Hydrogen supply chains: barriers and drivers for implementation of the Dutch hydrogen economy

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Abstract

Through signing the Paris Climate Agreement and national policy programs, the Netherlands has set ambitious GHG emission targets to become virtually climate neutral by 2050. To design and operate a new energy system, based on carbon-free green energy, the supply and demand side of this energy has to be developed with a different approach. Out of the multitude of potential solutions, hydrogen is increasingly considered as the energy carrier with the most versatile field of applications. This has also been recognised by the Dutch Government through a large number of research and development programs with the aim of establishing a comprehensive hydrogen economy throughout all major industrial sectors. This thesis project analyses the expectable challenges and drivers along the Dutch hydrogen supply chain by using an innovation and transition framework (TIS) paired with qualitative data collection through expert interviews. After applying the TIS framework to examine the current status of the hydrogen supply chain and receiving additional data through the interviews, several challenges and drivers were identified.

From the challenges point of view, factors like missing or unclear regulation, lack of public acceptance or undeveloped market structures were identified as major barriers to the development of a Dutch hydrogen economy. In addition to that, often overlooked circumstances such as a lack of technical workforce or the largely insufficient generation capacity for clean electricity were also highlighted by respondents. These challenges and barriers make a fast switch towards a predominantly green hydrogen economy difficult to achieve and transition periods with alternative solutions increasingly more important.

The most significant drivers for establishing a Dutch hydrogen economy were the geographic conditions of the Netherlands, the level of entrepreneurial and innovative activity and the existing infrastructure and knowledge for gas technologies. The close proximity to the sea with major international ports and harbours is seen as a valuable asset for complementing the national hydrogen production with imported hydrogen. These ports also function as trading hubs towards large industrial clusters on the demand side, which are typical for the Netherlands. Historically evolved knowledge and expertise about extracting and handling of gas functions as a foundation for developing new solutions with the energy carrier hydrogen.

This thesis report provides possible solutions for overcoming the existing challenges on the way towards a Dutch hydrogen economy while also leveraging the power behind the driving forces in the Netherlands. It should act as an incentive for cooperation between the involved parties to accelerate the transition of the Dutch energy system towards a more sustainable form.

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Acronyms List

ACER	Agency for the Cooperation of Energy Regulators
ACM	Authority for Consumers & Markets
ADR	Agreement Concerning the International Carriage of Dangerous Goods by Road
AGBZW	Natural gas buffer Zuidwending
bcm	Billion cubicmeters
BRZO	Dutch Major Accidents (Risks) Decree
CAPEX	Capital Expenditure
CCUS	Carbon capture utilisation and storage
CEER	Council of European Energy Regulators
CGH2	Compressed gaseous hydrogen
CHP	Combined heat and power
CO2	Carbon dioxide
DEI+	Energy and Climate Innovation grant scheme
DSO	Distribution system operator
EBN	Energie Beheer Nederland
ECCM	Electro-Chemical Conversion & Materials
EEA	European Economic Area
EECS	European Energy Certificate System
EU	European Union
EUR	Euro
FCH-JU	Fuel Cell and Hydrogen Joint Undertaking
FID	Final investment decision
FME	Employers Organisation for the Technological Industry
GHG	Greenhouse gas
GOO	Guarantees of origin
GTS	Gasunie Transport Services
GW	Gigawatt
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IPCC	International Panel on Climate Change
IPHE	International Partnership for Hydrogen in the Economy
ISPT	Institute for Sustainable Process Technology
kg	kilogramm
km	kilometer
LH2	Liquified hydrogen
LOHC	Liquid organic hydrogen carrier
MINEZK	Ministry of Economic Affairs and Climate Policy
MLP	Multi-level perspective
MOOI	Mission-Oriented Research, Development and Innovation scheme
Mtoe	Million tons of oil equivalent
Mton	Million tons
MW	Megawatt
NERA	Netherlands Energy Research Alliance
NIMBY	Not in my backyard
NOW	Dutch Research Council
NOx	Nitrogen oxides
OPEX	Operational Expenditure

PJ	Peta joules
RED II	Renewable Energy Directive II
Rli	Dutch Council for the Environment and Infrastructure
RVO	Netherlands Enterprise Agency
SDE++	Stimulation of sustainable energy production and climate transition scheme
SMR	Steam methane reforming
SNM	Strategic Niche Management
SodM	State Supervision of Mines
SSCM	Sustainable Supply Chain Management
TIS	Technological innovation system
TKI	Top consortium for Knowledge and Innovation
TM	Transition Management
TNO	Netherlands Organisation for Applied Scientific Research
TRL	Technology readiness level
TS	Top Sector
TSO	Transmission system operator
TU	Technical University
TWh	Terawatt hours
USD	US Dollar
WABO	General provisions environmental legislation Act
WCED	World Commission on Environment and Development
WEC	World Energy Council

1. Introduction

The introduction chapter situates the research project in the global context of the energy transition and climate protection topic. It is followed by the problem statement where the reasons for the research are presented. The research objectives and research questions are presented as the main guidelines along the thesis project. Short descriptions of key concepts are in introduced as an introduction to the theoretical framework. The chapter is concluded with a reading guide for the thesis.

1.1 Background

In recent years, governments around the world have begun to concentrate their resources on achieving accelerated and successful decarbonisation of their primary energy-consuming sectors. This effort is being made to achieve the ambitious goals and priorities set out in numerous national and international development plans, most prominently in the Paris Climate Agreement, which came into force in 2015. Here the signing countries agreed to set the maximum increase in average global temperature to 2 degrees Celsius, with the strong aim to limit this at 1.5 degrees, compared to the reference year of 1990. This goal can only be achieved with a drastic reduction in greenhouse gas (GHG) emissions from fossil-based resources and a strong expansion of renewable energy technologies (IEA, 2018).

The Netherlands, as stated in their National Climate Agreement, aspire to be a European (and global) leader in enabling a climate-neutral society with a clean, secure, and accessible energy supply by the middle of this century. As a first step towards this ambitious goal, the Dutch government has agreed on drastic measures leading up to 2030 and, ultimately, 2050. This agreement contains the different measures that are required to achieve the targeted emission reduction, which is anchored in the Climate Act to ensure by law that all involved parties consequently follow the long-term objectives. The first target was reducing greenhouse gases by 49 %, compared to the amount emitted in 1990 by the year 2030. By doing so, the Netherlands wanted to outperform the other member states of the European Union, which initially agreed on a 40% reduction in GHG emissions by the end of this decade. However, this first target was revised in December 2020 by the European Commission and a new goal was set at a 55% reduction rate by the end of 2030. The Netherlands were one of the first countries to support this idea actively. Therefore, this additional legislative pressure to perform the required tasks for achieving climate neutrality is in line with the national efforts before this acceptance. The Dutch national agreement further emphasises the importance of a genuinely inclusive strategy that encourages a diverse variety of actors and stakeholders to directly engage in policymaking and adopting appropriate steps (MINEZK, 2019).

To keep moving forward on the road towards a low-carbon society, hydrogen, with its unique chemical and physical properties and a diverse range of potential applications, is expected to play a vital role in achieving the goals and targets. Therefore, it has become the centre of attention for ongoing research to assist the global energy transition. The International Energy Agency (IEA) mentions hydrogen as an energy carrier with a solid potential to support the renewable energy industry by providing a solution for the variable nature of renewables in the form of long- and short-term storage options. Additionally, the opportunities of utilising ports as important hubs, launching international trade routes for global markets and using existing transport infrastructure in the form of natural gas pipelines are mentioned as essential springboards for scale-up (IEA, 2019). Priorities and objectives were also proposed in the National Climate Agreement in the Netherlands, with hydrogen as a core area of concern and growth.

Besides that, several key concepts were formulated to underline the importance of continuous development in the areas of innovation, upscaling and cost reduction. Given its geographical conditions, the Dutch strategy currently focuses mainly on large industrial clusters and port areas, primarily located in the northeast (Eemshaven area) and southwest (Rotterdam area) regions. They serve as major international trading centres and critical energy hubs for national and regional demand (Rijksoverheid, 2020). Therefore, the success of the proposed national hydrogen economy would depend on whether higher urban/industrial and lower rural demand can be met continuously and efficiently by a closely interwoven network of reliable producers and the corresponding transmission, distribution, and storage infrastructure.

1.2 Energy Transition

Despite a binding climate agreement and significant efforts in the renewable energy industry, global carbon emissions related to energy have continuously risen within the five years of 2014 to 2019 (Global Carbon Project, 2020). Regardless of the seemingly positive runaway value of the year 2020, the major decrease (-7%) due to the Covid 19 pandemic will likely not have a lasting positive impact, with a short-term negative rebound effect very likely to happen instead (Le Quéré et al., 2020).

The undisputed cause for a human-induced global average temperature increase (ca. 0.2 °C per decade) is the multitude of industrial activities paired with a constant rise in the world's population, which both leads to exploding resource demand (IPCC, 2018). However, several positive changes have also occurred recently, with record rates for newly installed renewable power generation capacities, rapid cost reductions for key technological components such as solar panels, fuel cells and battery packs, as well as promising growth within the e-mobility sector (IRENA, 2021).

Based on the target plans and policy frameworks currently in place, the global energy transition process will not reach its goal of being net-zero by 2050 in terms of CO2 emissions. The change process's speed needs to be increased drastically to prevent stagnation of emitted greenhouse gases on a high level. The worst-case scenario, caused by a lack of (current) policy implementation, can even lead to a linear increase in global GHG emissions of up to 27 % in the following decades. The shift towards the 1.5 °C pathway can only be accomplished when immediate steps towards fast and continuous decarbonisation are being taken. The energy industry is expected to act as a frontrunner since it accounts for roughly 80% of all anthropogenic CO2 emissions. The IRENA report mentions six components with the most significant carbon abatement potential, "Hydrogen and its derivatives" being one of them. They all have in common one characteristic: that renewable energy is involved in 90% of the solutions for decarbonisation through green hydrogen, energy efficiency, electrification, etc. However, the share of renewables in the global total primary energy supply was still only a mere 14% in 2018. This share needs to grow to 75% to stay on track with the 1.5°C scenario, outlined in the Paris Climate Agreement. Out of the roughly 37 Gigatons of annually required CO2 reduction (compared to current numbers) by the year 2050, hydrogen is projected to be responsible for around 10% (3,7 Gt/year) of the total abatements. Simultaneously, hydrogen is expected to account for 12% of total final energy consumption in the world, together with its derivatives of methanol and ammonia (IRENA, 2021).

To ensure that hydrogen can provide the previously mentioned percentage of final energy use, around 30 % of the total electricity demand needs to be channelled towards the production of predominantly green hydrogen. This will mean that an enormous scale-up, from currently 0.3 Gigawatts to around 5000 gigawatts, of production capacity has to be accomplished in the following three decades. The cost per kilogram of produced hydrogen will largely depend on the cost of electricity for the fleet of electrolysers' operation.

The IRENA report projects an average production cost for hydrogen by the year 2030 of USD 2.18/kg, in case cheap renewable electricity can be utilised at a price of around USD 20/MWh. This will mean that the currently high-priced green hydrogen can become cost-competitive with blue hydrogen in less than ten years (IRENA, 2021). To put this into relation, in 2019, average production costs for grey hydrogen in the Netherlands were EUR 1.04/kg (International Energy Agency, 2020).

The global energy transition will inevitably be one of society's most significant projects in the 21st century. Besides hydrogen as an essential energy carrier of the future, utilising other components of the transition strategy, such as comprehensive electrification, carbon capture and storage techniques and increasing energy efficiency, can put us on the right track towards achieving the ambitious goals of the Paris Agreement. However, factors such as legislative/policy background, geopolitical conditions and active stakeholder participation, among others, will remain crucial along the road. To research the development and growth of new technical fields and markets

1.3 Problem Statement

The need for a steady supply of affordable clean energy and high-quality industrial feedstock material is currently posing a significant obstacle to a successful transition to low-carbon energy sources. This is especially true for a country like the Netherlands, where a highly developed industrial sector (petrochemical, agriculture, steel, harbours etc.) is currently strongly dependent on fossil energy. At the same time, primary national natural gas extraction is being phased out, mainly for security (earthquake) reasons. The combination of high energy demand and decreasing national production of fossil-based energy acts as an additional urgency to develop alternative ways of energy supply, both for industrial and residential needs (Bakhuis, 2020). The Dutch government has assigned the energy carrier of hydrogen a central role in solving this complex challenge. In order to succeed with this plan, an extensive supply chain for clean hydrogen has to be established. Due to its complex interdependencies, made up of supply, demand, storage and infrastructure, it is vital to tackle this issue with a holistic approach that utilises multiple instruments within a policy framework (Rijksoverheid, 2020). Figure 1 gives an overview of the main parts that build up a hydrogen economy.

