mix consumed by the transportation sector, supporting the broader goals of environmental sustainability and carbon emission reduction.

4.3 Current progress of institutional aspect

To achieve the objectives of the European Green Deal by 2050, aiming for a society with zero CO_2 emissions, various policy initiatives have been introduced to align with this goal. At the European level, initiatives such as the Fit-For-55 and REPowerEU packages are developed to align with the objectives of the council and European parliament. Particularly for the HDT sector in the Netherlands, it is imperative to meet the targets effectively. Policies on the European scale provide subsidies for hydrogen projects, create a supportive regulatory environment, and ensure infrastructure accessibility by mandating the establishment of a network for heavy-duty trucks by 2030. Similarly, policies within the Netherlands play a crucial role in domestic hydrogen infrastructure development. These policies offer subsidies for hydrogen electrolyzer construction, incentivize entrepreneurs to contribute to the realization of the entire value chain, and impose regulatory requirements on transport companies. Collectively, these policies aim to foster a society where HDTs fuelled by green hydrogen are widespread.

5. Process

This chapter will delve into the current stakeholders involved in establishing the hydrogen infrastructure value chain for the HDT sector in the Netherlands, examining their interests, and exploring their strategies and collaborative efforts. The social acceptance of the technology will be covered in section 5.4. Section 5.5 reflects on the current progress of the process aspect. Chapter 5 provides a response to SQ3: *Who are the common stakeholders within this socio-technical system, and how do they collectively coordinate the realization of the hydrogen infrastructure?*

5.1 Stakeholders in the STS and their interests

The landscape can be broadly divided into several key players, encompassing governments, green hydrogen suppliers, hydrogen infrastructure developers, knowledge institutions, original equipment manufacturers, transport companies, and the public (Figure 9).

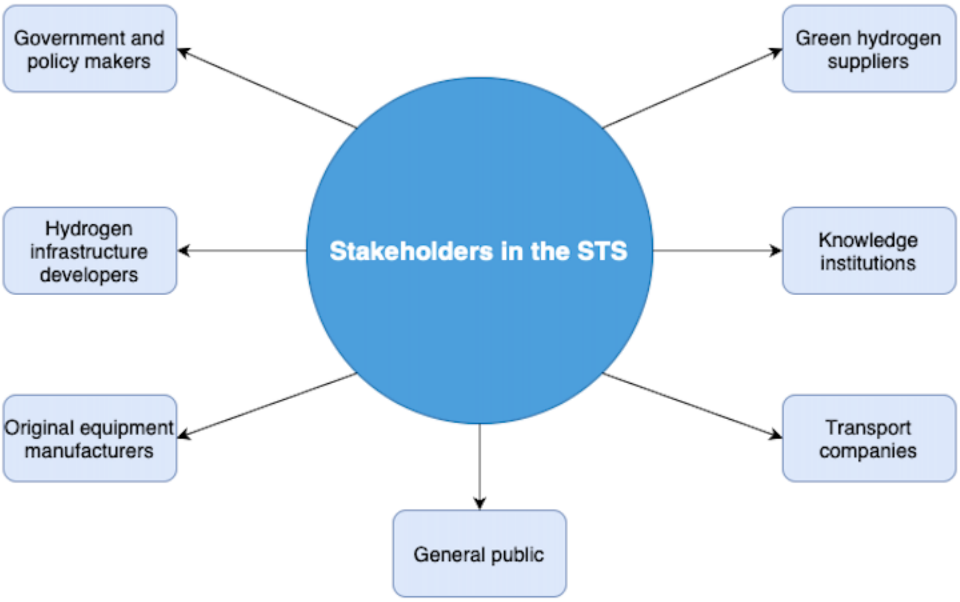

Figure 9: Overview of stakeholders in the socio-technical system

- Government and policy makers. Policy makers aim to achieve environmental and climate targets by promoting the application of hydrogen in heavy-duty road transport. They are willing to establish regulatory frameworks, incentives, and funding to stimulate the development of the hydrogen infrastructure.
- Green hydrogen suppliers/producers. Green hydrogen suppliers need a market for green hydrogen and reliable infrastructure for production, storage, and distribution. They want a clear regulatory framework, financial support, and partnerships with infrastructure developers.
- Hydrogen infrastructure developers. Developers seek for opportunities to build and expand hydrogen storage facilities, distribution networks, and refuelling stations. They prefer clear and supportive government policies, access to funding, and a growing market demand for hydrogen.

- Original equipment manufacturers (OEMs). Manufacturers need a market for hydrogen-powered HD vehicles. They want incentives for the production and purchase of hydrogen vehicles and a well-established refuelling infrastructure.
- Knowledge institutions. Knowledge institutions require funding for studies on improving hydrogen technologies and infrastructure. Collaborations with industry players, government support, and a focus on innovation are preferred by the knowledge institutions.
- Transport companies. Transport companies require accessible and reliable hydrogen refuelling stations to operate hydrogen-powered fleets. They want cost-effective solutions, support from the government, and incentives for transitioning to hydrogen-based transport.
- General public: The public expects improved air quality and reduced emissions from the adoption of hydrogen technology. The public also desires accessible and convenient refuelling stations, along with assurance of safety and reliability. Additionally, public awareness and education initiatives can help increase acceptance and understanding of hydrogen as a sustainable transportation solution.

5.2 Regional hydrogen ecosystems

Diverse stakeholders collectively address the challenges that are occurring during the process of realizing the infrastructure. Such coalitions involve not only hydrogen suppliers or technology providers but also the engagement of carriers essential for market demand. Collaborative efforts along the supply chain, from production and distribution to establishing sufficient guaranteed off-take through refuelling infrastructure, are giving rise to hydrogen ecosystems at regional or local levels in the Netherlands. Notably, North Netherlands has achieved recognition as the first Hydrogen Valley sanctioned by the EU. Major seaports such as Rotterdam, Amsterdam, Den Helder, Delfzijl, and Vlissingen are actively engaged in energy transition programs, emphasizing a significant role for hydrogen. The Regional Energy Strategies (RES) are witnessing growing interest in hydrogen as an energy storage medium. Many regions, including provinces and municipal collaborations, are actively shaping regional plans for 'Hydrogen in Mobility.' Provinces are formulating hydrogen strategies, as seen in Noord-Holland, and regional agreements, such as those in Utrecht, to stimulate the establishment of refuelling options and the acquisition and deployment of hydrogen vehicles, involving businesses, research institutions, and governmental bodies. International collaboration is also actively sought, exemplified by programs like the European Clean Hydrogen Alliance (elaborated on in the next section), supported by the European Commission (Ekinetix, 2021).

5.3 Coalitions for hydrogen implementation in the Dutch HDT sector

Collaborating in coalitions or partnerships is seen as a necessary approach, especially since the hydrogen market for road transport is still in a pre-commercial phase. In this phase, where the commercial business case is not fully defined, collaboration among competitors offers advantages. It allows working together to break the 'chicken and egg dilemma,' where investments, interests, and the complexity of the field require a joint effort (EI-1). Several existing European and Dutch coalitions in advance of a hydrogen economy for the HD freight road transport are presented in Table 10.

Table 10: Overview of insights from technological aspect evaluation.

European coalitions	
European Clean Hydrogen Alliance	Launched alongside the EU hydrogen strategy, this coalition brings together industry, authorities at all levels, civil society, and other stakeholders to ambitiously implement hydrogen technologies by 2030, focusing on aligning renewable and low-carbon hydrogen production with demand across industry, transport, and other sectors, while improving hydrogen transmission and distribution (European Commission, n.d.-e).
Clean Hydrogen Partnership	This initiative, supported by the European Commission under Horizon Europe, represents a public-private collaborative effort to advance the EU green deal and hydrogen strategy by strategically funding research and innovation projects in the entire hydrogen infrastructure value chain (European Commission, n.d.-e).
Dutch coalitions	
Mission H2	Mission H2 leads the charge in developing the Dutch hydrogen economy, emphasizing the need to stimulate this sector through collaboration between companies and government entities to secure a substantial number of investment decisions by the summer of 2024, with the goal of achieving significant green hydrogen capacity by 2030 (MissieH2, n.d.).
The Hydrogen Coalition	The Hydrogen Coalition, uniting grid operators, industrial companies, energy providers, governmental bodies, environmental organizations, and scientists, has formed a widely supported agreement to propel the development of the Dutch hydrogen sector, with the formalization of this pact within the coalition aiming to speed up decision-making on hydrogen, thereby enhancing the resilience of the Netherlands' climate and energy strategies (Gasunie, 2021).
The New Energy Coalition	The New Energy Coalition actively promotes the development and integration of hydrogen technologies into sustainable energy systems, collaborating with a range of stakeholders to encourage research, innovation, and the adoption of hydrogen solutions across transportation, industry, and energy production to reduce carbon emissions, and through a multidisciplinary approach, contributes to building hydrogen infrastructure, shaping policy frameworks, and achieving technological advancements essential for a hydrogen-driven economy (New Energy Coalition, 2024).
HyDelta	HyDelta is a public-private partnership, a Dutch national research program and collaboration facilitating the large-scale implementation of hydrogen. The aim of the program is to empower the hydrogen economy by resolving technical, scientific, and social barriers (HyDelta, n.d.).
H2platform	The 'H2Platform,' a collaboration of companies and government bodies, advances hydrogen's role in the Dutch energy system, fostering cooperation and knowledge exchange, and in 2021, it spearheaded the expansion of a national hydrogen refuelling network and introduced an "Action Program for the Application of Hydrogen in Mobility," proposing a €175 million budget to enhance tank infrastructure and promote heavy-duty hydrogen vehicles (RVO, 2022b).
North H2	North H2 is a consortium exploring the viability of large-scale production, storage, and transportation of green hydrogen (NortH2, n.d.).
HyTrucks	The HyTrucks consortium, comprising partners across the entire supply chain including truck manufacturers, transport companies, and fuel cell suppliers, aims to deploy 1,000 heavy hydrogen trucks and establish 25 refuelling stations by 2025, creating a self-sustaining hydrogen-based road transport ecosystem and achieving a significant market impact through a cascading effect (Air Liquide, n.d.).

Hy-Speed for H2-trucks	The Hy-Speed for H2-trucks consortium is a collective effort aimed at propelling hydrogen fuel cell technology forward for heavy-duty trucks. Bringing together key players from industry, research institutions, and government entities, the consortium is dedicated to expediting the advancement and implementation of hydrogen-powered trucks for eco-friendly transportation. Through pooling expertise and resources from its diverse membership, the consortium undertakes research, development, and demonstration endeavors to tackle technical obstacles and advocate for the uptake of hydrogen fuel cell technology within the trucking industry (RVO, 2020).

5.3.1 European coalitions/partnerships for hydrogen implementation

In the context of the European Union's strategic focus on hydrogen as a cornerstone of its energy transition, various collaborative efforts have significantly advanced the implementation of hydrogen technologies. These European collaborations, initiated under the broad umbrella of the EU's hydrogen and green energy strategies, are central to driving the development and integration of hydrogen infrastructure across the continent (EI-1).

These collaborations bring together a wide array of stakeholders from industries, governmental bodies, and civil society to foster cooperation and align efforts towards common objectives. With ambitious targets set for the upcoming decade, the focus is on ensuring that renewable hydrogen production meets the growing needs of the transportation sector and that the necessary transmission and distribution infrastructure is in place. Such coordinated efforts are essential for accelerating the widespread adoption of hydrogen technologies, paving the way for the integration of hydrogen-powered trucks, and supporting the transition towards a sustainable energy system (European Commission, n.d.-e).

Additionally, strategic funding of research and innovation projects related to hydrogen technologies is a key aspect of these efforts, aiming to support the EU's broader environmental energy goals. This includes streamlining the market integration of critical hydrogen and fuel cell technologies and promoting the production of clean hydrogen, sustainable transportation methods, and efficient storage solutions to ensure grid stability. These initiatives leverage hydrogen's role as a multifunctional energy carrier while aiming to minimize the dependency on scarce raw materials (European Commission, n.d.-e).

Alignment with Dutch transition goals

European initiatives are closely aligned with Dutch efforts to transition the heavy freight road transport sector towards a hydrogen-based infrastructure. The focus on aligning renewable hydrogen production with transportation demand within these European initiatives mirrors the Dutch objective of weaving hydrogen into its transport landscape (NWP, 2022). This alignment ensures that efforts at the European level complement existing Dutch initiatives, fostering synergy rather than redundancy or inefficiency. As the Netherlands aims to shift towards sustainable transportation systems, the objectives of these collaborative efforts become increasingly relevant for harmonizing national efforts with broader, continent-wide goals.

These European initiatives play a critical role in facilitating market integration and innovation, which are key components of the Netherlands' strategy for developing its hydrogen infrastructure (NWP, 2022). By fostering collaboration among various stakeholders, they contribute to enhancing hydrogen transmission and distribution (European Commission, n.d.-e), an essential step for establishing a comprehensive hydrogen infrastructure network within the Netherlands. Additionally, the strategic funding of research and innovation projects by European efforts drives technological advancements, further stimulating the Netherlands' transition to sustainable transportation solutions. Through these aligned efforts, the Netherlands can leverage European collaboration to accelerate its own hydrogen infrastructure development, ensuring a cohesive approach to achieve a sustainable and efficient transportation system.

5.3.2 Dutch coalitions/partnerships for hydrogen implementation

Coalitions within the Netherlands for hydrogen infrastructure development, as presented in Table 10, play important roles in shaping policy, attracting investments, promoting innovation, fostering collaboration, and advocating for market growth in the country. By pooling their knowledge and resources, these coalitions speed up the shift towards a sustainable and environmentally friendly transportation sector in the Netherlands, in line with the country's goals for climate action and energy transition.

Knowledge exchange and market development

The progression towards a hydrogen-powered future, particularly in the context of market development and the deployment of hydrogen infrastructure, is significantly supported by platforms dedicated to fostering collaboration and knowledge exchange. These platforms serve as crucial hubs for dialogue and cooperation among businesses, government entities, and academic institutions, aiming to streamline the adoption of hydrogen across various sectors of the Dutch energy landscape. Focusing on the collaborative exploration of the possibilities for large-scale production, storage, and transportation of green hydrogen, directly supporting the goals outlined in the Dutch Climate Agreement. By conducting feasibility studies and advancing research, this effort aligns with national objectives to reduce carbon emissions and transition towards renewable energy sources. The coalitions do not only facilitate the exchange of vital knowledge and innovative ideas but also advocate for the development of a conducive market environment for hydrogen technologies (NortH2, n.d.; RVO, 2022b).

Technological advancements and innovation

The advancement of hydrogen technology and innovation, particularly within the realm of hydrogen infrastructure development, is significantly influenced by collaborations across the sector. These collaborations, exemplified by initiatives as public-private partnerships and research coalitions, are at the forefront of steering research, innovation, and the practical adoption of hydrogen solutions in various domains, including the transportation sector. Through partnerships with industry leaders and academic institutions, these collaborations adopt a multidisciplinary approach to address the technological challenges of establishing a comprehensive hydrogen infrastructure. Their efforts contribute to the creation of technological breakthroughs and the development of a hydrogen-based economy, focusing on aspects critical to the integration of hydrogen in transportation and beyond (New Energy Coalition, 2024).

Overcoming technological, scientific, and societal hurdles is essential for advancing hydrogen deployment and catalyzing the hydrogen economy. By addressing these challenges directly, coalitions play a crucial role in fostering the development of pioneering technologies and solutions necessary for efficient hydrogen production, storage, and utilization. This encompasses innovations in HD freight road transportation (HyDelta, n.d.).

Shaping policies and attracting investments

In the realm of policy development and economic stimulation within the Dutch hydrogen sector, collective efforts are important for crafting the necessary policy frameworks and garnering the investments vital for the rollout of hydrogen infrastructure (MissieH2, n.d.).

Coalitions shaping policy frameworks bring together a broad spectrum of participants, including grid operators, industrial firms, energy companies, government entities, environmental organizations, and scientific experts, to facilitate swift policy implementation. By enhancing decision-making processes and fostering collaboration, these efforts significantly speed up the adoption of hydrogen-related policies, aligning them with the Netherlands' long-term climate and energy goals. This streamlined approach to decision-making is crucial for advancing the nation's hydrogen agenda, ensuring that policies are not only future-oriented but also actionable in the short term (Gasunie, 2021).

Moreover, by acting as catalysts for attracting investments, some coalitions create a regulatory environment that is highly favorable for the development of essential hydrogen infrastructure. This includes the establishment of refuelling stations, production facilities, and distribution networks, each a cornerstone in the broader vision of a hydrogen-powered future.

Advancing hydrogen-based freight road transport

Collaborative initiatives in the Netherlands that are dedicated to transforming HD freight road transportation through hydrogen are gaining momentum, setting ambitious goals to deploy a significant number of heavy hydrogen trucks and establish a network of hydrogen refuelling stations within the next few years. These plans are aimed at radically altering the transportation landscape, making it cleaner and more sustainable. By engaging in partnerships across the supply chain, including with truck manufacturers, transport companies, and fuel cell providers, a collaborative environment crucial for the successful rollout of hydrogen trucks is fostered. The collective effort is focused not just on the vehicles themselves but also on creating the necessary infrastructure to support them, from production through to distribution and refuelling. This comprehensive approach is designed to catalyze further investments and innovations in the hydrogen sector, with the vision of establishing a self-sustaining market for hydrogen in heavy freight road transportation (Air Liquide, n.d.).

5.4 Social acceptance

In the current phase, the level of support for hydrogen as an energy carrier in society remains uncertain. This is mainly because societal backing for hydrogen is not yet a significant factor at this stage. Fossil hydrogen is primarily utilized by the industry, along with ammonia and methanol. In society, renewable hydrogen is most visible in terms of mobility and, to a limited extent, in pilot projects within the built environment. The anticipation is that low-carbon and renewable hydrogen will play a more substantial role in the energy system over the coming years. However, these concepts are still relatively new and unfamiliar to most of the population. Providing a nuanced explanation of hydrogen use in the Netherlands is crucial, addressing both the advantages and disadvantages. With only a limited number of active hydrogen initiatives, public knowledge about hydrogen is still quite limited. While it might seem like there's support for hydrogen now, the lack of underlying public knowledge makes this assumption fragile. Support and acceptance aren't just about imparting more knowledge or understanding; they also involve making room for people's concerns and interests (NWP, 2022).

Social barriers

Obstacles to societal acceptance of green hydrogen infrastructure in the Netherlands present significant challenges, including high costs, resistance to wind turbines and solar parks, opposition to large-scale hydrogen storage in salt caverns, and objections to CO_2 storage in empty gas fields for blue hydrogen production. There is debate over the role of blue hydrogen as an interim step versus an immediate transition to green hydrogen, despite potential initial cost implications. The limited availability of suitable salt caverns, primarily located in the northern part of the country, supplement these challenges, particularly in areas already facing resistance due to natural gas extraction, earthquakes, and wind turbines. Alternative solutions, such as storing hydrogen in empty natural gas fields beneath the North Sea, are being explored to address storage concerns (Entrance, 2024).

Local support plays a crucial role in the acceptance of hydrogen infrastructure, encompassing various elements such as hydrogen plants, filling stations, heating boilers, pipelines, storage facilities, and renewable energy sources like wind turbines and solar panels. However, acceptance diminishes significantly when proposals for hydrogen infrastructure development infringe residential areas, highlighting the importance of location choice and community consultation (Entrance, 2024).

