Seeing Green

Data Visualisation as a Catalyst for Hydrogen Powered Decarbonisation

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Master Thesis

TU Delft

Master's thesis

Seeing Green : Data Visualisation as a Catalyst for Hydrogen Powered Decarbonisation

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Summary

This project delves into the intricate challenges and potential opportunities within the Dutch hydrogen ecosystem as the country strives to meet its ambitious goal of achieving net-zero carbon emissions by 2050. The research highlights several significant barriers to the widespread adoption of renewable hydrogen, such as high production costs, financial risks, and the lack of sufficient infrastructure. These challenges have created a “chicken and egg” scenario in the market, where both hydrogen suppliers and off-takers are hesitant to commit without guarantees from the other side, stalling progress in the development of the hydrogen economy.

To address these issues, the study proposes the development of Local Hydrogen Networks (LHNs). These networks are envisioned as clusters of industries within specific regions that are connected to hydrogen suppliers, who use renewable energy sources like wind and solar to power electrolysers. By localising hydrogen production and distribution, these networks can tailor infrastructure to meet regional needs, reduce costs, and stimulate demand. LHNs also offer the added benefit of being scalable, allowing for gradual implementation that aligns with the existing infrastructure and market conditions.

A critical component of this project is the development of HySynth, an interactive online tool designed to facilitate the adoption of green hydrogen. HySynth provides stakeholders with clear, data-driven visualisations of hydrogen infrastructure, including the locations of potential off-takers and current projects. By making complex data more accessible and understandable, HySynth aims to foster greater collaboration among stakeholders, helping to align interests and reduce the risks associated with investing in hydrogen projects.

The project highlights the importance of regional collaboration and strategic partnerships as essential elements in overcoming the current inertia in the hydrogen market. By focusing on localised solutions and enhancing stakeholder engagement through data visualisation, the research contributes to the development of a more robust and integrated hydrogen infrastructure.

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Glossary and Abbreviations

Auto-thermal Reforming (ATR) - A hydrogen production process combining steam reforming and partial oxidation of hydrocarbons.

Capital Expenditure (CAPEX) - The funds used by an organization to acquire, upgrade, and maintain physical assets such as property, industrial buildings, or equipment.

Carbon Capture and Storage (CCS) - A technology used to capture and store carbon dioxide emissions from industrial processes or energy production.

Carbon Neutrality - Achieving net-zero carbon dioxide emissions by balancing emissions with carbon removal or offsets.

Certification of Green Hydrogen - The process of verifying that hydrogen production meets specific environmental and quality standards related to its sustainability.

Distribution System Operator (DSO) - A DSO manages and distributes electricity through the power distribution system, delivering energy to the majority of end users.

Electrolyser - A device that uses electricity to split water into hydrogen and oxygen.

Geographic Information System (GIS) - A framework for gathering, managing, and analysing spatial and geographic data.

Geospatial Data - Information that describes objects, events, or other features with a location on or near the Earth's surface.

Hydrogen Backbone - A large-scale infrastructure network designed to transport hydrogen across the Netherlands.

Hydrogen Blending - The process of mixing hydrogen with natural gas to reduce carbon emissions while using existing infrastructure.

Hydrogen Economy - An economic system in which hydrogen is a central energy carrier, replacing fossil fuels.

Local Hydrogen Network (LHN) - A network of industries within a region connected to a hydrogen supplier, utilising renewable energy sources for hydrogen production.

Off-takers - Industries or companies that consume hydrogen produced by suppliers.

Operational Expenditure (OPEX) - The ongoing costs for running a product, business, or system.

RED 3 (Renewable Energy Directive III) - A directive by the European Commission setting targets for renewable energy use, including the incorporation of green hydrogen.

Scalability - The ability of a system, network, or process to handle an increased level of demand or expansion without compromising performance.

Spatial Analysis - The examination of geographic patterns to understand the relationships and trends across different regions.

Steam Methane Reforming (SMR) - A process for producing hydrogen by reacting methane with steam.

Supply Chain Security - The assurance that the supply chain is reliable and resilient, particularly for critical resources like hydrogen.

Synoptic Tasks - Tasks that involve understanding a dataset as a whole, often involving the identification of patterns and trends.

VUCA (Volatility, Uncertainty, Complexity, Ambiguity) - A concept describing the challenging conditions in which decisions must be made, often used in strategic planning.

Introduction

Chapter 1

Introduction

1.1 Assignment

The Netherlands faces a critical challenge in meeting its climate goals, particularly its commitment to reducing carbon emissions to net zero by 2050. A significant part of this challenge lies in reducing the carbon emissions from our energy system as there is a high reliance on fossil fuels. Hydrogen has emerged as an alternative to natural gas because of its properties as an energy vector. It is also used as feedstock in many industries and can be used to power vehicles. Hydrogen produced using renewable energy can reduce our dependency on fossil fuels; however, hydrogen production in the Netherlands is predominantly reliant on steam reforming of natural gas, a carbon-intensive process (Weeda & Segers, 2020). This reliance poses a problem, as it is still dependent on carbon-based fuels for production. Regulations like the European Commission mandate that 42% of industrial hydrogen must be renewable by 2030 and 60% by 2035 (Erbach with Sara Svensson, 2023). However, the lack of investment in renewable hydrogen infrastructure aggravates this issue, raising concerns about the feasibility of hydrogen as a solution for decarbonisation.

In this project, I analysed the Dutch hydrogen ecosystem to identify opportunities for increasing collaboration and strategic partnerships among stakeholders. By examining open-source data and conducting qualitative research, I explored the following research questions :

1. **What are the main challenges industries in the Netherlands face in transitioning to renewable hydrogen?**
2. **How can stakeholders leverage strategic partnerships to overcome the challenges of transitioning to renewable hydrogen?**
3. **How can we enhance collaboration between stakeholders to increase investment in hydrogen infrastructure?**

The results indicate that stakeholders are hesitant to invest in hydrogen due to financial risks associated with the high cost of green hydrogen and the lack of a guaranteed market. However, clustering demand, and creating local hydrogen networks through strategic partnerships, might mitigate these risks and facilitate the transition from natural gas. This process is complex as it involves combining different resources and infrastructure to create an optimal solution. Additionally, this process requires effective and efficient collaboration and cross-domain communication of knowledge between different stakeholders. To drive innovation in such situations, Mintzberg & Westley (2001) recommend taking a 'seeing first' approach where decisions and actions are driven by what people see. The use of a collaborative visualisation tool also helps define the problem from different perspectives and provides the decision-makers with the ability to distil knowledge, explore simulations and communicate the results with other stakeholders (Isenberg et al., 2011). Hence, I created an interactive online tool to help stakeholders find locations of potential off-takers, enabling matchmaking between industries to form local hydrogen networks. Supported by additional visualizations, this tool allows stakeholders to understand both existing and potential hydrogen demand.

The contributions of this study are as follows: (1) analysis of the Dutch hydrogen ecosystem, (2) identification of key barriers and opportunities for renewable hydrogen adoption, (3) design of intervention to support stakeholders in the transition.

The remainder of this thesis report is structured as follows: chapter 2 reviews related work on hydrogen energy systems. Chapter 3 describes the research methodology. Chapter 4 presents the findings from the data analysis and interviews. Chapter 5 discusses the proposed interventions and their potential impact. Chapter 6 discusses the project's academic and practical relevance, discusses limitations and suggests future research directions. Finally, Chapter 7 concludes the study with a reflection on the project.

1.2 Scope

The scope of this research project is to analyse the Dutch hydrogen ecosystem and find opportunities to increase collaboration and strategic partnership between different stakeholders involved in the ecosystem. This study combines analysis of open-source data from TNO, IEA, and the Dutch government on industries and hydrogen infrastructure in the Netherlands with qualitative research to gain insights into the circumstances surrounding the adoption of green hydrogen in the Netherlands and the challenges industries face in transitioning to hydrogen. The research uses these insights to design an intervention that helps stakeholders counter these challenges and accelerate decarbonization.

1.3 Stakeholders

I conducted primary research based on literature about hydrogen and energy infrastructure to identify the following list of key stakeholders relevant to the project:

1. **Suppliers:** Companies that produce and supply renewable hydrogen

2. **Off-takers**: Companies and factories that consume hydrogen

3. **Policymakers**: Since renewable hydrogen is a novel proposition, policymakers have an integral role to play in creating rules and regulations around hydrogen.

4. **Transmission and Distribution partners**: Companies that transport hydrogen and distribute hydrogen. Hynetwork is making a national hydrogen pipeline that will connect all the major industrial clusters to ports, while other organisations like DSOs take care of local distribution.

5. **Energy providers**: Electrolysers need renewable energy to create green hydrogen. This energy can either directly come from solar farms, wind farms etc, or can be bought from the grid.

6. **Technical partners**: Companies that design and manufacture electrolysers, and other technology needed for generation and transmission of hydrogen.

7. **Ports**: Ports will be importing green hydrogen from overseas to fulfil the deficit.

8. **Local governments** like municipalities

9. **Countries** that export hydrogen to the Netherlands

They are further mapped in an onion model (Ian Alexander, 2003) along with other stakeholders where the ones that are most essential to this project are at the centre, enveloped by secondary and tertiary stakeholders respectively. The secondary stakeholders are responsible for the storage and transmission of hydrogen from suppliers to off-takers, while the tertiary stakeholders support and facilitate the whole system.

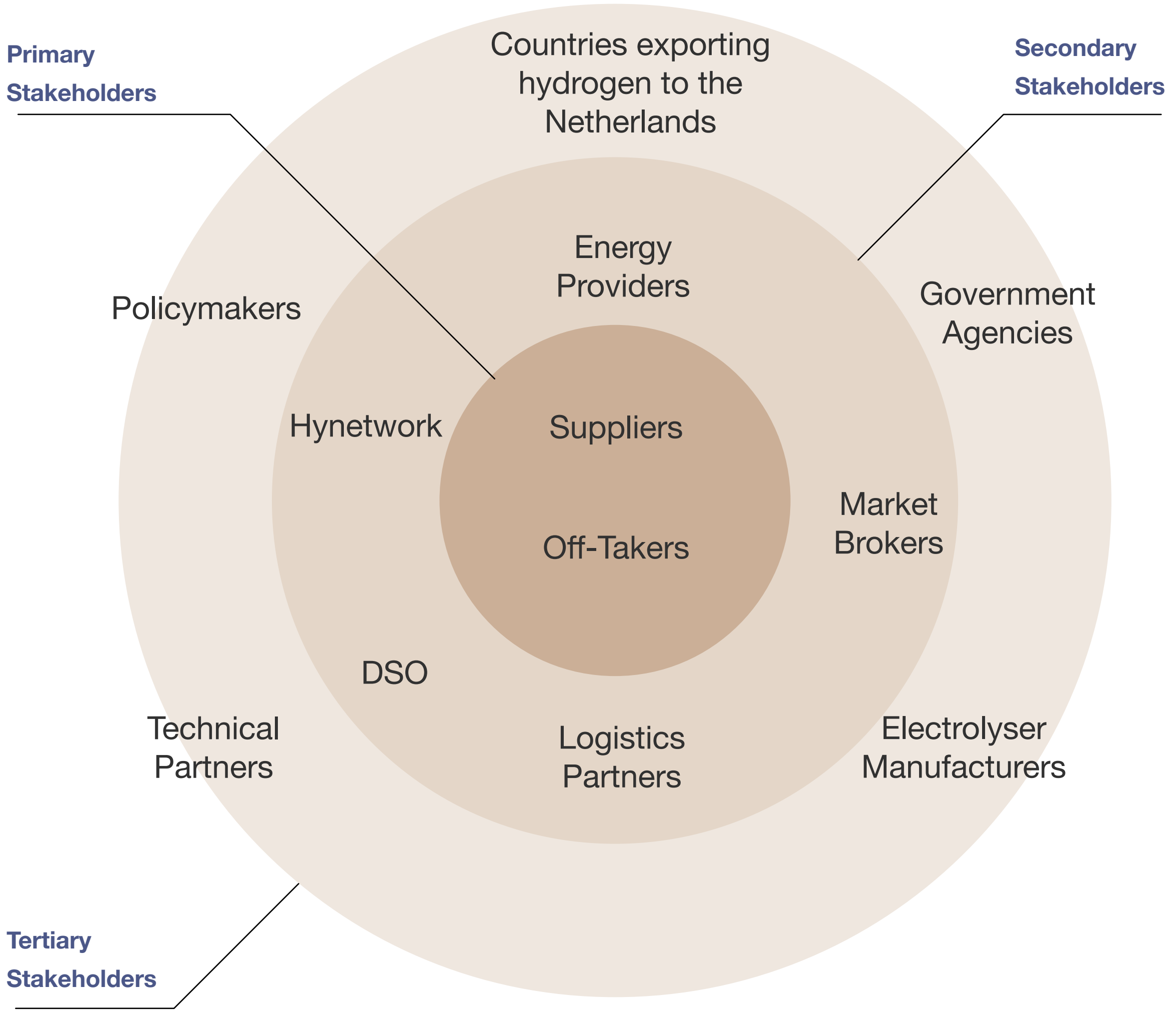


Figure 1 : Stakeholder map with primary, secondary and tertiary stakeholders.

1.4 Personal Ambition

Throughout the research project, my ambition was to learn more about energy infrastructure and the complexity of the task of lighting up our world. I wanted to investigate the efforts being made to move away from fossil fuels and the potential economic impacts on the companies making that move. Additionally, I wanted to enhance my skills in qualitative research and data analysis. This project also helped me gain a deeper understanding of data visualisation and using visualisations as a tool for communication.

1.5 Approach

I used an iterative design process based on the double diamond model as I have been using this model for many years as a designer. The project was broadly divided into two phases - discovery and design. The discovery phase focused on understanding the context, complexity and pain points of stakeholders. The insights from this phase helped the researcher to converge on the problem that is being tackled. This was followed by the design process where several broad directions and concepts were explored. These directions were narrowed down based on qualitative and grounded theoretical research leading to the further development of remaining concepts and the design of the final solution. Feedback on the concept was taken from the target users for future development and implementation. The qualitative research was based on an interview study with experts from the domain of hydrogen energy. It was supplemented by an analysis of publicly available datasets on emissions, industries, energy and infrastructure in the Netherlands.

There were two guiding principles that I followed during this project – contextual and adaptable. I wanted this solution to be unique to this context but also adaptable to different ones with few changes. This often prompted me to look at different perspectives and pain points and explore ideas that I would not have done otherwise.

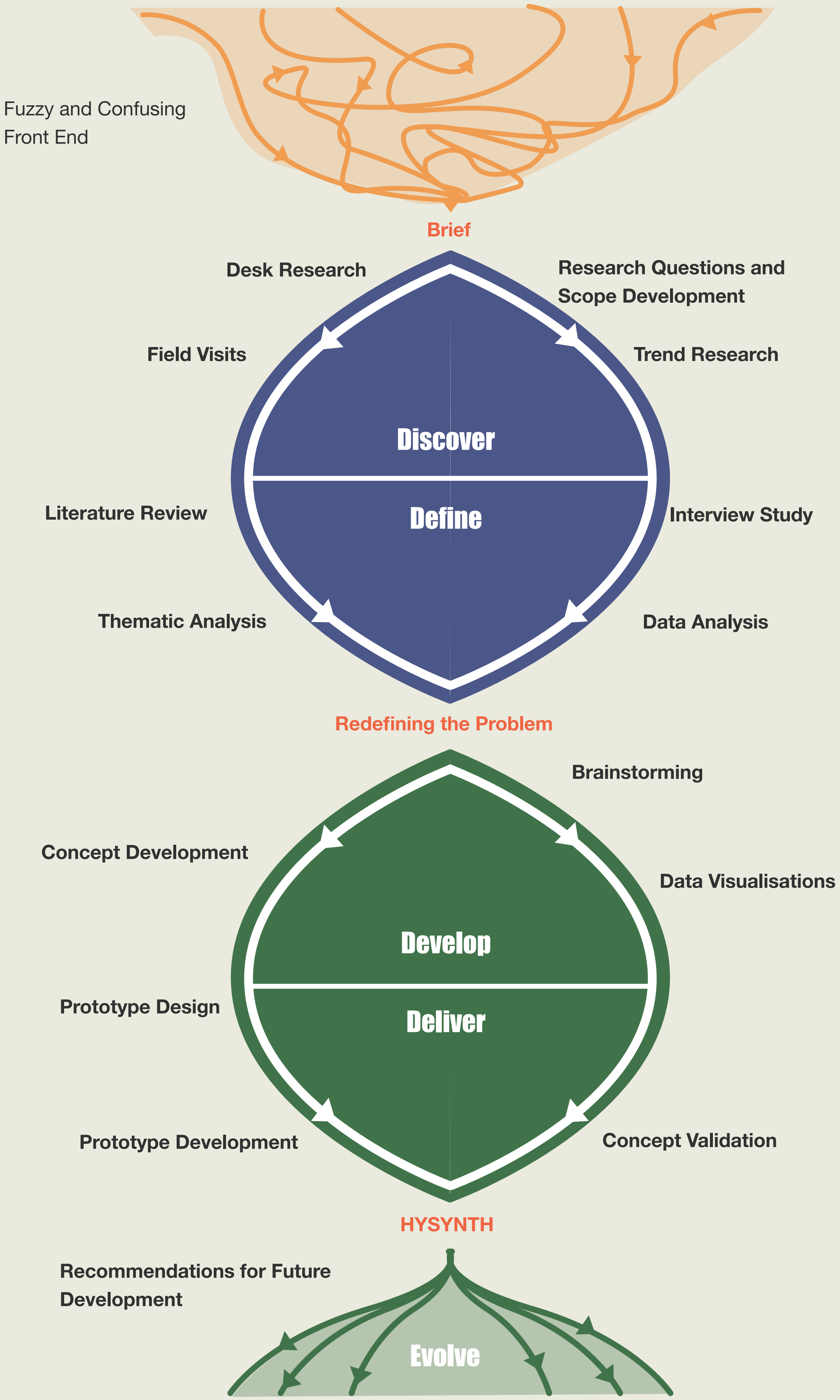


Figure 2: Design process

Background

Chapter 2

Background

This chapter discusses the multifaceted role of hydrogen as a clean energy source, exploring its potential in decarbonisation and supporting the transition to a sustainable energy system. It covers the production and challenges of hydrogen, particularly in the Netherlands, exploring infrastructure development. The chapter also explores the various methods of hydrogen production, known as the "hydrogen rainbow," and highlights the Dutch government's strategy to scale up hydrogen production, integrate it with renewable energy sources, and address the significant challenges associated with cost, infrastructure, and international standardization.