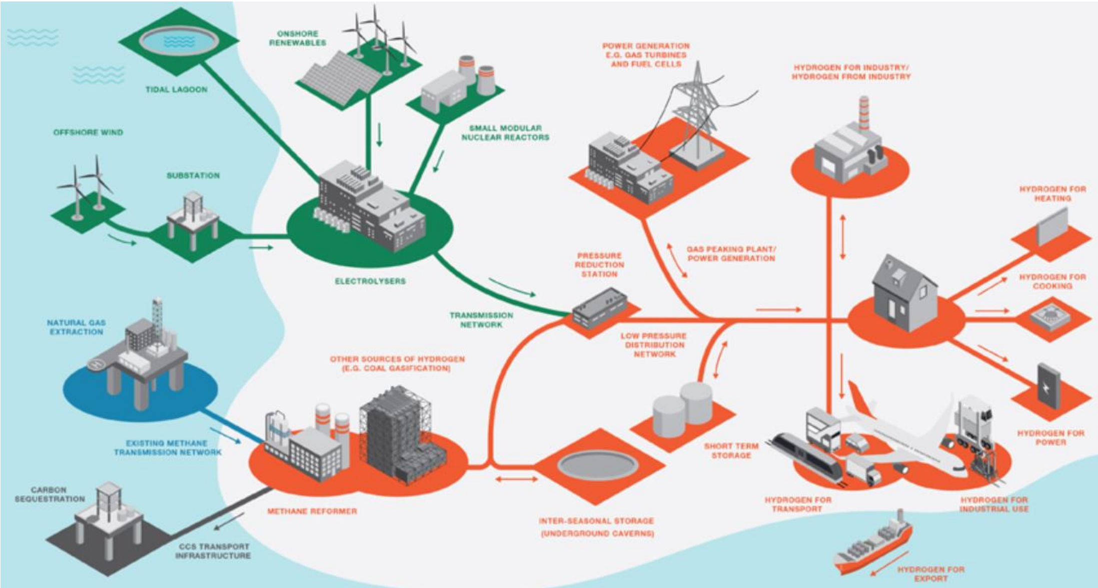


Figure 1: Overview of the hydrogen economy with supply chain phases (Source: Arup Group, 2019)

The vast potential for hydrogen, which can be used in an extensive range of applications, is also a burden because distinct supply chains are lacking, making it momentarily impossible to achieve the much-needed scale-up of technology. As a result, capital and operating costs are frequently far too high to cope with inexpensive and often subsidised fossil fuels. Here, economies of scale are needed to reduce the cost of deployment and operation. Despite becoming a leading force in the European hydrogen landscape, the Netherlands still faces significant challenges in developing a truly inclusive hydrogen economy that considers technological, social, financial, and environmental factors all at the same time. The execution of such capital-intensive projects can present plenty of challenges, for example, when the total ownership costs are very high (Cardella et al., 2017). Aside from the critical cost factor, supply chains are affected by factors such as spatial distribution, storage technologies, transportation and distribution methods, and market penetration of hydrogen appliances, among others (Emonts et al., 2019), all of which need to be considered.

The IEA mentions similar challenges in its future outlook on hydrogen. Current prices for hydrogen from renewable energy are still too high to compete with the costs of hydrogen produced with fossil fuels (but no carbon-capture step), also known as grey hydrogen. A high price acts as a significant barrier towards developing the necessary infrastructure and therefore slows the widespread adoption of these technologies. The report also mentions that this production technology unfortunately still accounts for the majority of today's hydrogen supply and is responsible for emitting an amount of CO2 equivalent to the annual emissions of the United Kingdom and Indonesia combined. This currently strong dependence on high-carbon raw materials for hydrogen production requires carbon capture technologies to be applied in a more comprehensive way, especially during the critical transition period, before clean electricity can take over a higher share of hydrogen production. Finally, the IEA points out that specific laws and regulations still act as obstacles for the development of a clean hydrogen industry. Therefore, industry representatives and governments need to cooperate in a more foresighted way to introduce industrial standards and certification schemes, for example, concerning environmental or logistical issues (IEA, 2019).

Despite the need to solve these complex socio-technical problems, little research has been done on how the Dutch supply chain for a hydrogen economy can be developed to achieve the Dutch energy transition's ambitious goals. Until now, the emphasis has been chiefly on outlining the proposed structure of regional solutions or the already fully developed economy of the future, rather than delving further into the particulars of how this can be accomplished in a more interconnected and systemic manner. It is important to consider what challenges must be overcome to succeed in this vital endeavour in a diverse playing field where many interested actors serve different interests and responsibilities.

Addressing potential problems by focusing on the current state of hydrogen-related infrastructure in the Netherlands can lead to a better understanding of how different levels of a supply chain are connected. This analysis can also uncover how they can contribute their part to a seamless transition towards a low-carbon Dutch hydrogen economy.

1.4 Research Objectives

In this research study, a general outline of the current situation in the structural dimensions of the Dutch hydrogen landscape will be given. Identifying driving forces and potential barriers that can support or hinder the development of supply chains will serve as a starting point for further analysis. By doing so, potential knowledge gaps that pose problems to the supply chain and ultimately to the energy transition process in the Netherlands can be recognised. This thesis focuses on supply chains by examining their current and future impact on the anticipated hydrogen economy in the coming decades. The report analyses the current situation and then uses the results to identify and clarify what improvements can be made and why they are essential.

The objectives of the research can be summarised as follows:

1. To describe the current state of development of the hydrogen supply chain phases and the Dutch hydrogen landscape's structural dimensions.
2. To elaborate on the different challenges and driving factors that affect the hydrogen supply chain phases in the Dutch hydrogen economy.
3. To explain how these challenges can be overcome by applying suitable measures for further development of the hydrogen economy

The first objective is accomplished by using a blended approach between a literature review, elements of the technological innovation system (TIS) framework, and interviews with experts.

The second objective is tackled by utilising the first sub-question findings and includes a combination of the TIS approach and information from semi-structured interviews with experts from various areas of expertise.

The third and final objective is fulfilled by summarising the previous sections' insights and utilising the expert knowledge through the interviews to give an outlook of future developments. Additionally, the stages of the TIS approach act as a supportive mechanism.

1.5 Research Questions

The preceding section has provided an overview of the reasons for a fast-paced decarbonisation strategy, with hydrogen acting as a central element in the new energy system of the future. The following section will outline the set of questions that serve as guidance for the upcoming research process. This will allow a deeper understanding of how supply chains can influence the transition process towards a low-carbon renewable energy system in the Netherlands that is underpinned by hydrogen as an important energy carrier.

Main Research Question:

How can a functioning Dutch hydrogen economy be established from a supply chain perspective?

A set of sub-questions act as support for answering the main research question. They aim to provide a more detailed view of the fundamental elements that need to be discussed before answering the main research question.

Sub-Research Questions:

1) *What is the present state of development within the Dutch hydrogen landscape's structural dimensions and the phases of the hydrogen supply chain?*

2) *What are the significant challenges and drivers along the phases of the supply chain that affect the build-up of a hydrogen economy?*

3) *Which improvements need to be made along the supply chain to secure the further development of the hydrogen economy?*

1.6 Key concepts

For researching the development and growth of new technical fields and markets, **the technological innovation systems model (TIS)** is frequently used. It concentrates on decoding the complexities of an innovation system based on a single technology. The method is often used to evaluate the efficiency of a TIS, find flaws and make suggestions for the design of policies to suit a particular technology (Markard et al., 2015).

Sustainable supply chain management is "the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements"(Seuring & Müller, 2008, p. 1700)

The **hydrogen economy** is an aspirational target that is pursued by a growing number of countries around the world to secure a low-carbon energy supply based on hydrogen. It includes an extensive network of physical production, storage and transportation facilities, and a developed demand side in the form of users within the sectors of industry, energy production, low-/high-temperature heating and transport.

Grey/blue/green hydrogen refers to the way hydrogen is produced. This can currently be either a production from natural gas (or coal) through the process of steam-methane-reforming (grey), production with a lower carbon content due to a subsequent carbon capture process (blue) or a fully carbon-free production process (green) by utilising renewable energy for water electrolysis.

A **stakeholder** is "any group or individual who can affect or is affected by the achievement of the organisation's objectives" (Freeman, 1984 p. 46)

The **energy transition** is a complex socio-technical shifting process from a mainly fossil-fuel-based energy system to a low-carbon system that is predominantly powered by renewable energy. A constantly increasing need for storage capacity and new electrification methods can be seen as the major drivers for this transition (S&P Global, 2020).

1.7 Thesis reading guide

In **Chapter 1** of the thesis report, the chosen topic's general background is presented and situated within the context of the ongoing energy transition debate. This is followed by the problem statement and the research objectives that will ultimately be fulfilled by answering the research questions. It is followed by **Chapter 2,** where a theoretical background is presented in the form of a literature review about key concepts of the thesis. In **Chapter 3,** the methodology and the research design is discussed while also mentioning the types of research materials and the gathered data. **Chapter 4** introduces the present state within the structural dimensions of the Dutch hydrogen landscape with the help of a literature review and parts of the TIS framework. This also answers the first sub-question by describing the status quo. Several factors (technical, legislative, environmental etc.) are considered as part of this review. After concluding the information gathering about the current state of the supply chain, **Chapter 5** dives deeper into the connection between the different phases/levels of the supply chain. It highlights the current barriers within the system and possible driving forces projected to influence the transition process significantly. Here a TIS approach will be utilised to identify systemic problems and challenges. This chapter will help to answer the second sub-question. In the discussion part of **Chapter 6,** possible solutions are outlined for the previously defined challenges while also referring to the driving factors which can act as stimulating forces. This helps to answer the third sub-question. In **Chapter 7** a reflection on the TIS theory is provided. Finally, **Chapter 8** summarises and presents general conclusions and recommendations for future research activity.

2 Conceptual Framework

The following chapter focuses on relevant key concepts that build up the conceptual framework of the thesis. The aim is to give a first overview of the research topic by formulating the context of the theoretical framework.

2.1 Sustainable Supply Chains

Our current understanding of the term sustainability can commonly be linked back to the 1987 published report of the World Commission on Environment and Development (WCED), known as the Brundtland Report. Here sustainability is connected to the subject of development and defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987).

However, this catchy but relatively vague formulation has raised a number of questions that still need to be answered for getting a clearer definition for the term sustainability in its different areas of application (Linton et al., 2007). By broadening the approach and application of sustainability in the last two decades, the focus has shifted towards including issues that go beyond the initial values of supply chain management and include, among others, Life Cycle Assessment, product/service management and the handling of certain by-products (Linton et al., 2007).

This is also of particular interest to the renewable energy industry and, more specifically, the hydrogen sector. The impacts of a certain value- and supply chain on sustainability issues, such as resource consumption, CO2 emissions and energy consumption, can be analysed with the help of an extensive life cycle assessment for various hydrogen production techniques. (Cetinkaya et al., 2012). However, the most advantageous method for a particular region cannot be decided by simply looking at the total CO2 equivalent values of hydrogen production. Factors like spatial distribution, production capacity, production reliability all play a role in the decision. Therefore, in the case of fossil fuel-based methods (e.g. coal gasification, steam methane reforming) the supply chain thought has to include the process steps of mining and refining the input material for energy production (Cetinkaya et al., 2012). Other scholars also argue that more extended parts of a supply chain have to be taken into account if the declared intention is truly sustainable management of said supply chain (Seuring & Müller, 2008). There is a need for more performance objectives that have to be considered if the criteria for environmental, social and economic issues want to be put on the agenda. This approach is also known as the triple bottom line. There has been a long-going debate about the grade of interconnection between these three dimensions. However, their impact on (sustainable) supply chain management has not been thoroughly investigated. Finding the correct equilibrium between these three cornerstones and moving from a strategic to an operational form of sustainable supply chain management poses a significant challenge (Seuring & Müller, 2008).