Hydrogen safety

Social acceptance of hydrogen is also intertwined with its safety, which in turn influences various aspects of hydrogen implementation. While hydrogen offers significant environmental benefits, concerns about safety can affect public perception and acceptance of hydrogen technologies. Issues such as the risk of explosions or leaks can create apprehension among stakeholders and communities, potentially leading to resistance against the deployment of hydrogen infrastructure. Addressing these safety concerns through robust safety measures, effective risk communication, and transparency in regulatory frameworks is crucial for fostering social acceptance. Currently, hydrogen installations are being designed with strict safety standards, including valves and material requirements familiar to the hydrogen industry. This ensures a high level of safety (EI-3).

5.5 Current progress of process aspect

Various stakeholders are actively engaged in the endeavor to transition the HDT sector towards sustainability. These include governmental bodies, green hydrogen suppliers, infrastructure developers, research institutions, OEMs, transportation companies, and the public, each driven by their respective interests in achieving the adoption of clean hydrogen trucks. In the Netherlands, these stakeholders are collaborating to establish hydrogen infrastructures on a regional scale, spanning the entire value chain of hydrogen production and utilization. To further enhance collaborative efforts, coalitions have been formed at both European and Dutch levels, fostering cooperation and alignment towards common objectives. At the European level, the focus is primarily on aligning renewable hydrogen production with demand and strategically funding research and innovation projects across the entire value chain. In the Netherlands, these coalitions are instrumental in shaping supportive policies, attracting investments, promoting technological advancements and innovation, and more concretely facilitating the deployment of a significant number of hydrogen trucks and refuelling stations. However, societal support for hydrogen as an energy carrier is uncertain. The hydrogen concepts are still novel and unfamiliar to most of the population, posing obstacles to social acceptance and raising safety concerns that need to be addressed.

6. Evaluation of and interactions between TIP aspects

In preceding chapters, the ongoing advancement of the technological, institutional, and process facets has been outlined. This chapter focuses on evaluating the performance of each aspect, a crucial step in assessing the present advancement of the hydrogen infrastructure value chain for heavy freight road transportation in the Netherlands. Next, we will explore how interactions between technology, institutions, and processes collectively influence the transition by evaluating their alignment and impact on hydrogen infrastructure development. An answer will be provided for SQ4: *How are the TIP aspects performing and to what extent are they aligned in the development of the hydrogen infrastructure?*

6.1 Technological aspect evaluation

In this section, the technological performance of the hydrogen infrastructure value chain is evaluated, constituting green hydrogen supply, storage and transportation, and lastly refuelling stations and trucks. In Table 11, insights are provided regarding the performance of the technological aspect. Subsequently, these insights are elaborated upon. The core findings of the technological aspect evaluation are provided in section 6.1.4.

Table 11: Overview of insights from technological aspect evaluation.

Technological aspect insights	
Green hydrogen supply	- Progress is made regarding green hydrogen production, however many plans do not pass the FID (Final Investment Decision) phase, because of an imbalance between supply and demand of green hydrogen which results in a high-cost price (EI-1). - There is limited experience with electrolyzers and substantial risks, resulting in low commercial readiness of the technology. Connecting electricity with hydrogen production seems not as straightforward as it looks like (EI-2). - In the first phase (2022-2025), it seems to be a challenge to produce green hydrogen in big quantities and to match electricity production with hydrogen production (EI-2). - Hydrogen import is needed to meet future demand (NWP, 2022).
Hydrogen storage and transportation	- The choice between storage and transportation techniques is influenced by economic considerations and its implementation mechanism. Hydrogen infrastructure developers need to think of complementing ways to store and transport hydrogen cost-efficiently (EI-1). - Liquid hydrogen, with its high energy density and purity, seems not to be an option to store and transport hydrogen in the short-term. But as was also the case with LNG (Liquid Natural Gas), this could happen in the long-term (EI-6). - Different end applications require different purity levels of hydrogen. This seems to be a critical aspect when considering storage and transportation techniques (EI-1).
Hydrogen refuelling stations and trucks	- Besides the efforts already made for the construction of hydrogen refuelling stations, it is also important that hydrogen trucks are being realized. Transport companies do not have sufficient incentives and security to commit to adopt hydrogen powered trucks (EI-2). - Large-scale implementation is deemed necessary to create proactive attitudes from OEMs (EI-4). - Hydrogen trucks with internal combustion engines are initially cheaper than fuel cell powered trucks yet emit minor CO_2; while fuel cell electric vehicles emit no CO_2, making them essential for long-term zero emission mandates despite higher upfront costs (EI-6). - The process is moving slowly, with challenges stemming from end-user acceptance, infrastructure development, and ongoing adaptation to new technologies (EI-3).

6.1.1 Green hydrogen supply

Green hydrogen production issues

Multiple green hydrogen production projects are being designed and constructed at present as shown in section 5.1, visualizing promising hydrogen electrolyzers in the Netherlands. However, among these initiatives, only a handful have progressed past the planning stage and into the Final Investment Decision (FID) phase. The main culprit behind the delay seems to be an imbalance between supply and demand of green hydrogen, resulting in the steep price of green hydrogen and a low efficiency for the hydrogen producers (EI-1). The price of green hydrogen is currently 5 to 6 times higher than that of natural gas (Staalkaart groene waterstof, n.d.).

Additionally, with limited experience and substantial risks, the commercial readiness level of electrolyzers remains low, making the attraction of financing a costly endeavor. To illustrate, there exist complexities and costs associated with securing the necessary electrical connection towards the electrolyzers. This connection is vital for synchronizing electricity production with hydrogen production, contingent upon the intermittent nature of renewable energy sources like wind and solar power. The practical difficulties in ensuring a consistent and reliable electricity supply highlight inherent challenges of integrating renewable energy into hydrogen production infrastructure, underscoring the need for technological solutions to address variability and optimize efficiency (EI-2).

A final issue related to green hydrogen production is that the initial phase (2022-2025) of implementing large-scale renewable hydrogen faces considerable uncertainty in both economic and technological aspects related to the production, import, and utilization of renewable hydrogen. Reservations exist regarding the current focus on green hydrogen, as generating substantial quantities of it appears to present a significant challenge. A key concern is whether there is sufficient green electricity in the short term to support green hydrogen production. The dilemma between ambitious goals and their feasibility is apparent, especially since achieving a gigawatt of green hydrogen production in the Netherlands seems to be an enormous challenge (EI-3). The share of renewable hydrogen in total hydrogen production is still negligible at this stage (NWP, 2022).

Green hydrogen import

The Netherlands could encounter difficulties in fulfilling its domestic hydrogen demand, particularly if the current industrial hydrogen consumption and heavy transport sectors shift towards hydrogen. The demand for renewable hydrogen is expected to significantly increase in the long term. It is not cost-effective to meet this demand solely through domestic production (EI-1). To supplement domestic hydrogen production, it is essential to contemplate the importation of hydrogen. The Dutch government will not directly import hydrogen; it will be done by companies (NWP, 2022).

6.1.2 Hydrogen storage and transportation

Considering cost-efficiency

In the realm of hydrogen storage and transportation, various methods exist to serve these purposes. One storage option is the utilization of salt caverns. It is acknowledged that these vast volumes can accommodate significant amounts of hydrogen, presenting a promising prospect, especially for locally produced gaseous hydrogen (EI-1). Alternatively, hydrogen storage in tanks offers the flexibility of storing hydrogen in liquid, compressed, or material-based forms as ammonia. But this happens in lower quantities. The choice between storage in a tank or in salt caverns is influenced by economic considerations and the implementation mechanism. From a financial perspective, storage as for example ammonia might be more favorable when imported in this form, while salt caverns might be preferable when the hydrogen is imported through a pipeline (EI-1).

Employing a combination of hydrogen tanks and pipelines for transportation could offer a cost-effective solution for hydrogen transport. The exclusive use of tube trailers for hydrogen transport might not be economically feasible. Pipeline transportation is significantly less expensive and operates more efficiently (EI-5). At the points where hydrogen transitions from one storage or transport medium to another, conversion and filtering methods are necessary. Additionally, at refuelling stations, hydrogen might undergo further conversion or cracking to achieve the desired form. However, this poses additional challenges, as a significant portion of the hydrogen may be lost due to leaks during these transition phases. This, in turn, could lead to safety concerns regarding the transportation of the energy carrier (EI-4).

Liquid hydrogen not feasible in the short-term

As mentioned, liquefied hydrogen has a higher energy density than gaseous or compressed hydrogen (Spectra, 2022). However, storage or transport via this way is not yet feasible. It poses significant challenges as without sufficient demand from trucking, the hydrogen would vaporize, necessitating constant cooling. Therefore, in the initial phase until 2030, the support for widespread adoption of liquefied hydrogen will be absent. The same happened with LNG (liquefied natural gas), which transitioned from compressed to liquefied forms over times as technology and infrastructure matured (EI-6).

Purity of hydrogen

A critical aspect revolves around the purity requirements of the energy carrier, especially for specific end-applications such as heavy-duty trucks. For fuel cell electric trucks, the hydrogen purity needs to be near 100 percent. Even minor contamination in the hydrogen supply poses risks to fuel cells. Therefore, purification processes are necessary to ensure the required purity levels. The complexity and cost of purification depend on the initial quality of the hydrogen being transported (EI-2). Employing a materials-based storage and transportation approach, such as using hydrogen in ammonia, appears favorable due to its higher purity compared to alternatives like storing hydrogen in salt caverns and transporting via the backbone (which is appropriate for big industries that require less pure hydrogen) (EI-1). However, the process of cracking ammonia to separate hydrogen from nitrogen proves to be costly, adding complexity to the storage and transportation of hydrogen via this way for fuel cell electric trucks.

6.1.3 Hydrogen refuelling stations and trucks

Revising the chicken-and-egg dilemma

The comparison to the chicken-and-egg problem highlights the importance of simultaneous development of infrastructure and trucks, acknowledging their mutual dependence. Without sufficient infrastructure for supplying green hydrogen to the HDT sector, the cost of the energy carrier will remain high. Likewise, without adequate demand from the freight transportation sector, it will not be profitable for hydrogen infrastructure developers to construct the infrastructure to supply green hydrogen to HD trucks.

While efforts to promote hydrogen infrastructures are underway, the lack of incentives for investments in hydrogen trucks remains a barrier. At present, subsidies are mitigating this issue to some degree. However, the reality remains that the cost of green hydrogen is significantly higher than that of diesel, rendering it a less appealing option for truck companies to switch to (EI-6). A balanced advancement of both trucks and infrastructure is stressed as essential. In the absence of a clear outlook for all stakeholders, hydrogen-powered truck manufacturers (OEMs) may opt to focus on other markets or hold off on scaling up production. Despite having sufficient production capacity, leading OEMs may find it more appealing to introduce these vehicles in countries where there is greater market interest due to more proactive incentives for transport companies (EI-3). It is important to have an integrated market where profitability for OEMs is contingent upon large-scale implementation (EI-4).

H_2ICE versus FCEV

Hydrogen trucks equipped with internal combustion engines are initially more cost-effective than those powered by fuel cells. However, fuel cell electric vehicles (FCEVs) emit zero CO_2 during operation, unlike hydrogen internal combustion engine vehicles (H_2ICEs), which produce minor CO_2 emissions due to the combustion of oil at the inside of their engines. These minor CO_2 emissions from H_2ICEs currently comply with EU regulations, therefore representing a short-term solution. Conversely, FCEVs, despite being more expensive upfront, are essential in the long run when zero CO_2 emission trucks are mandated (EI-6).

Slow progress

The rollout and availability of multiple hydrogen refuelling stations and trucks appear to be a realistic consideration soon, likely around 2027-2028, indicating that immediate developments are not expected. Although progress is being made, the process is moving slowly, with challenges stemming from acceptance, infrastructure development, and ongoing adaptation to new technologies (EI-3).

6.1.4 Core findings of technological aspect evaluation

Several green hydrogen production projects encounter hurdles in reaching the final investment decision due to an imbalance between supply and demand for green hydrogen. This disparity leads to high production costs and inefficiency for hydrogen producers. Also, limited experience with electrolyzers make financing a costly endeavor. Importing green hydrogen from regions with favorable conditions can alleviate the cost burden. Meanwhile, hydrogen storage and transportation methods are still in early stages, necessitating careful consideration of cost efficiency. The purity of hydrogen is crucial for fuel cell electric vehicle (FCEV) trucks, while lower purity levels are acceptable for hydrogen internal combustion engine (H_2ICE) trucks, which need to be considered when storing and transporting the hydrogen. Fuel cell electric vehicle (FCEV) trucks are generally more costly, rendering them less favored by transport companies compared to hydrogen internal combustion engine (H_2ICE) trucks. However, H_2ICEs do emit minor CO_2 emissions, albeit still within EU norms, while FCEVs offer complete sustainability. The simultaneous construction of hydrogen infrastructure and hydrogen-powered trucks is essential. While progress is gradual, addressing the supply-demand imbalance for green hydrogen can propel the hydrogen infrastructure value chain closer to reality.

6.2 Institutional aspect evaluation

In this segment, insights for the evaluation of the institutional aspect will be provided (Table 12) and explained to analyze how the construction of the physical hydrogen infrastructure is organized and supported by current European and Dutch policy initiatives.

Table 12: Overview of insights from institutional aspect evaluation.

Institutional aspect insights
- EU goals provide clear impetus for hydrogen infrastructure development (EI-3). - Transport companies might relocate their operations to other countries with less stringent sustainability regulations, resulting in lacking green hydrogen demand and infrastructure development (EI-5). - Institutional organization and a clear government vision are crucial for attracting investments in hydrogen import, production, and infrastructure. There is a call for stable regulations influencing the hydrogen infrastructure effectively (EI-3). - Concerns exist about the institutional strategy of the Netherlands regarding its efficacy in closing the price gap with conventional fuels. There's a demand for more targeted regulations tailored to the unique characteristics of hydrogen vehicles (EI-1). - Significant subsidies have been directed towards capital investment in hydrogen production and station construction, not at stimulating the demand side, particularly the adoption of hydrogen trucks. (EI-2). - Germany has proven more successful in reducing the cost of green hydrogen (EI-5).

European institutional level

At the European level, initiatives as the Fit-for-55 package and REPowerEU play a crucial role. European policy sufficiently stimulates the transition to clean HD freight road transportation (EI-5). The European Union's ambitious goals, for instance the installation of hydrogen stations every 200 kilometers along the main road network, provide a clear impetus for hydrogen infrastructure development (EI-3).

On the controverse, there is a clear trend emerging within the transport sector, where certain companies are considering relocating their operations to other countries with less stringent regulations. This is primarily due to the international nature of the transport industry, where companies seek jurisdictions with more favorable regulatory environments. However, this presents a significant problem: if companies indeed relocate, it will result in a decreased demand for green hydrogen within the Netherlands, particularly in the HDT sector. This decline in demand would, in turn, have a detrimental effect on the development of the hydrogen infrastructure in the country, posing challenges to the progress of sustainability initiatives within the transportation industry (EI-5).

There is a call for better organization from institutional entities and a consistent, long-term vision from the government to drive large-scale investments in hydrogen import, production, and infrastructure. Stability in regulations, particularly concerning new technologies, is emphasized as essential for successfully promoting hydrogen infrastructure (EI-3).

Dutch institutional level

In the quest to achieve climate neutrality by 2050, Dutch policy initiatives are playing an important role in steering the HDT sector away from diesel towards more sustainable alternatives like hydrogen. Rather than focusing on individual policies, it's the combined effect of various regulations and incentives that are shaping this transition. By offering substantial large-scale support, the government is creating a conducive environment for the widespread adoption of hydrogen vehicles, encouraging investment in long-term hydrogen infrastructure (EI-1). This comprehensive institutional strategy exemplifies a commitment to a sustainable future, highlighting its crucial role in driving the transition towards hydrogen-powered freight road transportation.

However, there are concerns about the effectiveness of this strategy in bridging the price gap with conventional fuels. There's a call for more specific regulations tailored to the realities of hydrogen vehicles (EI-1). The transition to hydrogen trucks is primarily hindered by their high acquisition costs, which significantly limit their widespread adoption. To address this, substantial financial support is deemed essential to make hydrogen trucks an economically viable option. In the Netherlands, significant subsidies have been allocated towards building hydrogen refuelling stations and production facilities. However, there's a notable shortfall in efforts aimed at stimulating the construction and adoption of hydrogen trucks. A substantial portion of the subsidies is invested in capital investments, underscored by initiatives like the Connecting European Facility and the Dutch Climate Agreement, yet incentives specifically targeting the demand side, particularly for vehicle adoption, remain insufficient (EI-2). To address this gap to some extent, the 'Hydrogen in Mobility' subsidy scheme has been introduced, aiming to establish a foundational demand for green hydrogen by subsidizing both the construction of refuelling stations and the purchase of hydrogen trucks.

Comparison with Germany

Comparatively, Germany's approach, embodied by the KKMSI (Klimaschutzprogramm für den Mittelstand der gewerblichen Wirtschaft) subsidy, is markedly more aggressive. This subsidy offsets 80% of the cost difference between diesel and hydrogen trucks, presenting a significantly more direct and impactful method to encourage the adoption of hydrogen trucks. This approach is groundbreaking, particularly in the context of lowering the price of green hydrogen, which remains notably cheaper in Germany than in the Netherlands (EI-2).

6.2.1 Core findings of institutional aspect evaluation

The European Union provides clear goals for hydrogen infrastructure development. However, transport companies in the EU countries might relocate their operations to other countries with less stringent sustainability regulations, resulting in lacking green hydrogen demand and infrastructure development. In the Netherlands, the government is actively fostering an environment conducive to the widespread adoption of hydrogen vehicles, including trucks. However, doubts persist regarding the efficacy of their policy approach in closing the price gap with conventional fuels. Existing regulations struggle to stimulate demand in the hydrogen market and encourage the adoption of hydrogen trucks. The combination of high acquisition costs and the high cost-price of green hydrogen renders it an unattractive option for transport companies. Germany's more aggressive subsidy allocations have proven more effective in driving down the cost of green hydrogen, substantially narrowing the price gap between green hydrogen and conventional fuels.

6.3 Process aspect evaluation

This part will evaluate the performance of the process aspect in this complex socio-technical system. Once more, insights stemming from the evaluation of this aspect are given in Table 13 below and subsequently expanded upon.

Table 13: Overview of insights from process aspect evaluation.

Process aspect insights
- Establishing a green hydrogen infrastructure for heavy-duty transport in the Netherlands requires balancing urgency with practicality. While swift progress is crucial, building a new industry takes time, necessitating a gradual approach (EI-1).
- Collaboration among stakeholders is crucial for realizing hydrogen infrastructure, standardizing technology, improving safety, and reducing costs ((EI-1).
- Collaboration within coalitions is important in the pre-commercial phase of the hydrogen market for road transport, to overcome the 'chicken and egg dilemma' through joint efforts (EI-3).
- Coalitions are important for fostering collaboration, insights sharing, and research. However, many of them are currently focusing on pilot projects or specific segments poses challenges for broader market standardization initiatives (EI-3).
- Even though coalitions foster collaboration, competitive dynamics, particularly regarding sensitive information like production plans and market strategies, persist within the industry. This cautious approach can impede progress and hinder the collective advancement of hydrogen infrastructure (EI-2).
- Difficulty arises in coordinating efforts among stakeholders, including customers, fuel suppliers, and government agencies, due to mismatched timelines and investment decisions, complicating the transition (EI-2).
- While the anticipation for hydrogen's role in the energy system is growing, its societal acceptance remains uncertain.
- Hydrogen technology currently achieves a high-level of safety, contributing to social acceptance. However, more attention should be given to emergency services coping with hydrogen incidents (EI-3).