2.1 Say 'Hy' to Hydrogen

Hydrogen, first noted by ancient Greeks for its flammable properties and officially recognized as an element in 1766 by Henry Cavendish, has a wide range of uses across various industries today. It is crucial in chemical production, refining, food processing, semiconductor manufacturing, metal production, and energy storage. Hydrogen's role in the Haver-Bosch process for ammonia synthesis revolutionized agriculture by enabling large-scale fertiliser production.

Hydrogen can be used as a clean energy source due to its high energy content and ability to produce electricity with water and heat as the only by-products. It can be produced from water through electrolysis, natural gas through steam reforming, and biomass. Hydrogen can be stored and transported in various forms, such as compressed gas or liquid, making it a flexible option for energy storage and distribution. Its use as an energy source can significantly reduce greenhouse gas emissions, contribute to energy security, and support the transition to a more sustainable energy system.

However, hydrogen has drawbacks as highlighted by Rosen & Koohi-Fayegh (2016). It is more expensive to produce than natural gas or fossil fuels, has a lower energy density, and requires significant costs for storage and transportation. Its small molecular size makes it prone to leakage, and it can cause material compatibility issues.

2.2 Renewable Energy and Hydrogen

In 2023, the Netherlands saw a 21% increase in renewable electricity production from sources like solar, wind, and water. Wind energy grew by 35%, and solar by 24% (Centraal Bureau voor de Statistiek, 2024). Despite a drop in biomass energy, total renewable production reached 57 billion kWh. Fossil fuel electricity generation declined. The Netherlands also hit a record high in electricity exports to Germany, Belgium, and the UK, driven by renewable energy growth. This shift supports the country's efforts to reduce its carbon footprint and enhance sustainability, bolstering its role in the European energy market.

Renewable energy also impacts public transportation. Since 2017, Nederlandse Spoorwegen, the state-owned railway operator, has used wind-generated electricity for all trains. Increased solar and wind capacity has led to grid congestion and higher fares.

A significant drawback of renewable electricity is that it is intermittent and has geographic limitations. Hence, the storage and transport of renewable energy is an essential piece of the puzzle of decarbonization. Once generated, renewable energy can be stored in batteries and transported using the electric grid, but due to their heavy weight batteries are not used for transporting energy and the high costs of building new grid infrastructure, coupled with the energy losses over long-distance transmission, make storage and transmission of intermittent renewable energy a big challenge. A potential solution is using hydrogen and hydrogen derivatives (like ammonia and liquid organic compounds) as carriers of energy. Renewable energy can be used to produce these molecules and they can be stored for a long time or transported via conventional means of transport.

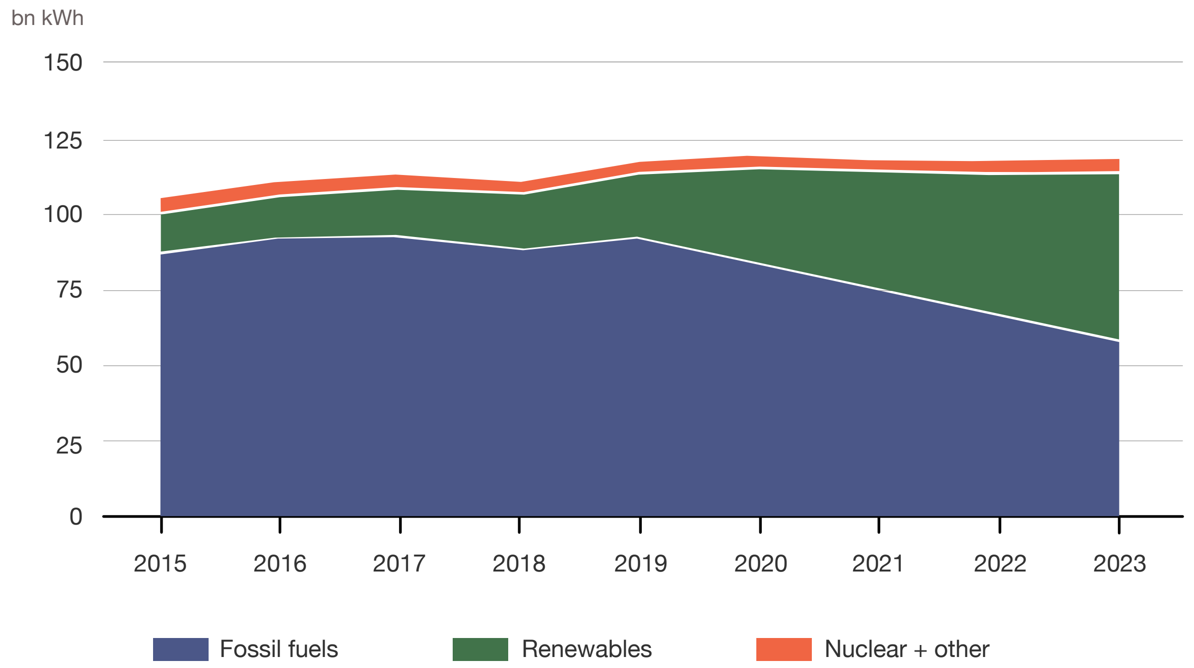


Figure 3: Renewable electricity production by source in bn kWh (Centraal Bureau voor de Statistiek, 2024)

2.3 Hydrogen Rainbow

The hydrogen rainbow categorizes the various methods of hydrogen production and their associated emissions. Green hydrogen, produced using renewable energy sources like wind, solar, or hydroelectric power to split water into its constituents, emits no greenhouse gases and is the most environmentally friendly option. Blue hydrogen is generated from fossil fuels, typically natural gas, with carbon capture and storage (CCS) technology to mitigate emissions, offering a transitional solution towards cleaner production. Grey hydrogen, the most common form, is produced by steam-reforming natural gas and releases carbon dioxide as a by-product, making it the least eco-friendly. Brown or black hydrogen, similar to grey hydrogen but produced from coal, is the dirtiest form, emitting significant CO2 and other pollutants. Lastly, pink hydrogen employs nuclear energy to electrolyze water, akin to green hydrogen but with a different energy source. These are some of the relevant 'colours of hydrogen' in the context of the project.

2.4 Challenges faced by green hydrogen

Green hydrogen is considered a very promising renewable energy vector. Governments and research institutes across the world are investigating its potential and implementing new strategies to tap into it. However, there are significant challenges green hydrogen has to overcome before it lives up to its potential. Ma et al. (2024) identified that high production, distribution, and storage costs are among the most significant challenges. Contributing factors to these high costs include low production volumes, insufficient green hydrogen infrastructure, and difficulties in efficient hydrogen storage. Differences in the definition and certification of green hydrogen across the world also create a challenge in international trade (Velazquez Abad & Dodds, 2020). Some studies also show that the Netherlands will have to import green hydrogen to meet the energy requirements of the country and northwest Europe as the renewable energy potential of the country can only contribute to a small share of the required amount (Port of Rotterdam Authority, 2020). In this project, I will be focusing on the challenges related to reduction of costs and infrastructure development.

2.5 International interest in green hydrogen – insights from World Energy Congress

During the initial phase of my research, I attended the 26th World Energy Congress in April 2024, which was held in Rotterdam. The theme for this year was 'Redesigning Energy for People and Planet'. The event hosted national delegations, companies, and stakeholders of the energy ecosystem from around the world. There was a significant focus on hydrogen for energy at the conference. The Port of Rotterdam authority was one of the leading organizations in facilitating discussions around hydrogen. The following insights were obtained during the interaction with delegates from around the world: Brazil aims to produce green hydrogen at $1.83/kg by 2030, leveraging its 88% renewable energy grid. They plan to use green hydrogen for sustainable aviation fuel, the iron and steel industry, and fertiliser production. China, the world's largest hydrogen producer, targets 200,000 tonnes annually by 2025 and is focusing on infrastructure and applications by 2030-2035. Japan, a pioneer in fuel cell technology, seeks to transition to a hydrogen-based economy with significant R&D investment, though not exclusively green hydrogen. Australia is investing in hydrogen infrastructure to export green hydrogen, with significant solar power capacity. The Middle East focuses on hydrogen from fossil fuels with carbon capture, with projects in Saudi Arabia and the UAE demonstrating blue hydrogen and waste-to-energy initiatives. More details are provided in the appendix of the report

2.6 Hydrogen in The Netherlands

This section describes the context surrounding hydrogen in the Netherlands. Insights from production and consumption patterns, government strategy and new infrastructure formed the basis of further research and analysis.

2.6.1 Production and Consumption - Hydrogen Balance

According to a report by Weeda & Segers (2020), the estimated annual amount of hydrogen produced was 1500 kton in 2019, out of which 1482 kton (98.8%) is produced using fossil fuels, natural gas holding the biggest share (863 kton). Natural gas is converted into H_2 using the Steam Methane Reforming(SMR) or Auto Thermal Reforming (ATR) process. The overall chemical reaction of the process is -

$$CH_4 + H_20 \rightarrow 4H_2 + CO_2$$

This process produces CO_2 as a bi-product. As discussed before, if the CO_2 is released into the atmosphere then the produced hydrogen is called grey hydrogen but if it is captured using carbon capture methods then the resultant hydrogen is called blue hydrogen.

Source Type	Estimated H_2 (kton/y)
Natural Gas	862
Oil	574
Coal	45
Electricity/Water	19
Total	**1500**

Table 1: Estimated annual amount of H_2 in industry by source type in 2019 (Weeda & Segers, 2020)

Application Type	Estimated H_2 (kton/y)
Ammonia	480
Refinery	544
Other pure H2 Use	143
Methanol	102
Fuel Gas	231
Total	**1500**

Table 2: Estimated annual amount of H_2 consumption in 2019 (Weeda & Segers, 2020)

If we look at the consumption of hydrogen, we will find that most of it is either used in refineries or used to produce ammonia, both of them amounting to almost 68.2% of the total consumption. The utilisation of hydrogen as a fuel gas is a distant third.

From a regional perspective, Rotterdam/Moerdijk consumes the most hydrogen (43%), mainly in the refineries, meanwhile, Zeeland (33%) is the second largest consumer and uses hydrogen mainly for ammonia production.

Location	**Estimated H_2 (kton/y)**	**Primary use**
Delfzijl	105	Methanol
IJmond	45	Coke oven gas
Rotterdam/ Moerdijk	644	Refineries
Zeeland	497	Ammonia
Zuid Limburg	209	Ammonia
Total	**1500**	

Table 3: Estimated annual amount of H2 in industry by geographical location (Weeda & Segers, 2020)

2.6.2 Government Strategy

In 2020, the Dutch government (Ministrie van Economische Zaken en Klimaat) unveiled a strategic document outlining the use of hydrogen to achieve climate goals. The strategy emphasises hydrogen as indispensable for zero-emission transport and high-temperature industrial processes, acknowledging its potential to improve air quality and facilitate the transition to sustainable energy sources. The Dutch government's strategic initiatives aim to scale up hydrogen production significantly, focusing on reducing production costs and fostering technological innovation. There is a strong emphasis on clean hydrogen, integrating it with sustainable practices like offshore wind energy. The strategy also promotes a collaborative approach involving both public investments and private sector initiatives to stimulate job creation and position the Netherlands as a key player in the international hydrogen market. Infrastructure development is another crucial aspect. The plan includes utilising existing gas networks for hydrogen transport, with necessary modifications for safety and efficiency, and developing new infrastructure to support the widespread adoption of hydrogen. The Netherlands aims to align its hydrogen strategy with international energy markets and policies, particularly within Northwest Europe, participating in global hydrogen production and supply chains, and emphasising the importance of imports and exports. Regulatory and safety measures are essential for managing the hydrogen economy, including guarantees of origin and market regulation. Safety standards are critical due to hydrogen's high energy content and specific handling requirements. The plan identifies four key sectors as important stakeholders: transportation clusters, regional governments, industrial clusters, and the agricultural sector.

To impact the transportation industry, the Dutch government announced a EUR 125 million subsidy to encourage the adoption of hydrogen-powered vehicles like trucks and vans. This subsidy supports the establishment of hydrogen filling stations and the acquisition of hydrogen vehicles, ensuring profitability from the outset. Entrepreneurs can apply for subsidies covering 40% of the costs for constructing hydrogen filling stations and 80% of the cost difference for hydrogen trucks or vans compared to diesel counterparts. The

subsidy scheme, running from 2024 to 2028, aims to construct approximately 40 modern hydrogen filling stations, aligning with European objectives for hydrogen stations along main highways by 2030. The Port of Rotterdam plays a central role in this system. Integral to Europe's hydrogen transition, the port aims to handle 20 million tonnes by 2050. Key initiatives by the port include building a hydrogen network, developing large-scale electrolysers, and establishing international green hydrogen corridors with partners like Brazil and Portugal, positioning it as a leading hydrogen hub.

4GW / 2030

The Dutch goal is to have 4GW of electrolysis capacity by 2030 (10% of the total EU target for that year).

136 000km

The country has over 1000 km of hydrogen pipeline and the network of 136 000 km long gas pipelines can be retrofitted to transport hydrogen.

11 GW / 2030

Planned projects in the Dutch sector of the North Sea add up to 11GW of offshore wind capacity by 2030.

9 Million m^3

The Netherlands is Europe's second largest hydrogen producers with annual production of over 9 million m^3 fossil-based hydrogen

Figure 4: Hydrogen potential in the Netherlands at a glance (Netherlands Enterprise Agency et al., 2021)

2.6.3 New infrastructure

In 2022, the *Ontwikkeling transportnet voor waterstof* was presented to the Dutch parliament, outlining a plan to create a hydrogen transport network in the Netherlands. This network will connect industrial clusters, port areas, landing points for offshore wind, storage facilities, and neighbouring countries like Belgium and Germany. The government reserved up to EUR 750 million for this network's development, with HyNetwork, a Gasunie subsidiary, responsible for its construction. The network will be built in three phases. The first phase focuses on developing infrastructure around coastal industrial centres and ports, including pipelines, import terminals, and storage solutions, with connections to Belgium and Germany. The second phase will connect various clusters to the transport network, constructing infrastructure for inland demand and establishing more connections with neighbouring countries. The final phase aims to increase capacity and supply security, creating a national hydrogen backbone connected to industries via a regional distribution network operated by Distribution System Operators (DSO).

Figure 5 : Route plan of the national hydrogen pipeline (HyNetwork Services, 2023)

2.7 Summary

The Netherlands is decarbonising and diversifying its energy mix, with almost half of its electricity needs coming from renewable sources. As a part of its decarbonisation efforts, the country is interested in using green hydrogen as an energy vector, potentially replacing natural gas.

The current supply of hydrogen heavily relies on fossil fuels, but there needs to be a shift towards green hydrogen to meet climate goals. This transition requires significant investment in renewable energy sources and electrolysis capacity. The demand from refineries and ammonia production can provide a stable base, but expanding the use of hydrogen in transportation and other sectors will be crucial for market growth.

The government strategy is aimed at facilitating this transition through subsidies and infrastructural development. The national hydrogen backbone being built by Hynetwork connects all the major industrial clusters of the country. However, there is a lack of production (electrolysers), distribution and storage solutions. This points to a fragmented approach for infrastructure development.