Unlike the first two pillars concerning economic and environmental issues, the third pillar of social responsibility, in managing supply chains, has been largely untouched by research (Fazli-khalaf & Naderi, 2020). The triple bottom line approach tries to pay more attention to this often underrepresented factor, as it directly affects all human capital. Focusing on human beings and their quality of life directly impacts both the economic and environmental sides of the triangle. By considering factors such as health and safety, customer satisfaction or social wealth creation along the supply chain, products and services can be made a lot more attractive to potential target groups. This, on the other hand, fuels financial return and ideally also yields environmental protection, in case the product or service can substitute an existing one with a more negative impact (Fazli-khalaf & Naderi, 2020). Succeeding with the transition from a strategic to operational level of supply chain management has been a great challenge numerous times due to the complex interconnection between the pillars of the triple bottom line approach (Mota et al., 2015). Multi-objective (programming) models can be utilised to include the three main factors and their corresponding performance indicators to assess certain impacts on a strategic level (Mota et al., 2015). In the case of hydrogen supply chains, the previously mentioned model, with more closed-loop characteristics, can turn out difficult to be applied, and therefore a network design model seems more appropriate (Fazli-khalaf & Naderi, 2020). In doing so, a maximisation of reliability and sustainability can be aimed for while minimising expenditures. By defining priorities in the form of objective functions, strategies can be developed depending on whether economic, environmental or social effects are being seen as more important. These kinds of design models allow a range of different parameters to be used to analyse certain phases of a supply chain or observe the whole network from a more holistic point of view (Fazli-khalaf & Naderi, 2020).

2.2 Technological Innovation System

The currently happening unsustainable economic development of the world poses a major threat to our environment's biodiversity. It causes a fast depletion of valuable natural resources while constantly polluting nature (Wieczorek & Hekkert, 2012). These problems are intensified by a combination of strong path-dependent techno-economic evolution and locked-in sectors, such as the powerful fossil fuel-based energy sector (Unruh, 2000). Innovation and transition scholars describe these well-established sectors as regimes with a strong regulative and institutional background structure and a tightly interwoven network of actors and stakeholders. (…) This urgent need for new policymaking approaches has brought up several theories and frameworks currently being used to analyse socio-technic and socio-economic transition processes towards a more sustainable way of producing and consuming goods and services (Markard et al., 2012). The four most prominent frameworks currently in use are Strategic Niche Management (SNM), Transition Management (TM), Multi-Level Perspective (MLP) and the Technological Innovation Systems (TIS) approach (Markard et al., 2012).

Like the other three frameworks, the TIS approach also focuses on innovations as a process of continuous improvement. Several different activities, market forces, and stakeholders networks are constantly interacting (Suurs et al., 2009). This involves both the private sector, as well as research institutes and governmental authorities. The idea behind TIS is to combine both structural and functional analyses for innovation systems that can help in providing components for a systemic policy framework (Wieczorek & Hekkert, 2012). This combined approach aims to ensure that both problems of systemic nature are identified, and suitable measures in the form of policy instruments are formulated to solve these. The structural analysis is facilitated by using structural elements that can be seen as stable forces over long periods with an expected rate of relatively slow change and usually only visible from a retrospective point of view. These building blocks can link the different areas to each other by forming a holistic structure (Suurs et al., 2009).

The structural dimensions used in this thesis include actors, networks and institutions, based on the recommendations from Wieczorek and Hekkert (2012) and Bergek et al. (2005). *Actors* are all network members in the form of either individual people or organisations that have a specific function in civil society, a government, or an enterprise's economic activity. They can also include non-governmental organisations, consultants or knowledge institutes. In this particular case, they are subdivided into governmental organisations, knowledge and research institutes and industrial actors. *Institutions* are generally made up of soft and hard institutions. The former includes all routines, concepts and habits of people, while the latter is based on the laws, rules and standards which regulate peoples' and organisations' behaviour. In the following sections, institutions are divided into financial institutions (investment programs, subsidies, grants etc.) and regulatory institutions such as rules, laws and strategies. The final dimension of *networks* comprises formal and informal collaborations between individual actors or groups. In this thesis, networks are oriented around covering scientific, economic or political issues in the form of knowledge developing networks or interest and representative groups. (Wieczorek & Hekkert, 2012; Bergek et al., 2005)

Next to the above mentioned structural dimensions, the other key element is a set of system functions that determine whether the chance for building up a successful TIS is given or not. Bergek (2002) describes them as a set of different activities that can help develop, disseminate, and use innovative technologies. One advantage of this approach is the fact that these system functions can be achieved in more than one way and even a negative influence of one activity can be taken into consideration. In this case, the TIS would suffer a partial drawback in its development process (Suurs et al., 2009). Table 1 presents the different functions and indicators for measuring their strength.

Table 1: Functions of the TIS framework and their respective indicators (Wieczorek & Hekkert, 2012)

Function	Indicators
Entrepreneurial activities	number of entrepreneurs/start-ups, new market entrants, experimentation activity, level of uncertainty
Knowledge development	size/number/type of R&D projects, availability of publications/reports and prototypes
Knowledge diffusion	network activity
Guidance of the search	targets/goals/visions/expectations of government and industries
Market formation	niche markets, tax incentives, environmental certificates/standards
Resource mobilisation	physical resources: infrastructure, natural resources human resources: know-how, education, training programs financial resources: private investment, government funds, venture capital
Creation of legitimacy	public opinion and acceptance, size of technology networks, size and influence of interest-/lobby groups

Especially for technologies in sustainability and energy sectors, it is essential that such system functions actively and constantly interact with each other to strengthen the virtuous cycle's overall structure. However, it is also possible that certain functions reinforce each other negatively, which leads to the opposite, a viscious cycle. (Suurs et al., 2009). A well-established and agreed-on list of seven functions was developed by Hekkert et al. (2007), which shows the current development state of an innovation system by assigning an evaluative score to each function from absent to very strong (Wieczorek & Hekkert, 2012).

By performing the structural-functional analysis and simultaneously detecting why some functions have different performance than others, the researcher can identify systemic problems that prevent the system from further development. After this analysis, the evaluation of the different functions and why certain functions are not performing as anticipated leads to the formulation of systemic problems. They can be related either to (the lack of) presence or capability and form the basis for formulating and designing systemic instruments to solve them. Problems can occur when at least one structural element is missing (presence-related); or its characteristics are either too strong or too weak (capacity-related). This analysis of functions allows us to investigate each structural element based on the presence- or capacity-related problems detected beforehand (Wieczorek & Hekkert, 2012)

The final step for closing the cyclical structure is the goal-formulation for the systemic policy instruments -that are expected to solve the identified problems- and the actual design of these instruments. By aligning the problems with the goals of the instruments, suggestions can be made about which policy can support the further development of the system. As mentioned in the last paragraph they are related to the structural dimensions (actors, infrastructure, institutions) and their type of (presence or capability) problem. This ultimately leads to the fulfilment of the instrument goals by designing and applying the instruments with the help of existing policy tools (Wieczorek & Hekkert, 2012).

3. Research design and methodology

The following paragraphs describe the design of the research project and the used methods. The research unit and boundaries are defined to demarcate the analysed area of the thesis. This is followed by a description of the different data sources and collection methods used during the thesis project. The last section explains the process of data analysis and evaluation of the findings.

3.1 Research Framework

The object of the research project

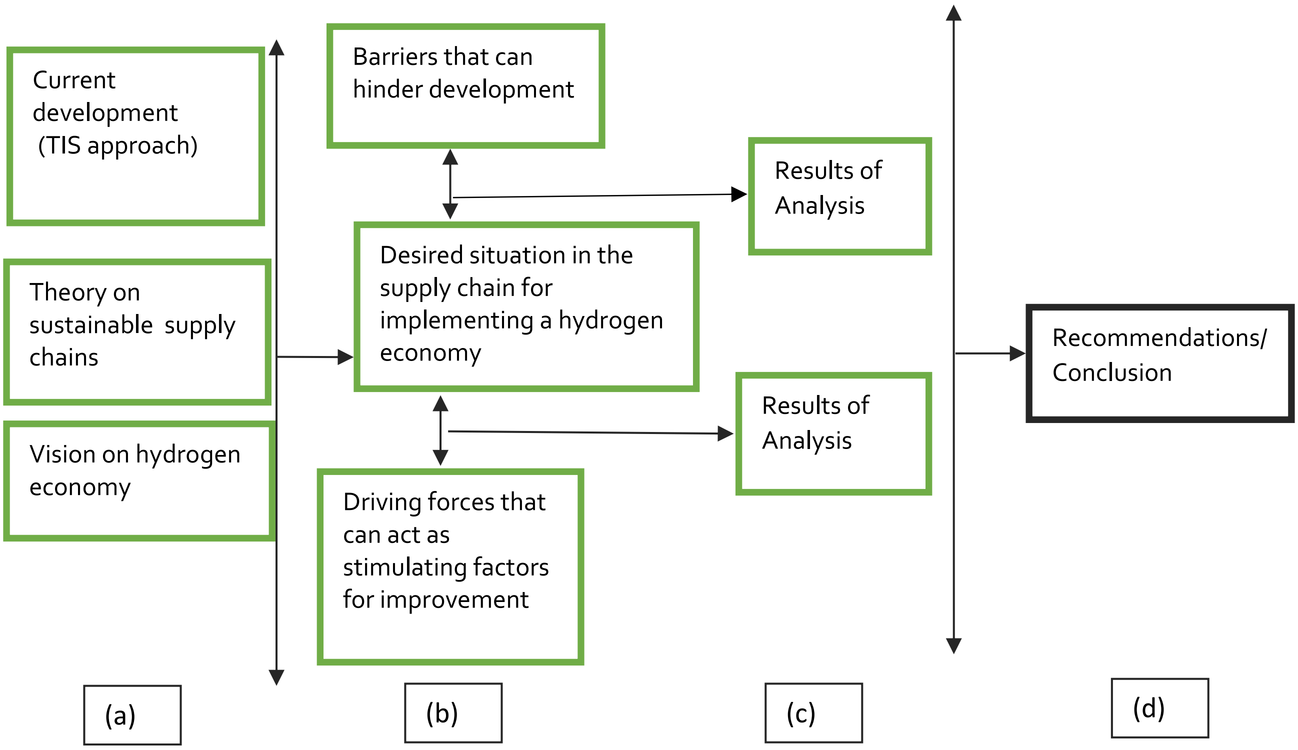
In line with the general objectives of the study, the object of this Master thesis is the development of a supply chain for the Dutch Hydrogen economy.

The nature of the research perspective

Based on the presented perspectives by Verschuren and Doorewaard (2010), the nature of the research prospect can be formulated as a combination of 2 different approaches of practice-oriented research. First, problem-analysing research determines the present state of the supply chain network and, at the same time, tries to identify the relationship between problems and driving factors that can lead to a change process.

This is blended with a diagnostic research approach that uses the background knowledge from the problem-analysis (causes) to address the challenges and ultimately finds solutions with the help of broad stakeholder involvement, for example, in the form of expert interviews and applying the TIS framework. This analysis will allow a better understanding of what needs to be changed or improved within the Dutch hydrogen supply chain and how these issues can be tackled.

Schematic presentation of the research framework



Formulating the research framework

(a) A literature study about the current state of development, preliminary research on socio-technical circumstances and a partial TIS approach
(b) By means of which the research object will be identified
(c) Comparing and evaluating results of the literature review and interviews to form a basis for recommendations
(d) Formulating a conclusion that can act as a recommendation for decision-makers

3.2 Research Strategy

Based on the above mentioned research design, the approach to achieve the research objectives is a blend between desk research and empirical research. The former allows generalisation and a more breadth focused overview of existing literature, while the latter is based on qualitative data gathering through interviews with people from relevant areas of expertise.