Stakeholder strategy

The strategy to establish a green hydrogen infrastructure for heavy-duty transport in the Netherlands requires a delicate balance between urgency and pragmatism. While there is a pressing need to advance swiftly, it is acknowledged that building an entirely new industry takes time. A gradual approach is deemed necessary, recognizing that a direct transition to completely clean trucks is not feasible given the industry's current readiness. To secure the necessary resources, stakeholders must provide clarity on timelines for vehicle introduction, scaling, and infrastructure deployment, enabling the government to anticipate these developments with appropriate policy measures. Collaboration among stakeholders is crucial for realizing the hydrogen infrastructure, facilitating standardization of technology, improving safety, and reducing costs through economies of scale (EI-1).

Coalitions advantages

Coalitions in the realm of hydrogen infrastructure development are important for progress, serving as platforms where stakeholders collaborate, share insights, and conduct research. They form a valuable platform where diverse parties collaborate to acquire knowledge and pool experiences. Crucially, coalitions encompass diverse stakeholders, including hydrogen suppliers, technology providers, carriers, and governments. Governments play a crucial role in creating a conducive institutional environment through supportive regulations. Collaboration within these coalitions is seen as essential, especially in the pre-commercial phase of the hydrogen market for road transport. It allows working together to break the 'chicken and egg dilemma,' where investments, interests, and the complexity of the field require a joint effort. The scale and complexity of the field necessitate ongoing efforts and collaboration to successfully realize the hydrogen infrastructure for heavy freight road transport (EI-3).

Coalitions drawbacks

Despite their importance, the current scope of these coalitions often revolves around pilot projects or specific segments of the hydrogen chain, posing a challenge to scale up initiatives for broader market standardization. Moreover, while coalitions play a vital role in safety and standardization, there is skepticism about their effectiveness in stimulating demand which seems to be a main problem. Furthermore, despite the collaborative nature of coalitions, there are still competitive dynamics within the industry, particularly regarding sensitive information such as production plans and market strategies. Competitors may be reluctant to share strategic details openly, leading to a stalemate where each party waits for the other to make a move. This cautious approach can impede progress and hinder the collective advancement of hydrogen infrastructure (EI-2). Ultimately, there is difficulty in coordinating efforts among various stakeholders, including customers, fuel suppliers, and government agencies, because of a mismatch in timelines and investment decisions, which complicates the collective effort required for a successful transition (EI-2). On the one side, hydrogen suppliers, for example, require assurance that there will be a significant uptake of hydrogen to justify starting production. They need to ensure that it is financially viable. On the other side, the HDT sector cannot guarantee this uptake because, in the short term, it needs to be cost-effective for them as well, which is currently not the case.

Social acceptance

While the anticipation for hydrogen's role in the energy system is growing, its societal acceptance remains uncertain. Public knowledge about hydrogen is limited, and there are obstacles to overcome, including high costs, resistance to infrastructure projects, and differing opinions on transition strategies.

The safety of hydrogen also plays a crucial role in the acceptance of this energy carrier. As a matter of fact, the technology is currently achieving a high standard of safety (EI-3). Nevertheless, attention must be given to the response of emergency services, particularly the fire department, in the case of hydrogen fires. A need for further steps is prevailing to enhance the fire department's ability to quickly diagnose and effectively respond to incidents involving hydrogen. It appears that there is a need for closer collaboration between the industry and emergency services to increase knowledge about hydrogen incidents and shorten response times (EI-3).

6.3.1 Core findings of process aspect evaluation

Establishing a green hydrogen infrastructure for heavy-duty transport in the Netherlands requires balancing urgency with practicality. While swift progress is crucial, building a new industry takes time, necessitating a gradual approach. Collaborative efforts among stakeholders are pivotal for constructing the hydrogen infrastructure, standardizing technology, ensuring safety, and driving down costs through economies of scale. Coalitions serve as essential platforms for stakeholder collaboration, knowledge sharing, and research, especially in the pre-commercial phase to overcome challenges like the chicken-and-egg dilemma. However, existing competing interests within coalitions may hinder information sharing and coordination, exacerbated by differences in timelines. Social acceptance of hydrogen technology remains uncertain due to limited public knowledge about the technology and various other obstacles, including high costs, resistance to infrastructure projects, safety concerns, and differing opinions on transition strategies.

6.4 Interactions between TIP aspects

In the journey towards a hydrogen-powered future for HD freight road transportation in the Netherlands, progress is indeed slow but steady (EI-3). The right blend of innovation, collaboration, and regulatory support holds the promise of making this vision a reality. This section tries to delve deeper into the interactions between the technological, institutional, and process aspects to determine how they collectively influence this economy.

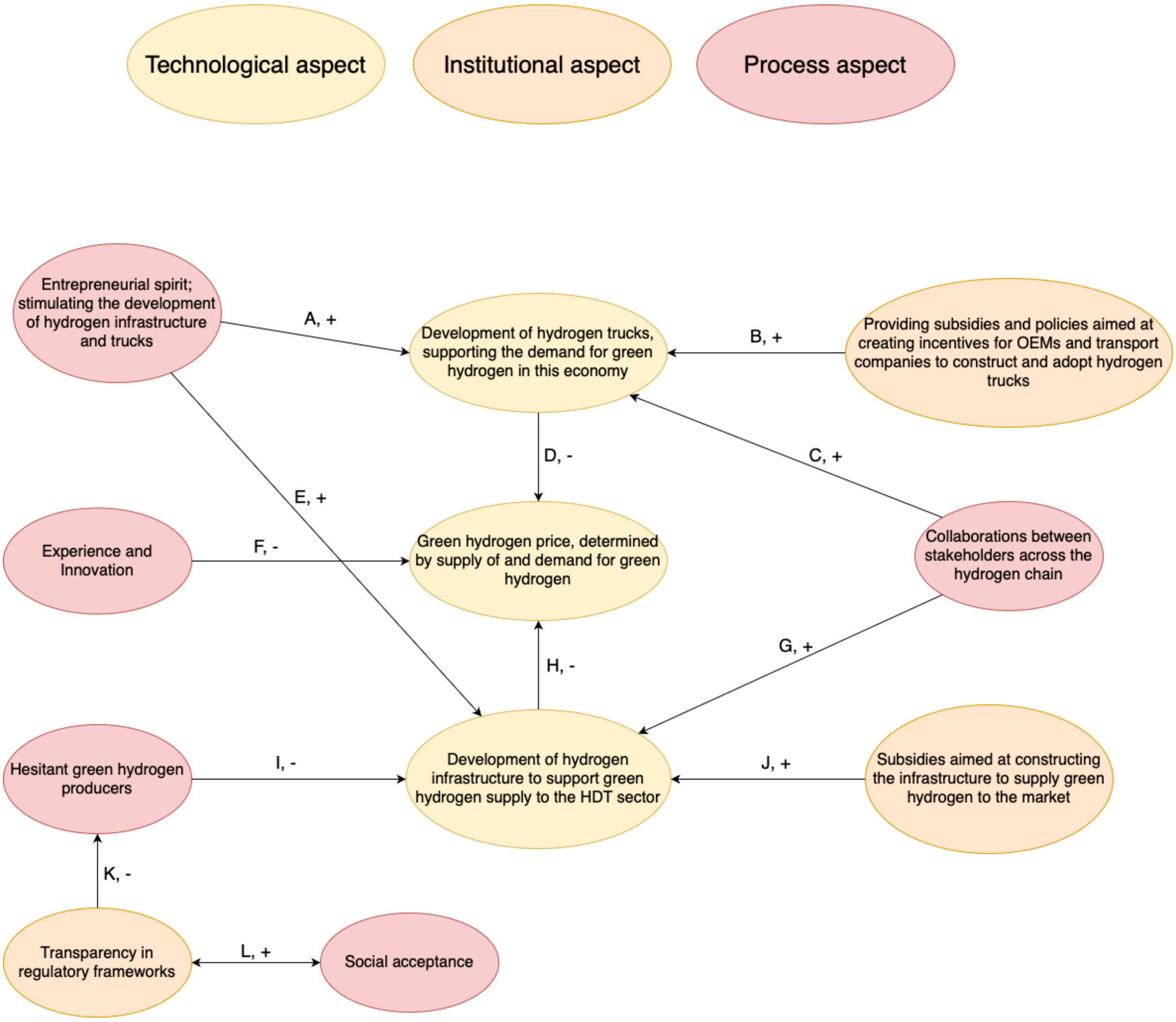

Figure 10: Relations (+; positive relation, -; negative relation) between TIP aspects.

In Figure 10, elements representing the technological aspect are depicted as yellow ovals, while those pertaining to the institutional aspect are shown as orange ovals, and elements concerning the process aspect are illustrated as red ovals. The arrows between these ovals denote relationships, which can be either positive (+), indicating reinforcement, or negative (-), signifying weakening. These relationships are further identified with letters, which are crucial for clarifying and elaborating on them in the two subsections below. First, we will delve into the current relationships that are performing well, followed by an examination of those that are less effective.

6.4.1 Well-performing relations

In Figure 10, three relationships are currently performing well. The first is relation J, followed by relation E, which positively influences relation A, as is further elaborated on below.

Technological aspect ⟺ Institutional aspect (J)

Relation A shows that, in recent years, policy initiatives have predominantly directed subsidies towards bolstering the supply side of the hydrogen economy. These subsidies play a pivotal role in incentivizing the development of essential infrastructure required to support hydrogen supply. Specifically, significant financial support has been allocated towards the construction of green hydrogen production facilities, storage and transportation projects, and refuelling stations (EI-2). By addressing the supply side of the 'chicken-and-egg' problem, these subsidies effectively catalyze the establishment of a robust hydrogen infrastructure network. Subsidies targeting the supply side of the hydrogen economy serve as a key driver in accelerating the development of the hydrogen infrastructure, indicating a positive relation.

Technological aspect ⟺ Process aspect (E, A)

Successfully achieving simultaneous developments of hydrogen infrastructure and hydrogen trucks is widely recognized as a formidable challenge. Effectively addressing this challenge necessitates proactive efforts from industry players, driven by entrepreneurial spirit. While government support undoubtedly plays a crucial role, it is equally imperative for companies to demonstrate courage and take the lead in driving innovation and progress. Currently, collaborative endeavors, exemplified by partnerships like the one between Total Energies and Airliquide to construct 100 heavy-duty refuelling stations across multiple countries, including the Netherlands, stand as a notable example of efforts aimed at overcoming the 'chicken-and-egg' dilemma. This initiative initially stimulates the development of the hydrogen infrastructure, indicated by relation E. On the longer term, it not only addresses infrastructure needs but also foster the development of hydrogen trucks, indicated by relation A (EI-3). The proactive stance and bold initiatives of entrepreneurial companies will positively impact the development of hydrogen infrastructure and trucks, reflecting positive relationships. Such endeavors showcase the potential for industry leaders to drive meaningful change and overcome existing barriers to adoption. Entrepreneurial spirit is key to realizing the full potential of hydrogen in the future, kickstarting the hydrogen market, and subsequently lower the price of green hydrogen, indicated by the negative relations D and H (EI-3).

6.4.2 Less well-performing relations

Most of the relationships depicted in Figure 10 are underperforming, posing obstacles to the current success of the hydrogen economy. To summarize, relations B, F, I, C, G, L and K are the ones that are less well-performing.

Technological aspect ⟺ Institutional aspect (B)

Institutional initiatives, as outlined in Chapter 4, play a pivotal role in incentivizing investment and fostering a favorable environment for the adoption of hydrogen-powered vehicles, particularly hydrogen trucks, within our society. These policies are instrumental in cultivating a positive attitude towards embracing hydrogen trucks amongst Dutch transport companies. Currently, insufficient incentives for investing in hydrogen trucks have hindered their successful adoption (EI-2), largely due to existing subsidy schemes focusing too little on stimulating the adoption of the trucks, indicated by relation B. If transport companies lack sufficient support and incentives to transition to hydrogen-powered trucks through subsidies, it is less probable that these stakeholders will adopt this mode, suggesting a positive correlation.

Technological aspect ⟺ Process aspect (F, I, C, G)

Despite regulatory efforts to promote green hydrogen production, the practical implementation remains challenging, especially for early adopters in the market. The economic viability of hydrogen projects is a significant concern, primarily due to uncertainties surrounding the lifetimes of electrolyzers and the return on investment. While the initial investments required are substantial, there is optimism about potential cost reductions through accumulated experience and innovation in design and manufacturing processes. However, it is crucial to acknowledge that the industry's current lack of experience and limited innovation in its early stages contribute to the consistently high price of green hydrogen, indicating a negative relationship as represented by relation F (EI-2).

Another less well-performing relation in the interaction between the technological and process aspect, is related to the engagement of multiple green hydrogen producers in the Netherlands. It is essential for these producers to invest in production facilities and electrolyzer development, but, currently, many producers have been hesitant to undertake such ventures due to concerns about rising electricity and connection expenses. Whereas certain stakeholders demonstrate courage and initiative, exemplified by entrepreneurial spirit mentioned earlier (relation A and E), relation I shows the hesitancy observed among hydrogen producers which represents a major obstacle to the development of hydrogen infrastructure. Without broader industry involvement and collective investment, achieving the necessary economies of scale becomes challenging, potentially hindering the widespread adoption of hydrogen technology in the transportation sector. As hesitant green hydrogen producers do hinder the development of hydrogen infrastructure, a negative relationship is prevalent (EI-2).

Relations C and G are final less well-performing relations in this domain and refer to collaborations among stakeholders in the hydrogen industry which do play important roles in promoting the development of hydrogen infrastructure and trucks, thereby standardizing the technology, and driving down the price of green hydrogen via relations D and H. However, presently, there are occurring competitive dynamics within the industry that impede the full potential of collaboration. Concerns about protecting sensitive information, such as production plans and market strategies, may lead stakeholders to adopt a cautious approach when engaging in collaborative ventures. This reluctance to openly share information and resources can hinder progress and slow down the collective development of hydrogen infrastructure and trucks. Additionally, it appears that collaborative efforts are too less focusing on stimulating the demand side of this hydrogen market, particularly the realization and adoption of hydrogen trucks. Despite these existing challenges, it's important to recognize that collaboration remains a key driver of progress in the hydrogen sector. By fostering a culture of trust, transparency, and cooperation among stakeholders, it's possible to overcome barriers to collaboration and unlock the full benefits of working together. Ultimately, successful collaborations have the potential to catalyze innovation, drive down costs, and accelerate the development of both hydrogen trucks and infrastructure, paving the way for a more sustainable and hydrogen-powered future (EI-2). This highlights C and G to be positive relationships.

Institutional aspect ⟺ Process aspect (L, K)

Currently, it appears that regulatory frameworks are not transparent which negatively influences social acceptance of the technology, indicated by relation L in Figure 10. Transparency in regulatory frameworks can significantly stimulate social acceptance and trust in the development of hydrogen infrastructure for HD freight road transport in the Netherlands. By addressing safety concerns through robust safety measures, effective risk communication, and transparent regulatory frameworks, stakeholders can build trust among the public and foster acceptance of hydrogen technologies (EI-3). In turn, social acceptance plays an important role in shaping regulatory frameworks and investment decisions. A positive public perception and support for hydrogen technologies can lead to the implementation of favorable policies and incentives, ultimately facilitating the widespread adoption of hydrogen as a clean energy solution. Thus, relation L between transparent regulatory frameworks and social acceptance is positive.

Finally, relation K shows the absence of transparent regulatory frameworks ensuring hydrogen producers to become hesitant. Admittedly, by providing clear guidelines and regulations, transparent frameworks offer stakeholders a better understanding of the legal and operational requirements for hydrogen production. This clarity can alleviate uncertainties and concerns that may deter producers from investing in hydrogen infrastructure. Moreover, transparent regulatory frameworks signal a commitment to accountability and fairness, which can instill confidence in stakeholders regarding their compliance with regulations and the overall regulatory environment. As a result, transparent regulatory frameworks may encourage stakeholders to become less hesitant and overcoming their reservations and actively participate in the development of hydrogen infrastructure. Ultimately, the negative relationship between transparency in regulatory frameworks and hesitant stakeholders highlights the importance of clear and accessible regulations in fostering industry engagement and investment in hydrogen projects (EI-2).

6.5 Recommendations from the TIP analysis

To stimulate the hydrogen infrastructure development for HD freight road transportation in the Netherlands, several recommendations out of the TIP framework analysis arise. The recommendations come forward out of the evaluation of the three aspects and the interactions between them.

6.5.1 Technological recommendations

To establish an effective hydrogen infrastructure for the HDT sector in the Netherlands, the primary goal is the comprehensive development of the physical infrastructure, encompassing green hydrogen supply (production + import), storage, transportation, refuelling stations, and hydrogen-powered trucks. However, a significant challenge arises from the disparity between the supply and demand of green hydrogen, leading to elevated prices and impeding infrastructure progress. Below, recommendations are provided to foster the development of the physical infrastructure, to eventually lower the cost-price of green hydrogen.

1. **Stimulate simultaneous development of hydrogen infrastructure and trucks:** to optimize the development of hydrogen infrastructure and the construction of hydrogen-powered trucks, infrastructure developers and OEMs necessitate substantial incentives and assurances. Encouraging the construction of infrastructure and the integration of hydrogen-powered trucks concurrently, which improves relations D and H, is important for fully harnessing the potential of hydrogen-powered transportation (Nauta & Geilenkirchen, 2021).

2. **Focus on blue hydrogen as an interim solution:** given the imbalance between green hydrogen supply and demand, prioritizing the production of blue hydrogen could be beneficial. Blue hydrogen, with its readily accessible technology and lower production costs, can serve as an interim solution. Additionally, blue hydrogen production methods, such as carbon capture and storage (CCS), efficiently manage CO_2 emissions, making it a viable option to catalyze infrastructure development and increase hydrogen demand from the HDT sector, represented by the upper yellow oval in Figure 10. Over time, via improving relation D, this strategy could make this renewable energy source more competitive with conventional fuels (Prins, 2023).

3. **Execute demonstration projects:** to address limited experience and uncertainty, the execution of demonstration projects like the PosHydon project could be pivotal. These projects, such as the pilot electrolyzer with a capacity of 1 MW, provide valuable insights and contribute to advancing hydrogen technology (TNO, 2023). As limited experience and uncertainty would be addressed, this results in an upgrade of relation F.

4. **Continue import projects of green hydrogen:** leveraging favorable weather conditions in regions like the Middle East for green hydrogen production. Continuing import projects could ensure a stable supply of green hydrogen at a lower cost. Importing green hydrogen from these regions can expedite the development of infrastructure in the Netherlands. By advancing link H, lower cost prices of green hydrogen can be realized. The Dutch government needs to establish appropriate conditions and tools for importation and transit, encompassing regulations, infrastructure, certification, and safety measures (NWP, 2022).

5. **Prioritize H_2ICE trucks on the short-term:** initially implementing hydrogen internal combustion engine (H_2ICE) trucks presents a cost-effective option for transport companies in the Netherlands (EI-6). These trucks emit minimal emissions, which are within EU norms, and can serve as an interim solution until fuel cell electric vehicles (FCEVs) become more widespread (EI-6). H_2ICE trucks could facilitate market expansion and provide a transitional step towards FCEV adoption. This would smooth the adoption of hydrogen trucks, therefore stimulating the demand for green hydrogen, and enhancing relation D.

6.5.2 Institutional recommendations

The successful development of hydrogen infrastructure hinges on its institutional framework. Thus, ensuring the establishment of an optimal institutional context is crucial. Below, recommendations are outlined to enhance this institutional framework and facilitate the transition to trucks powered by green hydrogen.

1. **Subsidies should focus more on stimulating green hydrogen demand:** policies in the Netherlands have primarily focused on incentivizing the supply side of the hydrogen market, such as providing subsidies for electrolyzers and other infrastructure projects. To address the chicken-and-egg dilemma and foster a hydrogen ecosystem for the HDT sector, it is essential to stimulate and subsidize the construction and adoption of hydrogen trucks, thus improving relation B. High acquisition costs currently hinder widespread adoption, necessitating substantial financial support to make the transition economically viable (EI-2). Government support on a large scale is crucial for driving meaningful change and accelerating adoption (EI-3).