The high cost of green hydrogen, the lack of international standardisation of green hydrogen and the requirement for infrastructural investments are some of the major challenges that are being faced. The lack of required renewable energy infrastructure in the country for hydrogen production might also lead to dependence on imports to meet domestic and regional demand.

Methods of Research

Chapter 3

Methods of research

This chapter outlines the methodology used in this study to analyse the current landscape of hydrogen in the Netherlands and answer the following research questions:

RQ 1. What are the main challenges industries in the Netherlands face in transitioning to renewable hydrogen?

RQ 2. How can stakeholders leverage strategic partnerships to overcome the challenges of transitioning to renewable hydrogen?

RQ 3. How can we enhance collaboration between stakeholders to increase investment in hydrogen infrastructure?

To address the research questions, a multi-method approach was employed. A qualitative study with interviews was used to explore current infrastructure, collaboration, and investment challenges, addressing RQ1. The interview transcripts were analysed using the thematic analysis framework (Braun & Clarke, 2012), identifying the main themes and sub-themes relevant to strategic partnerships and collaboration, thereby addressing RQ2 and RQ3. Additionally, datasets from the IEA and the Dutch MIDDEN project were analysed to assess hydrogen production, usage, and investment trends in the country.

A validation study was conducted in the post-design phase with the help of domain experts to test the visualisation concepts. Results from this served as the basis of the iterative process for further development and refinement of concepts.

3.1 Interviews

I conducted an interview study with participants who are experts in the domain of energy from hydrogen in the Netherlands. The participants were chosen based on their expertise and the projects they were working on. The participants are involved in different projects related to hydrogen, which resulted in diverse answers and insights. The goal of the interview study was to shed light on the current state of hydrogen infrastructure and future developments and challenges that arise during transitioning to green hydrogen. All the interviews were based on the Dutch context. The interviews were semi-structured and were designed to explore a range of topics like the current state of hydrogen infrastructure, the importance of collaboration, and investments in green hydrogen to name a few.

Interview No	Role	Organisation	Expertise
P1	Project Leader	EBN	Policy development
P2	Innovation Lead	PlatformZero	Investment in new startups operating in this space
P3	Business Manager	Port of Rotterdam	Energy infrastructure, energy transition
P4	Expert Asset Management	Stedin	Hydrogen using gas infrastructure, energy transition
P5	Expert Asset Management	Stedin	Future of gas networks
P6	Project Manager	Gementee Hoogeveen	Hydrogen for domestic use
P7	Sr Strategist	Liander	Hydrogen grid
P8	Project Manager	HyStream	Development of new hydrogen projects

Table 4: List of interview participants and their expertise

3.2 Thematic analysis

The transcripts of interviews were analysed and descriptive codes were generated based on the in vivo coding method. The codes were iteratively grouped based on common features. The groups were further organised into themes using the thematic analysis framework by Braun & Clarke (2012). Over 200 codes were generated and were classified into three themes and nine sub-themes.

3.3 Data analysis

Datasets by the International Energy Agency and the Dutch government (MIDDEN project) formed the basis of this analysis. MIDDEN or Manufacturing Industry Decarbonisation Data Exchange Network is an initiative by TNO and PBL (Netherlands Environmental Assessment Agency) to build a network and knowledge base for decarbonisation for all the stakeholders involved(PBL & TNO, 2021). This project lasted from 2018 to 2021 and involved gathering Dutch industrial locations, processes, and products, along with a wide variety of decarbonisation options for those processes. The aim of building this knowledge base was to help discover new insights and make decisions for the reduction of emissions. The data from these industries was analysed to investigate the hydrogen balance in the country. The first part of the analysis focused on finding out the number of companies that produce hydrogen and its derivatives like ammonia; this was done by inspecting the industrial output of these companies. The next step was focused on finding the companies that use hydrogen in their manufacturing processes. I examined the list of manufacturing processes provided in the database and listed out the ones that required hydrogen, either as a reagent or as a catalyst. ChatGPT by OpenAI was used in this step to automate the analysis of manufacturing processes. The output delivered by ChatGPT was verified manually. This was followed by the analysis of companies that are looking to replace natural gas with other alternatives.

The IEA datasets have information about new hydrogen-related projects that are being built in the Netherlands and Europe. This dataset was analyzed to discover trends related to investment and infrastructure.

3.4 Validation study

The visualization concepts were tested with some participants from the interview pool to validate their effectiveness. Four experts from the group of interview participants were chosen for the validation study. During the testing session, participants were introduced to the tool and given time to interact with and analyze the visualizations. This hands-on interaction was followed by an in-depth discussion where stakeholders provided feedback on the visualizations' clarity, usability, and relevance. The session aimed to ensure the tool meets the needs of diverse users and facilitates better decision-making in the hydrogen ecosystem. Feedback from the participants was incorporated in subsequent rounds of concept development.

Findings of Research

Chapter 4

Findings of research

This chapter summarises the results of the research phase of the project. The first section is based on the thematic analysis of the interview study, the next section discusses the results of data analysis. In the final section, a problem statement based on insights from background study, thematic and data analysis is introduced. The problem statement guides the design concepts for the solution.

4.1 Thematic Analysis of Interviews

The descriptive codes generated from transcripts of the interviews were grouped based on the common features. The codes were made based on the current landscape of infrastructure, regulations and the market of hydrogen in the country. Over 200 codes were generated and were classified into 9 sub-themes, which were clustered to form 3 main themes. Table 5 shows the categorisation of sub-themes and themes. Some of the example codes and quotes from each sub-theme can be seen in Appendix B. The insights from each theme are presented with different quotes. First, you will see the insight, followed by the quote.

Themes	Sub-themes
Landscape of green hydrogen investment & infrastructure in the country	Infrastructural challenges – the ‘chicken and egg’ problem
	High cost of green hydrogen
	Storage and Transport
Market and Competition	The market for green hydrogen
	Blue Hydrogen as an alternative
	Electricity as a competitor of hydrogen
Regional Collaborative Effort	Risk Mitigation and Diversification
	Regulations
	Collaboration between stakeholders

Table 5: Themes and sub-themes that emerge from the analysis

Theme 1 – Landscape of green hydrogen investment and infrastructure in the country

Infrastructural challenges – the ‘chicken and egg’ problem

The first theme that emerged was the challenges faced by companies if they want to adopt hydrogen. An expert noted that there was hype around hydrogen which is now reaching its tipping point. Multiple barriers to entry for organisations to adopt hydrogen have an impact on the interest in this technology. ‘Difference between costs and willingness to pay’ emerged as a notable reason for waning interest. Transitioning to hydrogen would require companies to invest in new infrastructure and energy supply chains. Adding to this is the requirement is price and security of supply once the infrastructure has been developed. Organisations would need to secure a constant hydrogen supply at costs comparable to natural gas. An example of the maritime shipping sector was given to illustrate the problem. Shipping companies are not investing in hydrogen-powered ships as they are not sure if the infrastructure to operate and refuel these ships be ready soon.

‘…they don't want to start investing without a commitment that the infrastructure will be there because otherwise, you will have a hydrogen or methanol Vessel ready, but nowhere to bunker or get fuel from.’- P2

High costs of renewable hydrogen would also deter new investments in hydrogen projects forcing them to look at other alternatives.

‘If it's not going to be affordable, then companies are also not going to invest in new projects that they can use that hydrogen and maybe they don't use the hydrogen but maybe electricity or maybe something else’- P3

It was pointed out that companies that use a lot of natural gas might be possible off-takers. However, it is important to note that they would not switch to hydrogen immediately, it would be a gradual process with the use of hydrogen blended with natural gas as the first stage of transition. Reusing existing natural gas pipelines and infrastructure with modifications for hydrogen is a cost-effective way to accelerate adoption.

For an effective transition to hydrogen, there needs to be enough off-taker demand for large-scale production to be financially viable. However, due to the high costs of hydrogen, there isn’t much demand right now. This has reduced the interest amongst potential suppliers to build large-scale electrolysers.

‘Currently, there is no incentive to do so… people have been talking a lot about building electrolyzers, but they're not building them because they're not sure whether there's going to be any demand.’- P1

‘suppliers are looking for the for large volumes with long security of delivery. And there are no companies that give that promise to the intended suppliers. That's the problem in NL right now, there are only very few large players that could do that.’ – P7

Suppliers are also looking at the security of delivery, however, they do not have enough off-takers who have committed to hydrogen. Apart from the refineries in Rotterdam and the industrial sectors in Germany, there isn’t much demand guaranteed. This situation has created a unique ‘chicken and egg’ problem where both suppliers and off-takers are waiting for the other party to act and provide security and guarantee before they invest.

One expert noted that if off-takers and suppliers start collaborating at the early stages of a project then it might be possible to solve the issues arising with security of supply and demand.

'…if we would for our own project not involve off-takers already in such an early stage. Then you would in the end have hydrogen and no off-taker. So typically also this collaboration to actually solve this chicken and the egg problem you could do this with collaborating because by providing more insights…'-P2

'…the consumers are waiting for the producers and the producers are waiting for the consumers. The transportation company has announced is waiting a little bit, a little bit for the backbone before they build on it to make sure that demand and supply will be there. And the electrolyzer factories are waiting for a big order to actually build the factory that they need to build to make it cheaper. So it's just quite unique to have something that where there's no nothing at all, there's no supply, there's no demand and it just has to be sort of. Sort of come out of nothing and I think that's the conundrum because everybody's just looking at each other and saying, like, well, you know, I'm not going to be the first.'- P1

High cost of green hydrogen in the Netherlands

'But what is the price of hydrogen? Nobody knows. And so if the pricing is right, hydrogen will fly. But if the pricing is not right for the industry, the industry has to look for another solution to get cheap energy.' -P6

This statement describes the predicament of stakeholders and investors. The price of green hydrogen has not been defined yet, which makes it less attractive. The high investment costs associated with installing machines compatible with hydrogen make it essential for companies to have access to cheap green hydrogen.

'That new factory or new installation is also really expensive, so yeah, if you don't have the assurance that you can offtake cheap green hydrogen then you're not going to invest in such an expensive new factory. '- P3

Production of green hydrogen in the Netherlands is also expensive because of high energy costs. This translates to a per-kilogram price of around $10 right now, which is significantly higher than natural gas. The high costs of installing new electrolysers and high operational costs deter potential producers from investing. However, with a large number of electrolysers over time, the economics of scale can reduce the costs of producing hydrogen.

Storage and transport solutions

For the hydrogen ecosystem to be up and running, we need to solve the problems associated with the storage and transport of hydrogen. Hydrogen has less energy density than fossil fuels and is difficult to store in large quantities in a gaseous state. Liquifying hydrogen takes up energy and reduces the overall energy efficiency of the gas. Transporting hydrogen in pipelines is claimed as an easy solution to this problem. Multiple studies by DSOs have found that hydrogen can be transported through natural gas pipelines with some modifications. It is also cost-effective as there is an existing network of natural gas pipelines in the country.

'I think that the Netherlands has the luxury that we have parallel pipelines on the DSO levels… already 80% of the infrastructure is already there in the ground. And I think that is the major advantage that we have.'-P5

The construction of the national hydrogen backbone by HyNetwork is helping connect different industrial clusters to import terminals at the port. This backbone will also connect to pipelines in Germany and Belgium. The challenge of storage remains. Studies show that salt caverns are a good place to store large amounts of hydrogen. However, we would need to build smaller storage systems as well for areas far away from the hydrogen backbone or for industries that require hydrogen at specific times of the year. Converting hydrogen into ammonia to transport and store is a potential solution to this problem.

Theme 2 - Market and Competition

The market for green hydrogen

'The green hydrogen market is non-existent' – P1

As stated before, there is no large-scale production of green hydrogen. Most of it is produced with the help of fossil fuels. The market for green hydrogen has to be created from scratch. The Netherlands is currently looking to import a majority of the hydrogen it requires from countries with an abundance of renewable energy like Brazil, Portugal and Canada. Oil-rich Middle Eastern are investing in the production of blue hydrogen that they want to supply overseas. Since there is no market for renewable or carbon-neutral hydrogen, it is difficult for suppliers to have security of demand. A regulated hydrogen market can regulate the prices too and make it competitive with other sources of energy.

'There's no market to even estimate what you could get for it.'-P1

The Port of Rotterdam Authority is expecting a trade of 20 million tonnes of hydrogen by 2050 through the port, 90% of which would be supplied to industries inland and in other European countries like Belgium and Germany. This estimation is based on changing regulations like European legislation on using 42% green hydrogen in industries (Erbach with Sara Svensson, 2003).

The certification of green hydrogen is also challenging as there is no uniform definition of green hydrogen across the world. Which makes compliance with different regulations difficult. This is a potential area of opportunity for companies to provide services.

'Well, certification is not very 100% clear yet. Like mass balancing certification, what do you do with your certificates? You sell them. That's not very clear. So you would be hesitant to invest if you're not sure yet. You know there's no market for these certificates' -P1

Blue Hydrogen as an alternative

Hydrogen is called blue if it is produced by natural gas and the carbon emitted during the process is captured. It has a significant financial advantage over green hydrogen as it is cheaper to produce. It can be an intermediate step in the transition from grey hydrogen to green hydrogen. However, the perception of blue hydrogen is not as positive and encouraging as green hydrogen. The policymakers prefer switching directly to green hydrogen as switching to blue would mean that the industry is still dependent on fossil fuels.

'…it also has a weird feeling that you are focusing on green and then you're going to Import liquid natural gas to crack it here to make blue hydrogen'- P3

'It's unclear where the blue hydrogen is going to be supported because carbon capture is not considered sustainable in the long run.' - P1

Electricity as a competitor of hydrogen

There is a case to be made for shifting to electricity instead of hydrogen for industrial applications. Renewable energy can be more efficiently stored in batteries with minimal losses and with more power density. Electric cars are the current trend in automobiles. A business case can be made for industries as well as we would not have to develop new technologies for electric heating. Electricity, though promising comes with its own set of problems. Though it is easy to store energy in batteries, it is difficult to transport large amounts of electricity efficiently over long distances. High-capacity transmission lines would need to be built and they need a lot of space. Grids are also more susceptible to shutdowns if there is a sudden spike in demand which is often the case with electric furnaces. It was also pointed out in an interview that the transmission of hydrogen is possible in existing gas pipelines and it would cost significantly less to transport gigawatts worth of energy as hydrogen compared to building new electric infrastructure to do the same.

'When you want to transport gigawatts of energy from A to B the high power cable lines are going to be nearly 60 metres wide on different poles and when you have a gas pipeline, you can have a pipeline of 200 millimetres for the same amount of energy going to the pipeline'- P5

And companies that use gas furnaces would have to invest in new electric furnaces. The operation of these electric furnaces would need to wait till the electric grid can handle the added demand. Hence, using electricity instead of natural gas for industrial use is not possible for everyone.

Theme 3 - Regional Collaborative Effort

Risk mitigation and diversification

For any transition to happen, there is always a risk involved. There is a significant financial risk for both suppliers and off-takers if they do not have a guarantee from the other party.

An expert noted that changing governments and regulations also pose a risk to new infrastructure development. One way of reducing the financial risk is by having a guarantee of supply and demand. A strategic partnership between suppliers and off-takers that ensures the security of the supply chain will make investments in hydrogen more attractive. Diversification of green hydrogen sources would also help mitigate risk, instead of having a single producer, it is better to have a variety of them. It increases competition and can reduce the prices of hydrogen.

'It's just important to have a wider mix of different producers'- P5

Overdependence on a single source of energy can have undesirable consequences during VUCA events as we found out during the Russia-Ukraine war. Dependence on Russian gas for heating had a significant impact on the European economy when Russia reduced the supply of gas. Having a large number of electrolysers in the Netherlands along with importing hydrogen from different countries can help mitigate this risk. The regulators can also help reduce financial risk by taking some of it themselves and subsidising greenfield projects.

'There is a big need of flexibility, so you have you can use different sources depending on the pricing and the availability.' - P6

Regulations

Regulations play an important role in the development of infrastructure. Directives like RED 3 have mandated bringing green hydrogen into the energy mix. It was noted in the interviews that these directives were the key drivers behind the interest in green hydrogen. There is a regulatory push to create consumer demand.

'...other than the government regulations, EU regulations and all, what is the key driver behind this growing interest in green hydrogen? Well, nothing except the climate policy. I mean, if there wasn't any climate policy, I don't think it would happen.' - P1

Multiple experts had the opinion that governments can take financial risks and subsidise green hydrogen to make it more affordable for the end users. The governments can also act as a broker between suppliers and off-takers, and start the ball rolling. They can also provide grants to bridge the gap in technical advancements to make the production of hydrogen cheaper.