3.2.1 Research Unit

The hydrogen supply chain has been selected as the research unit for the present study. In this case the unit can be defined as the 4 phases of production, transportation (transmission and distribution) storage and usage (demand) of hydrogen. Since this thesis was written in the Netherlands, the unit was narrowed down further, specifically to the Dutch situation, allowing the analysis by in-field interviews with regional experts.

3.2.2 Research Boundary

In order to narrow down the scope of the thesis and fulfil the objectives, the research project was limited to the previously mentioned 4 phases of the hydrogen supply chain. Due to the high number but low levels of technology readiness of possible end use applications and services, the demand side of the chain was only examined in general, without additional qualitative data collection through interviews. Furthermore, another boundary at the beginning of the chain ensures that the various production technologies for hydrogen are also not addressed in a detailed manner.

3.3 Data Sources and Collection Methods

The required data were collected through a review process of several different literature sources such as articles, reports, books and semi-structured interviews to answer the research questions. The details about the interviews, regarding structure, length and the background of the interviewees, are explained in the paragraph below Table 2. The required data and the sources of information for each sub-question are presented in Table 2, while also mentioning the accessing method.

3.3.1 Literature Review

The main sources of data for answering the first sub-question are various types of scientific and non-scientific literature in the form of journal articles, books, reports, company and government websites and news articles. Most of the scientific articles and book chapters were located through the database of Scopus and Web of Science, while reports, company profiles and governmental authorities were mainly found through entries on online search engines. The second and third sub-questions are also answered partially by a similar literature review but have a stronger focus on the data gathered through the interview process. Table 2 gives an overview about the types and sources of literature needed to extract data and information for the different sub-questions.

Table 2. Research Material Matrix

Research (Sub)-Question	Data/Information required to answer question	Sources of data	Accessing data
What is the present state of development within the Dutch hydrogen landscape's structural dimensions and the hydrogen supply chain?	The current state of development within the different phases of the Dutch hydrogen supply chain and the structural dimensions of a TIS	Secondary Data published articles, reports, books and policy documents	Content Analysis, Search method
What are the significant challenges and drivers along the phases of the supply chain that affect the build-up of a hydrogen economy?	Technical, economic and social factors that currently act as barriers for the further development of the system Demand and supply sided stimulating forces that act as drivers for technical and non-technical development	Secondary Data published articles, reports, books and policy documents Primary Data People: gov. auth., energy companies, research institutes etc.	Content Analysis, Search method Questioning, Interview
Which improvements need to be made along the supply chain to secure the further development of the hydrogen economy?	Possible knowledge gaps, policy structures, consumer behaviour, types of incentives, research programs, regulation	Primary Data People: gov. auth., energy companies, research institutes etc. Secondary Data published articles, reports, books and policy documents	Content Analysis, Search method Questioning, Interview

3.3.2 Interviews

A total of 15 interviews were conducted with actors from every phase of the hydrogen supply chain and representatives from government agencies and research institutions. These 45 to 60 minutes long interviews were used to validate previously found data during the literature review and to provide additional insights into areas with less available literature. At least two interview partners represented each of the three supply chain phases of production, transportation (transmission/distribution) and storage. Every interview had a semi-structured form, which allowed both pre-arranged questions for guidance and room for each interviewee's personal remarks. The different interview questions were formulated based on the previously mentioned TIS functions and their indicators, as seen in Table 1. By doing so, the different aspects of emerging socio-technological innovations, such as the hydrogen supply chain and -economy, were analysed and highlighted. Due to the different areas of expertise of the interviewees, a pool of possible questions was used to select the most appropriate ones for a specific role or sector. A list of questions assigned to the different functions and indicators can be found in the Appendix.

3.4 Data Analysis

After receiving the signed consent forms from the interviewees, the conversations were recorded for the purpose of transcription. For this task a voice recognition software (Amberscript) was used to create a text format. After correcting and summarising the content, a draft version was provided to the interviewee for revision and correction. Once the approved version of the transcription was received from the interviewee, coding was used as the main analysis method of the text files. For this task the coding software Atlas.ti 9 was utilised to highlight and arrange the different codes and code groups into a more simplified structure. By doing so, relevant passages of the interviews could be linked to the research objectives/questions and key concepts. By combining the standards used in the TIS framework with personal preferences, a stakeholder overview was created in chapter 4. This should act as a general overview of the involved parties, before the analysis with the TIS structure goes more into detail.

3.5 Evaluation of qualitative data

The three criteria for measuring the level of quality for qualitative data are validity, reliability and replicability. Validity in general, shows how appropriate the used methodology is to answer the research questions and whether this also holds true for sampling and analysing the collected data (Leung, 2015).

The criteria of validity can be summarised as the correctness, truth and strength of a statement. Validity is given when the chosen research method examines what it intends to investigate (Kvale, 2007). The criteria of validity can be divided into external and internal validity. External validity examines how a specific finding from a study can be generalized across other groups of people and how stable it stays in a different context (Allen, 2017). Due to the relatively small sample size of 15 interviews, external validity is rather low. With the help of triangulation, the external validity can be increased by reviewing scientific articles, company reports, and enterprises and organisations' web presence. In this case validity is increased by recording and transcribing the interviews with a certified transcription software. Besides that, every participant was provided with a preliminary version of the transcript for personal validation of the content. The interviewee itself reviewed the grammatically corrected interpretation of the software and an opportunity for clarification and modification was provided.

Reliability refers to how trustworthy and consistent the research findings are and is linked to the level of replicability. External reliability cannot be fully guaranteed because conducting the same interviews with different respondents at a different date would likely not deliver the same results. In these interviews, the level of reliability was also increased by triangulation and by taking notes, recording the conversation and transcribing it into a written format (Kvale, 2007).

4. Hydrogen economy and supply chain

This chapter aims to give a general understanding of the hydrogen economy and the current state of development for the supply chain elements of production, transmission/distribution, storage and demand of hydrogen in the Netherlands. Furthermore, it provides an overview of the most relevant stakeholder groups (4.2) and separately analyses the hydrogen supply chain phases and their structural dimensions through the TIS framework. Because the formation of the Dutch hydrogen economy has just begun recently, certain subpoints in this section, especially concerning transport and storage, are still strongly related or even defined by the natural gas system. This, however, will ultimately become the aforesaid backbone structure for the national and international supply with hydrogen. Therefore, the mentioned points for transporting and storing natural gas will eventually become relevant for similar processes with hydrogen.

Within the Netherlands, the northern part of the country is taking up a special role in the build-up of the hydrogen economy. At the end of 2020, government bodies and enterprises have published a comprehensive investment plan, outlining possible investments of around 9 billion Euro. While securing more than 60.000 jobs linked to the current gas infrastructure, this can also create 25.000 additional jobs by 2030 and another 41.000 jobs by the end of 2050. They will be situated mainly in the areas of operation and maintenance. (IPHE, 2020a)

Announcements of this kind inevitably raise the question of funding. The Netherlands Enterprise Agency (RVO) supports various institutes and organisations and by supporting entrepreneurial collaboration, networking and compliance with regulations and laws. It is an agency situated beneath the Ministry of Economic Affairs and Climate Policy (MINEZK) and commissioned by national ministries and the European Union (RVO, 2021c). The total energy research funding in 2019 amounted to 287 Mio. Euro, from which 5 % (14 Mio. Euro) were dedicated to hydrogen and fuel cell projects. Figure 2 shows the share of hydrogen-related funding of the last years with the number above the columns indicating the total energy research budget share.

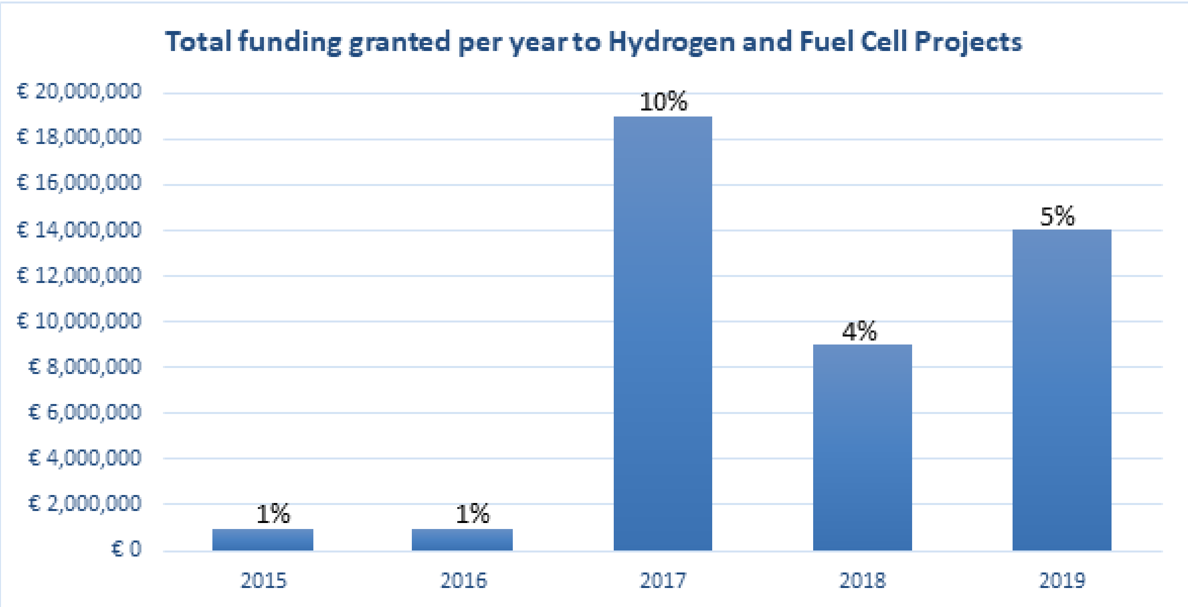


Figure 2: Total funding of Dutch hydrogen and fuel cell projects between 2015 and 2019

(Source: IPHE, 2020a)

4.1 Hydrogen economy

The desire and possibility for a hydrogen economy have been mentioned multiple times throughout the last two decades. The desire is usually related to the ongoing debate about climate change and its consequences for our environment, and energy security issues that arise due to increased population and economic activity (Agnolucci & Ekins, 2007). After a powerful development during the turbulent year 2020, hydrogen as an energy carrier is set to become a leading force in national and international efforts towards climate-neutral societies by the middle of the century. Its versatile portfolio of uses can support the energy transition by acting as an industrial feedstock material and therefore replacing fossil resources like oil, gas or coal. Next to the advantage of decarbonisation, this energy vector function of hydrogen can also be utilised to increase a regions, especially for a political and economic union like the EU, economic stability and efficiency on the global stage, with the help of innovative solutions (HydrogenEurope, 2021).

Hydrogen is the most frequently found element of the periodic system, but it can't be used directly in its atomic form unlike conventional energy sources like coal, gas or oil. Therefore, it has to be extracted from other molecules beforehand. It can release its stored energy either through combustion or in a fuel cell by redox reactions. This combination of being available in (a seemingly) abundant form and the very versatile portfolio of possible uses has resulted in the emergence of hydrogen hype-cycles, first with high expectations followed by the disillusioning truth of reality (WEC, 2019).

This was especially the case in the early 2000s, where the aftermath of the last oil crisis (1970's) and simultaneously the ratification of the Kyoto Protocol acted as strong drivers for the first real hydrogen hype (Moliner et al., 2016).