2. **Coordinate policy implementation across EU member states:** given the international scale of the transport sector, it is imperative to coordinate policy implementation across all European Union (EU) member states. This coordinated approach prevents companies from relocating to neighboring countries with less stringent regulations, ensuring a level playing field and promoting sustainability initiatives across borders (EI-5). As a result, demand for green hydrogen by transport companies will be stable, and relation D will be reinforced.

3. **Establish long-term contracts:** implementing long-term contracts between hydrogen producers and consumers could kickstart the hydrogen market. By committing to supply a specific quantity of hydrogen at a predetermined price, producers like Shell can incentivize consumers such as TataSteel or truck companies to guarantee the purchase of a significant amount of hydrogen. As a result, hydrogen infrastructure to supply green hydrogen to the market could be realized, and via relation H, this would contribute to lower green hydrogen prices. This approach, previously effective in initiating the LNG (Liquid Natural Ga) market, provides stability and confidence for investment in hydrogen projects (EI-4).

4. **Embrace clear, targeted policies and incentives:** there is an urgent need for clear, targeted policies and incentives that not only support the production and utilization of renewable hydrogen but also mitigate cost concerns and market uncertainties. Adopting a model like Germany's, where focused subsidies and supportive policies have led to decreasing hydrogen prices, could provide substantial benefits for the Netherlands (EI-5). Drawing lessons from Germany's policy formulation could prove beneficial for the Netherlands. Adopting Germany's model, which has seen decreasing hydrogen prices due to focused subsidies and supportive policies, holds significant potential for the Netherlands. This improves the effectiveness of amongst other subsidies for stimulating the demand side, so improving relation B.

5. **Create transparent regulatory frameworks:** transparent regulatory frameworks should be established to foster social acceptance and alleviate concerns of hesitant stakeholders (EI-3), thereby improving the less well-performing links K and L in Figure 10. As the government fosters a favorable transparent policy landscape, it encourages increased involvement from the private sector, leading to technological advancements and cost reductions. This, in turn, boosts the economic viability of hydrogen for HD transportation, attracting more investment and supporting innovation in turn. Moreover, as the infrastructure expands and becomes more accessible, it facilitates the wider adoption of hydrogen-powered vehicles, thereby driving up demand for hydrogen fuel and supporting further infrastructure development (visualization in Figure 11).

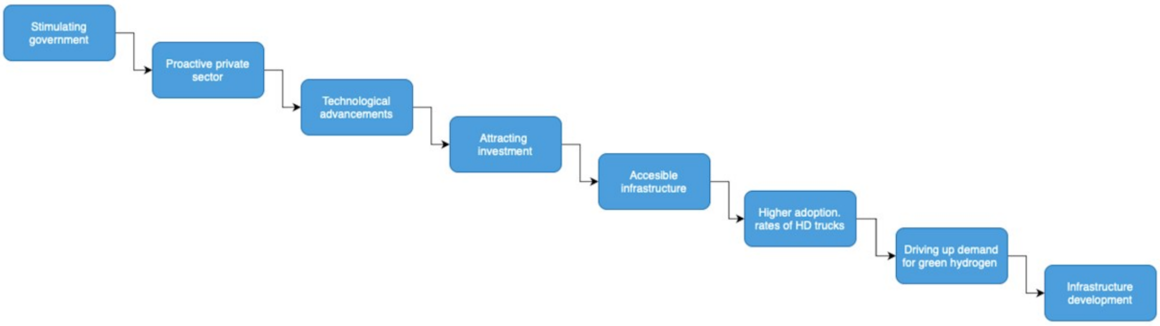

Figure 11: stimulating government leading to infrastructure development.

6.5.3 Process recommendations

The collective strategy of the stakeholders is important for successful implementation the hydrogen infrastructure for the HDT sector in the Netherlands. Below, recommendations are provided to improve the performance of this aspect of the system.

1. **Clarity on timelines for adoption, scaling, and infrastructure development:** stakeholders within the socio-technical system (STS) should provide clear timelines for truck adoption, scaling, and infrastructure development. This clarity enables the government to enact timely policy measures. For instance, hydrogen suppliers need assurance of consumption from truck operators to justify production, while truck operators require certainty of hydrogen availability to commit to adoption (EI-1). Via this clarity, hydrogen infrastructure and trucks can be built with more confidence, thereby enhancing relations D and H.

2. **Collaborative efforts should focus more on stimulating demand for green hydrogen:** coalitions should prioritize the demand side of the hydrogen infrastructure value chain, particularly the adoption of hydrogen trucks. The construction of trucks, and therefore stimulating demand for green hydrogen, would improve relation D.

3. **Mitigate competitive dynamics and foster collaboration within the hydrogen industry:** establish clear frameworks for information sharing and collaboration agreements is crucial. Standardized contracts outlining terms of collaboration, confidentiality mechanisms, and data protection protocols can address concerns about sharing sensitive information. Additionally, cultivating a culture of trust through regular communication, joint workshops, and collaborative problem-solving sessions can promote openness among stakeholders. Incentivizing collaboration through government policies or industry initiatives, such as financial incentives or regulatory support, can further encourage stakeholders to work together towards common goals. By implementing these measures, stakeholders can overcome reluctance to share information and resources, facilitating collective progress in hydrogen infrastructure development. Relations C and G will be improved consequently.

4. **Corporate commitment and community engagement to foster social acceptance:** corporate commitment to emission-free investments and local community engagement are crucial for building trust and fostering support for hydrogen projects. The involvement of

corporations in hydrogen projects is essential for boosting the social acceptance of the technology, as it enhances its visibility, builds credibility, and showcases the practicality and reliability of hydrogen energy. Engaging with communities in site selection, addressing concerns, and highlighting the benefits of hydrogen energy can enhance acceptance and pave the way for a sustainable energy future (Entrance, 2024). As social acceptance is cultivated, the effectiveness of relation L will improve, thereby contributing to the reduction of green hydrogen prices through the connections K, I, and H.

7. Discussion

This chapter starts with an analysis of the chosen research approach applied to tackle the main research question along with its sub-questions. Subsequently, it delves into the data collection and analysis techniques utilized in the study. The chapter concludes by suggesting directions for future research.

7.1 Reflection on research approach

To explore the progression of hydrogen infrastructure development for HD freight road transportation in the Netherlands, a design science approach was used, particularly employing the TIP (Technology, Institutions, and Process) framework. This framework facilitated an in-depth analysis across three critical dimensions: the technological advancements underpinning the infrastructure, the institutional support propelling this development, and the coordination processes among stakeholders driving these efforts. This comprehensive approach was instrumental in unveiling insights that could catalyze the shift toward green hydrogen-powered trucks within the Dutch context. By evaluating technological development, institutional initiatives, and stakeholder processes, and examining relations between these aspects, the study illuminated areas requiring targeted interventions.

However, applying the TIP framework presented challenges, particularly in delineating the scope of each aspect. For the technological dimension, the focus was on the entire hydrogen value chain, encompassing all physical components (green hydrogen supply, storage, transportation, refuelling stations, and trucks) essential for facilitating heavy-duty trucks powered by green hydrogen. This included an analysis of current important projects, participating companies, and the stage of development of critical technologies like electrolyzers. In terms of institutional support, the research aimed to encapsulate all policy initiatives potentially impacting this transition. Though it acknowledged the impossibility of guaranteeing complete coverage of the present physical infrastructure and its institutional context. Similarly, the process aspect attempted to account for existing collaborations and coalitions, yet there remained uncertainty about whether all significant stakeholders and coalitions were identified. The study encountered inherent uncertainties in fully capturing the performance and interrelations among technology, institutions, and processes, reflecting the complexity of accurately mapping out an emergent and dynamic field. While striving to identify well-performing and less well-performing interplays, it was recognized that not every consequential relation might have been captured. This reflective acknowledgment underscores the study's thorough yet modest approach to mapping the complex landscape of hydrogen infrastructure development in the Netherlands, offering valuable insights while openly noting the journey's inherent limitations.

7.2 Reflection on data collection and analysis methods

Desk Research

Desk research was conducted to gather information about the technological, institutional, and process dimensions of developing hydrogen infrastructure for HD freight road transportation in the Netherlands. This approach involved an extensive review of existing literature, including academic papers, industry reports, policy documents, and relevant case studies, to form a comprehensive understanding of the current state and challenges in the field. Through this method, the study aimed to delineate the interplay between the technologies required for the realization of the hydrogen infrastructure value chain, the institutional frameworks that govern these technologies, and the processes that enable stakeholder engagement and project implementation. This foundational knowledge was crucial for visualizing the current research landscape, understanding the present initiatives that enables hydrogen infrastructure development for HD freight road transportation in the Netherlands.

However, reliance on desk research also presented certain challenges. The quality and relevance of information varied greatly across sources, necessitating critical evaluation and selection to ensure that data incorporated into the analysis were both credible and relevant. Also, since some materials used in desk research don't always get updated, they might not reflect the latest changes or trends in a field that's changing quickly.

Expert Interviews

Building on desk research, online semi-structured expert interviews were carried out with specialists inside the STS. These interviews aimed to bridge the gaps identified in the desk research and to gain deeper insights into the functioning and interconnectedness of different aspects of the hydrogen infrastructure.

Conversely, using expert interviews comes with its own set of challenges. One key issue is the potential for subjectivity and bias—the interviewed individuals might have tailored their responses to what they think is expected or acceptable form their point of view, and memories of past events can sometimes be unreliable. Furthermore, conducting, transcribing, and analyzing interviews is time-consuming. The insights obtained tend to be specific to the individuals interviewed, which might not always reflect the broader scenario, making it tough to generalize the findings. Also, the interpretation of the data could be swayed by the researcher's own perspectives, which risks misrepresenting what participants meant as all the interviews were conducted online. When interviews aren't conducted in person, it's also possible to miss out on non-verbal cues that could add important context.

Qualitative software analysis tool: ChatGPT

The qualitative software analysis tool ChatGPT has played a crucial role in revealing connections within the study, facilitating clearer and more coherent communication of relationships and patterns discerned from the data. Its ability to process and interpret large volumes of text makes it an invaluable tool for qualitative analysis, facilitating deeper insights into complex datasets. Moreover, ChatGPT's capacity to generate concise summaries and highlight key themes has streamlined the analytical process, allowing for a more focused exploration of the data. This has not only enhanced the efficiency of the research process but also improved the quality of the analysis by ensuring that critical information is accurately captured and presented in a way that is both accessible and meaningful. Consequently, ChatGPT has emerged as a critical asset in qualitative research, offering a blend of efficiency, clarity, and depth in data analysis that significantly has contributed to the study's overall rigor and insightfulness.

7.3 Future research

Building upon the qualitative insights obtained from this thesis on the development of hydrogen infrastructure for HD freight road transportation in the Netherlands, there is a convincing case for broadening the research scope to include quantitative analyses and other diverse methodologies. This thesis, underpinned by the application of the TIP framework, has laid a solid foundation, identifying key areas for further exploration, and offering stakeholders a roadmap through the complexities of hydrogen infrastructure development. To enhance the robustness of these findings and address the identified gaps, future research directions could encompass:

Integration of quantitative data: future studies should aim to supplement qualitative insights with quantitative research to provide a more rounded understanding of the field. Quantitative analyses could include evaluating investment patterns, conducting cost-benefit analyses of hydrogen infrastructure projects, and tracking the adoption rates of hydrogen-powered trucks. Such data are crucial for clarifying the economic and logistical feasibilities of scaling up hydrogen infrastructure, offering stakeholders concrete metrics for decision-making.

Longitudinal research approaches: adopting longitudinal research designs would allow for the tracking of hydrogen infrastructure development over time. This approach is invaluable for understanding the temporal dynamics of policy implementations, technological evolutions, and stakeholder commitments within the hydrogen economy.

Comparative international studies: expanding the scope to include a comparative analysis with countries at various stages of hydrogen infrastructure implementation can unearth global best practices and lessons. This could reveal adaptive strategies and innovations applicable within the Dutch context, fostering a more globally informed approach to hydrogen infrastructure development.

Focused technological innovation studies: given the rapid pace of technological advancement in the hydrogen sector, dedicated studies into specific technological breakthroughs and their applicability within the hydrogen value chain are needed. This includes advancements in production, storage, and distribution technologies that could significantly impact the scalability and efficiency of hydrogen infrastructure.

Impact analysis of stakeholder engagement and policy initiatives: delving deeper into the effects of specific policy measures and stakeholder engagement strategies on the deployment of hydrogen infrastructure offers insights into the mechanisms of successful implementation. Analyzing the outcomes of these initiatives can pinpoint effective models of collaboration and policy design.

Environmental and socio-economic impact evaluations: as environmental sustainability and social equity are key drivers behind the hydrogen economy, future research should assess the broader impacts of hydrogen infrastructure development. This encompasses studies on emissions reductions, air quality improvements, and the socio-economic benefits and challenges posed by the transition to hydrogen fuel.

By embracing these research avenues, future work can significantly augment the qualitative findings of this thesis, offering a comprehensive, multi-dimensional perspective on the evolution of hydrogen infrastructure for HD freight road transportation in the Netherlands. This expanded approach not only promises to fill existing knowledge gaps but also to equip policymakers, industry stakeholders, and the research community with the insights needed to navigate and accelerate the transition to a sustainable hydrogen economy.

8. Conclusion

In this thesis research has been conducted on the current development of the hydrogen infrastructure for heavy-duty freight road transportation in the Netherlands. This involved analyzing three system aspects—technology, institutions, and processes—guided by the TIP framework. The current performance of each aspect was assessed, and interactions between these aspects were investigated to gain insights for future sustainability initiatives in this domain, enhancing the likelihood of success of the transition towards clean HD trucks. The conclusion will answer the main research question:

How promising is the current development of hydrogen infrastructure in the Netherlands to support the integration of green hydrogen as a fuel for the heavy-duty truck (HDT) sector?

This study offers insights into both positive and negative developments concerning the current progress of hydrogen infrastructure necessary for integrating green hydrogen into the HDT sector in the Netherlands.

Presently, the development of the supply side of the hydrogen infrastructure value chain, encompassing green hydrogen supply (production + import), storage, transportation, and refuelling stations, is showing promising advancements. This progress is supported by substantial support from specific European and national policies, incentivizing the development of essential infrastructure to facilitate green hydrogen supply. Additionally, alongside governmental support, the presence of entrepreneurial spirit among hydrogen infrastructure developers is noteworthy. This spirit encourages companies to take initiative and demonstrate courage in committing to hydrogen infrastructure projects.

While this supply-side progress has been made, significant areas still demand attention to foster the development of the hydrogen infrastructure value chain for the HDT sector in the Netherlands. A primary obstacle hindering the growth of the hydrogen economy is the absence of sufficient incentives prompting transport companies to transition their fleets to hydrogen-powered trucks, which constitute the demand for green hydrogen in this hydrogen economy. For the transport companies, the current cost-price of green hydrogen is too high as well as the acquisition costs of hydrogen-powered trucks. While the Dutch government is actively fostering an environment conducive to the widespread adoption of hydrogen vehicles, including trucks, doubts persist among the interviewees in this research regarding the efficacy of existing policy measures in closing the price gap between green hydrogen and conventional fuels. Furthermore, collaborative endeavors amongst stakeholders in the socio-technical system are insufficiently directed towards the realization and adoption of hydrogen trucks, impeding the demand for green hydrogen in this domain.

Additional important challenges arise in the practical implementation and economic viability of green hydrogen, often leading to hesitancy among key stakeholders, particularly hydrogen producers, in the early stages of the transition. This hesitancy represents a major obstacle, hindering the widespread adoption of hydrogen technology in the transportation sector. Contributing to this hesitancy is the absence of transparent regulatory frameworks in the Netherlands. Finally, the social acceptance of the technology by the public remains uncertain. The limited public knowledge about hydrogen, combined with obstacles such as high costs, resistance to infrastructure projects, and differing opinions on transition strategies, act as significant barriers to the development of the infrastructure.

Overcoming these challenges and leveraging positive relationships are essential to accelerate the development of hydrogen infrastructure and realize a sustainable future for heavy-duty freight road transport in the Netherlands. Establishing a green hydrogen infrastructure value chain requires balancing urgency with practicality, emphasizing the gradual approach needed for building a new industry. Recommendations for future sustainability initiatives, as outlined in section 6.5, ought to prioritize optimizing the supply side of the economy by addressing uncertainties surrounding green hydrogen technology, while simultaneously fostering demand for green hydrogen via creating adequate incentives for transport companies to transit to hydrogen-powered trucks. Ultimately, green hydrogen holds the potential to replace fossil fuels in powering the HDT sector not only in the Netherlands but also in other countries.

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Appendix

A. Reviewed literature

Table 14: Reviewed Literature.

Author(s)	Year	Scientific/Grey Literature	Title
Faye et al.	2022	Scientific	"A critical review on the current technologies for the generation, storage, and transportation of hydrogen".
Ishaq et al.	2022	Scientific	"A review on hydrogen production and utilization: Challenges and Opportunities".
Germscheidt et al.	2021	Scientific	"Hydrogen environmental benefits depend on the way of production; An overview of the main processes production and challenges by 2050".
Le et al.	2023	Scientific	"Fueling the future: A comprehensive review of hydrogen energy systems and their challenges".
Liu et al.	2020	Scientific	"Trends and future challenges in hydrogen production and storage research".
Schönauer & Glanz	2021	Scientific	"Hydrogen in future energy systems: social acceptance of the technology and its large-scale infrastructure".
Rasul et al.	2022	Scientific	"The future of hydrogen; Challenges on production, storage and applications".
Litvinenko et al.	2020	Scientific	"Barriers to implementation of hydrogen initiatives in the context of global energy sustainable development".
Van der Spek et al.	2022	Scientific	"Perspective on the hydrogen economy as a pathway to reach net-

			zero CO 2 emissions in Europe”.
Sharma et al.	2023	Scientific	“Socio-economic aspects of hydrogen energy: An integrative review”.
Emodi et al.	2021	Scientific	“A systematic literature review of social acceptance and stakeholders’ perception of hydrogen technologies”.
Kurtz et al.	2019	Scientific	“Review of transportation hydrogen infrastructure performance and reliability”.
Apostolou & Xydis	2019	Scientific	“A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects”.
Sadik-Zada	2021	Scientific	“Political Economy of Green Hydrogen Rollout: A Global Perspective”.
Falcone et al.	2021	Scientific	“Hydrogen economy and sustainable development goals: Review and policy insights”.
Rijksoverheid	2022	Grey	“Kabinet investeert in meer waterstoftankstations”.
Nauta & Geilenkirchen	2021	Grey	“Waterstof tot nadenken”
Nationaal Waterstof Programma	2022	Grey	“Routekaart Waterstof”.
Ekinetix	2021	Grey	“Waterstof in Mobiliteit 2030”.

B. Hydrogen backbone development

Phase 1, finished in 2025-2026: big industrial clusters at the coast and the connection with a first storage cavern.