'I think that government has to play a role somewhere. Maybe together with the large energy suppliers, whether that will be companies like Eneco, or maybe companies like Shell or Exxon, the government should try to get a contract going and start importing hydrogen and be the broker between the the buyers and the sellers.' - P7

The regulations around hydrogen are not clearly defined yet as it is a novel domain. Currently, the DSOs that are supplying hydrogen have obtained an interim permit for supply as there are no permanent regulations around hydrogen.

'The Dutch permitting system is really flexible,' - P5

An interesting insight that came from the interviews was that the policymakers always look at a long-term plan while the industries look at a short-term one. Bridging the gap between these perspectives might help in the adoption of hydrogen.

Collaboration between stakeholders

Collaboration between stakeholders emerged as a key theme during the interviews. The chicken and egg problem is happening because the stakeholders are waiting for each other to take the first step. A participant in the interview said that there are signs of collaboration in chemical industry clusters. They are trying to have a common demand for a cluster of industries. Communicating and educating stakeholders about the nuances of the hydrogen ecosystem can also help in driving the demand. Good collaboration can also drive technological advancements in the right direction, as quoted by an expert :

'First and foremost is that the collaboration would be key to develop this technology. Because there's no use in only developing technology without getting industry input because you will very much need to understand what clients want to use it for.'-P2

Having different stakeholders come together also helps in looking at the overall value chain of hydrogen, focusing beyond the economic implications. Changing perspective from a national supply and demand to a local one can show many areas of opportunity. Regional ecosystems can be created with suppliers only focusing on certain regions and the combined off-taker demand from that region. Hydrogen can be produced on a smaller scale and can be scaled up based on the growth of demand. This also gives an added advantage of using by-products of electrolysers in industries. Electrolysers produce oxygen and heat as by-products and these can be sold to companies, diversifying the income of producers. HyStream works on identifying and creating local demand clusters for hydrogen. A project manager at the Gementee of Hoogeveen also shared their plans of building an electrolyser and using excess hydrogen and heat in a nearby cheese factory and oxygen for the sewage treatment plant.

'But in the summer we don't have much demand for hydrogen. We are in talks with the the cheese industry so that they can use the summer production of hydrogen for blending in, with their energy system. You can blend it with natural gas for example. So in that way, we look after the flexibility of the industry... – P6

4.2 Analysis of MIDDEN and IEA Database

The analysis of the MIDDEN database revealed that most current hydrogen demand is concentrated in and around the five industrial clusters (Figure 6), with refineries in Rotterdam and fertilizer factories in Zeeland being the largest consumers. However, there are a lot of industries that are not located in these clusters. These industries mainly produce bricks, glass, paper and food products. These industries form what is known as the sixth cluster (zesde cluster). The sixth cluster is not located in an area but rather spread across the whole of the Netherlands. An interesting insight was the number of industries exploring alternatives to natural gas, with many considering hydrogen and blended gas. These industries are currently using natural gas for powering furnaces for their processes. Most of the industries in the sixth cluster are exploring alternatives to natural gas for energy. If they transition to hydrogen, the combined demand from the sixth cluster might make it one of the largest hydrogen consumers.

Hydrogen production is concentrated in the Port of Rotterdam and Friesland. In 2020, 98% of the hydrogen produced used fossil fuels for production (Weeda & Segers, 2020). The IEA database on upcoming hydrogen infrastructure in the Netherlands revealed that most of these projects are still in the nascent stage. A significant amount of these projects are being built as a technology demonstrator or as a pilot project, and in some cases, electrolysers are purpose-built for a single off-taker. A lot of these projects are not situated in the five industrial clusters, where high consumption is expected. Some of the new projects are investigating infrastructural requirements for domestic use of hydrogen. Some of the interesting new developments are the North Sea Wind Power Hub and the PosHyDon project, these projects are exploring energy and hydrogen generation potential in the North Sea.

Figure 6 : Five industrial clusters of the Netherlands

4.3 Problem to Tackle

The research highlighted that one of the key obstacles to accelerating hydrogen infrastructure development is the fragmented efforts among stakeholders, leading to slow progress. Participants of the interviews suggest that stakeholders, while interested in hydrogen, are hesitant to fully commit due to the high costs and uncertainties associated with infrastructure development.

By building strong strategic partnerships, stakeholders can pool resources, share knowledge, and coordinate efforts more effectively, leading to more efficient infrastructure development. Regional collaboration, in particular, could play a crucial role in scaling up hydrogen projects. By aligning local industries, government bodies, and technology providers, these collaborations can tailor infrastructure solutions to specific regional needs, reduce costs, and streamline the implementation process. This approach also opens up opportunities to utilize shared resources like renewable energy sources, further increasing the efficiency of hydrogen infrastructure.

The challenge lies in facilitating effective communication and collaboration among diverse stakeholders, ensuring that all parties are aligned. Overcoming these barriers requires clear decision-making and a shared vision for the role of hydrogen in the energy transition. The following 'how might we' statement was generated to guide the concepts and design:

How might we leverage stakeholder collaboration to accelerate hydrogen infrastructure development

Concept Development

Chapter 5

Concept Development

5.1 Local Hydrogen Networks

Based on the analysis of the interviews, it can be said that local hydrogen networks can be an effective way of transitioning towards hydrogen for energy. What are regional hydrogen hubs? In this project, local hydrogen networks (LHN) are defined as a network of industries in an area connected to a hydrogen supplier with electrolysers. The suppliers also provide heat and oxygen, which are the byproducts of electrolysis, to companies that need them. Renewable energy farms like solar farms and wind farms in the region provide energy for the electrolysers. These hubs are tailor-made to the regional requirements based on factors like geography, demand, regulations and infrastructure. By coordinating regional resources and energy needs, these networks can optimise the use of hydrogen and renewable energy potential. Regional hubs have the added advantage that they can be rolled out gradually, which gives DSOs time to convert natural gas pipelines to hydrogen pipelines and build new ones based on the volume and network and scale it up as required. The establishment of these hubs can stimulate the local economy, attract investments, and create jobs in the operation and maintenance of infrastructure. Local governing bodies like municipalities can collaborate with other stakeholders to develop regulatory policies based on local needs and requirements. These networks can also be connected to the national hydrogen backbone (Hynetwork) instead of local electrolysers for the supply of hydrogen.

Analysis of the Midden database shows that there are a significant number of companies that are looking at hydrogen as an option for decarbonisation. Additionally, the database also shows companies that already use hydrogen(mostly grey) as feedstock for their processes. Information from databases like this can be used to solve the issue of suppliers not knowing who the off-takers are. Suppliers can form strategic partnerships with these companies to secure demand for hydrogen. The location data in the database can be used for creating regional hubs and developing local pipeline networks.

Figure 7 illustrates an example of this concept in action. In this simulated scenario, we look at the industrial area with a steel factory in IJmuiden. An electrolyser is set up near the steel factory. The primary off-taker of hydrogen produced by the electrolyser is the steel factory. The energy and water for the production of hydrogen come from nearby off-shore wind farms and the river respectively. To increase sources of revenue, the electrolyser also provides hydrogen to a local ferry terminal (for powering ferries and boats), a hydrogen refuelling station (for cars and trucks) and a district heating company that uses hydrogen to generate and supply heat to nearby neighbourhoods. The oxygen that is generated during electrolysis is supplied to a nearby hospital and an oxygen steel fabrication facility. Excess heat generated from electrolysis is used for domestic or district heating solutions. This example was inspired by the results of a workshop hosted by Hystream during the All Energy Day event in the Hague on 28th May 2024.

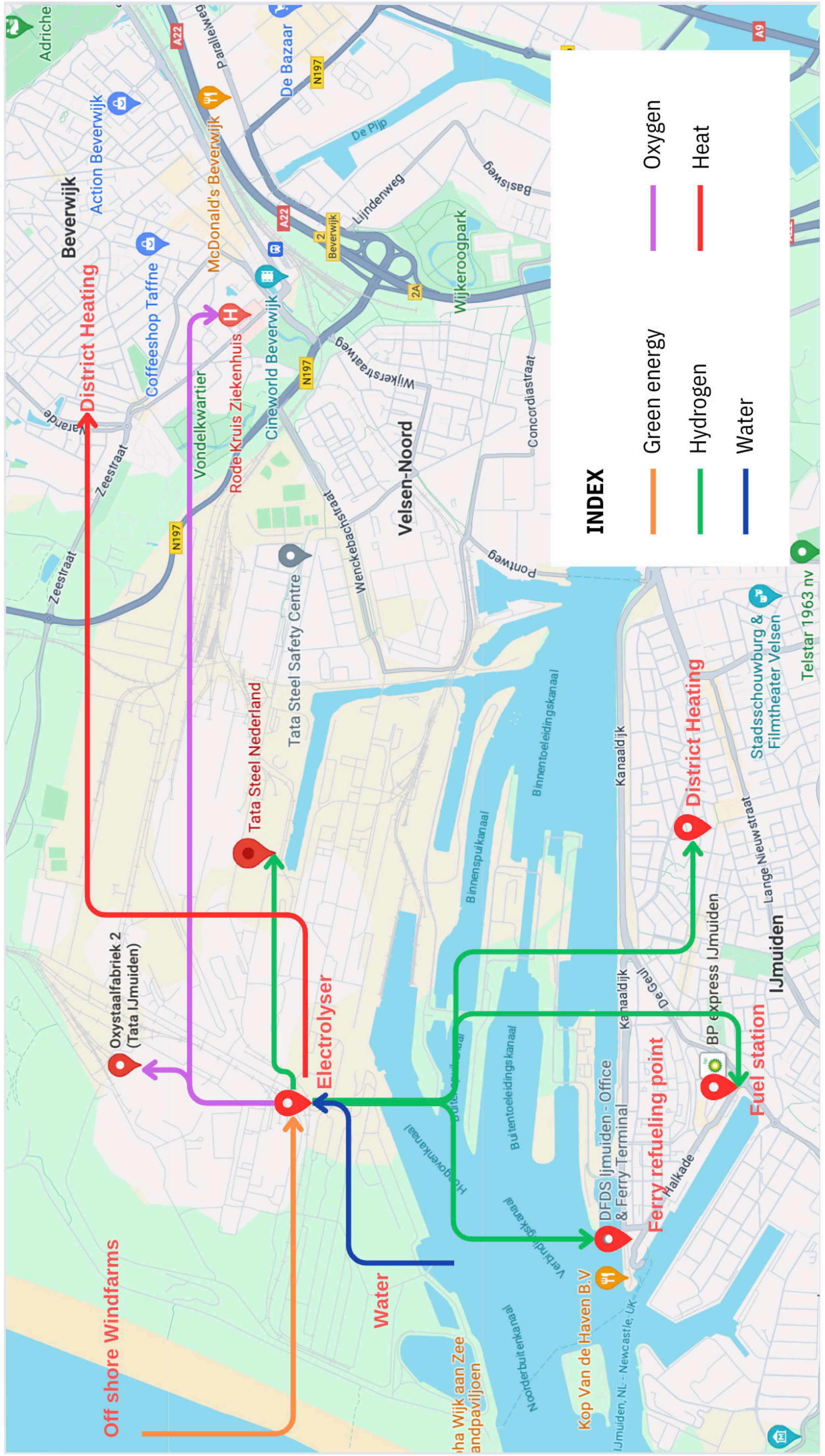


Figure 7: An example of a Local Hydrogen Network

The challenges faced while developing such networks revolve around identifying locations with companies that are suited for building these networks, forming strategic partnerships among them and developing the infrastructure needed to power the electrolyser and distribute its output. This concept can be implemented in a cost-effective way by using the techno-economic model (section 5.1.1) to identify key locations that are favourable to producing and distributing hydrogen at a cheaper cost.

Techno-economic model

The techno-economic model for hydrogen by Moran et al. (2023) is a flexible tool designed to evaluate hydrogen production, storage, and distribution costs within a region. It uses hourly data on renewable energy availability, electricity prices, and hydrogen demand to optimise electrolyser capacity and minimise costs. It helps identify the most cost-effective and sustainable hydrogen hub configurations by analysing various scenarios, accounting for different renewable energy sources, storage capacities, and economic parameters. Using this tool, stakeholders can develop better and more cost-efficient ways of producing and transporting hydrogen and its by-products. This tool can be used for the calculation of the ever-so-critical levelized cost of hydrogen while planning and building LHNs.

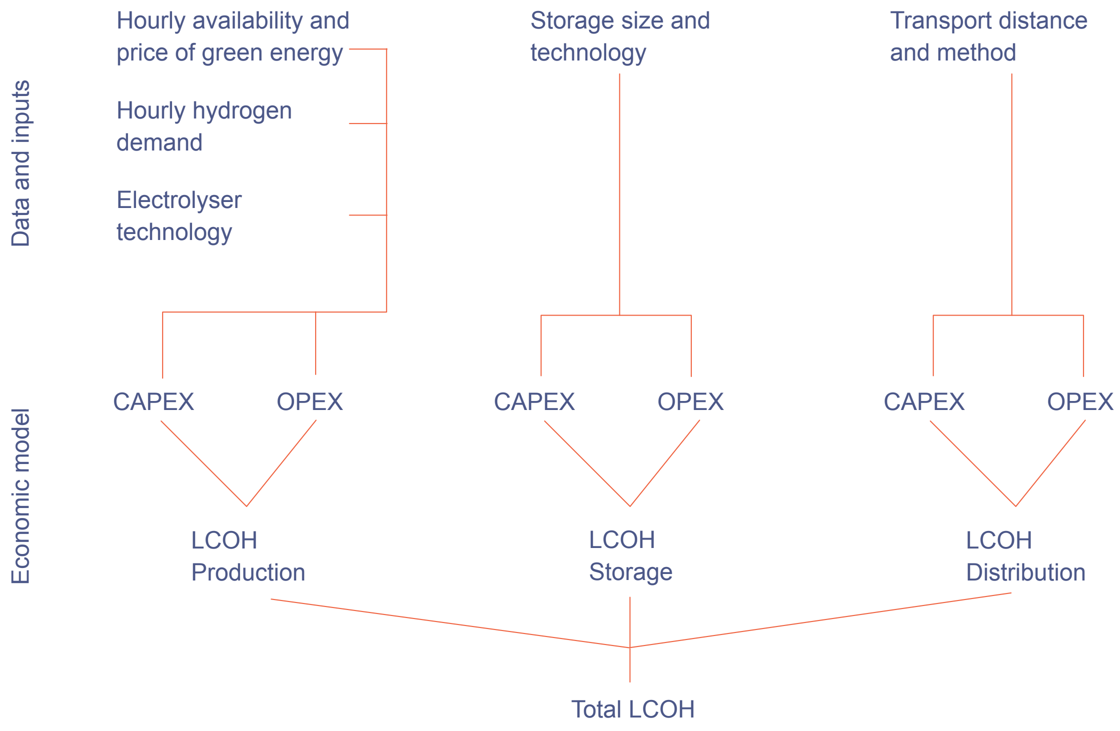


Figure 8: Techno-economic analysis tool flowchart for Levelized Cost of Hydrogen (LCOH) calculation

5.2 Facilitating decision-making and collaboration through data visualisation

Based on the concept of Local Hydrogen Networks (LHNs) that optimise the use of hydrogen and renewable energy through context and location-specific tailored infrastructure and strategic partnerships, the solution to enhance stakeholder collaboration and decision-making lies in effective data management and visualisation. Since LHNs rely on understanding regional industrial needs, industrial ecosystems, hydrogen infrastructure and energy resources, a comprehensive database (like the MIDDEN and IEA databases) can act as the base of this solution, providing important information on industry locations and hydrogen projects within a region. This data is essential for stakeholders to analyse and develop regional hydrogen networks effectively.

However, there are two challenges– 1) collecting all of the required data(this will be further discussed in section 5.5), and 2) making this extensive data easy to access, interpret, and interact with, particularly for stakeholders with varying levels of technical expertise. To address the second challenge, data visualisation is employed as a powerful tool to transform complex datasets into visual formats. Data visualisation is a useful tool as it amplifies cognition by providing visual representations that make complex data more accessible and interpretable. It excels in exploratory tasks, enabling users to discover patterns and insights from large datasets without specific questions in mind. By enhancing perceptual inference and extending memory and processing capabilities, data visualisation aids in recognising patterns and reducing cognitive load. It supports complex analyses by allowing for visual exploration, which can lead to new hypotheses and insights. Additionally, data and information visualisation plays a unique epistemological role by accelerating the filtering and selection of theories through visual perception (Fekete et al., 2008). Data visualisation helps in better comprehension and interaction of users with the data and aids stakeholders in understanding hidden patterns and making informed decisions by transforming raw data into graphical formats that can be easily interpreted by human perception (Andrienko & Andrienko, 1998). This method of using visualisations for planning and decision-making is also supported by Mintzberg & Westley (2001) who suggest taking a visual, ‘seeing first’ approach in decision-making strategies by using visual tools when many elements have to be combined into creative solutions and communication across different domains is essential. Visuals also make data more accessible to a non-technical audience, ensuring that all stakeholders, regardless of their data literacy, can understand the insights. EverVIEW (Romañach et al., 2014), a data visualisation tool for environmental and biological planning has served as an inspiration for the design of the solution. EverVIEW has been successfully used in planning restoration activities in the Everglades and coastal planning in Louisiana, demonstrating the effectiveness of data visualisation in environmental and spatial planning projects.