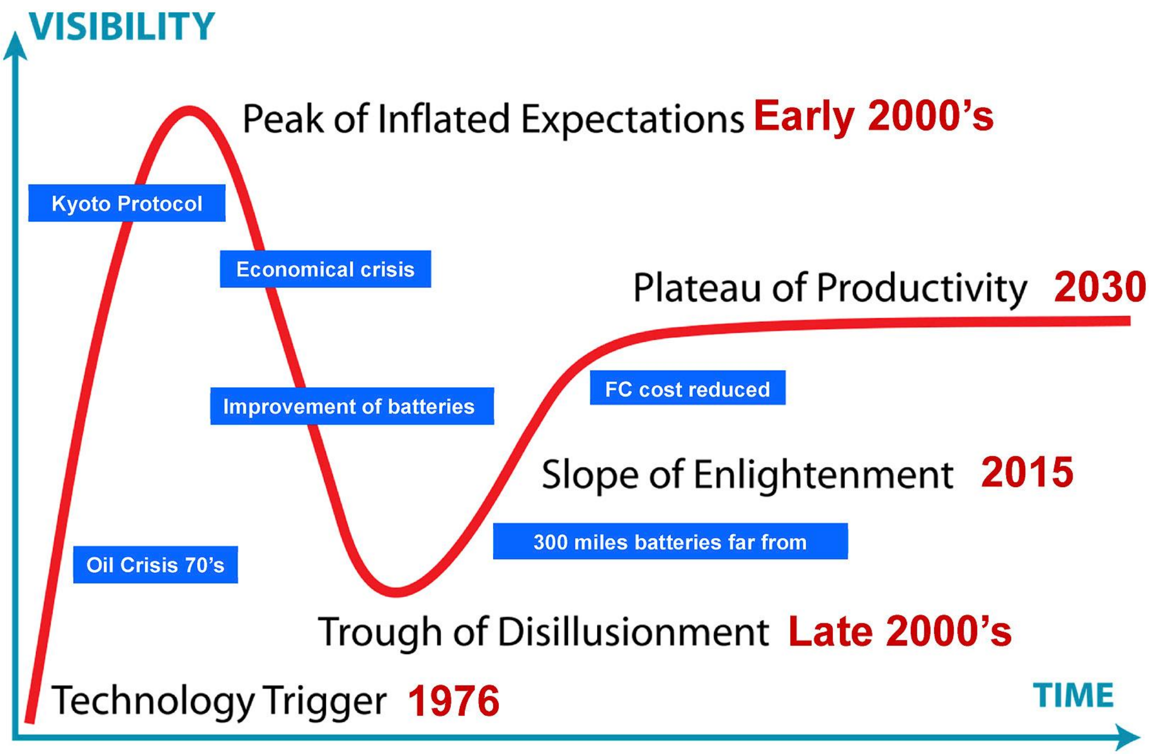


Figure 3: Timeline of hydrogen visibility (Moliner et al., 2016)

The significant difference between the last decade and the current situation is that major technological development has happened in recent years. This is currently paired with a strong socio-economic and environmental incentive in massive cost reductions and national/international development plans for the green energy transition. Geographical and climatic conditions, time periods, and types of applications are leading factors for governments and enterprises to formulate their respective goals and targets for decarbonising and transforming their long-term operational strategies (WEC, 2019).

However, a hydrogen economy can't evolve simply through the driving force of external geopolitical or environmental circumstances. Especially the economic part (markets etc.) requires certain preconditions to begin its development process. The Dutch Council for the Environment and Infrastructure (Rli) describes in its newest report that without a solid overarching legal framework throughout the supply chain, hydrogen-related technologies and services will struggle with an area-wide dispersion throughout countries or even smaller regions. As this is a highly complex socio-technical transition process, the question of public acceptance arises. The authors mention a strong need for governments to thoroughly inform and prepare the general public for significant changes in certain parts of their everyday life. This has to include technical details about new appliances and the fact that a share of the costs arising during the transition period will have to be covered by everyone. Lastly, the safety issue concerning the highly volatile and flammable hydrogen molecules needs to be tackled in a thoughtful way. Introducing a set of new safety standards and certifications for purity/quality will be inevitable for the large-scale implementation of new hydrogen technologies. Here, active public participation is seen as a helpful instrument to gain trust and acceptance from society (RLI, 2021)

Agnolucci and Ekins (2007) conclude that like any other (mainly) technologically based transition, the transition towards a hydrogen economy can only be successful if both the physical and socio-economic function is fulfilled. In a predominantly market-based economy, this means a robust competitive force from well-established fossil-fuel-based technologies that currently enjoy the advantages of being mature solutions with a highly developed infrastructure and strong legislative background to support them. Therefore, major investments, transacted over long time periods, will be needed to situate new technologies and habits into a social and economic context to grow into mature and accepted new regimes under beneficial circumstances (Agnolucci & Ekins, 2007).

4.2 Stakeholder overview

The following paragraph presents the stakeholders of the Dutch hydrogen landscape, based on the supply chain phases. The members of the six identified stakeholder groups and their functions are further explained below. This overview aims to provide an understanding about why certain interview partners were selected for qualitative data collection.

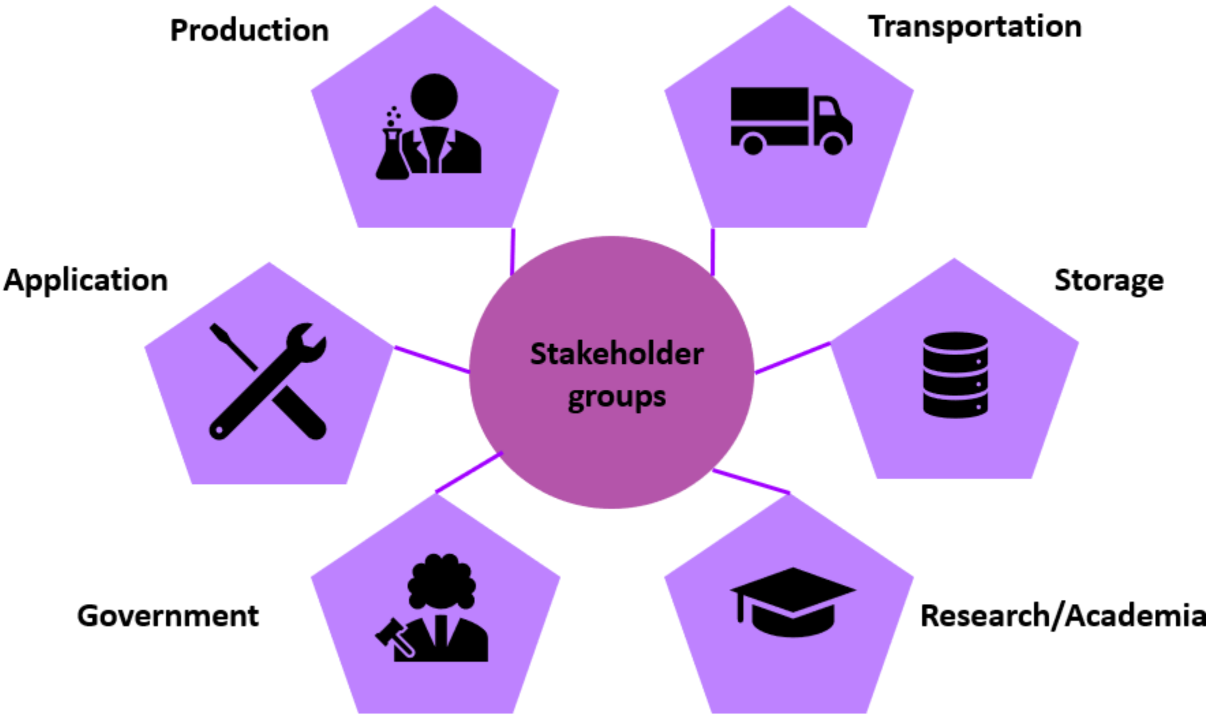


Figure 4: Overview of stakeholder groups

Producers of hydrogen can be grouped depending on the type of hydrogen they supply. In the Netherlands, hydrogen is mainly produced in industrial cluster zones using fossil sources and the steam methane reforming (SMR) process without any downstream carbon capture technology (DNV, 2019). Companies in the oil and gas and chemical sectors have been using this grey hydrogen for a long time in their production and refining processes. Today they represent both the largest producers and consumers of hydrogen on the market. Suppliers of blue hydrogen can also be seen as grey hydrogen production facilities but with the important difference in using carbon capture and storage solutions to prevent carbon emissions from entering the atmosphere. Blue hydrogen projects in the Netherlands are still in the early phases of their development but are expected to contribute significantly to shorter-term emission reduction in the Rotterdam Port area (RVO, 2021). Green hydrogen projects are based on the electrochemical conversion of water into hydrogen, using renewable electricity. They are globally on the uprise but are mostly still fighting economic and regulatory difficulties. Hydrogen from renewable sources is seen as an excellent opportunity to realise deep decarbonisation of our global energy consumption through many possible application areas (Staffell et al., 2019). Currently, only one Dutch project is listed as actively producing green hydrogen on a commercial scale (TKI Nieuw Gas, 2021a).

Transportation, including transmission and distribution, of hydrogen can happen in different aggregate states, depending on the amount needed, intended use, transportation distances, and demand urgency. Large scale transmission and distribution of gas in the Netherlands lies in the hands of the TSO Gasunie Transport Services (GTS) and the regional DSOs with the different high-, medium- and low-pressure pipeline networks. Local pipelines, mainly connecting industrial plants, are also being used in the Netherlands and certain cross-border areas (DNV, 2019). If smaller volumes are required, other actors from the transportation sector can take over the task by providing pressurized cylinder tanks, tube trailers or liquid hydrogen containers. If the transportation distance increases substantially and pipelines can´t be utilized, large vessels of shipping companies can be used to carry hydrogen in a pure, liquified form or chemically bound to a liquid organic hydrogen carrier (LOHC), like methanol or ammonia. This allows hydrogen to be stored and transported with a much higher energy density than in its gaseous state (Gasunie, 2019). However, only a small number of large-scale hydrogen transport projects are currently being pursued on the Dutch market, focused on either building new or repurposing old pipelines transportation (TKI Nieuw Gas, 2021a).

Stakeholders within the *storage* part of the supply chain can partially be linked to some representatives of the transportation domain. Short-term and small-scale storage can happen in pressurized gas tanks or even cylinders containing liquified hydrogen, which can then be moved in case of rising demand at a different location. Research concerning hydrogen storage in the Netherlands is mainly aimed at large-scale facilities of the TSO for gas, in the form of salt caverns or depleted gas fields of major energy companies. Additional opportunities can arise from providers of large-scale tank storage that are now located on the premises of major ports along the Dutch coast (TKI Nieuw Gas, 2021a). Additional new storage opportunities are currently being researched by a small number of universities and companies. These efforts are done in the areas of nano carbon materials and organic and metal hydrides, using both lower and higher temperatures (Yartys & Lototsky, 2004).

Research and knowledge institutions act as continuous suppliers of innovative solutions and often function as a binding element between the private sector and governmental (funding) institutions. In the Netherlands, they are actively supported by a dense network of Top Sectors and their respective consortia of knowledge and innovation (TKI), which stimulate cooperation between the government, research institutes, funding agencies and social institutions (Topsector Energie, 2021a). NOW and RVO act as the leading national funding bodies, depending on the type of research project and its TRL. Once funding has been decided, TS and the TKIs take over to facilitate the cooperation process between the different stakeholders by setting an innovation strategy, providing opportunities for networking and communicating with the public. For hydrogen- and energy-related research, the Netherlands Organisation for Applied Scientific Research (TNO) is currently the most important Dutch research and knowledge institution (Energy advisor M). This also includes the Energy Research Centre Netherlands (ECN), which recently merged into TNO.