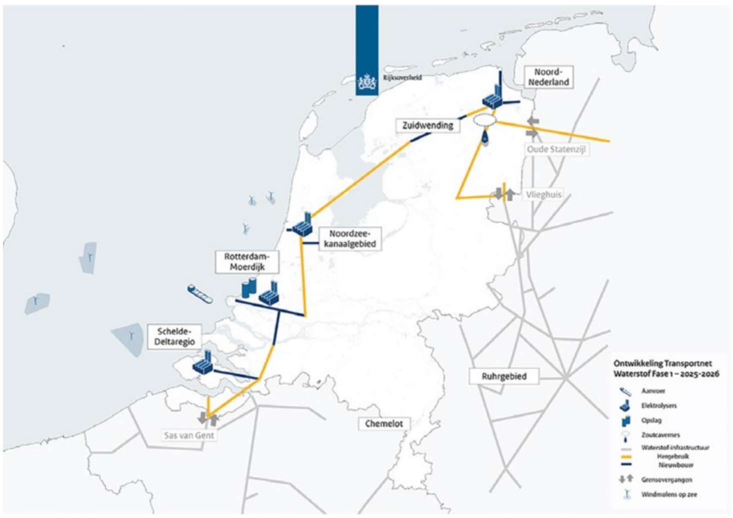

Figure 12: First phase of Hydrogen Backbone.

Phase 2, finished in 2027-2028: connection cluster Chemelot + other industrial clusters.

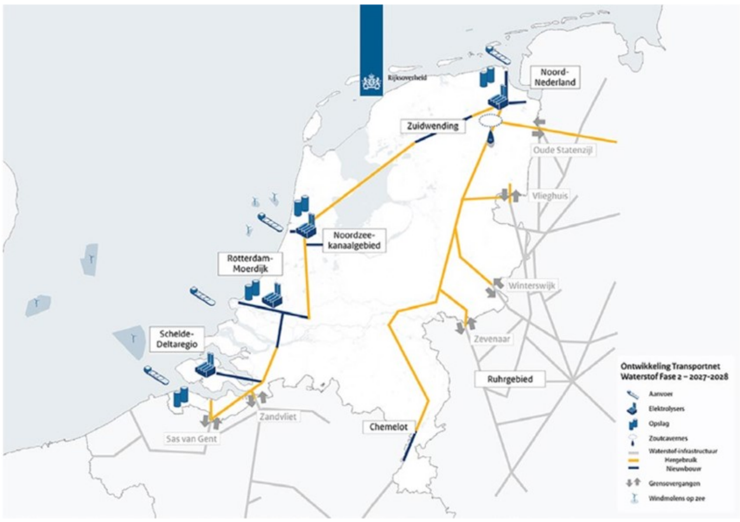

Figure 13: Second phase of Hydrogen Backbone.

Phase 3, finished in 2030: other traces.

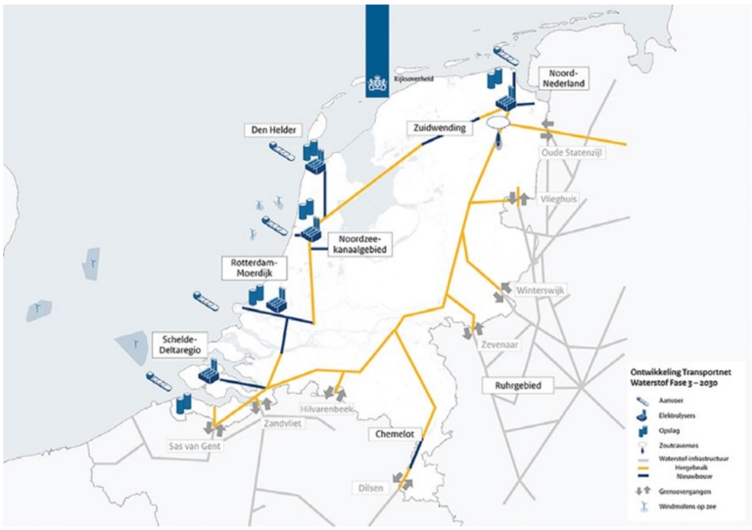

Figure 14: Last phase of Hydrogen Backbone.

C. Description of policy initiatives

C1. EU policy initiatives

Table 15: European Coalitions (broad description).

General description of EU Policy Initiatives	
Renewable Energy Directive	The initial Renewable Energy Directive, commonly referred to as RED I (2009/28/EC), had the objective of inducing a 20% share of renewable energy in the overall energy consumption compared to 1990 levels. This 20% target was obligatory and entailed individual national targets for each member state. Alongside overarching objectives, RED I also incorporated sector-specific sub-goals for member states, including a target of 10% renewable energy in the transport sector. Furthermore, RED I outlined criteria that formed the basis for an impartial evaluation of the sustainability of specific energy sources. After RED I, RED II was introduced. RED II covers the period up to 2030 and the most significant target is that by 2030, at least 32% of Europe's energy should come from renewable sources and comprises measures for the different sectors to make it happen. This directive was set up in 2018. Revision of this directive was the consequence of the introduction of the Fit-for-55 package. RED III is a refinement of RED II. RED III includes a 60% reduction in CO2 emissions by 2030 (net-zero by 2050). Additionally, there is a binding target to achieve 42.5% of renewable energy in total energy consumption by 2030 (van Ahnee, 2023).
Gas and Hydrogen Decarbonization Package	The Gas and Hydrogen Decarbonization Package, published in December 2021, is commonly known as the review and revision of the Gas Directive 2009/73/EC and Gas Regulation (EC) No 715/2009. This package aims to facilitate the decarbonization of gas consumption in the market and introduces necessary policy measures to support the establishment of dedicated and efficient infrastructure, fostering more optimal market conditions. Its purpose is to eliminate obstacles hindering decarbonization efforts and set the stage for a more cost-effective transition. Numerous barriers currently impede the development of a cost-effective, cross-border hydrogen infrastructure and a competitive hydrogen market, both critical for the widespread adoption of hydrogen production and consumption. The proposed revision seeks to establish a level playing field with EU-wide rules governing the hydrogen market and infrastructure, eliminating hindrances that impede their progress. Additionally, it lays the groundwork for repurposing natural gas infrastructure for hydrogen, resulting in cost savings and simultaneous contributions to decarbonization efforts (European Commission, n.d.-f).
EU Taxonomy	The EU Taxonomy is a fundamental component of the EU's sustainable finance framework and a key tool for enhancing market transparency. It plays a crucial role in channeling investments toward economic activities essential for the transition, aligning with the objectives of the European Green Deal. This classification system outlines criteria for economic activities that follow a net-zero trajectory by 2050 and broader environmental goals beyond climate considerations. Meeting the EU's climate and energy targets for 2030, as well as fulfilling the objectives of the European Green Deal, requires directing investments toward sustainable projects and activities. To achieve this, a common language and a clear definition of sustainability are essential, leading to the development of the EU Taxonomy. Given the mobility sector's commitment to a net-zero trajectory by 2050, the incorporation of hydrogen and its supporting infrastructure will be integral to the EU's sustainable finance framework (European Commission, n.d.-b).
Energy Taxation Directive	The Energy Taxation Directive is a taxation initiative which, both at the EU and Member State levels, plays a crucial role in achieving our climate policy objectives by incentivizing a shift towards cleaner energy, fostering sustainable industry practices, and encouraging environmentally friendly choices, all within the context of a socially equitable green transition. The Energy Taxation Directive (ETD), serving as the EU's common framework for energy taxation, holds a pivotal position in guiding these initiatives. By ensuring that the taxation of motor and heating fuels, as well as electricity in the EU, accurately reflects their environmental impact and impact on public health, the ETD contributes to a holistic approach in driving sustainable and climate-conscious practices. Nevertheless, it is evident that the current Energy Taxation Directive (ETD) is outdated and does not align with the EU's evolving climate and energy policy frameworks, nor does it reflect the EU's legal commitment to achieving at least a 55% reduction in greenhouse gas emissions by 2030 and realizing a climate-neutral continent by 2050. The ETD lacks a connection between the minimum tax rates of fuels and their energy content or environmental impact. Furthermore, the rules have fallen behind in adapting to the progress made in alternative fuels, such as cleaner and sustainable biofuels and hydrogen. The design and structure of the directive do not effectively encourage energy efficiency, the adoption of cleaner and sustainable alternative fuels, or investment and innovation in clean technologies and sustainable energy (European Commission, n.d.-h).

Important Projects of Common European Interest (IPCEI)	The IPCEI Hydrogen instrument (Important Projects of Common European Interest) provides the opportunity to extensively support significant projects with government funding. With this supportive framework, projects across the entire hydrogen chain are eligible for subsidies. The Netherlands is engaged in all four waves within the IPCEI-hydrogen program, totaling over 1.6 billion euros in budget. Each wave focuses on a distinct theme and unfolds sequentially. Wave 1 has just concluded. Selection of projects and allocation of subsidies will take place in the three subsequent waves (RVO, 2022c).
Horizon Europe	Horizon Europe stands as the primary funding program for research and innovation within the European Union. Addressing climate change and enhancing the EU's competitiveness and growth, this program offers crucial support to researchers and innovators, fostering systemic changes for a green, healthy, and resilient EU. A substantial 35% of its expenditure is earmarked to bolster Europe's climate objectives. Structured into three pillars, Horizon Europe focuses on fostering excellent science (Pillar I), addressing global challenges, and promoting European industrial competitiveness (Pillar II), and driving innovation across Europe (Pillar III). Pillars II and III specifically play a key role in advancing the deployment of low-carbon industry applications and groundbreaking technologies, with a particular emphasis on hydrogen (European Commission, n.d.-d).
Connecting European Facility	The Connecting European Facility is a crucial funding tool for implementing the European Green Deal and a significant facilitator in achieving the Union's decarbonization goals for both 2030 and 2050. Specifically geared towards transport, the CEF for Transport serves as the financial mechanism for realizing European transport infrastructure policy. Its primary objective is to bolster investments in constructing new transport infrastructure across Europe, including hydrogen infrastructure, as well as renovating or enhancing existing ones. Additionally, it fosters innovation within the transport system to optimize infrastructure utilization, mitigate environmental impacts, boost energy efficiency, and enhance safety standards. With a budget totalling 25.81 billion euros, the CEF plays a pivotal role in advancing sustainable transportation initiatives throughout the European Union (European Commission, n.d.-a).
Alternative Fuel Infrastructure Regulation (AFIR)	The updated regulation governing the implementation of alternative fuels infrastructure (AFIR) establishes compulsory deployment targets for electric recharging and hydrogen refueling infrastructure in the road sector. By ensuring a minimum availability of recharging and refueling stations throughout the EU, the regulation addresses consumer concerns regarding the accessibility of vehicle recharging or refueling. AFIR also sets the stage for a user-friendly experience, incorporating full price transparency, standardized minimum payments, and consistent customer information across the EU. Ultimately, this facilitates the adoption of zero-emission heavy-duty vehicles. Starting from 2030, hydrogen refueling infrastructure must be strategically deployed to serve both cars and lorries, with coverage in all urban nodes and at intervals of 200 km along the TEN-T core network, creating a sufficiently dense network for hydrogen vehicles to traverse the EU (Europese Raad, 2023).

C2. Dutch policy initiatives

Table 16: Dutch coalitions (broad description).

General description of Dutch Policy Initiatives	
Dutch Climate Agreement	The Dutch government is now focusing extensively on the development of hydrogen applications and the generation of green hydrogen. The development of blue hydrogen is intended to make an optimal contribution to the broader hydrogen system, paving the way for green hydrogen. The goal is to scale up hydrogen production to 3 to 4 GW electrolysis capacity by 2030 (for comparison, Germany aims for 5 GW in 2030 and 10 GW in 2040). In the Dutch Climate Agreement, the ambition for 2030 is stated to achieve a total annual hydrogen consumption of 141 million kg from the mobility sector. This is equivalent to the usage of 300,000 hydrogen-powered passenger cars. Additionally, an interim goal is formulated to establish at least 50 hydrogen refueling stations by 2025, with 15,000 passenger cars and 3,000 heavier vehicles utilizing this fuel infrastructure. This can be translated into a consumption of 18 million kg of hydrogen and a TTW (Tank-to-Wheel) emission reduction of approximately 0.2 Mtons CO2. The Climate Agreement highlights the formulation of an ambitious Hydrogen Mobility Promotion Covenant as a specific commitment (Rijksoverheid, n.d.).
Hydrogen in Mobility	The Ministry of Infrastructure and Water Management identifies a crucial challenge in the hydrogen mobility market: the 'chicken and egg problem,' where the absence of vehicles leads to a lack of fuel infrastructure and vice versa. To address this deadlock and encourage investments, a new subsidy scheme targets heavy road transport, aiming to promote collaborations across the hydrogen value chain. This subsidy, focusing solely on hydrogen, requires consortia applications involving infrastructure operators, transport companies, and shippers, ensuring both vehicle and

	fuel infrastructure development. With a modest budget of 22 million euros, the scheme aims to establish fuel stations and trucks in 5 to 10 locations nationwide, intending to scale up green hydrogen production and achieve a balanced distribution of refueling stations. Despite this positive start, more efforts are needed to advance hydrogen initiatives and meet climate targets. The Netherlands, among other nations, aims for all new trucks to operate emission-free by 2040, encouraging entrepreneurs to transition to clean trucks using subsidies. Additionally, the government's investment extends beyond transportation, encompassing plans for industry and residential heating (EGEN, 2023).
SDE ++	The Stimulus for Sustainable Energy Production and Climate Transition (SDE++) is a subsidy instrument for large-scale production of sustainable (renewable) energy and technologies that reduce CO2 emissions (NWP). This subsidy could be used by companies that build electrolyzers (RVO, 2023b).
National Growth Fund	The National Growth Fund: this fund is initiated by the Ministry of Economic Affairs and Climate and Finance, allocates 20 billion euros to projects aimed at positively impacting the long-term growth of the Dutch economy from 2021 to 2025. The current investment focus is on Knowledge Development & Research and Development & Innovation periods. Proposals seeking a minimum subsidy of 30 million euros are eligible for evaluation by the government (NWP). In the quest for an eco-friendly energy system characterized by dependability, cleanliness, cost-effectiveness, safety, and spatial adaptability, hydrogen assumes a crucial role as both an energy carrier and raw material. The financial backing for this initiative is drawn from the Fund. This represents the DEI+ subsidy, serving as a supplement to the overarching objective of DEI+ to significantly reduce CO2 emissions in the Netherlands within a decade of project initiation. This theme is dedicated to supporting pilot and demonstration projects, along with testing facilities. These initiatives contribute to the rapid and secure implementation of water electrolysis technology, electrochemistry, as well as the transportation, storage, and final applications of green hydrogen (RVO, 2023a).
Temporary Scaling Instrument	The government is actively working on a scaling tool for electrolysis, allocating a budget of 250 million euros for the inaugural tender dedicated to electrolyzers ranging from 0.5 to 50 MW, also called the Temporary Scaling Instrument. This initiative aims to lay the groundwork for subsequent scaling through smaller, swiftly executable projects that can offer valuable insights to other stakeholders. The inaugural tender was conducted in the early 2023 (NWP, 2022).
EIA	The Energy Investment Allowance (EIA) is a fiscal arrangement that allows businesses to deduct 45.5% of the investment costs for an initiative resulting in CO2 reduction from their profits. To qualify for this scheme, companies must invest in a technology listed on the Energy List. The relevant categories under the EIA currently focus primarily on the use of hydrogen as fuel and hydrogen storage and distribution (NWP, 2022).
Zero-emission zones	The establishment of the absence of diesel vehicles on the roads from 2040 onwards creates the need for alternatives, and currently, hydrogen is mentioned as one of those alternatives. A significant growth in electric driving is noticed, especially in cities with zero-emission zones that prohibit vehicles with polluting emissions. It is mentioned that such developments serve as an incentive for electric vehicles as well as hydrogen (EI-1). In the Netherlands, the 'zero emission zones' policy within cities ensures that diesel vehicles will no longer be welcome from 2028. With 29 cities and more implementing such zones, the pressure on the transport sector to opt for zero-emission vehicles is significantly increased. The importance of hydrogen as one of the zero-emission options is thus highlighted (EI-3).
CO2 emission restrictions	CO2-emission restrictions (mandatory legislation) might be necessary to accelerate the transition to hydrogen vehicles. This could involve legally requiring OEMs to produce trucks that collectively emit no more than a certain amount of CO2, thereby forcing them to transition to sustainable vehicles (Interview 1). Emission reduction goals for trucks, aiming for a 45-65% reduction in emissions by 2030-2035, is subject to substantial fines (EI-3).
Truck toll	On the 22nd of March in 2022, the Dutch Parliament endorsed the legislation for initiating a truck levy (RailGood, 2022). From 2026 onwards, a toll based on the distance traveled will be applied to trucks on Dutch highways Trucks that are not environmentally friendly will incur higher per-kilometer toll charges compared to their sustainable counterparts. Via this way the government is trying to drive back the use of diesel trucks (EI-5). A portion of the proceeds will be allocated back to the transportation industry to fund investments in environmentally friendly trucks.
HBE-regulation	The establishment of a minimum share of delivered sustainable energy, also called HBE-regulation, as is currently the case within the transportation sector. Energy suppliers providing fuels to the transportation sector must meet an annual minimum for sustainably generated energy. This is monitored based on the number of Renewable Fuel Units (RFUs) that an energy supplier possesses. RFUs are tradable units that energy suppliers must use to meet the annual obligation of renewable energy for transportation. This annual obligation is intended to ensure a growing share of renewable energy in the total energy consumption of the transportation sector. RFUs are awarded, among other things, in the production of green hydrogen (Koolen Industries, 2023).

D. Policy initiatives objective trees

D1. EU policy initiatives objective tree

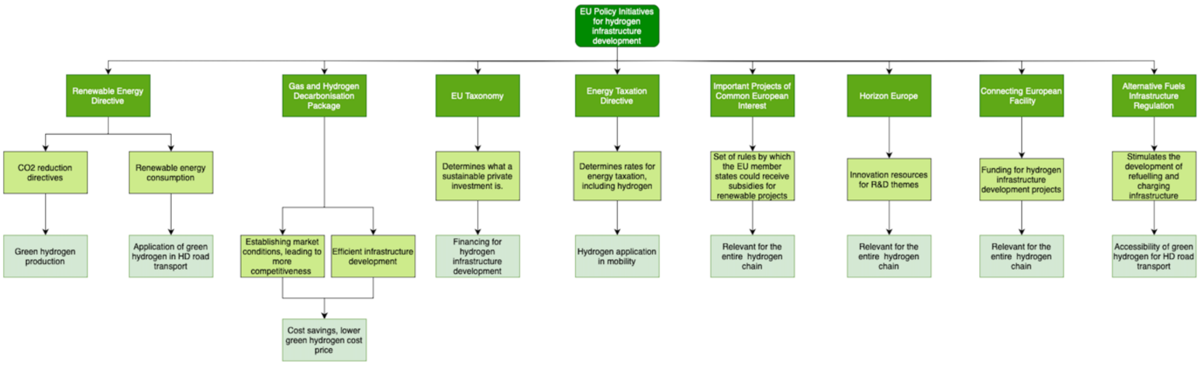

Figure 15: EU policy initiatives objectives tree.

D2. Dutch policy initiatives objective tree

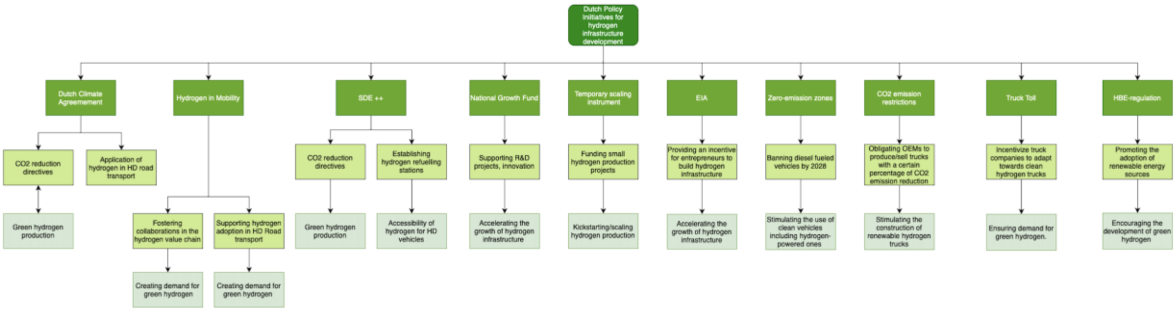

Figure 16: Dutch policy initiatives objectives tree.