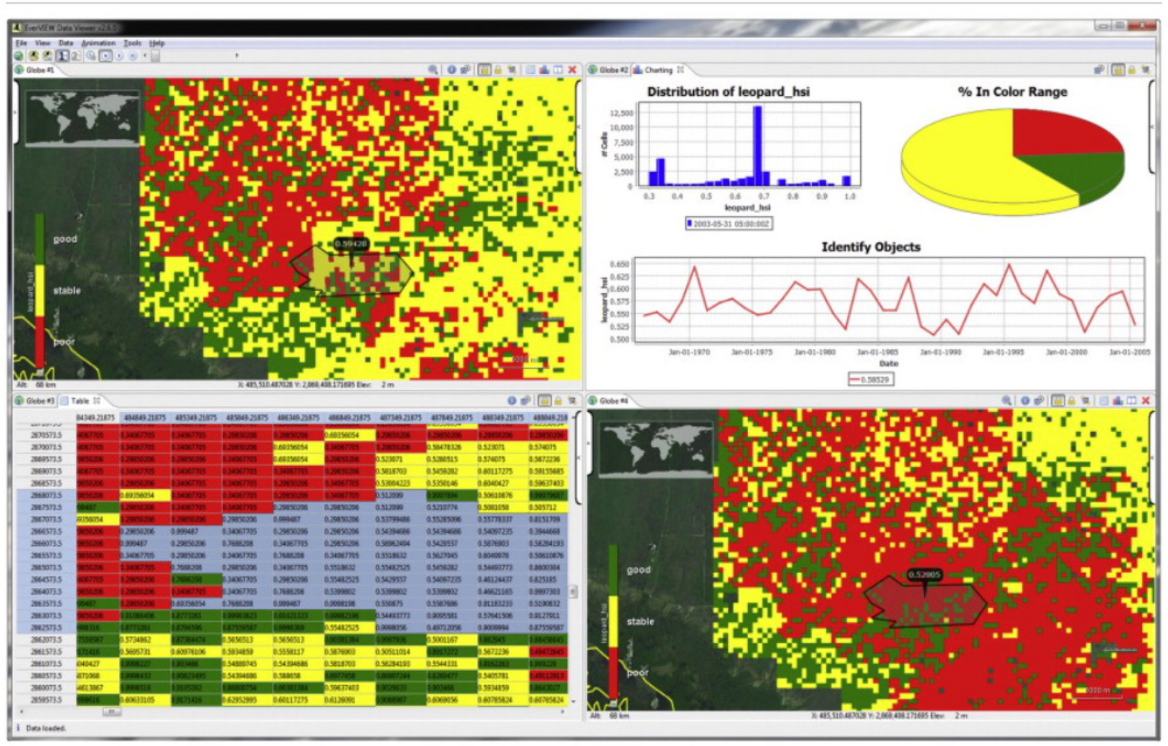


Figure 9: EverVIEW is a versatile data visualisation platform that displays the same dataset across four different visual sections, each offering a different perspective. This multi-visual approach allows users to explore various aspects of the data, making it a powerful tool for analysis.

5.3 Design Requirements

The desired solution should incorporate the following key requirements. These requirements are based on the results of the study –

1. Help stakeholders find industries that are potential off-takers of hydrogen or by-products of electrolysis. During the qualitative study it was noted that experts would comment on the lack of information on off-takers, this design requirement aims to address it. Additionally, it also aims to help decision-makers find off-takers of by-products of electrolysis.

2. Stakeholders with different domain expertise should be able to use it without much training. Making it easy to use will help more stakeholders adopt the solution, regardless of their domain expertise, thereby increasing collaboration and cross-pollination of ideas.

3. Provide a macro overview while having the ability to communicate more detailed information. Enhance understanding of the needs and requirements related to hydrogen infrastructure development, and increase collaboration between stakeholders.

5.4 User Task Identification

The users, in this case, would be stakeholders who are involved in the development of new hydrogen infrastructure. DSOs are expected to be among the primary users, as they would want to conduct feasibility studies of using existing natural gas pipelines for hydrogen or conduct an investigation if they need to build new ones. Infrastructure planners are another group of primary users as they would need information on the location of suppliers and off-takers, the volume of production and demand and availability of renewable energy. The users perform a set of analyses to achieve their goals. These analyses can be abstracted into tasks. In the context of data analysis, tasks refer to the specific questions or objectives that an analyst seeks to answer or achieve through the exploration of data (Andrienko & Andrienko, 1998). Tasks guide the process of data analysis by providing clear goals and can range from simple lookups to complex pattern discovery. Tasks are essential in defining what an analyst aims to accomplish, such as identifying trends, comparing data points, or discovering relationships between variables. The authors divided tasks into elementary and synoptic tasks. Elementary tasks involve basic operations like looking up values or making simple comparisons. Examples include finding a stock's value on a specific date or comparing population sizes between years. Synoptic tasks, on the other hand, deal with understanding the dataset as a whole or significant subsets. They include identifying patterns, summarising data, and making broader comparisons. Synoptic tasks are often more complex and provide a higher level of abstraction. Tools are the instruments or software used to perform the tasks defined in data analysis. Visualisation tools help in representing data visually to uncover patterns and relationships. Examples include graphing software, GIS for mapping spatial data, and dashboards for interactive data exploration. Task abstraction is the process of generalising specific data analysis questions or tasks into more abstract, generalised forms. This process helps in identifying the essential components and structures of tasks that can be applied across different datasets and contexts. This method was used to identify appropriate visualisation tools and methods to perform the given analysis.

The following tasks were identified as essential for the stakeholders to work on local hydrogen networks, they include both elementary and synoptic tasks -

1. Find off-takers of hydrogen (search and explore)

2. Identify and analyse spatial patterns and distributions of industries in a region

3. Manage and allocate energy and infrastructure resources effectively

4. Determine optimal routes for pipelines

5. Find and analyse patterns involving off-takers and suppliers

6. Determine optimal locations for storage solutions

7. Present and communicate findings with other stakeholders

5.5 Cartographic tools

Based on the design parameters and task analysis, cartographic tools are being used as the tool for data analysis and communication. Salichtchev's (1982) work suggests cartographic tools and cartographic research methods, use maps for scientific description, analysis, and comprehension of phenomena (as cited in Andrienko & Andrienko, 1998). The essence of these methods is that one explores maps as models of reality instead of exploring reality itself Maps are highly effective for visualising data with spatial components, particularly for exploring geographical distributions and understanding spatial relationships and patterns. They allow users to perceive spatial relationships, such as distances and sizes. Maps also handle heterogeneous data well, reflecting variations between regions. They support visual analysis by representing spatial relations in a perceivable form, aiding in insight generation. Additionally, maps facilitate the comparison of multiple attributes, linking data points for a comprehensive view. When comparing multiple attributes, maps can visually link different data points and provide a coherent image of the data distribution. This visual association facilitates the perception of the distribution as a whole, which is essential for synoptic tasks. Cartographic tools require data on location and maps. The location data of producers, infrastructure and potential off-takers in the Netherlands is obtained using MIDDEN and IEA databases. Open-source mapping and GIS software Google Maps and Kepler.gl (developed by Uber) are being used in this project.

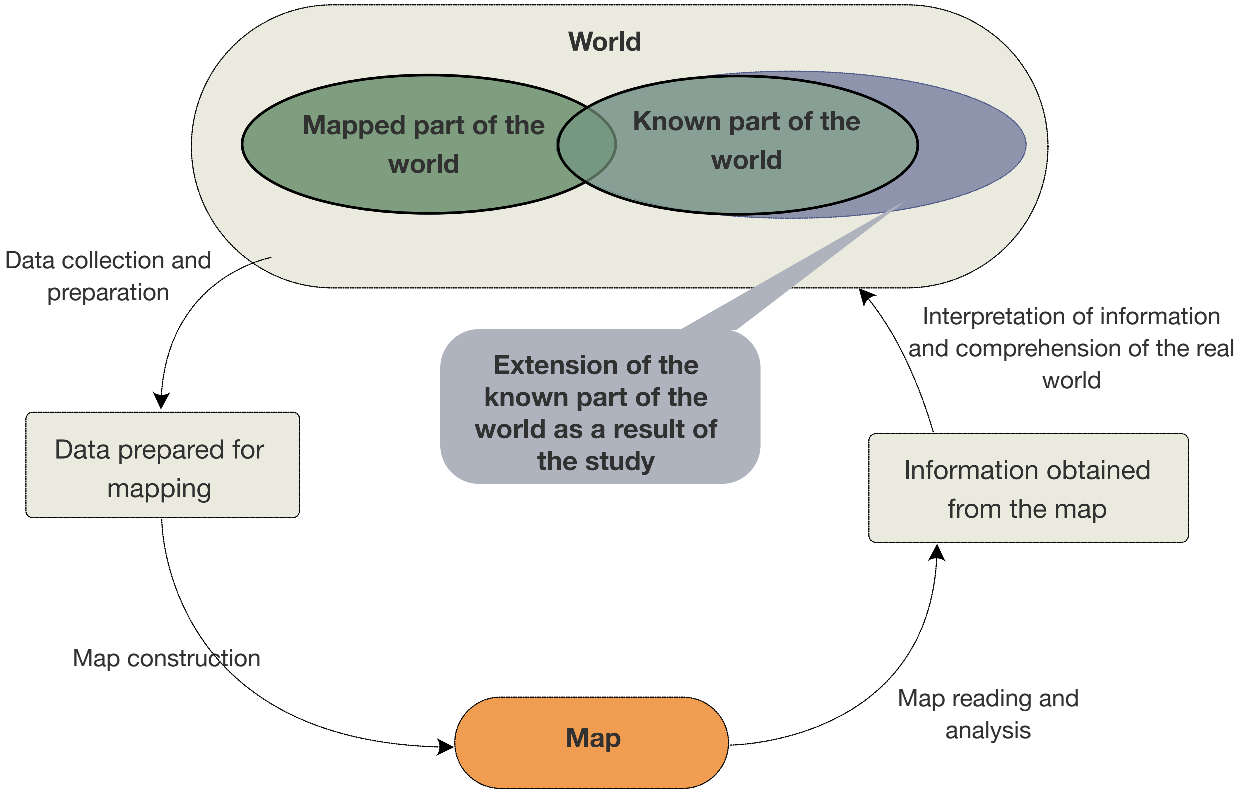


*Figure 10: Schematic representation of cartographic research method (*Andrienko & Andrienko, 1998*)*

The following types of maps are being used in the solution –

A. Dot distribution map

A dot distribution map, also known as a dot density map or simply a dot map, is a map that uses point symbols to visualise the geographic distribution of related phenomena. These maps rely on a visual scatter to show spatial patterns, particularly variations in density. A dot distribution map helps identify spatial patterns and distributions of industries. It also helps in searching for industries in a region. A dot distribution map of producers and off-takers in the Netherlands was created using location data from the MIDDEN database. It is further divided into multiple layers – industries producing hydrogen, industries using hydrogen, industries interested in using hydrogen, industries seeking replacement for natural gas. This map is complemented with another dot distribution map showing all the new hydrogen related projects being developed in the country (IEA data). The map is hosted on google maps, making the interface familiar and easy to work with. When the user selects a dot, they reveal more information on the industry, giving a richer description to the user. The search bar allows users to search for specific areas or industries of interest. Since this map is hosted on google maps, the map data from google maps can also be found through the search bar. The interaction features of zoom and pan solve the issue of resolution of data display.

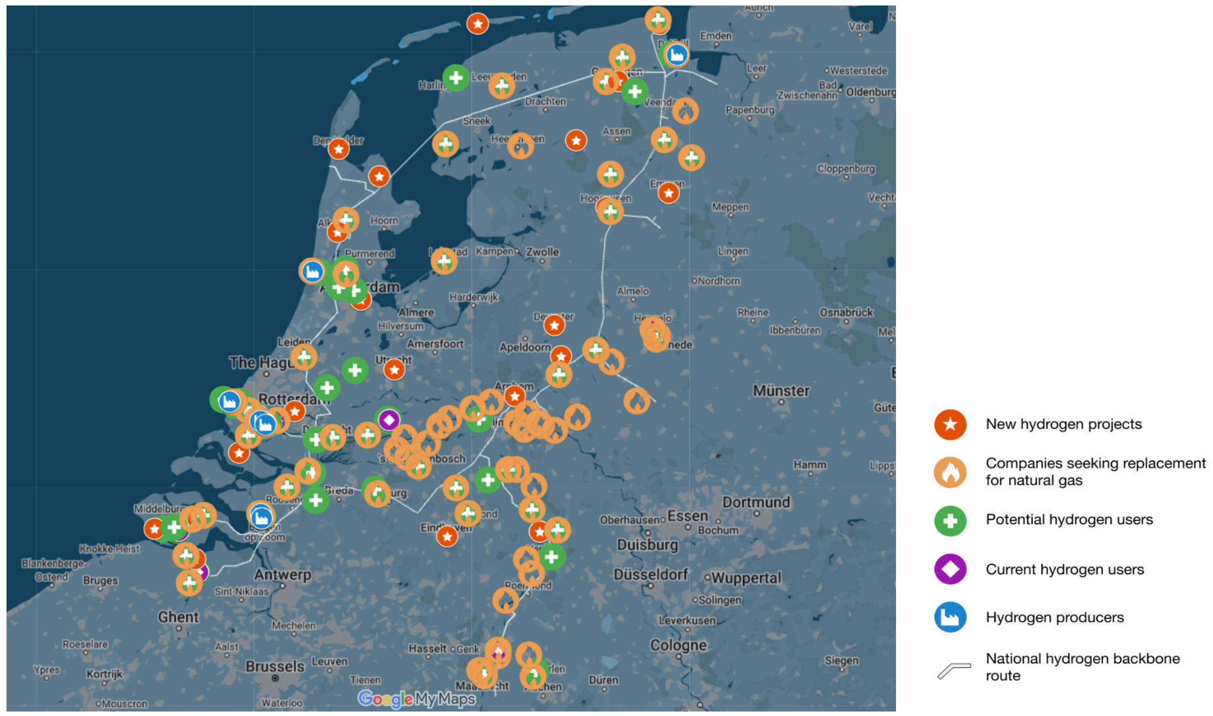


Figure 11: Dot distribution map with legend

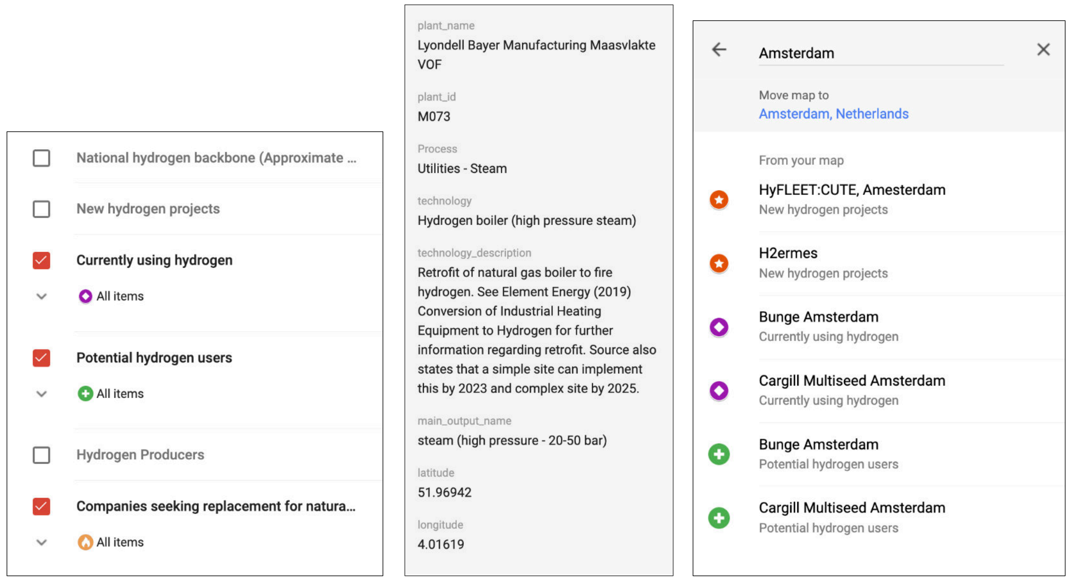


Figure 12: The image on the left illustrates how users can toggle between different information layers on the map. The central image shows the detailed information that appears when a user selects a dot for more details. The image on the right illustrates the search feature.