A multitude of stakeholders on the *application* side of the hydrogen value chain ensures a steady consumption of the produced hydrogen. Especially the transportation sector is seen as suitable for implementing a wide range of hydrogen-powered vehicles. On a small scale, this is already happening in passenger cars, heavy-duty trucks and trains and is expected to be expanded towards the aviation and marine industry in the following decades. Besides that, the usage of hydrogen for low-emission industrial processes is expected to take off in an accelerated way. By providing a feedstock material and heating energy for low-/high-temperature heating purposes as well as the possibility to generate clean electricity through using new hydrogen- or existing gas boilers, hydrogen offers a wide range of possibilities for various industry sectors. This can help replace vast amounts of fossil fuels, which still account for roughly 75% of the global industrial fuel mix and causes around 20% of direct greenhouse gas emissions. Electricity generators can benefit from hydrogen both in the form of fuel cells for flexible peak demand production and the possibility of burning hydrogen in gas turbines for the production of combined heat and power (CHP) but with lower efficiency and higher costs included (Staffell et al., 2019)

The *government* and its different institutions are responsible for setting the legal and regulatory playground for a country's energy policy. Both the parliament with the various ministries and committees and independent regulators linked to the government are part of this stakeholder group. Governmental institutions have to ensure constant environmental and social justice by utilizing the innovative power of clean energy technologies democratically and inclusively (Burke & Stephens, 2018). Furthermore, the government has to ensure that the general public is involved at the local, regional, and national levels in the decision-finding processes. This concerns the development and operation of renewable energy generation facilities, transportation and storage infrastructure and application options as an end-user. The ultimate goal with this is to assert that benefits from the products and services generated are reaching members of society (Burke & Stephens, 2018). The Dutch government has introduced a national hydrogen strategy as an essential cornerstone of its clean energy and decarbonisation efforts for the coming decades. This major public-private partnership undertaking is based on a policy agenda of four main pillars to enable a comprehensive hydrogen supply chain. These are legislation and regulation concerning existing and prospective infrastructure, major cost reduction and financial support for developing and operating hydrogen facilities, making the final consumption more sustainable and support policies for international cooperation and research activity (Rijksoverheid, 2020).

4.3 Analysis of supply chain phases

The following subsections discuss the current state of development of the four hydrogen supply chain phases in the Netherlands. This general analysis is complemented by section 4.4, where the TIS approach examines the three structural dimensions more thoroughly.

4.3.1 Hydrogen production

Due to the significant natural gas resources and an expected transition period on the road towards a fully developed hydrogen economy, fossil fuel-related activities will continue to play an important role in the energy transition efforts of the Netherlands. With subsequent capturing of CO2, the production of blue hydrogen from natural gas is an attractive opportunity to bypass the currently still underdeveloped and cost-inefficient green hydrogen industry.

Besides its neighbour Germany, the Netherlands is currently the second-largest producer of hydrogen in Europe. One of the latest estimates for the total annual production volume is around 16 billion cubic meters (bcm), which equals 48.8 TWh, 1.5 Mton or 175 petajoules (PJ) per year (DNV, 2019). In 2019 the (grey) hydrogen production plants in the Netherlands consumed around 10% of the total Dutch natural gas demand, which resulted in emitting 7 million tonnes of CO2. This is equivalent to 5% of all energy related emission in the Netherlands (International Energy Agency, 2020). Other sources (Weeda & Segers, 2020) mention a total supply of 180 PJ where hydrogen as a pure product, by-product and part of other residual gas mixtures is included. In this case, the pure form of hydrogen and the residual gas form account for 150 PJ in total. The two main production routes are either through steam reforming of natural gas (105 PJ) or through desulphurisation of oil products (70 PJ) in refineries.

Here the total estimated volume is roughly 16.7 bcm, which accounts for 1.5 Mton per year(Weeda & Segers, 2020).

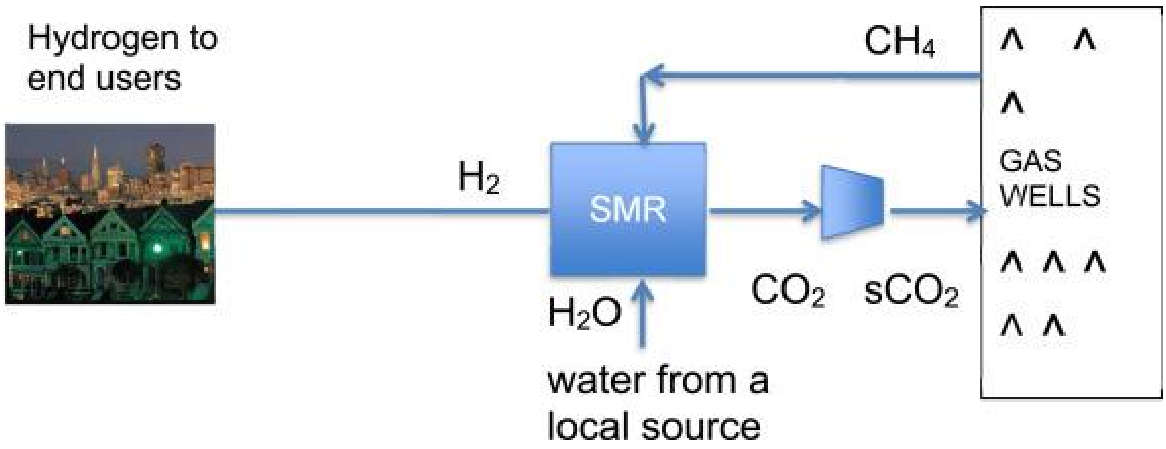


Figure 5: Steam methane reforming process with downstream CCS (Andrews, 2020)

The difficulty of gathering data about concrete amounts of supplied and used hydrogen comes from the fact that currently, hydrogen does not have its own entry in the Dutch energy statistics. This happens because it is not used for direct energy production purposes in the different end-use sectors and mainly produced on-site for captive use. However, it is part of the energy statistics as it is produced almost entirely from fossil fuels. The extraction of data on hydrogen is, therefore, tricky (Weeda & Segers, 2020).

The previously mentioned estimates by DNV GL (2019) were based on an extensive report from the Roads2Hycom (2007) project and recalculated due to increased economic activity in the main geographical areas of use. The report focuses on the five biggest industrial clusters of the Netherlands, namely Eemshaven, IJmond, Maasdelta, Zeeuws-Vlaanderen and Limburg. This increase of almost 60 % (from 110 PJ to 175 PJ) can be traced back to the build-up of additional hydrogen-producing facilities, mainly in the petrochemical sector around the Maasdelta region, and previously underestimated assumptions in the fertiliser industry (DNV, 2019). Figures 6 and 7 visualise the estimated difference per cluster and the geographical distribution of production.

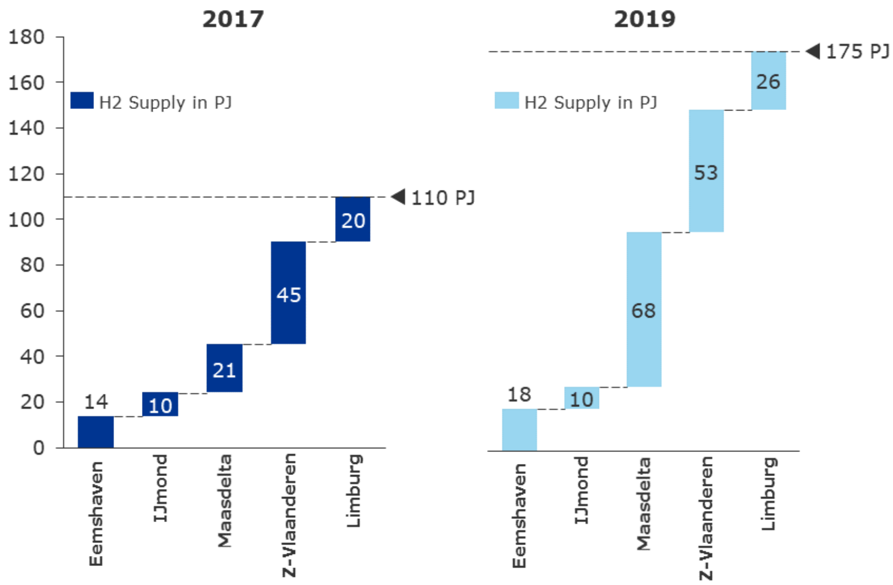


Figure 6: Differences in hydrogen production per industrial cluster (DNV, 2019)

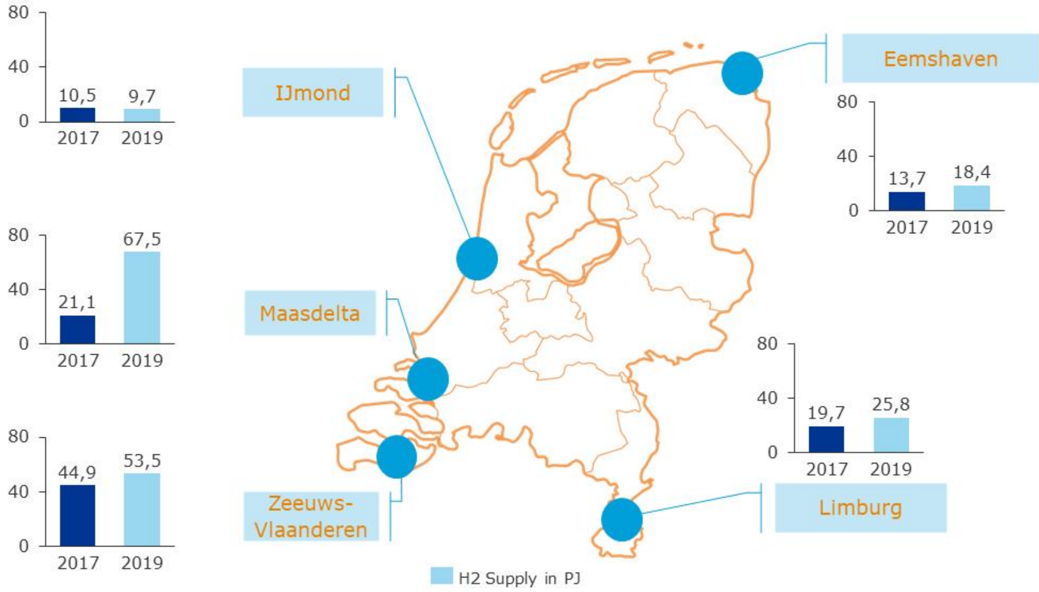


Figure 7: Geographic distribution of hydrogen supply in the Netherlands (DNV, 2019)

There is currently very low fluctuation between hydrogen supply and demand in the Netherlands due to a well-balanced production and consumption in the industrial clusters. (Gasunie, 2019). Based on the numbers from the report of DNV GL (2017), a small amount of around 9 PJ/year is exported to neighbouring Belgium and further on to France, while an even smaller share of around 1 PJ is imported (Detz et al., 2019). Due to the increased activity mentioned above, these numbers are likely to be somewhat higher by now. This slight fluctuation is the explanation for predominantly domestic production and captive use on industrial sites that is currently taking place in the Netherlands (Weeda & Segers, 2020).+

According to an overview provided by TKI Nieuw Gas (May 2021), there are currently around 40 projects being pursued throughout the Netherlands, which can be linked to hydrogen production. Most of them are still in their earlier phases of development, such as concepts, feasibility studies or business case development, but some larger ones are already in the execution (e.g. HEAVENN) or commissioning (e.g. HyStock) stage. These projects show a solid interdisciplinary character where production, storage and transportation issues are handled simultaneously, aiming for both industrial and non-industrial uses (TKI Nieuw Gas, 2021).

Currently, the only commercially operated green hydrogen production project in the Netherlands belongs to the country's gas transmission system operator Gasunie and is situated on the premises of their natural gas storage facility in Zuidwending. With a total hydrogen production capacity of 1 Megawatt (MW), this power to gas installation uses 100 % renewable energy from ca. 8500 solar panels to power its electrolyser units. A set of three sea containers is used to host the electrolyser, the electronic equipment and the gas compressor for filling tube trailers with hydrogen. A distribution station from TenneT, the electricity transmission system operator of the country, ensures the safe supply of electricity. Power can come from either national sources or through transnational cables from wind farms in Denmark or Germany (AGBZW, 2021a).