E. General description of European and Dutch hydrogen coalitions

Table 17: Broad description European and Dutch coalitions.

Coalitions	
European Hydrogen Alliance	This coalition commenced in tandem with the 2020 EU hydrogen strategy as a component of the fresh industrial strategy for the EU. It unites various sectors, including industry, national and local authorities, civil society, and additional stakeholders. The goal is to realize a bold implementation of hydrogen technologies by 2030, aligning renewable and low-carbon hydrogen production, catering to demand in industry, transport, and various sectors, and enhancing hydrogen transmission and distribution (European Commission, n.d.-e).
Clean Hydrogen partnership	This represents a collaborative effort between the public and private sectors, backed by the European Commission under Horizon Europe. Its primary aim is to support the EU Green Deal and Hydrogen Strategy by strategically funding Research and Innovation projects. The partnership serves as the follow-up to the Fuel Cells and Hydrogen 2 Joint Undertaking. The objective of this initiative was to streamline the market integration of Fuel Cell Hydrogen (FCH) technologies in Europe, unlocking their potential within a zero-emission energy framework. Leveraging hydrogen's qualities as an energy carrier, the project aimed at achieving goals such as eco-friendly hydrogen production, sustainable transportation, effective H2 storage for grid balance, and the generation of heat and electricity, all while minimizing reliance on critical raw materials (European Commission, n.d.-e).
Mission H2	Mission H2 is at the forefront of building the Dutch hydrogen economy. The need to give a boost to the hydrogen economy is pressing. Companies and governmental bodies must work together to secure an ample number of signed investment decisions by the summer of 2024, aiming to achieve significant capacity from green hydrogen by 2030. Parties involved are amongst others Gasunie, Shell, Vopak, Toyota and Port of Amsterdam (MissieH2, n.d.)
Hydrogen coalition	The Hydrogen Coalition is a joint effort comprising 39 grid operators, industrial entities, energy firms, governmental bodies, nature and environmental organizations, and scientists. This coalition establishes a broadly endorsed pact for advancing the development of the Dutch hydrogen chain. By formalizing this pact within the coalition's framework, the decision-making process concerning hydrogen can be accelerated, contributing to the future proofing of Dutch climate and energy policies (Gasunie, 2021).
New Energy Coalition	The New Energy Coalition plays an active role in advancing hydrogen technologies and their incorporation into sustainable energy systems. Working in collaboration with diverse stakeholders, the organization fosters research, innovation, and the adoption of hydrogen solutions across sectors like transportation, industry, and energy production to combat carbon emissions. Employing a multidisciplinary strategy, the New Energy Coalition contributes to the establishment of hydrogen infrastructure, the formulation of policy frameworks, and the development of technological breakthroughs crucial for realizing a hydrogen-based economy. Parties as Gasunie, Actemium, TNO, University of Groningen, Kiwa, and Shell are involved (New Energy Coalition, 2024).
HyDelta	HyDelta is a public-private partnership, a Dutch national research program and collaboration facilitating the large-scale implementation of hydrogen. The aim of the program is to empower the hydrogen economy by resolving technical, scientific, and social barriers. TKI Nieuw Gas, Gasunie, Netbeheer Nederland, New Energy Coalition, TNO, DNV, Kiwa, Hanzehogeschool Groningen are involved in this partnership (HyDelta, n.d.).
H2Platform	The 'H2Platform' is a collaboration of companies and government bodies dedicated to the application of hydrogen in the Dutch energy system. The H2Platform is an expanding alliance comprising 55 companies and organizations dedicated to hydrogen. It also maintains close partnerships with the ministries of Infrastructure and Water Management, and Economic Affairs and Climate. The platform facilitates collaborative vision development, advocacy, publicity, and fosters cooperation and knowledge exchange among businesses, government entities, and research institutions. Lastly, the platform hosts events tailored for its members and publicly accessible for anyone intrigued by hydrogen. In 2021, there was a further expansion of Fuel Cell Electric Vehicles (FCEVs) and hydrogen refueling stations, resulting in what can be considered a comprehensive national network by the end of the year. To catalyze this momentum, the H2 Platform introduced the "Action Program for the Application of Hydrogen in Mobility" in 2021, along with an associated agreement submitted to the government. The proposal sought a budget of €175 million specifically allocated for tank infrastructure and the promotion of heavy-duty vehicles (NortH2, n.d.; RVO, 2022b).
North H2	North H2 is a consortium exploring the viability of large-scale production, storage, and transportation of green hydrogen. The goal is to ensure a minimum of 2 to 4 GW availability

	by 2030, aligning with the objectives outlined in the Dutch Climate Agreement, which serve as the guiding principles for the coalition. Eneco, Equinor, RWE, Shell Netherlands are the involves parties.
HyTrucks	HyTrucks is a consortium focused on fostering hydrogen-based road transport. The triumph of an inventive and extensive initiative such as HyTrucks relies on the active participation of an ample number of partners. Numerous partners, spanning the entire supply chain (including truck manufacturers, transport companies, and leading fuel cell suppliers), have already committed to joining this ambitious consortium (Air Liquide, n.d.). The goal is to achieve a critical mass of 1,000 heavy hydrogen trucks, supplied through 25 hydrogen refueling stations for heavy-duty trucks by 2025. This will create an ecosystem within the largest logistics hotspots across Europe. Upon reaching this critical mass, we anticipate a self-sustaining market development through a cascading effect (Deltalinqs, n.d.). The HyTrucks consortium is described as a multi-stakeholder project involving various stakeholders. This includes companies involved in hydrogen supply and infrastructure rollout, as well as shippers, carriers, and governments. The goal of this consortium is clear: achieving the ambitious target of having up to 1000 hydrogen trucks by 2025 between the ports of Rotterdam, Duisburg, and Antwerp.
Hy-Speed for H2-Trucks	The Hy-Speed for H2-trucks consortium is a collective effort aimed at propelling hydrogen fuel cell technology forward for heavy-duty trucks. Bringing together key players from industry, research institutions, and government entities, the consortium is dedicated to expediting the advancement and implementation of hydrogen-powered trucks for eco-friendly transportation. Through pooling expertise and resources from its diverse membership, the consortium undertakes research, development, and demonstration endeavors to tackle technical obstacles and advocate for the uptake of hydrogen fuel cell technology within the trucking industry. Participating parties are amongst others Green Planet Real Estate, H2 Storage, HyTruck consult, and The New Energy Coalition (RVO, 2020).

F. Summaries of interview outputs

F.1 Interview Total Energies (2 respondents)

- *With which green hydrogen production projects are you familiar? What are the most promising projects in the Netherlands at the moment? Which projects have actually been realized? And which ones do you think will be realized in the future? Will all plans truly come to fruition?*

The interviewed individuals are acquainted with several green hydrogen projects, acknowledging that numerous plans are in progress, but few projects have been realized. Many projects are currently in the Final Investment Decision (FID) phase. They view Shell's green electrolyzer on the Second Maasvlakte in Rotterdam as the most compelling project, as they believe this company has control over the entire chain. However, there is skepticism about the realization of all plans in the future, emphasizing the need for significant changes for widespread implementation. The achievement of plans is considered uncertain, with challenges such as costs and project complexity, as expressed by Shell. The responses from the interviewed individuals suggest a cautious outlook on the overall implementation of green hydrogen projects in the Netherlands at the moment.

- *What are the challenges related to green hydrogen production in the Netherlands?*

The current challenges associated with green hydrogen production in the Netherlands reflect a notable phenomenon in the market. There is a noticeable imbalance among the many ambitious plans circulating. The crucial aspect of supply and demand that needs to be in equilibrium is strongly emphasized. Making investments becomes a challenging decision when you cannot effectively bring your product to the market. The energy transition, which everyone is striving for, seems to be a race to create an entirely new market, bringing significant difficulties. The challenge is intensified by comparing it to the previous energy transition to gas, which took place gradually after the discovery of Slochteren and spanned decades. Now, within just a few years, there is an attempt to achieve a similar transformation, perceived as nearly impossible.

- *The Netherlands is also engaged in hydrogen import. What is the idea behind it, according to you, and do you find it necessary?*

In the realm of green hydrogen import and its underlying strategy, an interesting perspective unfolds. It begins with the understanding that stimulating this development is necessary and plays a crucial role in the broader context of hydrogen usage. The question that arises goes beyond whether we should or should not import; it involves a look into the future, where the end goal becomes clear. In the ultimate scenario, green hydrogen is obtained in the most cost-effective manner, driving the choice for import. An example from Saudi Arabia illustrates this principle. There, solar power yields significantly more than in the Netherlands, substantially reducing the production costs of hydrogen. Although it still needs to be transported to Europe, this proves to be financially feasible. The flexibility in the supply chain is emphasized, acknowledging that ships will traverse the globe to transport hydrogen from point A to B. This is further supported by the construction of import facilities, albeit still in development. It is a long-term option being considered to balance the green hydrogen ecosystem. Although not fully realized yet, it is seen as a forward-thinking approach.

- *Hydrogen Storage, in salt caverns, what are your thoughts on that? And how do you feel about storage in the form of hydrogen tanks, where it is stored in other forms such as ammonia or liquid hydrogen?*

The option to store hydrogen in the form of ammonia, where hydrogen is generated only at the moment of use, is considered an efficient approach. This avoids the additional step of conversion and double storage, potentially saving costs. Regarding salt caverns, it is acknowledged that these vast volumes can accommodate significant amounts of hydrogen, presenting a promising prospect, especially for locally produced gaseous hydrogen. However, the choice between storage as ammonia or in salt caverns is influenced by economic considerations and the implementation mechanism. From a financial perspective, storage as ammonia might be more favorable when imported in this form, while salt caverns might be preferable for import through a pipeline. An additional consideration is the purity of hydrogen at the end of the storage process, with specific requirements for, for example, fueling stations that demand highly pure hydrogen. Filtering hydrogen from salt caverns to achieve the desired purity, however, might be considered challenging. Overall, hydrogen storage forms a fascinating domain where technological, economic, and purity aspects converge.

- *Hydrogen Transport in the Netherlands; Is the backbone (current natural gas network) with its pipelines the way to go, or are there other interesting alternatives (hydrogen tanks with liquid hydrogen or ammonia)?*

There is a suggestion that hydrogen transport might not occur directly in the form of hydrogen itself, but rather in the form of ammonia or other substances. The ammonia market is already established, with containers being shipped globally, potentially leading to an expansion of the network if its commencement is straightforward. Although current discussions revolve around a hydrogen quality of 98% in the backbone, it appears that this might not be sufficient for fuel cell applications. A transitional step is suggested, possibly at gas stations or at the dispensing point during delivery via a tube trailer. The possibility of using ammonia as a transport medium raises questions about the quality in the backbone and the necessity to purify hydrogen at the point of sale, incurring additional costs. While this approach seems challenging, it may be suitable for certain industries with lower purity requirements or the ability to apply purification at the end of the chain. The complexity of hydrogen transport requires careful considerations and coordination across different sectors.

- *What are your thoughts on the feasibility of realizing the hydrogen infrastructure for heavy road transport in the Netherlands? What are the challenges, and what is the potential?*

The discussion on the feasibility of the hydrogen infrastructure for heavy road transport in the Netherlands is considered somewhat futile by the interviewee. The importance of both hydrogen and battery-electric vehicles is emphasized, with the expectation that the development will unfold somewhat disjointedly. The initiation of development is likely to occur in the industry, where large volumes are available in the short term, especially at companies like ArcelorMittal looking to green their polluting processes. It is noted that the hydrogen economy currently experiences a price mismatch, primarily because grey hydrogen is significantly cheaper than green hydrogen. The challenge lies in improving economic feasibility, where subsidies play a role, but ultimately should no longer be necessary. Entry into the market by certain parties and the promotion of market development are crucial for broader engagement. Developments are currently not progressing quickly, and the interviewee emphasizes the need for a coordinated approach where supply and demand progress in tandem. The comparison to the chicken-and-egg problem illustrates the necessity of a joint development of vehicles and infrastructure, recognizing that both are essential. While the promotion of hydrogen stations is currently active, there is still no incentive for investments in hydrogen vehicles. The need for a balanced development of both vehicles and infrastructure is emphasized, with awareness of the challenges and potential for hydrogen in various usage scenarios.

- *Regarding regulations, is there sufficient support for the realization of the hydrogen infrastructure at both the European and national levels?*

The interviewed individuals point to historical support in the form of subsidies for the construction of hydrogen stations in the Netherlands, which has contributed to the realization of a significant number of stations. However, recent changes in subsidy conditions are mentioned. Reference is made to a recent article discussing stringent emission standards, likely leading to the absence of diesel vehicles on the roads from 2040 onwards. This creates the need for alternatives, and at the moment, hydrogen is mentioned as one of those alternatives. The interviewee acknowledges the growth in electric driving, especially in cities with zero-emission zones that prohibit vehicles with polluting emissions. It is mentioned that such developments serve as an incentive for electric vehicles as well as hydrogen. Additionally, schemes like SDE+ and the HBE scheme in the Netherlands, using certificates to green fuels, are discussed. This is seen as a good start, but the interviewed individuals note that it may not be fully sufficient yet to bridge the price gap with conventional fuels. Challenges in regulations are still recognized, including the length of trucks and the impact of additional tanks on vehicles carrying hydrogen. There is a call for more specific regulations that consider the new reality of hydrogen vehicles.

- *What needs to be better organized from a regulatory perspective?*

There is a strong advocacy for stimulating and subsidizing hydrogen transport, especially for trucks, buses, and smaller vehicles. The high acquisition costs of hydrogen trucks currently pose a barrier, making financial support essential to make the transition financially feasible. The interviewed individuals emphasize that this financial support must happen on a large scale to have a real impact. While individual companies might hesitate to invest in hydrogen vehicles due to costs, widespread government support could significantly boost the adoption of hydrogen vehicles. In the current transport sector, there is insufficient incentive for carriers to switch to hydrogen vehicles, especially given the low profit margins. Subsidization is seen as a crucial tool to encourage companies to make the transition. In addition to financial support, the interviewee also suggests that legislation can play a role. Mandatory legislation might be necessary to accelerate the transition to hydrogen vehicles. This could involve legally requiring transport companies to emit no more than a certain percentage of CO2, thereby forcing them to transition to sustainable vehicles.

- *Who are the (relevant) stakeholders in this system? The government, hydrogen infrastructure developers (electrolysis, storage, transport, refueling stations), heavy road transport (trucks) manufacturers, research institutions, transport companies (consumers). Am I missing anything?*

No, nothing that the interviewees could list.

- *How do you perceive the importance of European coalitions (Clean Hydrogen Alliance, Clean Hydrogen Partnership) and national coalitions (HyDelta, Hydrogen Coalition, HyTrucks consortium, The New Energy Coalition)?*

These coalitions play a crucial role in exploring new developments, conducting research, gaining experience, and sharing insights among various stakeholders in the market. They form a valuable platform where diverse parties collaborate to acquire knowledge and pool experiences. However, the interviewee emphasizes that the current role of these coalitions often remains limited to pilot projects or specific segments of the hydrogen chain. The essential challenge is to scale up these initiatives to standardize the hydrogen market on a broad scale. The goal is to reach a point where such coalitions are no longer necessary because the market can function independently and economically.

- *Are there enough coalitions, or is there a particular coalition/collaboration missing between certain stakeholders?*

According to the interviewed individuals, it seems that collaboration between industrial parties is already taking place, and when there is a demand, these parties can connect. However, the main stumbling block appears to be in the financial aspect and regulatory framework. Financial considerations and existing regulations may have more impact on the success of hydrogen implementation than the presence of collaborating industrial parties, as these collaborations are already taking place.

- *Is the strategy from stakeholders towards realizing a (green) hydrogen infrastructure for heavy-duty transport in The Netherlands correct?*

According to the interviewed individuals, the strategy of stakeholders to realize a green hydrogen infrastructure for heavy-duty transport in the Netherlands is a matter of balance. While there is an urgent need to make progress quickly, they emphasize that establishing an entirely new industry takes time. A direct transition to completely clean trucks would not work because the industry as a whole is not yet ready for it. Therefore, it is necessary to approach this process incrementally.

F.2 Interview Shell (2 respondents)

- *Regarding the production of hydrogen, such as the electrolyzer project by Shell in Rotterdam, how is its development progressing? What are the main challenges in making such a project successful?*

The development of hydrogen production, particularly concerning Shell's electrolyzer project in Rotterdam, is making significant progress. The interviewee provided insights into the project's status and the challenges it faces. Construction is well underway, with the foundation laid and the electrolyzer building in progress. Utilizing resources from various EU countries, such as the fact that the electrolyzers are constructed in Spain and the technology that is used is developed by Thyssenkrupp in Germany, has been instrumental in advancing the project. It's anticipated that operations could commence around 2025 or 2026, indicating promising progress. However, several challenges must be addressed to ensure the project's success. Access to electricity is crucial, particularly green electricity, with a requirement for new green electricity starting from 2028. Although a wind farm bid was secured at Hollandse Kust Noord, obtaining the necessary electrical connection through Tennet has proven more complex and costly than anticipated. Despite initial plans for external assistance, the project ended up managing the connection independently, albeit at a higher cost. Additionally, acquiring permits for the project site has been crucial, with assistance from the Port of Rotterdam Authority. Gasunie is currently working on developing a pipeline to transport hydrogen to customers, adding another layer of complexity to the project. Furthermore, ensuring a reliable customer base willing to adapt to intermittent hydrogen production is essential. While most customers prefer a continuous supply, the refinery partner involved in the project can balance out intermittent supply fluctuations due to its substantial hydrogen usage and production capacity. The interviewee emphasized the importance of maintaining the value of hydrogen, given its significant cost. Grey hydrogen costs approximately 1.5 euros per kilo, while green hydrogen is substantially more expensive. Regulations offering credits for using green fuel, such as the refining route in Europe and the Netherlands, help justify investment in green hydrogen production. Despite the project's progress, competitors have been hesitant to embark on similar ventures due to rising electricity and connection costs, compounded by regulatory uncertainty. Many are adopting a cautious approach and holding off on similar projects until the regulatory landscape becomes clearer. In conclusion, while the electrolyzer project in Rotterdam is progressing well, navigating the challenges associated with access to green electricity, obtaining permits, and ensuring a reliable customer base remains critical for its ultimate success.

- *What other green hydrogen production projects are you aware of in the Netherlands?*

The interviewee began by discussing Important Projects of Common European Interest (IPCEI), emphasizing their significance in obtaining subsidies for hydrogen projects. Notable projects in the Netherlands and neighboring regions include HyCC and BP's venture on the Maasvlakte, where Shell is also involved. Uniper is exploring options for hydrogen production on the Maasvlakte, while Eneco and RWA are planning substantial projects, each aiming for 600 megawatts. These initiatives highlight a growing interest in green hydrogen production across the region. However, the question again shifted towards the challenges associated with transitioning to green hydrogen production. The interviewee highlighted the regulatory requirement for additional green electricity from 2028 onwards. This poses a significant challenge, as it necessitates matching electricity production with hydrogen production, contingent upon wind and solar energy availability. While the goal is commendable, it presents practical difficulties, especially given the intermittent nature of renewable energy sources. Furthermore, the interviewee touched upon the complexity of balancing electricity and hydrogen production on an hourly basis, emphasizing the need for market liquidity and flexibility. Despite regulatory efforts to incentivize green hydrogen production, practical implementation remains challenging, particularly for early adopters in the market. The interviewee also addressed the economic viability of hydrogen projects, citing the uncertainty surrounding electrolyzer lifetimes and return on investment. While initial investments are substantial, the interviewee expressed optimism about cost reductions through experience and innovation in design and manufacturing processes. In conclusion, while the green hydrogen industry in the Netherlands is witnessing significant growth and interest, several challenges remain, particularly concerning regulatory compliance, market liquidity, and economic viability. Despite these hurdles, stakeholders are optimistic about the long-term prospects of green hydrogen production, driven by technological advancements and increasing environmental awareness.