B. Choropleth map

A choropleth map is a type of map where areas are shaded or patterned in proportion to the value of a variable being represented. This type of map is particularly useful for visualising how a measurement varies across a geographic area or for illustrating the level

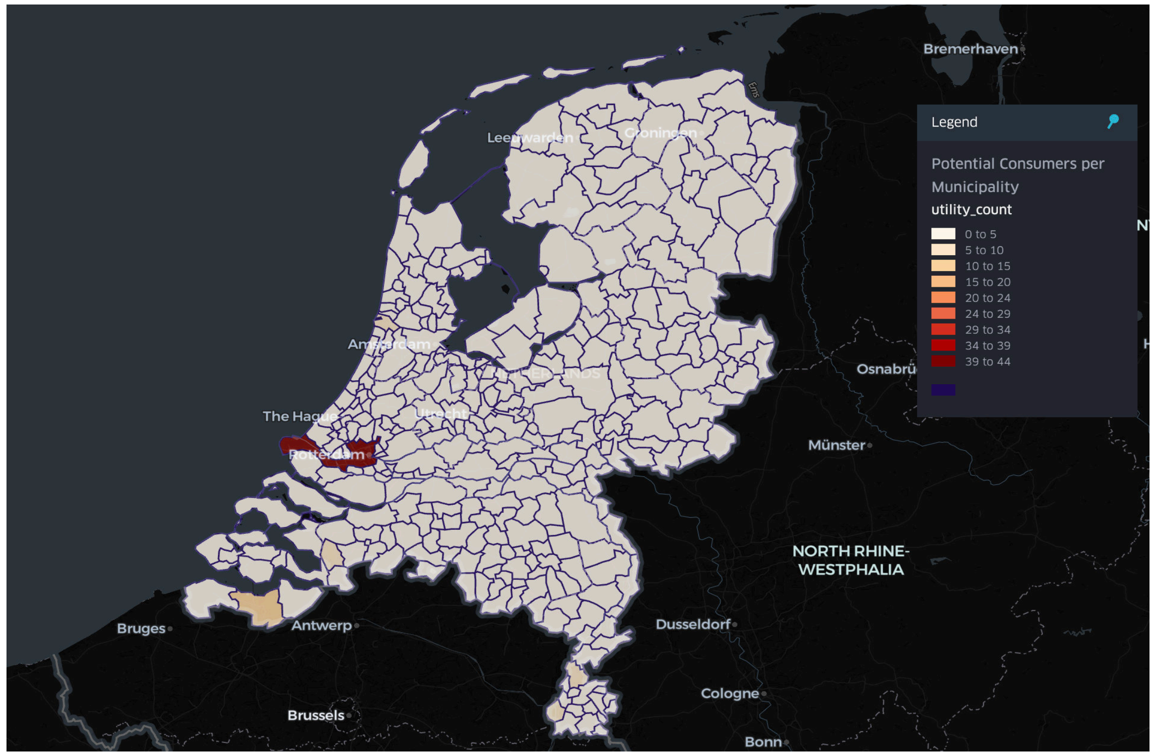


Figure 13: A choropleth map showing number of potential hydrogen off-takers per municipality in the Netherlands

of variability within a region. This type of map is an effective tool for analysts and decision-makers who need to understand spatial patterns and trends within their data. A choropleth map comparing the number of off-takers in different municipalities was created to understand the needs and requirements on a municipal level. This map is mainly aimed at decision-makers in government and municipal bodies. The colours used in this visualisation have been chosen to ensure accessibility for people with colour blindness. The same palette is used for all other maps except the dot map.

C. Heatmap

A heat map is a data visualisation method that uses colour gradients to depict the magnitude of data values within a matrix or spatial area. In this heat map, regions are colour-coded based on the density of industries within them, highlighting areas with high potential for hydrogen use. This visualisation provides a quick, intuitive overview of regions that are prime candidates for further development and investment in hydrogen infrastructure.

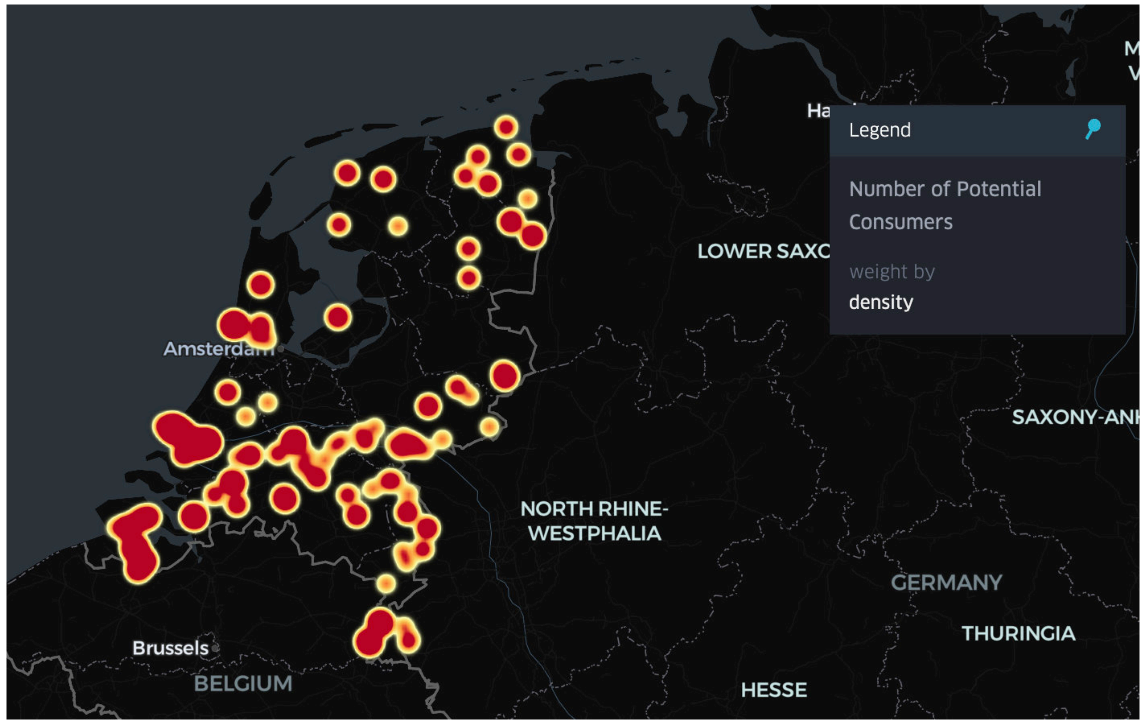
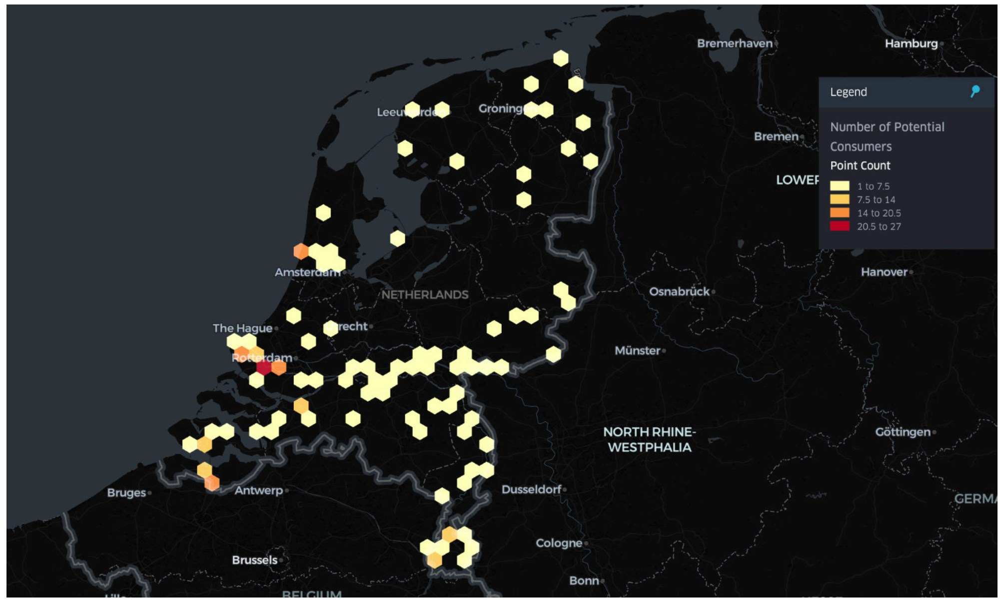


Figure 14: A heatmap showing density of potential hydrogen off-takers in the Netherlands

D. Grid Maps

Grid maps were created to visualise the density of industries requiring hydrogen in a specific region. Unlike choropleth maps, which can introduce perception bias due to varying polygon sizes, grid maps represent each region equally using bins. Two types of grid maps are employed here: square and hexagonal. Both display industry density within a unit area, but the hexagonal grid is particularly advantageous for calculating distances, as each cell has six equidistant neighbours, minimising distortions and providing a more accurate representation of the globe (Birch et al., 2007). On the other hand, the square grid is beneficial for planning purposes, as satellite images can be easily converted into square cells, making analysis straightforward and efficient. These two grid maps cater to different needs and use cases, ensuring flexibility in analysis and planning.



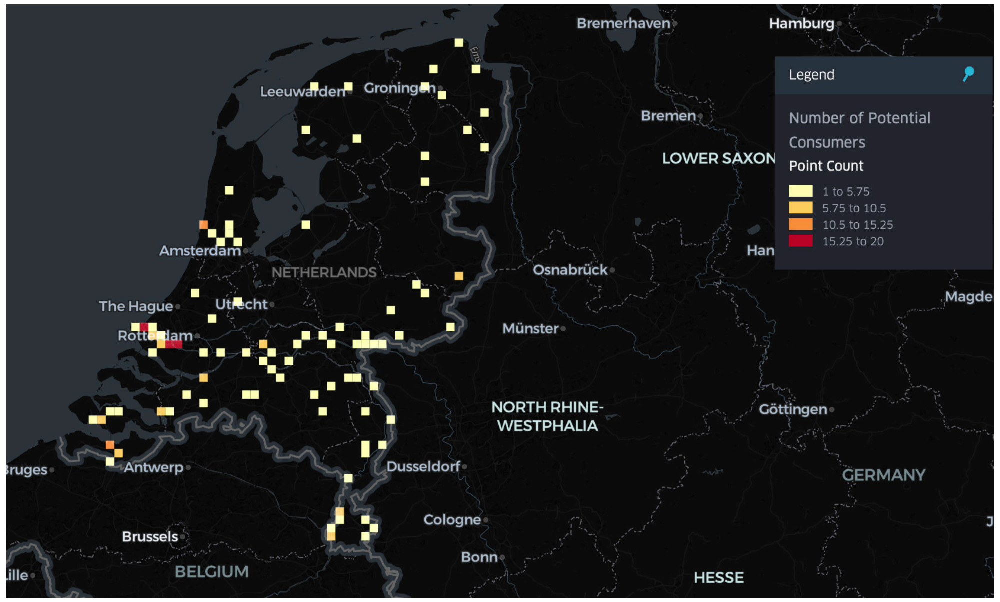


Figure 15: The map on top is a hexbin grid map with radius of hexagon of 5km. The map on the bottom is a square grid map with each square having the size of 5km. Both the maps show the number of potential hydrogen off-takers per unit area.

5.6 HySynth

HySynth is an online digital platform designed to use data visualisation tools to help stakeholders comprehend trends in the Dutch hydrogen ecosystem. The primary aim is to simplify complex data for users, regardless of their expertise. By leveraging visualisations, the tool assists stakeholders in understanding hydrogen consumption and production trends, fostering collaboration in building new infrastructure, creating supply and demand partnerships, and establishing local networks for hydrogen, heat, and oxygen trade.

Developed for EBN Netherlands, a state-owned company traditionally involved in natural gas and oil but now focused on sustainable energy sources like geothermal energy, carbon capture, and hydrogen, HySynth supports EBN's mission to accelerate the energy transition and achieve a carbon-neutral energy system in the country by 2050. Incorporating HySynth into EBN's services will have a positive impact on their green heating and hydrogen storage projects. The platform can be expanded to include carbon capture and green gas technologies, by using EBN's extensive knowledge base.

HySynth offers various uses: suppliers can find clients in specific regions, Distribution System Operators (DSOs) can develop transmission infrastructure, off-takers can locate suppliers and other off-takers, companies like HyStream can utilise it for business development, and government agencies can adopt a more region-focused approach to hydrogen development. A key component of the platform is the data collection page. Here, industries can input details regarding their feedstock requirements and their outputs. This information is then incorporated into the database used for creating visualisations, thereby expanding the data available to users. This feature invites industries to become collaborators in this initiative and move towards decarbonisation.

The prototype of HySynth can be found on **www.yallaling.design/h2**

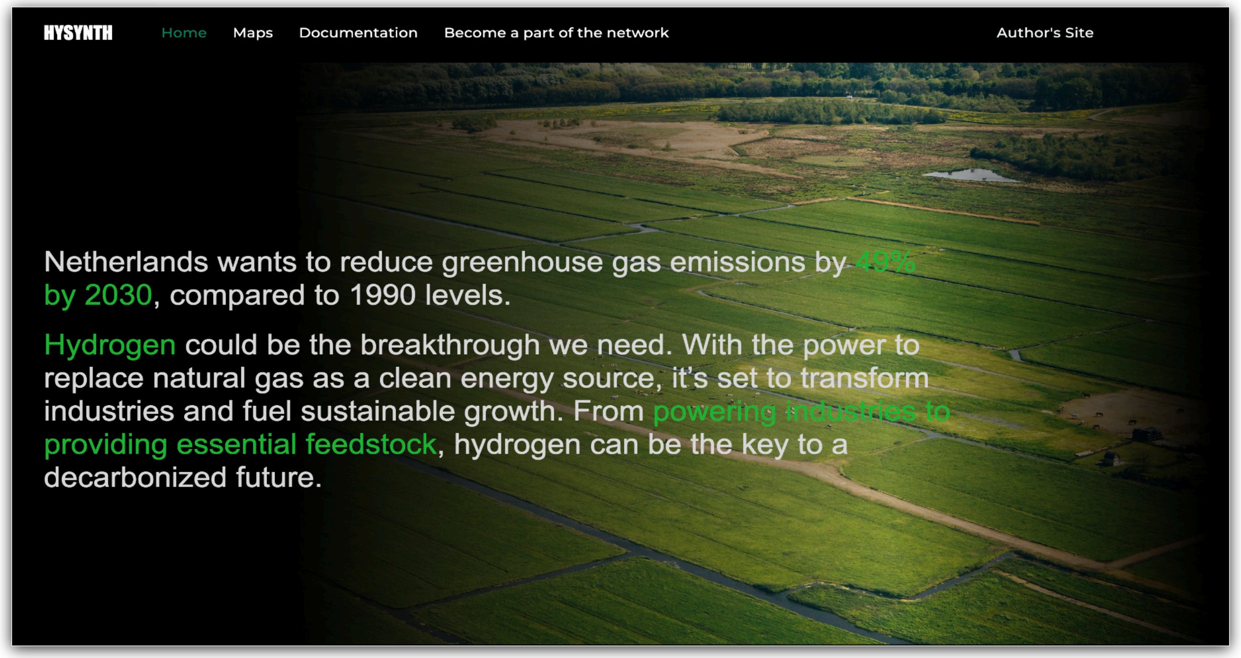
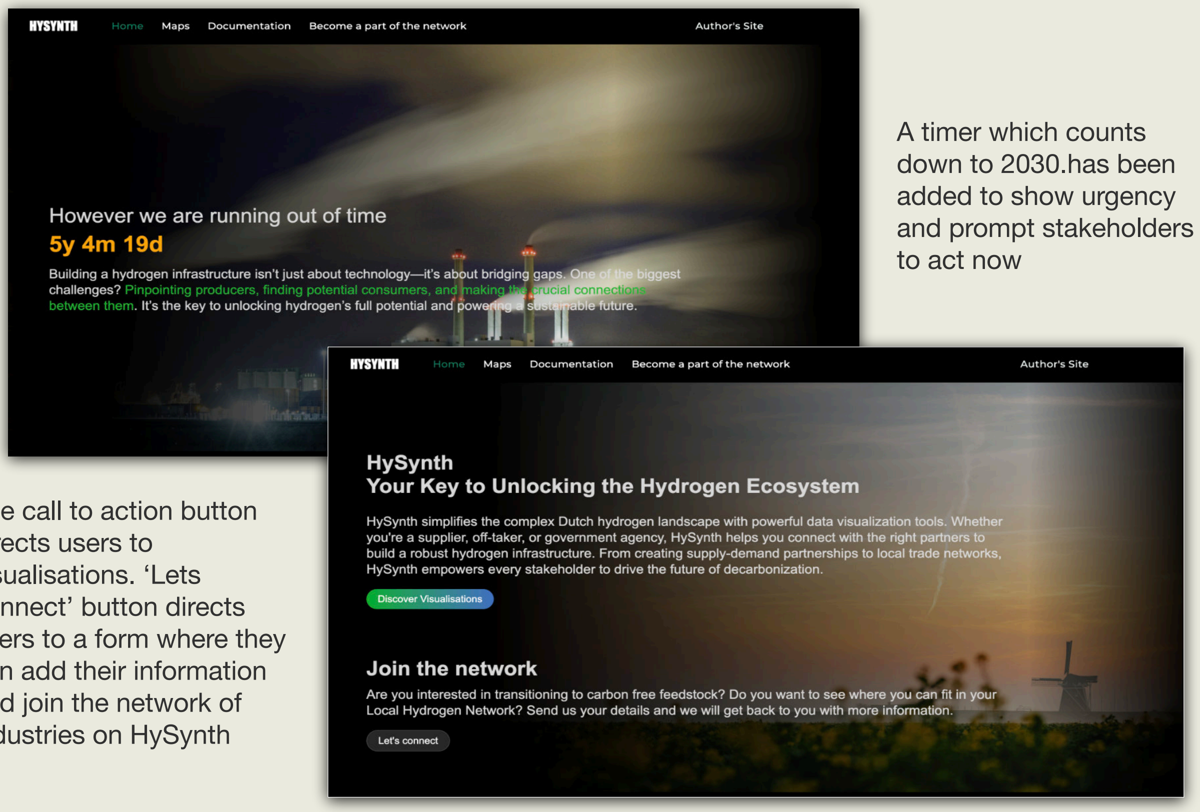


Figure 16: Landing page of HySynth.