4.3.2 Transmission and distribution

The typical industrial clusters of the Netherlands currently lead to a geographically concentrated bulk demand for hydrogen (Detz et al., 2019). Having a large number of both producers and consumers within close proximity has the advantage of shorter distances for transport. Another positive side effect of large industry-oriented infrastructure is that a decentralised demand for low-temperature heat (built environment) and mobility fuel can strongly benefit from this system (ISPT, 2019a)

The currently operated Dutch pipeline infrastructure for hydrogen consists of a network owned by Air Products (140 km) in and around the Port of Rotterdam and a more extensive network from Air Liquide that stretches from Rotterdam through Belgium to the northern part of France (Weeda & Segers, 2020). A separate network is used in Germany close to the Dutch border. Altogether, these pipeline systems have a length of around 1200 km, which accounts for approximately 75% of the total European hydrogen pipeline network currently in use (H2Tools, 2016). Figure 8 gives an overview of the pipeline systems in the Netherlands and adjacent regions.

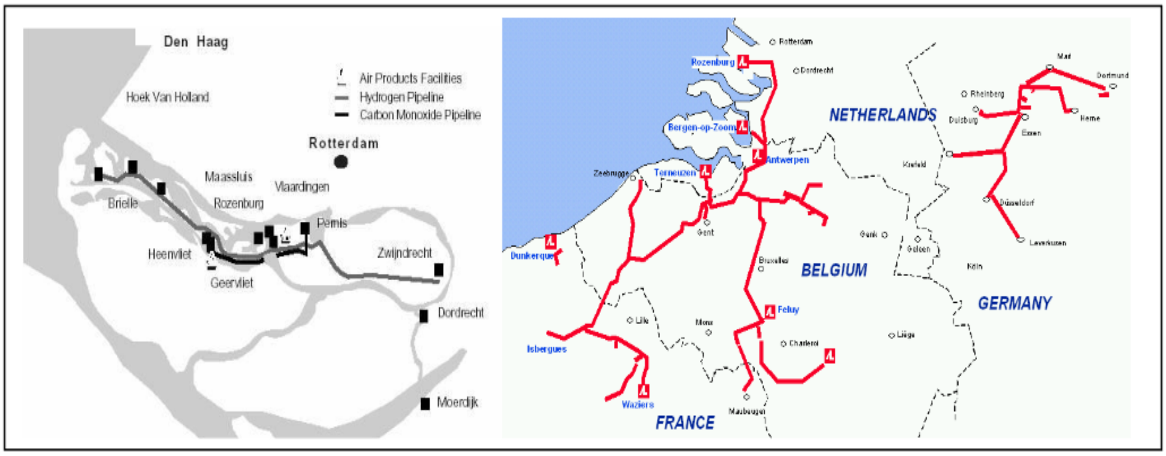


Figure 8: Hydrogen pipelines in the Netherlands and neighbouring regions (DNV GL 2017)

Following the extension and repurposing of the current pipeline infrastructure, the Netherlands aims to connect many smaller-scale end-users to the main hydrogen backbone in the future. Figure 9 illustrates the anticipated hydrogen backbone structure with the main branches running towards the previously mentioned industrial clusters. Besides the high-pressure transmission pipeline system, owned and operated by Gasunie and Gasunie Transport Services (GTS), the Netherlands is also home to an extensive distribution system network for natural gas. This lower pressure grid is managed by 7 (see Figure 10) distribution system operators (DSOs) and currently has a total length of over 124.000 km, connecting more than 7 million customers (ISPT, 2019b).

Figure 9: Anticipated hydrogen backbone network of the Netherlands
(https://www.theworldofhydrogen.com/gasunie/infrastructure/)

Figure 10: Distribution system operators for natural gas in the Netherlands (https://www.energieleveranciers.nl/netbeheerders/gas)

At the end of June 2021, an important milestone was reached for the Dutch hydrogen backbone network. After reviewing the HyWay 27 report, the MINEZK announced that the Government sees it as safe, cost-efficient and feasible to continue developing the pipeline network. Furthermore, the announcement specifically mentioned the need to use existing pipelines for hydrogen transportation after repurposing and upgrading them. This means that TSO Gasunie will be given the task of introducing large-scale CO2-free hydrogen into the national pipeline grid to transform the Dutch energy system (Rijksoverheid, 2021).

4.3.3 Gas storage

Energy storage will play a crucial role in the future, where high amounts of fluctuating green electricity will be a central element of our energy system. The daily and seasonal use of energy, especially gas, in the Netherlands is subject to fluctuations of different magnitude. While the daily differences are relatively small, the seasonal examination shows a much higher fluctuation, mainly linked to increased heating energy demand during the colder months of the year. (Visser, 2020).

4.3.3.1 Reasons for storing hydrogen

The rising share of renewable energy in the total energy mix and the ambitious European targets of 2050 make the storage of energy increasingly more important. Energy from power plants with variable production patterns can currently only be stored on a large scale and efficiently if it is converted into a non-electric form. This has the advantage that in case of overproduction (lower demand) electricity can be transformed into, for example, hydrogen for short- or long-term storage. On the other hand, when demand is reaching its peak, previously stored energy can be released from storage facilities and converted back into the required electricity (Preuster et al., 2017). By storing energy in a chemical form, a stabilization of electricity grids and a secure energy supply can be facilitated simultaneously. In case of hydrogen a number of different storage options already exist on the market. Depending on the storage period, transportation distance and types of usage, hydrogen can be stored both in (compressed) gaseous (CGH2) and liquefied form (LH2). If physical storage methods cannot be utilized, material-based solution, such as metal hydrides or liquid organic hydrogen carriers (LOHC) are alternative options (Shell & Wuppertal Institut, 2017). Hydrogen also brings the advantage of having favorable chemical properties for storage. In a liquified form its gravimetric (mass-based) calorific value exceeds the one of other liquid hydrocarbons by a factor of almost three. On the other hand, the volume-based calorific value is very low under ambient conditions, which makes in increase in calorific value through compression necessary. Figure 11 shows the volumetric and gravimetric energy density (as the lower heating value) of hydrogen compared to other hydrocarbons.

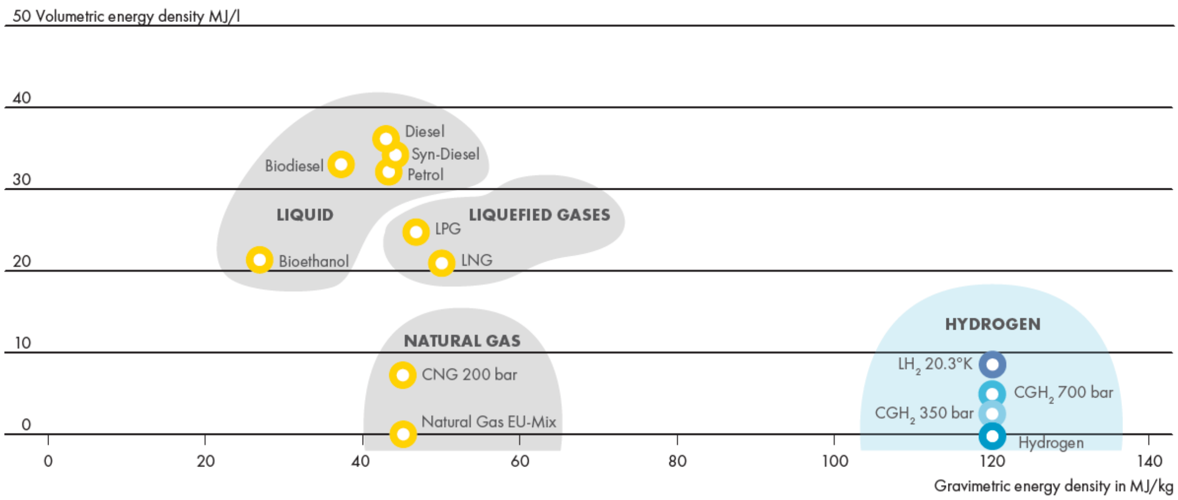


Figure 11: Volumetric and gravimetric energy densities (lower heating value) of fuels and energy carriers (Shell & Wuppertal Institut, 2017)

Storage of hydrogen can happen in different types of presseured vessels, such as spherical or tube tanks and pipeline storage, both under and above ground (Andersson & Grönkvist, 2019). In case large-scale storage of industrial dimensions is required, salt caverns, depleted oil and gas fields or aquifers can be utilized. Salt caverns are considered as the currently most viable option out of the three mentioned (Shell & Wuppertal Institut, 2017)

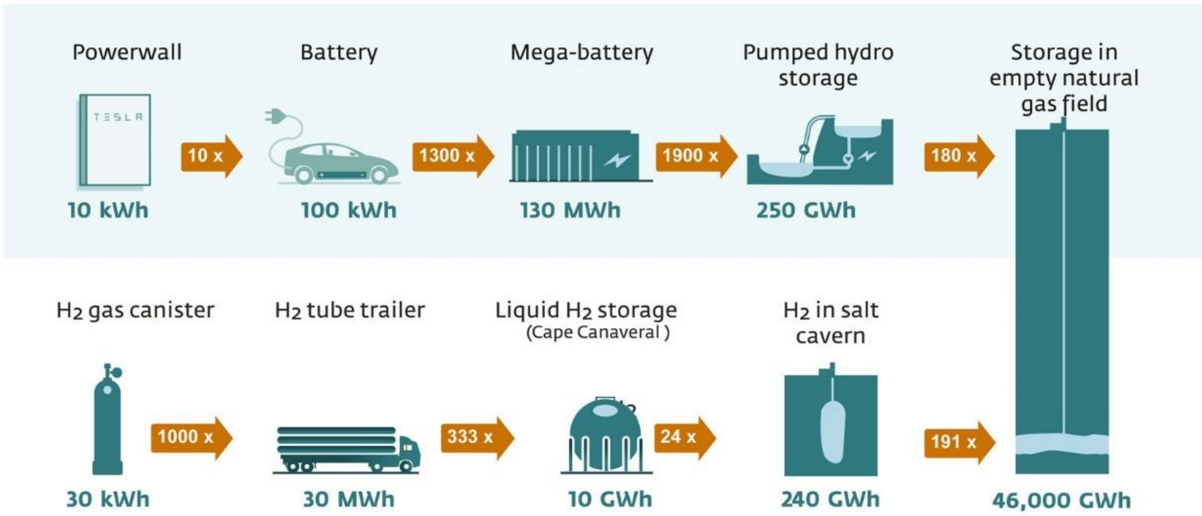


Figure 12: Storage and transport options for hydrogen in comparison to electricity (https://www.theworldofhydrogen.com/gasunie/infrastructure/)

4.3.3.2 Gas storage in the Netherlands

Currently, there are seven locations in the Netherlands where large-scale underground storage for natural gas, nitrogen and diesel is allowed. Substances like CO2 or hydrogen are not yet stored in subsurface areas of the Netherlands (SodM, 2021a). The daily and seasonal differences in energy demand can partially be compensated by keeping excess gas stored in underground reservoirs during times of lower demand, as it has already been done in the Netherlands for decades. Natural gas is currently stored in one of four depleted gas fields (porous reservoirs) or two constructed salt caverns (Netherlands Enterprise Agency, 2017).

Figure 13 gives an overview of the geographical locations of gas storage facilities in the Netherlands. Presently, only a handful of research projects are involved in the storage of hydrogen in the Netherlands. As underground hydrogen storage is still not actively pursued in the Netherlands, current storage-related projects focus more on short term storage in tanks or tube trailers as mobility fuel for cars, trucks or buses (TKI Nieuw Gas, 2021).

Figure 13: Underground gas storage areas in the Netherlands (RVO, 2017 based on http://www.nlog.nl/en/map-production)

As mentioned above, underground hydrogen storage in the Netherlands is still in its first phase of development. The only project where storage is actively researched and tested is located in the northeastern city of Zuidwending. Here Gasunie and its subsidiary EnergyStock are in the process of developing four additional salt caverns for hydrogen that have a total storage capacity of 20 kilotons. These caverns will be conveniently located next to existing caverns where natural gas storage has been practised for decades. Besides that, the future hydrogen backbone network will also be connected to this facility, allowing a direct injection into the grid in case of peak demand. After concluding the feasibility study in 2020, it is expected that the first test in a borehole of the future cavern will commence this year (Gasunie New Energy, 2021).