- *When it comes to hydrogen import, do you think the Netherlands needs it? And where should this hydrogen come from?*

The interviewee referenced studies conducted by CE Delft, which analyzed the demand and supply dynamics of hydrogen in the Netherlands. According to these studies, the Netherlands may face challenges in meeting its hydrogen demand domestically, especially if the existing industrial hydrogen consumption and heavy transport sectors transition to hydrogen. This would particularly hold true for green hydrogen production, which requires substantial renewable energy inputs. Regarding potential sources of imported hydrogen, the interviewee highlighted various regions across the globe positioning themselves as potential "energy centers." These regions include the Middle East, where abundant solar and wind resources offer favorable conditions for hydrogen production. Additionally, North Africa, including countries like Morocco, Algeria, and Egypt, boasts similar renewable energy potential. Other regions of interest for hydrogen production include Namibia, Chile, Brazil, the United States, and Australia, all characterized by ample sunlight and wind. The interviewee's insights underscore the potential role of hydrogen importation in meeting the Netherlands' future energy needs. As the country seeks to transition to cleaner energy sources, exploring partnerships and import opportunities with hydrogen-rich regions worldwide could play a crucial role in ensuring a sustainable and reliable hydrogen supply chain.

- *How do you believe hydrogen should be stored and transported in the Netherlands, considering its intended uses (industry, mobility)?*

The interviewee shed light on the gas pipeline network being developed by Gasunie, which is partially based on the existing natural gas infrastructure in the Netherlands. With the country's extensive pipeline network originally built for Groningen gas, which is now being phased out due to its low calorific value and environmental concerns, there are plans to repurpose existing pipelines for hydrogen transport. This repurposing involves converting certain sections of the pipeline network, including valves and compression stations, to accommodate hydrogen. This approach is deemed more cost-effective than laying entirely new pipelines. However, in areas where existing gas pipelines are unavailable or unsuitable for conversion, new pipeline sections are being constructed. For instance, a new pipeline segment from Maasvlakte to Pernis is being built to facilitate the transportation of hydrogen produced by electrolyzers, such as the one under construction at Maasvlakte, to industrial facilities in Pernis. Regarding the quality of hydrogen transported through pipelines, the interviewee emphasized the need for stringent purity standards, especially for applications like fueling hydrogen-powered vehicles.

Even minor contamination in the hydrogen supply poses risks to fuel cells. Therefore, purification processes are necessary to ensure the required purity levels. The complexity and cost of purification depend on the initial quality of the hydrogen being transported. Furthermore, the interviewee noted that internal combustion engines are more tolerant of lower-quality hydrogen compared to fuel cells, as they can combust a wider range of hydrogen compositions without significant issues.

- *How is the development of the hydrogen infrastructure for heavy road transport in the Netherlands supported by the government and at the European level (through regulations, subsidies, etc. -> Renewable Energy Directive, Fit-for-55, AFIR, Dutch Climate Agreement)? What should be better organized by institutional authorities?*

The interviewee noted that while significant subsidies have been allocated to the construction of hydrogen refueling stations, there has been a lack of focus on stimulating demand. Many subsidies have been directed towards capital investment in station construction, such as the Connecting European Facility and the Dutch Climate Agreement's DKTI (Demonstratie Klimaat Technologies en Innovaties) program. However, the interviewee emphasized the need for subsidies targeting the demand side, particularly incentives for vehicle adoption. Germany's KKMSI (Klimaschutzprogramm für den Mittelstand der gewerblichen Wirtschaft) subsidy, which covers 80% of the price difference between diesel and hydrogen trucks, was highlighted as a successful example. The interviewee expressed concern about the thin profit margins in the transportation industry and the importance of stimulating demand to ensure the viability of hydrogen infrastructure. They emphasized the necessity of attracting customers to cover operational costs, as the absence of a customer base could lead to financial challenges for hydrogen station operators. Furthermore, the interviewee mentioned a legal dispute in Germany regarding the allocation of a substantial budget for amongst others hydrogen-related initiatives, indicating challenges in government funding allocation and highlighting the importance of effective budget management to support hydrogen infrastructure development. Overall, the interview highlighted the need for a balanced approach to government support, focusing not only on infrastructure investment but also on demand-side incentives to foster the growth of hydrogen-powered transportation in the Netherlands and across Europe.

- *How do you view the importance of coalitions concerning the realization of the hydrogen infrastructure for heavy road transport? There are both European coalitions (Clean Hydrogen Alliance) and Dutch coalitions (Hydrogen Coalition, HyTrucks consortium, The New Energy Coalition). Is the strategy from the stakeholders to realize the green hydrogen infrastructure correct? Are we doing enough?*

The interviewee highlighted the significance of coalitions in standardization and safety within the industry. Collaborative efforts among competitors can establish crucial safety protocols and industry standards, ensuring uniformity across the sector. Standardization not only enhances safety but also streamlines processes, driving cost reductions through economies of scale. However, while coalitions play a crucial role in safety and standardization, the interviewee expressed skepticism about their effectiveness in stimulating demand. Despite the collaborative nature of coalitions, the interviewee noted the competitive dynamics within the industry, particularly regarding sensitive information such as production plans and market strategies. Competitors may be reluctant to share strategic details openly, leading to a stalemate where each party waits for the other to make a move. This cautious approach can impede progress and hinder the collective advancement of hydrogen infrastructure. Moreover, the interviewee emphasized the importance of government support and regulatory clarity in incentivizing industry-wide adoption. Without adequate stimulation from policymakers and clear regulatory frameworks, companies may hesitate to invest in hydrogen infrastructure, opting for more accessible alternatives. The interviewee raised concerns about the slow pace of development in the face of uncertainty surrounding costs and regulations. Inadequate government support and regulatory ambiguity may deter potential investors and slow down infrastructure development, exacerbating the risk of falling behind on green hydrogen targets. In conclusion, while coalitions play a crucial role in establishing safety standards and industry norms, their effectiveness in driving demand and accelerating infrastructure development remains uncertain. Clear government support and regulatory frameworks are essential to incentivize industry-wide adoption and ensure the timely realization of green hydrogen infrastructure for heavy road transport.

- *How do you perceive the feasibility of the hydrogen economy in heavy road transport in the Netherlands? Goals have been set for 2025, 2030, and beyond. Are those goals realistic? For example, 3 to 4 GW of electrolysis capacity by 2030 and 50 refueling stations by 2025.*

The interviewee expressed skepticism regarding the feasibility of the ambitious goals set for the hydrogen economy. They acknowledged the importance of aiming high to drive action but emphasized the risk of losing hope if these goals are consistently missed. They pointed out that while setting high ambitions can be motivating, the lack of certainty and the absence of supporting policies and investments pose significant challenges. In terms of infrastructure, the interviewee highlighted the transition in focus from personal vehicles to heavy-duty transport, which presents challenges in aligning existing infrastructure with evolving needs. They noted that the current infrastructure might not be suitable for the demands of heavy-duty transport, adding an extra layer of complexity to the transition. Furthermore, the interviewee discussed the difficulty in coordinating efforts among various stakeholders, including customers, fuel suppliers, and government agencies. They emphasized the mismatch in timelines and investment decisions, which complicates the collective effort required for a successful transition. The discussion also touched upon the importance of hedging bets between hydrogen and other alternatives, such as batteries, considering the capacity limitations of existing charging infrastructure. They noted that the existing electrical infrastructure is already under pressure, and the additional demand from a fleet of trucks would exacerbate this strain. If, in five years, it becomes apparent that the infrastructure cannot keep up with the demand, there would be a significant delay in transitioning to hydrogen. They emphasized the need for proactive investment to anticipate and address potential challenges, even if there's uncertainty about future needs. Overall, the interview provided insights into the complexities and uncertainties surrounding the implementation of a hydrogen economy in heavy road transport in the Netherlands, highlighting the importance of supportive policies, investments, and coordinated efforts among stakeholders to achieve the set goals.

F.3 Interview AirLiquide

- *How are we currently doing with the realization of trucks powered by hydrogen in the Netherlands? What are the challenges?*

The development of hydrogen-powered trucks is gradually gaining momentum. The HyTrucks program initially aimed to have as many as 1000 hydrogen trucks operating between the ports of Rotterdam, Duisburg, and Antwerp by 2025. However, achieving this goal currently appears to be quite challenging. Despite some growth, the process is not advancing as swiftly as anticipated, both in terms of expanding the necessary infrastructure and the availability of hydrogen trucks themselves. Recently, there has been a focus on electric trucks powered by hydrogen, particularly in the past two years. The emergence of internal combustion engines adds an intriguing element. While these trucks may be more cost-effective, the acceptance and adaptation by transport companies are of paramount importance. Historically, regulatory constraints and acceptance issues have posed significant obstacles to large-scale implementation. Nevertheless, there is hope, given the recent removal or addressing of these barriers. Currently, the rollout and availability of hydrogen trucks seem to be seriously addressed in the near future, probably around 2027-2028. It's crucial to note that this is not an immediate development and is not expected next year. In essence, despite being on the right track, the process is progressing slowly. Challenges lie in acceptance, infrastructure development, and the ongoing adaptation to new technologies.

- *How do you view the realization of hydrogen refueling stations (infrastructure) and trucks in the Netherlands, often referred to as a chicken-and-egg problem? How can you ensure that both are realized?*

According to the respondent, the question arises whether the chicken-and-egg problem is related to market failure or not. Essentially, government intervention might be necessary to kick-start the market. This intervention can take place through various mechanisms, such as subsidies, tax benefits, or even levies on alternatives like diesel. Concerning the hydrogen infrastructure, a separate investment is required for heavy-duty vehicles capable of quick refueling, similar to diesel refueling within approximately 15 minutes. Although this technology has been in development for an extended period, it now seems ready for large-scale deployment. However, for a retailer to invest in a hydrogen fueling station, a certain loading rate is necessary. Achieving this loading rate appears to be a challenge, and the respondent points out a potential mismatch between the supply of hydrogen trucks and the total ownership costs for the user. To address this issue, the respondent suggests that the industry itself needs to organize and take initiative. While the government can assist by providing support, it is also crucial for companies within the sector to demonstrate courage and take the lead. As an example, the recently announced partnership between Total Energies and Airliquide is cited, where they are jointly building 1000 heavy-duty fueling stations in the Benelux, Germany, and France. All in all, the key to overcoming the chicken-and-egg problem seems to lie in entrepreneurship, coupled with the right government support, both financially and in terms of regulations.

- *How is the development of the hydrogen infrastructure for heavy-duty road transport in the Netherlands supported by the government and at the European level (through regulations, subsidies, etc. -> Renewable Energy Directive, Fit-for-55, AFIR, Dutch Climate Agreement)? What should be better organized by institutional authorities?*

At the European level, Fit-for-55 plays a crucial role. The European Union has set ambitious goals, requiring hydrogen stations to be installed every 200 kilometers along the European main road network. This ambition serves as a clear stimulus from the European government to promote hydrogen infrastructure. Looking at the Netherlands, the respondent emphasizes the 'zero emission zones' policy within cities, where diesel vehicles will no longer be welcome from 2028. With 29 cities and more implementing such zones, the pressure on the transport sector to opt for zero-emission vehicles is significantly increased. The importance of hydrogen as one of the zero-emission options is thus highlighted. Furthermore, the respondent points out emission reduction goals for trucks, aiming for a 45-65% reduction in emissions by 2030-2035, subject to substantial fines. Financial incentives, such as mileage fees and tax benefits for zero-emission vehicles, play a significant role in promoting hydrogen use. The climate agreement and the ETS system are other mechanisms contributing to the commitment to CO2 reduction. Additionally, the government provides subsidies to end-users for the purchase of hydrogen trucks, with potentially substantial budgets, and regulations are focused on stability to encourage long-term investments. Nevertheless, the respondent emphasizes the need for better organization from institutional entities. He underscores the importance of a consistent and long-term vision from the government to encourage private parties to make large-scale investments in hydrogen import, production, and infrastructure. The stability of regulations, especially in the context of new technologies, is highlighted as a crucial aspect for successfully promoting hydrogen infrastructure.

- *What is your view on the importance of coalitions for the realization of the hydrogen infrastructure for heavy-duty road transport? There are both European coalitions (Clean Hydrogen Alliance) and Dutch coalitions (Waterstofcoalitie, HyTrucks consortium, The New Energy Coalition). Can you tell me more about the HyTrucks consortium? Does the strategy from stakeholders to realize the hydrogen infrastructure for heavy-duty road transport align correctly? Are we doing enough?*

In the respondent's vision, forming coalitions is crucial for realizing the hydrogen infrastructure for heavy road transport. He emphasizes a concrete example, the 'HyTrucks consortium,' as an illustration of such collaboration. The HyTrucks consortium is described as a multi-stakeholder project involving various stakeholders. This includes companies involved in hydrogen supply and infrastructure rollout, as well as shippers, carriers, and governments. The goal of this consortium is clear: achieving the ambitious target of having up to 1000 hydrogen trucks by 2025 between the ports of Rotterdam, Duisburg, and Antwerp. The respondent emphasizes the importance of this coalition, where diverse stakeholders collectively address the challenges. It involves not only hydrogen suppliers or technology providers but also the engagement of carriers essential for market demand. Additionally, governments play a role in creating a favorable institutional environment and providing supportive regulations. Collaborating in such coalitions is seen as a necessary approach, especially since the hydrogen market for road transport is still in a pre-commercial phase. In this phase, where the commercial business case is not fully defined, collaboration among competitors offers advantages. It allows working together to break the 'chicken and egg dilemma,' where investments, interests, and the complexity of the field require a joint effort. While there are clear benefits to this collaboration, the respondent remains critical, questioning whether enough is being done. It underscores the scale and complexity of the field, indicating the need for ongoing efforts and collaboration to successfully realize the hydrogen infrastructure for heavy road transport.

- *What is your opinion on the feasibility of the hydrogen economy in heavy-duty road transport in the Netherlands? Goals have been set for 2025, 2030, and beyond; are* *these goals realistic? For example, the goal that at least 10 hydrogen refueling stations for heavy-duty road transport should be developed by 2025, along with enough trucks using hydrogen: 3,000 heavy-duty trucks.*

The respondent takes a critical look at the feasibility of the hydrogen economy in heavy road transport in the Netherlands, with specific goals set for 2025, 2030, and beyond. Reference is made to the TNO study, addressing the development of at least 10 hydrogen refueling stations for heavy road transport by 2025, along with 3,000 heavy-duty trucks. The discussion also encompasses broader European goals, such as the aim for 2100 hydrogen refueling stations in Europe by 2030, which the respondent considers an ambitious but challenging objective. In addition to infrastructure, hydrogen production is a key element, with TNO citing a need for 4.5 petajoules of hydrogen for 2100 stations. The respondent acknowledges the efforts of the company, including work on electrolysis projects and making Final Investment Decisions (FID). However, he emphasizes some reservation regarding the current emphasis on green hydrogen, as producing significant quantities of it seems to pose a massive challenge. The dilemma between ambitious goals and their feasibility is indicated, especially since achieving a gigawatt of green hydrogen production in the Netherlands appears to be an enormous challenge. The respondent advocates for a more balanced approach, allowing room for blue hydrogen, as the technology for it is already available, and the CO2 emissions are effectively captured. In pursuing these goals, the respondent acknowledges the complexity and the necessity of a systematic approach, including collaboration among stakeholders and well-thought-out policies to promote the transition to a hydrogen economy in heavy road transport.

- *How do you feel about its safety, and societal acceptance?*

The respondent shares his thoughts on the safety of hydrogen installations and their societal acceptance. He emphasizes that the installations themselves will be designed with strict safety standards, including valves and material requirements familiar to the hydrogen industry. This ensures a high level of safety.
He further mentioned that safety concerns can be addressed through robust safety measures, effective risk communication, and transparency in regulatory frameworks to foster social acceptance. Additionally, the respondent underscored the significance of positive attitudes of the public towards hydrogen, as the formation of institutions consider these attitudes.
However, the respondent points out a specific concern regarding the response of emergency services, particularly the fire department, in the case of hydrogen fires. He notes that there may be a need for further steps to enhance the fire department's ability to quickly diagnose and effectively respond to incidents involving hydrogen. It appears that there is a need for closer collaboration between the industry and emergency services to increase knowledge about hydrogen incidents and shorten response times. Overall, the respondent underscores the commitment to safety in the hydrogen sector while simultaneously recognizing the necessity of continuous efforts to improve, especially in the ability of emergency services to respond adequately to hydrogen-related emergencies. This level of effort is seen as an essential aspect to enhance societal acceptance of hydrogen as an energy carrier.

F.4 Interview LH2 Europe

- *How is the technology situation of your business? Is it ready to be implemented? What are the challenges on the technological front?*

The interviewee noted that the technology is essentially ready for implementation, having undertaken comprehensive preparatory measures. However, the subsequent phases will necessitate substantial financial investment. Detailed designs for their hydrogen plant have been drafted, and discussions with local authorities and potential partners are underway. Current negotiations involve a major company willing to provide power. Additionally, a letter of intent has been received from a prominent shipping company, indicating its willingness to finance and manage the vessel. Presently, the project is in the detailed design and negotiation phase, entailing significant costs. Engagements with various banks and potential partners are ongoing throughout this process. Furthermore, quotations have been obtained for essential hardware, such as electrolysis equipment, with some companies expressing interest in potential investments. Although progress has been substantial, complete fruition has yet to be achieved. Fortunately, nearly all required technology is readily available. While storage tanks have been in production for decades, several parts of the vessel have been previously designed. The only non-standard component is the coupling for liquid hydrogen transfer. The interviewee argues that in terms of mobility, advancements are being made in hydrogen applications for trains, large vehicles, and heavy trucks. Notably, Mercedes is establishing a sizable factory for hydrogen trucks. However, the market remains highly fragmented, with the project's profitability contingent upon large-scale implementation. Nevertheless, the interviewee anticipates increased hydrogen demand in the future, particularly for liquid hydrogen. The prevalence of technology in Europe is largely attributed to the substantial volume of global hydrogen trade, a significant portion of which occurs within the continent. Additionally, the existing extensive hydrogen pipeline infrastructure further bolsters the project's feasibility.