A timer which counts down to 2030.has been added to show urgency and prompt stakeholders to act now

The call to action button directs users to visualisations. 'Lets connect' button directs users to a form where they can add their information and join the network of industries on HySynth

Figure 17: More information and call to action on the landing page

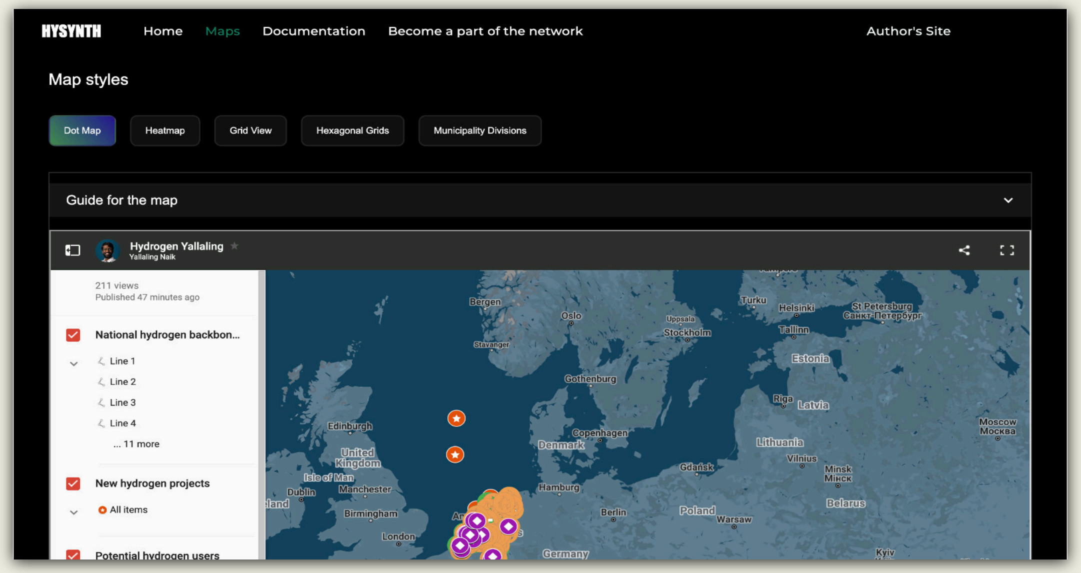
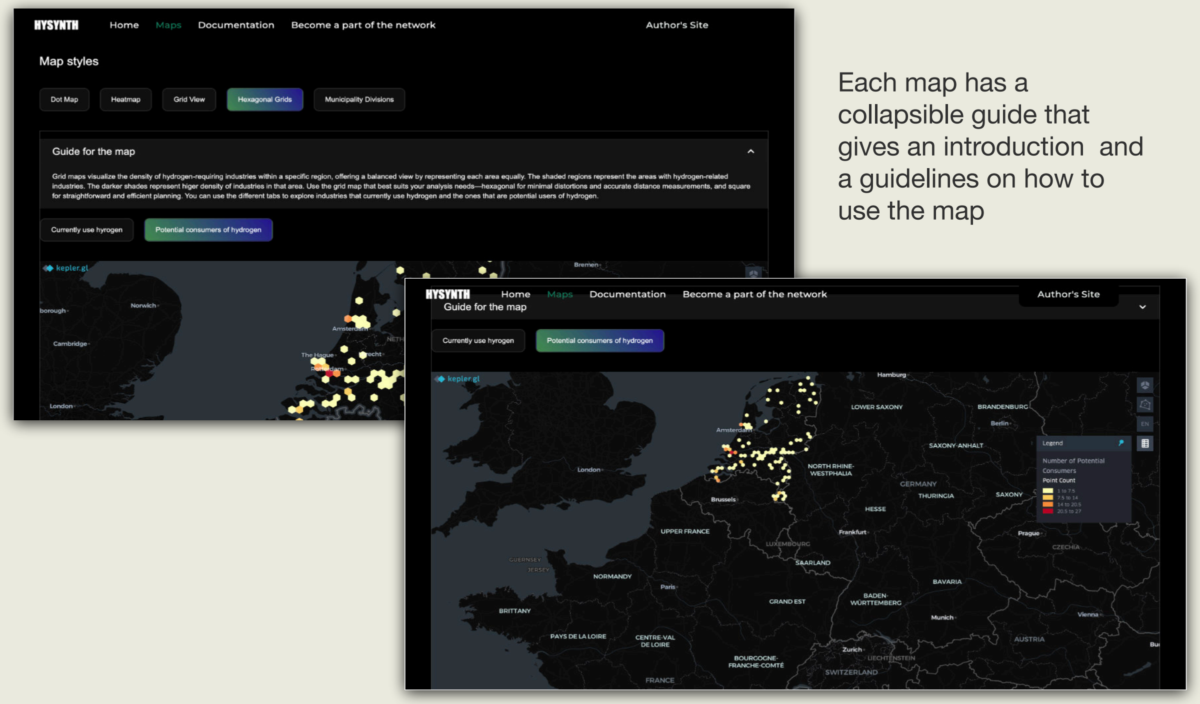


Figure 18: Maps Page with different types of maps. In this tab the user can interact with the dot distribution map that is embedded in the website



Each map has a collapsible guide that gives an introduction and a guidelines on how to use the map

Figure 19: Different maps that users can interact with on the website

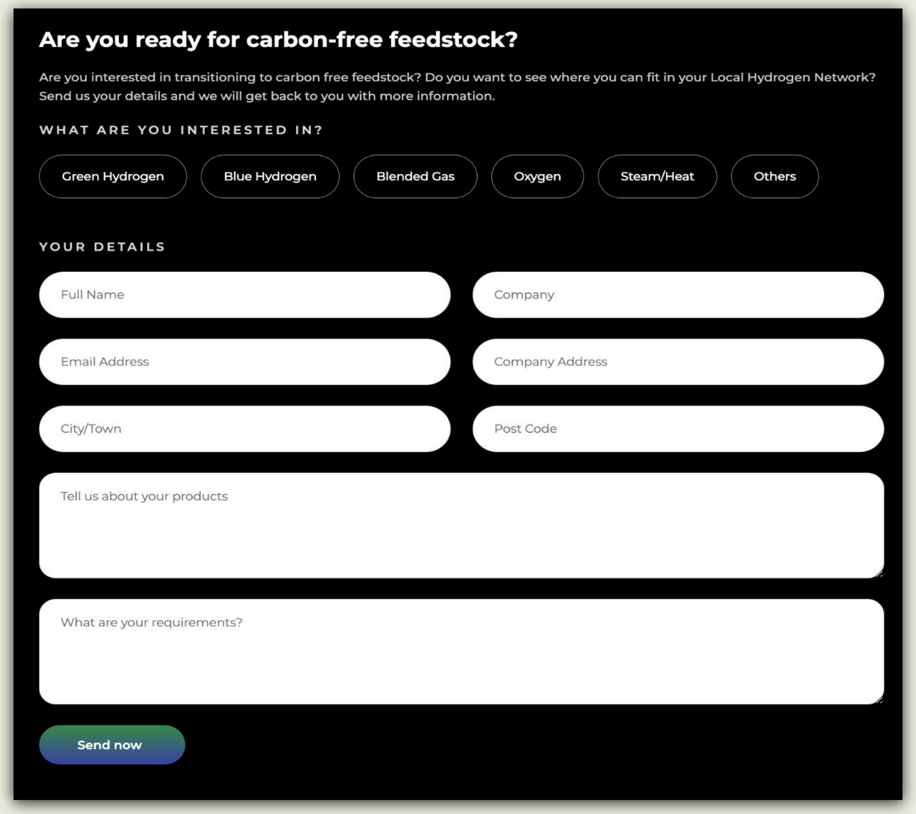


Figure 20: This form allows users to share the information about their industrial requirements. This information will be verified and processed and added to the database and displayed on the map

5.7 Testing and evaluation

The testing involved four participants (P1, P4, P7, P8) selected from the original interview group. These participants were specifically chosen for their active roles in planning and developing new hydrogen infrastructure. The testing session involved introducing the tool to the participants and letting them interact with the visualisations and analyse them. This was followed by a discussion about the visualisations. The participants found the dot distribution map to be informative and insightful as it gave them information on off-takers in the Netherlands at a glance. They agreed that this would help in performing matchmaking between different industries to create combined supply and demand. They also noted that this map showcases the sixth cluster of industries in the Netherlands. One participant suggested that this map can also help in identifying locations for blue hydrogen production. The dot distribution map also highlights different regions that are not connected by the national hydrogen backbone but have potential hydrogen off-takers. The participants also suggested that this concept can help stakeholders in localising the balance between supply and demand, and identify storage solutions needed for different regions.

Since the heatmap is based on the density of industries, it resembles the different industrial clusters in the country. The major feedback on this concept was to create a heatmap based on the volume of hydrogen consumed in a region, instead of the number of off-takers, as this would give the stakeholders more information on the balance of hydrogen. The choropleth map based on municipalities was criticised, with P4 calling it ‘pretty random’. The huge discrepancy between the size of municipalities, the number of industries in a municipality and a lack of correlation between them were pointed out as major drawbacks. The grid visualisation concept was received more positively, as it gave a better and more precise indication of the density of industries in an area and allowed users to focus on specific places.

The participants suggested adding the following data points and features -

1. Locations of blue hydrogen producers and suppliers
2. Visualising the flow of hydrogen - which producers are supplying to which consumers.
3. Adding layers to differentiate the different forms of hydrogen or its derivatives (liquid hydrogen, ammonia) being supplied and consumed in the region.
4. Adding district heating providers as potential off-takers
5. Adding locations of hydrogen fuel stations for automobiles

Discussion

Chapter 6

Discussion

The academic relevance of this thesis lies in the answering of the question What are the main challenges industries in the Netherlands face in transitioning to renewable hydrogen? The results of this research provide a comprehensive understanding of the current landscape and challenges faced by industries in the Netherlands in transitioning to renewable hydrogen. The key contributions to academic literature are identifying key barriers, such as the 'chicken and egg' problem, high costs, and infrastructure limitations, that hinder the adoption of green hydrogen as a sustainable energy vector. Insights from the thematic analysis offer a foundation for future research on strategic partnerships and stakeholder collaboration in the energy sector, particularly in the context of hydrogen infrastructure development.. This research highlights the importance of localised hydrogen networks (LHNs) and the role of regional hubs in overcoming these challenges, thus contributing to the broader discourse on decentralised energy systems and the transition to renewable energy. The study also explored how data visualisation can be a tool for increasing collaboration between different stakeholders in the system.

The practical implications of this research are significant for policymakers, industry stakeholders, and energy companies. The findings highlight the need for early-stage collaboration between hydrogen suppliers and off-takers to mitigate risks and build a secure supply chain. The study suggests that strategic partnerships and regional collaboration can accelerate the development of hydrogen infrastructure by aligning the interests of different stakeholders. Data analysis highlighted the need to include industries outside the five main industrial clusters in infrastructure planning, as they constitute a significant portion of the Dutch industrial ecosystem. These industries could become a major consumer of hydrogen when they transition from natural gas. The research also emphasises the importance of developing infrastructure to off-take oxygen and heat generated from electrolysers to mitigate financial risk by diversifying income sources. This also supports the growth of the hydrogen market. Policymakers can use these insights to create supportive regulations and financial incentives that encourage investment in hydrogen projects, while other stakeholders can explore opportunities for collaboration and infrastructure development based on the regional needs. HySynth can serve as a foundation for stakeholders to gain a deeper understanding of the hydrogen landscape and explore various opportunities for collaboration.

6.1 Limitations

This research primarily concentrates on green hydrogen. However, throughout the thesis, blue hydrogen has been identified as a transitional step towards green hydrogen. Therefore, a similar study on blue hydrogen will also be necessary. This project is centred on infrastructural development. However, it has become evident that social acceptance, policies, and regulatory frameworks significantly influence the adoption of hydrogen. These aspects require further study to fully understand their impact.

The qualitative research interviews engaged solely with domain experts. To gain deeper insights, a study involving other stakeholders from industries, including producers and off-takers, is recommended. MIDDEN database was last updated in 2021, hence, the data used might be outdated.

The current maps do not accurately display the location of the Hynetwork pipeline and also do not have the locations of renewable energy producers. Including these details would provide more comprehensive information to stakeholders.

In this project, Hydrogen is viewed as a crucial part of the decarbonisation strategy, but decarbonisation should involve a multi-pronged approach, combining various resources and methods. This more holistic method increases the likelihood of significant and long-lasting positive impact on the environment and enhances the resilience of our energy infrastructure.

6.2 Recommendations for Future Work

Given the project's limitations, the following recommendations are proposed as a foundation for enhancing the solution and developing it into a more comprehensive collaboration and data visualisation platform.

Since the production of green hydrogen needs renewable energy, mapping the locations of renewable energy producers and adding it to HySynth will add more value for the decision-makers. It will also be valuable to map out oxygen and heat requirements as these are essential to create LHNs.

There is also great scope in adding currently existing natural gas pipelines in the visualisations as they can be reused for hydrogen. Or they can serve as a guidelines to lay new hydrogen pipelines along them. This might also help in visualising connections between suppliers and off-takers.

This project has primarily concentrated on the industrial applications of hydrogen. However, hydrogen also holds potential benefits for domestic heating, particularly with district heating systems in cities like Utrecht. Since domestic heating is a significant consumer of natural gas, transitioning to hydrogen-based heating or integrating hydrogen into district heating could have a significant impact on emissions.

There is also great scope in visualising CO2 emissions, as this might help in the development of carbon capture infrastructure and its integration with the national climate policy. This might also help in developing infrastructure for blue hydrogen.

Ultimately, once green hydrogen is being utilised on a large scale, visualising the local hydrogen balance—including production and consumption—and real-time hydrogen flow can significantly aid in further development and enhancing the supply chain of green hydrogen.

Conclusion

Chapter 7

Conclusion

7.1 Conclusion

The Netherlands' commitment to achieving net-zero carbon emissions by 2050 is a formidable challenge, with hydrogen poised to play a crucial role in this transition. This research analysed the Dutch hydrogen ecosystem, focusing on the hurdles and opportunities in adopting renewable hydrogen. Despite the significant potential, the high costs of green hydrogen production, financial risks, and inadequate infrastructure present substantial barriers.

The study's findings indicate that stakeholders are cautious about investing in hydrogen due to the lack of a guaranteed market and high initial costs. However, creating local hydrogen networks, clustering demand, and fostering strategic partnerships among stakeholders could reduce these risks and facilitate the transition. The interactive online tool developed as part of this research enables stakeholders to locate potential off-takers and optimise hydrogen usage, thereby enhancing collaboration and informed decision-making.

Several key insights emerged from the research. Firstly, there is a pressing need for financial and regulatory support to make green hydrogen economically viable. The government and regulatory bodies can play a pivotal role by providing subsidies, ensuring stable pricing, and acting as intermediaries between suppliers and off-takers. Secondly, leveraging existing natural gas infrastructure for hydrogen transport can significantly reduce transition costs. Thirdly, international collaboration, especially with countries rich in renewable energy resources, is vital for securing a stable supply of green hydrogen.

The study also highlights the importance of diversifying hydrogen production sources and improving technological advancements to bring down costs. Effective stakeholder communication and education about the benefits and logistics of hydrogen adoption are essential to drive interest and investment.

In conclusion, while the path to a hydrogen economy in the Netherlands is riddled with challenges, strategic interventions, robust policy frameworks, and collaborative efforts can pave the way for a sustainable and economically viable hydrogen ecosystem.

7.2 Personal Reflection

Before starting my thesis, I knew it would be a challenging and interesting journey, but I was pleasantly surprised by just how captivating the project became. Initially, my main goal was simple - dive deeper into the energy sector and understand how hydrogen can aid the shift toward clean energy. However, as I progressed, I encountered numerous problems and challenges that pushed me to learn new things constantly and kept me on my toes.

I gained a lot of knowledge in areas like data visualisation, cartography, and energy networks. I also discovered how various, seemingly unrelated factors can intersect and impact the financial aspects of infrastructure projects. The challenge of integrating insights from both qualitative studies and data analysis improved my ability to observe small details and read between the lines. The most significant challenge came when I hit a roadblock during the conceptualisation stage and didn't know how to proceed. I realised that the only way forward was to trust the process and not overthink. Slowly but surely, the process guided me to the right path. Approaching the energy domain as an outsider was challenging, but it also gave me a unique perspective to understand the entire system from a design standpoint. This allowed me to explore beyond the obvious and venture into uncharted territories. While this exploration often led to dead ends, the final outcome was well worth the effort.

Throughout the project, my role evolved from researcher to data analyst to designer and even web developer. This pushed me out of my comfort zone and created an environment for personal and professional growth. I am incredibly fortunate to have had the support of a wonderful supervisory team. Senthil and Mahshid were invaluable guides, each offering expertise in different areas, which constantly expanded my knowledge and perspective. Their support and encouragement were crucial to the success of this project.

Interacting with stakeholders during interviews and field visits opened my eyes to the broader context of the renewable energy push. I learned how seemingly "boring" industries can have a significant impact on climate change. I also had the chance to visit renewable energy-producing facilities like solar farms and wind parks and explore different parts of the Netherlands, which I might not have done otherwise. The biggest lesson I've taken from the past few months is that no problem exists in isolation—everything is connected in some way. But you can't solve everything at once, so it's important to focus on a smaller area. I feel this project has significantly enhanced my skills and understanding in the field of energy transition.

This process has been complex, yet incredibly rewarding. Facing setbacks and continuously improving were key parts of this iterative journey. This project allowed me to step outside my comfort zone and embrace the uncertainty that came with it. I'm excited to apply what I've learned in future projects within the energy sector.

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Appendix

Appendix A: Interview Guide

1. Brief introduction about what they do. How are you associated with hydrogen projects ?
2. Can you provide an overview of the current state of the hydrogen network in the Netherlands, particularly in terms of production capacity and distribution infrastructure?
3. What are the main sources of green hydrogen production in the Netherlands, and how have they evolved in recent years?
4. 3Could you explain the key drivers behind the growing interest in green hydrogen as an energy carrier in the Netherlands?
5. What are the main challenges or barriers to the widespread adoption of green hydrogen in the Netherlands, and how are they being addressed?
6. How does the Netherlands compare to other countries in terms of its efforts to develop a hydrogen economy?
7. What role do government policies and regulations play in supporting the development of the hydrogen sector in the Netherlands?
8. Are there any notable projects or initiatives related to green hydrogen that are currently underway or planned in the Netherlands?
9. How do you see the future of the hydrogen industry evolving in the Netherlands, particularly in terms of scale, technology, and market penetration?
10. What opportunities do you see for collaboration between different stakeholders, such as government agencies, industry players, and research institutions, to accelerate the growth of the hydrogen sector?
11. Finally, what advice would you give to policymakers, investors, and other stakeholders who are interested in contributing to the advancement of the hydrogen economy in the Netherlands?
12.

Appendix B : Examples of codes and quotes

Themes	Sub-themes	Codes	Quotes
Landscape of green hydrogen investment & infrastructure in the country	Infrastructural challenges – the 'chicken and egg' problem	Challenge for maritime sector in adopting hydrogen	'…they don't want to start investing without a commitment that the infrastructure will be there because otherwise, you will have a hydrogen or methanol Vessel ready, but nowhere to bunker or get fuel from.'- P2
		Lack of information about future demand	'Currently, there is no incentive to do so… people have been talking a lot about building electrolyzers, but they're not building them because they're not sure whether there's going to be any demand.'- P1
	High cost of green hydrogen	Uncertainty in price of green hydrogen	'But what is the price of hydrogen? Nobody knows. And so if the pricing is right, hydrogen will fly. But if the pricing is not right for the industry, the industry has to look for another solution to get cheap energy.' -P6
		Production of green hydrogen is expensive	'That new factory or new installation is also really expensive, so yeah, if you don't have the assurance that you can offtake cheap green hydrogen then you're not going to invest in such an expensive new factory. '- P3
	Storage and Transport	Gas grid for transport	'I think that the Netherlands has the luxury that we have parallel pipelines on the DSO levels… already 80% of the infrastructure is already there in the ground. And I think that is the major advantage that we have.'-P5
		Storage infrastructure	I think already four or five terminals for ammonia are under development. So a lot of storage facilities is being built or will be built.- P3
Market and Competition	The market for green hydrogen	Certification of green hydrogen	'Well, certification is not very 100% clear yet. Like mass balancing certification, what do you do with your certificates? You sell them. That's not very clear. So you would be hesitant to invest if you're not sure yet. You know there's no market for these certificates' -P1
		Market for green hydrogen in the Netherlands	'There's no market to even estimate what you could get for it.'-P1

Themes	Sub-themes	Codes	Quotes
Market and Competition	Blue Hydrogen as an alternative	Hesitancy in moving towards blue hydrogen	'...it also has a weird feeling that you are focusing on green and then you're going to Import liquid natural gas to crack it here to make blue hydrogen'- P3
		Blue hydrogen is cheaper than green energy	Having an hydrogen molecule maybe Blue will will be better and more cheap than intermittent sources like electricity or solar. Blue can have more cost advantage, than green. - P5
	Electricity as a competitor of hydrogen	Electricity Demand Increasing	...industries are moving away from natural gas. But this also means that we have a lot more electricity demand. - P5
		New electrical infrastructure compared to new hydrogen infrastructure	'When you want to transport gigawatts of energy from A to B the high power cable lines are going to be nearly 60 metres wide on different poles and when you have a gas pipeline, you can have a pipeline of 200 millimetres for the same amount of energy going to the pipeline'-P5
Regional Collaborative Effort	Risk Mitigation and Diversification	Diversification of Green Hydrogen sources	It's just important to have a wider mix of different producers'-P5
		Financial risk of developing new projects	if it's just too expensive then company is not going to invest in it... A company doesn't want a lot of financial risk if they have to invest in a really large project.- P1
	Regulations	Permits in the Netherlands	Dutch permitting system is really flexible. - P6
		Regulatory Push	There's a lot of regulator regulatory push to create consumer demand. - P1
	Collaboration between stakeholders	Importance of collaboration	We will need to get technical insights, economic insights and location insights to develop projects the best way. - P2
		Looking at the full value chain - ecosystem	What really makes a difference is if you can look at it as a full value chain. So not just one part of the of the supply chain, but making hydrogen is looking at full value chain.- P3

Appendix C : Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Yallaling Naik **Student number**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Decarbonising Industries: The Value of Hydrogen in Energy Transition

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Context

The current objectives outlined within climate policies prioritise diminishing our dependency on fossil fuels for energy production. A viable strategy to achieve this involves transitioning towards renewable energy sources and broadening our energy portfolio. Nevertheless, significant hurdles exist in shifting away from fossil fuels within sectors like heating, manufacturing, and transportation.

1. In the case of domestic heating, there hasn't been a significant breakthrough in recent times. In the Netherlands, around half of the final energy consumption for heat is energy consumed in the built environment (households and services), and around 80% of this energy is produced using natural gas [1] (figure1 and 2).
2. While advancements in battery technology for electric vehicles and trains have been notable, limitations persist in efficiently powering large-scale transportation like cargo ships and aircraft, primarily due to spatial and weight constraints. This has prompted companies and states to invest in the development of e-fuels or synthetic fuel alternatives.
3. The manufacturing sector, especially the iron and steel industry and the chemical industry, requires large amounts of hydrocarbons and fossil fuels for power and chemical reactions. In the iron and steel industry, iron ore is heated with fossil fuels to purify iron. This has a significant impact on the climate due to emissions. The Dutch steelmaking industry was responsible for producing 12.6 Megatons of CO_2 in 2017, making it the greatest CO_2-emitting entity within the Dutch industry [2].

Where hydrogen fits in

Hydrogen is the most abundant element in the universe and one of the most versatile elements. It is currently used on a large scale for industrial purposes. It can be used as a source of energy and can be converted into heat or electricity using fuel cells. Another interesting application of hydrogen is its use as a storage medium for excess energy generated by renewable sources. For example, extra electricity generated by sunlight can be stored as hydrogen for later use instead of being wasted.

Synthetic fuels, produced with the help of hydrogen are also playing a key role in mobility. The advantage of synthetic fuels is that they don't require specialised power units; existing engines and turbines can make use of

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introduction (continued): space for images

them. In 2023, the EU voted for the ban on sales of ICE (internal combustion engine) vehicles by 2035; however, it was announced that ICE vehicles that run on synthetic fuels are exempt from this ban [3]. Shipping companies like Maersk are also transitioning to e-methanol to power their container ships and reduce emissions[4]. Instead of using fossil fuel powered furnaces to remove oxygen and other impurities from iron in iron and steel factories, hydrogen can be used as a reducing agent to create pure nuggets of iron. This method has been implemented by SSAB in Sweden. [5] A study by McKinsey in 2023 found that the manufacturing industry and mobility industry would be the biggest consumers of hydrogen by 2050 [6] (figure 3).

Stakeholders
In this context, the primary stakeholders would be broadly classified into two domains. Producers and consumers. The producers would be companies manufacturing technologies (like fuel cells, PEM electrolysers, etc), energy providers (solar parks and wind farms), and hydrogen generation plants. The consumers would be industries (steel, chemical, etc), synthetic fuel manufacturers, the mobility industry and domestic heating industry. Policymakers and researchers are also key stakeholders in this context as they are responsible for driving the hydrogen economy forward.

Figure 1

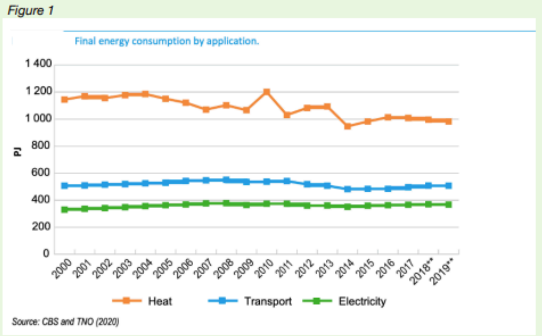


Figure 2

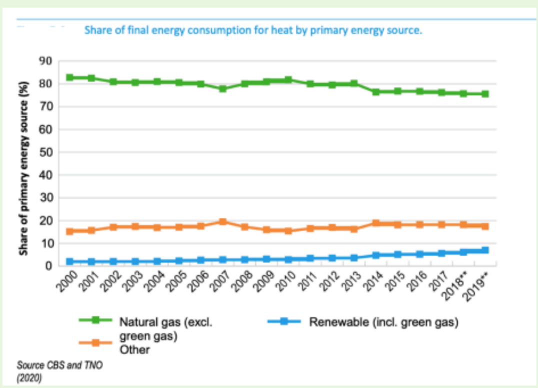
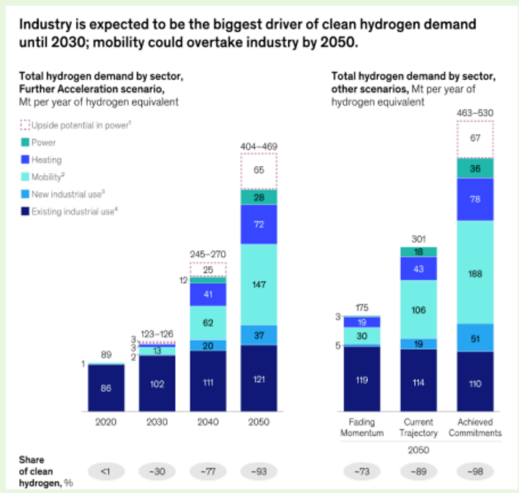


Figure 3



Source: McKinsey Energy Solutions' Global Energy Perspective (2023)

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (=Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Currently, the biggest challenges in using hydrogen as a source of energy are fuel cell technology and the lack of infrastructure for the storage and transport of hydrogen gas. Hydrogen has been used in industrial processes for around a century; however, the gas used is created using fossil fuels. This hydrogen is called grey hydrogen, and it is abundantly available. Hydrogen produced using renewable sources of energy is called green hydrogen. To achieve our carbon goals, we must have more generation plants of green hydrogen and reduce our reliance on grey/black hydrogen. Companies are now investing heavily in creating the said plants. Shell has started building Europe's largest green hydrogen plant at Maasvlakte Rotterdam, which will produce 60,000 kilograms of hydrogen every day after its completion in 2025 [7].

I want to explore the values created by green hydrogen manufacturing facilities like the one mentioned above, in and around the port of Rotterdam and look into potential design interventions in the supply chain. My focus would be on using data analysis to compare the capacity of production of Hydrogen and the capacity of power generated by renewable resources and finding areas of opportunities for new product service systems involving hydrogen. I will start by exploring the industrial and power related applications of hydrogen and adjust the scope after primary research.

The targeted stakeholders for this project are the policymakers and strategic decision makers of the companies who are looking towards green hydrogen and other alternatives to meet their decarbonisation goals.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Explore the values created by renewable energy and green hydrogen for manufacturing and energy sector and identify opportunities for enhancements of the supply chain.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

My project will initiate with a comprehensive analysis of ongoing and planned hydrogen initiatives, focusing on the Port of Rotterdam. This phase includes systematic collection of datasets from IEA[10] and the Dutch government[11] to identify trends in hydrogen infrastructure development, including geographic distribution, technology preferences, and investment patterns. The insights gained will evaluate the growth prospects of the hydrogen industry and pinpoint regions or sectors showing rapid advancements.

In addition to data analysis, I will explore gaps in hydrogen storage and transportation infrastructure using case studies, aiming to highlight deficiencies that impede widespread adoption. This will be complemented by qualitative insights derived from interviews with stakeholders in heavy transport and heavy industry, focusing on their specific challenges and opportunities related to hydrogen use.

Further, my research will encompass analyzing data on renewables, hydrogen production, hydrogen consumption, and power generation. I aim to discover patterns and relationships within this data, supported by visualizations of data to delve deeper into these connections. I will use these visualisations in interviews with the domain experts to gather more insights from the data. These insights along with the visualisations aim to enhance communication amongst the stakeholders and facilitating more efficient decision-making[8,9].

introduction (continued): space for images

The findings from the analysis and visualizations will be utilized to develop of strategic interventions in the hydrogen supply chain, aimed at achieving effective decarbonization of industries in Rotterdam and surrounding areas.

References

1. https://energy.ec.europa.eu/system/files/2021-03/nl_ca_2020_en_0.pdf
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3. https://www.euronews.com/green/2023/03/22/eu-to-ban-petrol-and-diesel-cars-by-2035-heres-why-some-countries-are-pushing-back#:~:text=Germany%20has%20made%20a%20deal,fuels%20after%20the%202035%20ban.
4. https://www.siemens-energy.com/global/en/home/stories/zero-emission-fuel-ramps-up-for-shipping.html
5. https://www.ssab.com/en/company/sustainability/first-in-fossil-free-steel/timeline
6. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-hydrogen-outlook
7. https://www.shell.nl/over-ons/nieuws/nieuwsberichten-2022/holland-hydrogen-1.html
8. Fekete, JD., van Wijk, J.J., Stasko, J.T., North, C. (2008). The Value of Information Visualization. In: Kerren, A., Stasko, J.T., Fekete, JD., North, C. (eds) Information Visualization. Lecture Notes in Computer Science, vol 4950. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-70956-5_1
9. van Wijk, J.J.: The value of visualization. In: Proceedings IEEE Visualization 2005, pp. 79–86 (2005)
10. https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database#hydrogen-production-projects
11. https://www.pbl.nl/en/middenweb/the-database

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting, mid-term evaluation meeting, green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	3/4/24
Mid-term evaluation	21/5/24
Green light meeting	15/7/24
Graduation ceremony	19/8/24

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

During my undergraduate studies, I undertook an internship with an energy company in India specializing in utilizing agricultural biomass to fuel boilers across various industrial sectors nationwide. During this experience, I recognized that the company's core operations were centered not solely on energy production but rather on the intricate supply chain management of agricultural biomass. My aim for this project is to delve into the distinctive value exchanges within the renewable energy supply chain. After my discussion with Mahshid, I decided to focus on the supply chain of hydrogen as it it an essential part of many industries and has huge potential in decarbonisation. I was also quite inspired by the Dream Teams on campus which build hydrogen powered cars, airplanes and boats.