- *From an institutional perspective, do you believe that projects like LH2 Europe are adequately supported by governments (specifically the Dutch government)? To what extent have you, for instance, received subsidies? What improvements could the Dutch government make to realize hydrogen projects like that of LH2 Europe?*

From an institutional perspective, the interviewee offered a thorough assessment of the support extended by governmental bodies, particularly focusing on the engagement of the Dutch government in projects like LH2 Europe. While acknowledging the collaborative efforts with Gasunie in constructing the hydrogen backbone as a positive development, the interviewee embarked on a nuanced exploration of the broader landscape, delving into both commendable aspects and areas warranting improvement. The interviewee's analysis revealed a multifaceted perspective on the H2Global initiative, originating from Germany with the objective of stimulating the hydrogen market. While acknowledging the initiative's intent, the interviewee expressed reservations about its foundational premise. He questioned the efficacy of soliciting bids for future hydrogen delivery without concrete assurances of feasibility, highlighting the inherent uncertainties surrounding future investments and infrastructure development. His skepticism stemmed from the complexity of committing to future delivery terms in the absence of firm foundations, such as secured investments and established infrastructure. In dissecting the prevailing challenge of low returns on investment, the interviewee provided insights into the cautious approach adopted by industry stakeholders like Shell. They underscored the significance of profitability considerations, which have influenced decisions regarding investment in hydrogen projects. Proposing innovative financial structures, such as debt-equity arrangements, he outlined potential avenues for enhancing investor returns and mitigating risk. Moreover, the interviewee emphasized the important role of long-term contracts in attracting necessary financing for hydrogen projects. Drawing parallels with successful models observed in the LNG industry, he advocated for proactive governmental intervention to mandate hydrogen utilization within specific sectors. Such directives, the interviewee argued, could serve as catalysts for widespread adoption and provide the necessary assurances for investors. Beyond domestic considerations, the interviewee scrutinized EU regulations pertaining to green energy classifications. He highlighted the complexities surrounding additional criteria and temporal correlation, suggesting potential implications for hydrogen production costs. His nuanced examination underscored the importance of careful consideration and potential revision of regulatory frameworks to ensure alignment with the objectives of fostering sustainable growth within the sector. In summation, the interviewee's detailed analysis offered a comprehensive exploration of governmental support for hydrogen projects. Their insights reflected a blend of optimism, caution, and actionable recommendations aimed at fostering an environment conducive to sustainable growth and innovation within the hydrogen sector.

- *How are collaborations with other parties going? How is the progress? What could be improved in terms of collaboration? Do you need any assistance?*

From a collaborative standpoint, the interviewee provided insights into the partnerships and interactions with other entities within the hydrogen sector. He expressed satisfaction with the level of cooperation thus far, citing the receipt of quotations and collaborative efforts in design development as indicative of positive engagement. However, he acknowledged that while significant progress has been made, the next phase will necessitate a transition from collaborative efforts to formalized agreements, which would require financial compensation for the engineering work contributed by various parties. Despite the encouraging collaborations, the interviewee highlighted the prevailing challenge of a limited market and supply within the hydrogen sector. He described a "chicken and egg" scenario, wherein the absence of a robust market impedes project progress, yet the realization of projects is essential for market development. This underscores the interconnected nature of supply and demand dynamics within the sector. Furthermore, the interviewee discussed the ambitious hydrogen import goals set by countries like Germany, emphasizing the urgency for project development to align with these objectives. They noted a disparity between the volume of projects discussed at conferences and those underway, citing a lack of tangible initiatives progressing towards implementation. While acknowledging ongoing endeavors such as the green steel project in Sweden, which has garnered investment and financing, he underscored the need for accelerated action to meet the ambitious targets set forth. In essence, the interviewee argues the importance of collaborative efforts in advancing hydrogen projects, while also highlighting the imperative for swift and decisive action to bridge the gap between aspirations and tangible outcomes in the hydrogen sector.

F.5 Interview Ministry of Infrastructure and Water Management

- *I am looking at how the development of the hydrogen infrastructure for heavy road transport in the Netherlands is currently being stimulated by national policy, considering the influence of initiatives such as the Dutch Climate Agreement, subsidies, zero-emission zones, CO2 restrictions, and HBE certificates. Are there any other significant policy initiatives within the Netherlands applicable to this development?*

The respondent mentioned one additional significant initiative which is the truck toll. This initiative introduces a levy per emission class. While this toll is not specifically targeted at hydrogen, it does apply to zero-emission vehicles, including hydrogen trucks. The respondent highlighted that there will be notable differences in costs between zero-emission and non-zero-emission trucks, with non-zero-emission trucks facing higher tolls. This factor is considered important in the total cost of ownership (TCO) and operational expenses (OPEX) of trucks. Additionally, the interviewee mentioned European regulations for truck manufacturers (OEMs), which also play a role in incentivizing zero-emission vehicles. Overall, the combination of policy measures, including the truck toll and European regulations, aims to make zero-emission driving increasingly attractive.

- *Is the supply side, meaning the production of green hydrogen, adequately supported to supply heavy road transport and other sectors with the energy carrier in the future?*

The interviewee discussed various aspects related to the support for green hydrogen production to meet the energy needs of heavy road transport in the future. They emphasized the importance of both domestic production and importation of green hydrogen for availability. They mentioned ongoing projects, such as one in Saudi Arabia focusing on green ammonia production, which could potentially supply green hydrogen to the Rotterdam port. The interviewee highlighted the significance of electrolysis projects for hydrogen production and noted the availability of subsidies for such initiatives. They mentioned Shell's "Holland Hydrogen One" project as the largest current endeavor in this field, emphasizing Shell's commitment to making it financially viable. Additionally, the interviewee discussed the Renewable Energy Directive and its aim to phase out fossil fuels, incentivizing the adoption of renewable alternatives like hydrogen. They mentioned the use of hydrogen and RFMBOs (Renewable Fuels of Non-Biological Origin) as a means of meeting emission reduction obligations, which can earn credits. Moreover, the interviewee pointed out the importance of using renewable hydrogen not only directly but also in refining processes. They explained that granting credits for using renewable hydrogen in refining could accelerate the business case for such projects. However, they expressed concerns about the potential cost implications for consumers and the need to strike a balance between encouraging renewable hydrogen production and ensuring its efficient utilization. Furthermore, the interviewee highlighted the uncertainty in the market due to ongoing discussions, particularly regarding the use of grey hydrogen by major consumers like refineries and fertilizer manufacturers. They stressed the importance of providing clarity on future demand to facilitate decision-making and investment in renewable hydrogen projects. Overall, the interviewee emphasized the need for clear policies and incentives to support the production and utilization of renewable hydrogen, while also addressing concerns about cost implications and market uncertainties.

- *Are the demand-side entities, such as transport companies, sufficiently incentivized and assisted to transition to clean hydrogen-powered trucks?*

The interviewee discussed the current support and assistance provided to transport companies to transition to clean hydrogen trucks. They noted that at present, there is not enough support specifically tailored to hydrogen vehicles, as existing schemes like the AZ subsidy are primarily designed for electric vehicles rather than hydrogen. However, efforts are underway to introduce a new subsidy scheme focused on hydrogen mobility, known as SWIM. SWIM aims to support the purchase of hydrogen vehicles and the establishment of hydrogen refueling infrastructure. The subsidy scheme is structured to encourage consortiums comprising fuel station operators and multiple transport companies to collaborate on the realization of hydrogen refueling stations. Under this scheme, consortiums are incentivized to cover 30% of the refueling station's capacity with hydrogen vehicles, for which they can receive subsidies. The subsidy amount is capped at a maximum of two million euros for the refueling stations and three million euros for trucks, allowing for significant financial support towards the adoption of hydrogen trucks. Furthermore, the interviewee highlighted that the SWIM subsidy scheme is expected to open soon, with a substantial budget allocated for the period 2024-2028. This budget allocation indicates a significant commitment to promoting the uptake of hydrogen trucks in the transportation sector.

- *What is the status of the development of the underground hydrogen transport network, the backbone, and hydrogen refueling stations? What role does the Dutch government play in this regard?*

The interviewee discussed the development of the underground hydrogen transport network, often referred to as the backbone, and the establishment of hydrogen refueling stations. They mentioned that this initiative is part of a broader plan, possibly under the EZK framework, aimed at repurposing old gas pipelines to create a foundational hydrogen infrastructure in the Netherlands. However, they clarified that the backbone infrastructure is quite rudimentary and may not directly support the connection of refueling stations due to its coarse design. Additionally, the purity of hydrogen transported through these pipelines may not meet the requirements for mobility applications, as it is primarily intended for industrial use. Therefore, further refinement may be necessary to meet the higher purity standards required for fueling hydrogen vehicles. Despite these limitations, the interviewee highlighted the potential of repurposing existing gas pipelines as a cost-effective option for establishing a foundational hydrogen infrastructure. They emphasized that while the current scale of hydrogen refueling stations can be adequately supplied using tube trailers, a more substantial infrastructure will be needed as hydrogen adoption increases. It was mentioned that there is a directive from the Ministry of Economic Affairs and Climate Policy (EZK) to collaborate with Gasunie on realizing this backbone infrastructure, indicating government involvement in the development of hydrogen transport networks.

- *Where else could Dutch policy be improved to facilitate this transition in the future?*

The respondent elaborated on several areas where Dutch policy could be further improved to facilitate the transition to hydrogen in the future. They emphasized the importance of establishing a favorable pricing structure for hydrogen, mentioning initiatives such as purchase subsidies for infrastructure and the absence of excise duties on hydrogen, which are intended to drive down its cost. They suggested that aligning with schemes like those in Germany, where hydrogen prices are decreasing, could significantly benefit the Netherlands. Additionally, the respondent highlighted the need for increased availability of hydrogen-powered vehicles, as currently, there is limited availability in the market. They mentioned the delays in the availability of hydrogen-fueled trucks and the growing availability of combustion engine options, which could potentially hinder the transition to hydrogen. The respondent also discussed the importance of addressing uncertainties in the market, particularly regarding the future demand for hydrogen-powered vehicles. They noted that many companies are hesitant to invest in hydrogen vehicles due to uncertainties surrounding their availability and cost-effectiveness compared to other alternatives like electric vehicles. Furthermore, the respondent emphasized the significance of lowering barriers to entry for hydrogen technologies, such as reducing the high upfront costs associated with purchasing hydrogen-powered vehicles. They highlighted the potential of hydrogen combustion engine technology as a more accessible option for some businesses, despite its minor emissions, as it could help bridge the gap until hydrogen fuel cell technology becomes more widespread and affordable.

- *When do we aim to have fully transitioned to sustainable heavy road transport in the Netherlands? Could you provide some insights into this?*

The respondent highlighted the complexity of transitioning to sustainable heavy road transport in the Netherlands, emphasizing the need for a coordinated approach at the European level. They noted that the transport sector operates on a supranational scale, and any significant changes must be implemented across Europe to avoid companies relocating to neighboring countries with less stringent regulations. In terms of specific measures, the respondent mentioned the initiatives already underway at the European level, such as the proposed ban on diesel trucks sales by 2040 and the requirement for OEMs to have a certain percentage of zero-emission vehicles in their offerings by 2030. These regulations indicate progress towards reducing emissions in the transportation sector. Regarding the Netherlands specifically, the respondent discussed the existence of zero-emission zones and the political challenges associated with them. While there is some support for zero-emission zones among businesses, there is also opposition, particularly due to concerns about congestion and access for zero-emission vehicles. The respondent suggested that the current political climate may not be conducive to further tightening regulations at the national level, especially considering potential backlash from affected industries. Despite these challenges, the respondent acknowledged the importance of continuing to work towards sustainability goals. However, they expressed skepticism about the likelihood of significant national policy changes in the near future, given the political landscape and the potential for opposition from various stakeholders.

- *Do you believe that European policies positively influence the transition to clean heavy road transport, thereby impacting policymaking in the Netherlands? Or do you think there are still areas that need improvement in this regard?*

The respondent believes that European policy sufficiently stimulates the transition to clean heavy road transport. They acknowledge the ambitious goals set by European policies and recognize the significant effort required to achieve them, especially concerning the direct deployment of hydrogen. However, the respondent notes a perceived contrast between battery and hydrogen technologies, which they consider unwarranted. They argue that both technologies have their merits and should not be set in opposition against each other. They emphasize the advantages of hydrogen, particularly in long-term energy storage and production in regions with abundant renewable resources, such as the Middle East or Spain. Despite acknowledging that hydrogen conversion may be less efficient in some contexts, the respondent emphasizes the importance of considering the broader picture, including factors like surplus energy in certain regions and the ability to transport hydrogen over long distances, which is not feasible with electricity alone.

F.6 Interview HyTrucks

- *Where does the hydrogen for the hydrogen filling stations come from? Is it from the large offshore electrolyzers, or also onshore?*

At present, there's a scarcity of available green hydrogen, making it challenging to purchase green hydrogen. The respondent expressed belief that most of the hydrogen will indeed come from offshore sources. This is due to the presence of wind farms, particularly near Scotland, where electrolyzers can be directly placed on turbines to produce hydrogen. This approach allows for the direct conversion of wind energy into hydrogen molecules. They also noted that the contribution of green hydrogen from existing onshore installations is expected to be limited. This limitation arises from regulatory constraints that prevent double claiming of subsidies for green hydrogen production. Additionally, existing contracts governing the distribution of green electricity make it unlikely for current installations to be repurposed for green hydrogen production. Nevertheless, the interviewee mentioned the possibility of seeing some locations emerging, particularly on the Maasvlakte, where wind turbines could directly produce green hydrogen. Hence, the answer is not straightforward. It will likely be a combination, but they estimate that most of the hydrogen for the Netherlands will come from offshore sources, supplemented by a considerable amount of import. Furthermore, they discussed the importance of efficiency in hydrogen production and highlighted efficiency calculations to determine the size required for electrolyzers to operate efficiently. Despite advancements in electrolyzer technology, they mentioned that smaller installations with minor capacities may not contribute significantly to overall production. In terms of market dynamics, the respondent emphasized the potential for green hydrogen utilization in the transportation sector, particularly in freight road transportation. They mentioned efforts being made to encourage truck manufacturers to produce hydrogen-powered vehicles, supported by government subsidies. Nonetheless, challenges remain, including the need for infrastructure development such as refueling stations and ensuring market readiness for hydrogen-powered transportation.

Moreover, the interviewee talked about three different application areas for green hydrogen. Firstly, they mentioned the industrial sector, where they estimate that industries can pay a maximum of €2 for green hydrogen based on calculations. However, this price may not be attractive enough for suppliers. Secondly, they discuss the refining route, particularly referencing Shell's approach. They note that while this method is logical and cost-effective, it may not directly address the demand for hydrogen in trucking. Despite its cost advantages, relying solely on the refining route may not fulfill the transportation sector's needs. The respondent stresses the importance of having a substantial market demand before large-scale production can occur, emphasizing the need for a balance between industrial and transportation hydrogen usage. They also highlight the ongoing efforts to encourage truck manufacturers to produce hydrogen-powered trucks and the challenges associated with building the necessary infrastructure. Overall, while the respondent believes in the potential of green hydrogen for trucks, they stress the importance of immediate action to address the current hurdles.

- *What do you think is the best way to transport/store hydrogen considering its application in hydrogen trucks, and why?*

According to the interviewee, due to the current market scale-up phase, liquid hydrogen transport/storage, is not yet feasible. They explained that liquid hydrogen, being at minus 260 degrees Celsius, poses challenges in transportation and storage. Without sufficient demand from trucking, the hydrogen would vaporize, necessitating constant cooling. Therefore, the interviewee believes that the first phase until around 2030 will not support widespread use of liquid hydrogen. They drew parallels to the evolution of natural gas, which transitioned from compressed to liquefied forms over time as technology and infrastructure matured. During this initial phase, they anticipate strategic considerations for the placement of hydrogen refueling stations, particularly leveraging existing industry infrastructure. Companies like Air Liquide are already positioned near industrial hydrogen sources, facilitating easy access for refueling stations. Additionally, locations near waterways could enable hydrogen transportation via ships, although logistical challenges remain due to limited cargo capacities of tube trailers. Looking ahead, the interviewee envisions gradual expansion of hydrogen refueling infrastructure, with options including building stations near waterways or converting liquid hydrogen to compressed hydrogen on-site. These strategies aim to support the initial group of companies adopting hydrogen trucks over the next five years. While regulatory restrictions may limit direct station construction on backbone routes initially, mobile refueling units could facilitate temporary solutions. Moreover, advancements in purification technologies could enable on-site hydrogen purification at refueling stations, ensuring the quality of hydrogen delivered to vehicles.

- *Do you happen to know which companies are involved in storing and transporting hydrogen in the Netherlands? I am researching what is happening in terms of storage and transport via hydrogen tanks. Any idea which companies are working on this and how far they are? I have noted companies such as Air Products Nederland, NPROXX, and H2Storage. Am I missing an important one?*

The respondent didn't know enough about which companies are exactly involved in this.

- *I have seen on a map from Airliquide that there are currently 22 refueling stations available for hydrogen in the Netherlands. Do you know how many hydrogen trucks have been realized today, do you have a source for this?*

The respondent estimated that there are around 10 hydrogen trucks operational in the country presently. Regarding the availability of refueling stations, they highlighted the potential challenges posed by simultaneous refuelling of multiple trucks at a single station. They explained that hydrogen pressure might become insufficient if a truck refuels before others, impacting the speed of subsequent refuelling attempts. They noted that only a few of the existing stations are well-suited for hydrogen trucks, citing examples such as the Apotex station in Botlek and the Total station in Utrecht. Additionally, they mentioned a station in Groningen operated by Holthausen, albeit with some reservations. The respondent further stressed the importance of station suitability for truck refuelling, considering factors such as space availability, buffer capacity, and maneuverability. A suitable station should accommodate multiple trucks simultaneously, provide adequate space for maneuvering, and ensure compatibility with truck configurations and fueling systems. These factors are critical for efficient hydrogen refuelling operations, ensuring that trucks can refuel promptly without causing traffic disruptions or operational constraints.

- *What is better? H2-combustion engines or the use of FCEVs? What are the considerations?*

The respondent provides insights into the considerations between hydrogen combustion engines and fuel cell electric vehicles (FCEVs) for trucks. He began by acknowledging the growing interest among transport companies in adopting hydrogen for trucks. They outlined two main technologies: hydrogen combustion engines and FCEVs. Initially, the focus was on FCEVs, but challenges in scaling up power demand for trucks led to advocacy for hydrogen combustion engines. They highlight the need to navigate through the process of scaling up power demand for trucks, which could take several years. The respondent suggested that three years ago, there was a shift towards advocating for hydrogen combustion engines, which has been embraced by the government and truck manufacturers. However, the speed of scaling up production remains a crucial factor in the success of this transition. They discussed the technical aspects of hydrogen combustion engines, emphasizing that while hydrogen does not inherently contain carbon, some carbon may be present in the engine's lubricating oil, resulting in minimal emissions. They compared different engine technologies, such as Spark Ignited and High-Pressure Injection (HPI), noting the low emissions associated with hydrogen combustion engines. The respondent raised questions about the widespread adoption of FCEVs for trucks, considering the substantial investment required for infrastructure. They argued that hydrogen combustion engines offer a cheaper alternative and prompt discussions about long-term efficiency and regulatory compliance. In conclusion, he suggested the need for a comprehensive evaluation, possibly in the form of a decision-making diagram, to weigh the pros and cons of each technology and navigate the transition towards hydrogen-powered trucks effectively.

- *How do you feel about feasibility? What do you think are the biggest challenges?*

The respondent expressed uncertainty regarding the widespread adoption of hydrogen-powered passenger cars, questioning whether it will ever become prevalent. However, they acknowledged the practicality of hydrogen for certain applications, such as delivery vans and trucks, where overnight charging of electric vehicles may not be feasible. The respondent suggested that there may be a market for fuel cell concepts in delivery vans, raising concerns about the quality of hydrogen available at refueling stations. They discussed the challenges associated with infrastructure development and the need for high-quality hydrogen fueling stations. Furthermore, he reflected on the issues facing the electric vehicle market, particularly regarding infrastructure for charging. He expressed confidence that hydrogen will play a role in the future but emphasize the importance of addressing challenges related to pricing and energy market dynamics. The potential for surplus renewable energy from sources like solar and wind to be used for electrolysis, producing hydrogen, was discussed. They further highlighted the need for significant overcapacity in renewable energy production to make green hydrogen feasible and stress the importance of balancing supply and demand in the hydrogen market. Overall, they advocated for organized efforts to address challenges in scaling up hydrogen production and distribution, recognizing the role of existing infrastructure, such as refineries, in facilitating the transition.