Besides the important technical part, the development of such a large-scale storage facility also requires careful examination of current and future market needs and environmental issues. The feasibility study has shown that the first need for hydrogen storage could be in 2026, which means that the preparation of different installations has to commence in 2023/2024 at the latest. There are permits for ten caverns to be developed, of which six are already in use for storing natural gas. Figure 14 shows the areal view of the storage facility with positions of the different caverns (AGBZW, 2021b).

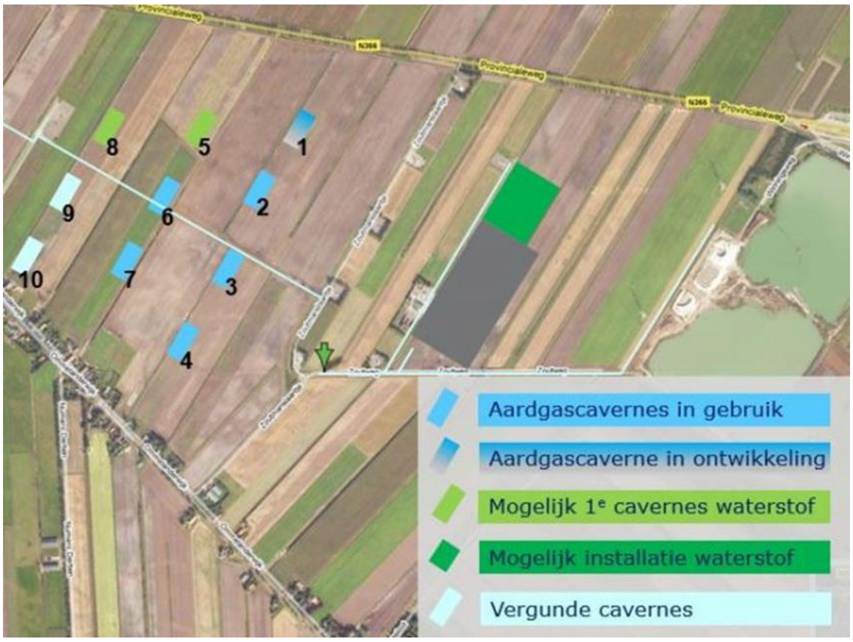


Figure 14: Areal view of the gas storage facility in Zuidwending (AGBZW, 2021b)

4.3.4 Consumption

Today, demand for hydrogen is strongly concentrated on a small number of industrial sectors, including oil refining, ammonia, methanol and steel production. Together they account for around three-quarters of the global hydrogen consumption (IEA, 2019). Consumption of hydrogen in the Netherlands follows similar patterns, as seen in Figure 17. Besides that, a number of other demand technologies are being developed in the sectors of mobility, built environment and energy production, but most of these applications are still in their early stages of development, such as demonstration projects or prototypes (IEA, 2020). Within the chemical industry, the oil refining sector acts as the largest single consumer for hydrogen these days. Refineries use hydrogen mainly for desulphurisation or hydrocracking during purification or upgrading processes of hydrocarbons. Supply of these large amounts of hydrogen can either happen through the production of by-products, local steam methane reforming, merchant supply or coal gasification (IEA, 2019). Figure 15 shows the percentage of different supply alternatives for selected regions.

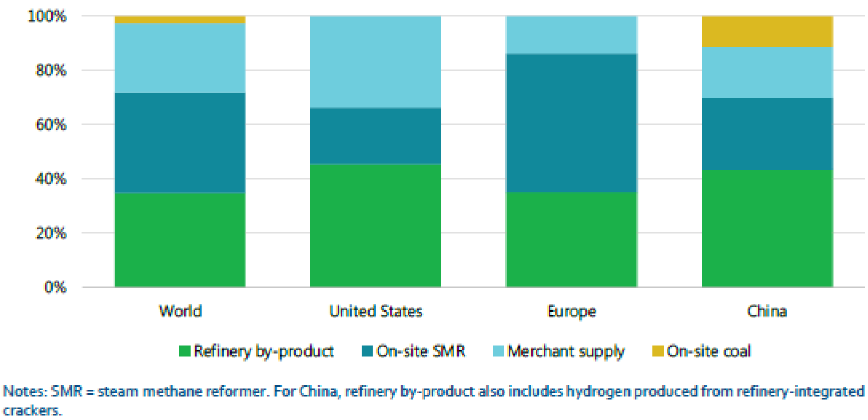
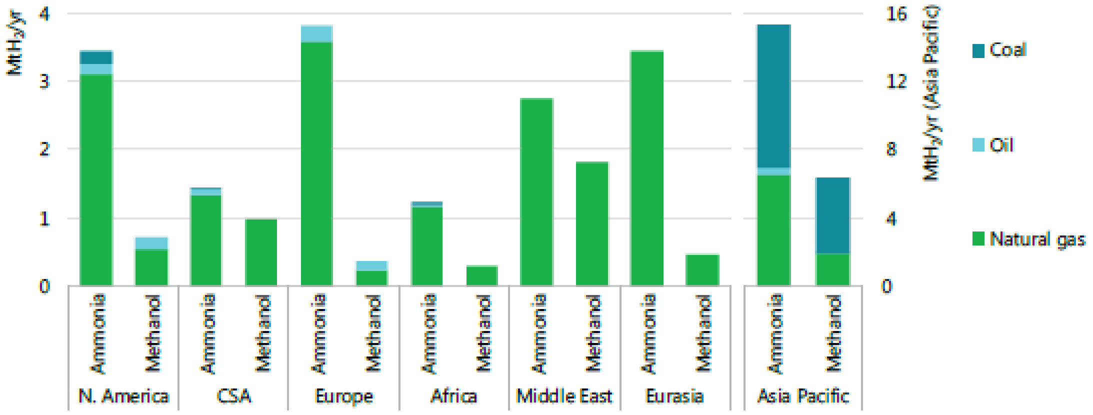


Figure 15: Sources of hydrogen supply for refineries (IEA, 2019)

The chemical industry itself, is the branch of industry with the largest use of hydrogen. Here it is often used as feedstock material in methanol and ammonia production, and it is also found in the molecular structure of almost all primary chemicals. Supply happens almost entirely through either natural gas- (65%) or coal-based (30%) production, with the former being the more efficient way. This accounts for roughly 270 million tons of oil equivalent (Mtoe) of fossil fuels (2018) to produce the required hydrogen for these two sectors and is equivalent to the yearly oil demand of Russia and Brazil combined (IEA, 2019). Figure 16 shows the hydrogen demand for methanol and ammonia production in different regions of the world.



Notes: Only production routes comprising > 1 Mt/yr of primary chemical production are included; oil refers to refined oil products including naphtha and LPG. CSA = Central and South America. Data for 2018 are estimates based on previous years' figures from the sources below.

Figure 16: Hydrogen demand for methanol and ammonia production in 2018 (IEA, 2019)

In the case of the Netherlands, demand for hydrogen follows the same patterns as the previously mentioned regions of the world. Industrial activities in the oil and gas and chemical industry have the highest demand for pure hydrogen, with oil refinery accounting for 37% and ammonia production for 32 % of the total amount. A wide range of other industries uses most of the remaining amounts of hydrogen. This includes, among others, the food industry, metallurgical industry, glass industry and electronic industry (Weeda & Segers, 2020). Figure 17 shows the amounts of hydrogen used by the primary application types in the Netherlands.

Application type	Estimated amount of hydrogen		
	bcm/y	kton/y	PJ/y (LHV)
Ammonia [a)]	5.3	480	58
Refinery [b)]	6.0	544	65
Other pure hydrogen use [c)]	1.6	143	17
Methanol [d)]	1.1	102	12
Fuel gas [e)]	2.6	231	28
Total	**16.7**	**1,500**	**180**

[a)] SMR-natural gas

[b)] SMR-natural gas and refinery gas; Shell Gasifier; Naphtha catalytic reforming

[c)] SMR/ATR-natural gas; by-product chlor-alkali; water-electrolysis

[d)] SMR-natural gas

[e)] Various catalytic reforming; naphtha steam cracking; by-product chlor-alkali; Flexicoker fuel gas (but excluding small fractions of hydrogen that may be present in other residual refinery gas) and coke oven gas.

Figure 17: Overview of estimated industrial hydrogen use in the Netherlands in 2019

(Weeda & Segers, 2020)

Another promising sector for future large-scale hydrogen demand are light- and heavy-duty vehicles for the transportation of people and goods (Staffell et al., 2019). Next to electric vehicles and biofuels, this represents another way for low-carbon vehicle movement. This is especially important because, unlike other industrial sectors (e.g. electricity production), the transportation industry is expected to decarbonise at a much slower rate. At the same time, cost-effective technologies will take longer to disseminate (Staffell et al., 2019). Whether hydrogen and fuel-cell technologies will develop as expected is strongly dependent on further increase in competitiveness, especially in terms of costs for fuel cells and the network of refuelling stations (IEA, 2019). Competition for light-duty vehicles in road transport means that (battery) electric vehicles are expected to grow faster in numbers than heavy-duty vehicles due to the more difficult electrification of the latter (Detz et al., 2019). In the Netherlands, there are currently approximately 350 vehicles equipped with a fuel cell, including buses, trucks and cars, and a refuelling network of 6 stations (IPHE, 2020a). Besides the few existing hydrogen and fuel-cell vehicles, there are still limited options for introducing low-carbon fuels into the marine and aviation industry. Even though hydrogen can reduce the negative environmental impacts of large ships and aircraft, high costs of production compared to conventional fossil fuels make them less attractive for the near future (IEA, 2019). Figure 18 describes the different options for hydrogen use in the transportation sector, based on their level of technology readiness.

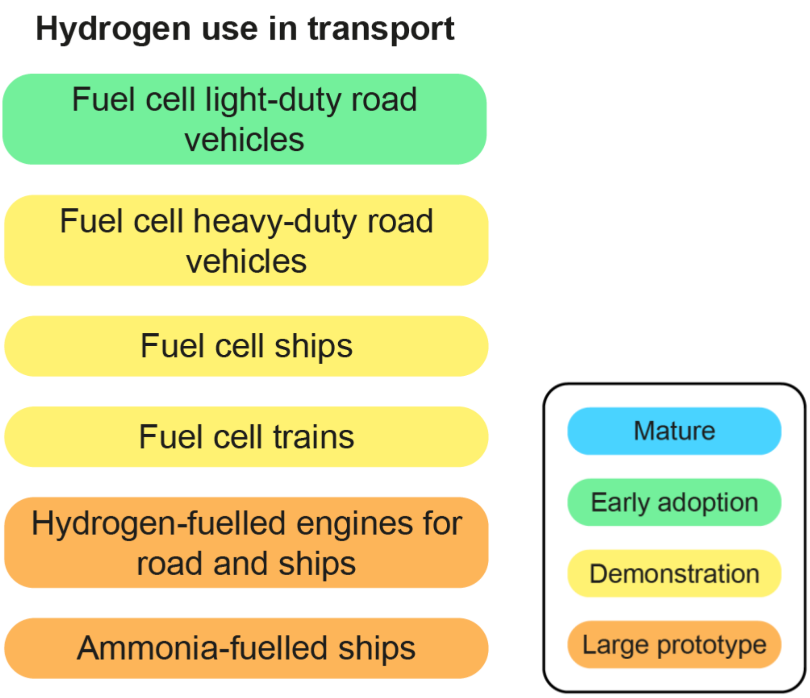


Figure 18: Technology readiness level of hydrogen transportation technologies (IEA, 2020)

Compared to the current energy use of the national transport sector (ca. 400 PJ/y), studies project an average hydrogen use of around 160 PJ/y. If fuels for international shipping and aviation are considered in the form of synthetic hydrocarbons made from carbon dioxide and hydrogen, the demand for hydrogen can surpass 700 PJ/y by 2050 (Detz et al., 2019).

Specific amounts of hydrogen used for other applications, such as the built environment and power generation, are currently unavailable in the Netherlands because only local, small-scale demonstration projects exist without official data gathering. However, predictions show a substantial increase for all mentioned application sectors towards 2050. One possible development curve for the demand side is shown in Figure 19, with the expected order (1 to 6) of application areas. Besides the previously mentioned sectors of industrial feedstock and mobility solutions, hydrogen is also expected to be used as a fuel for electricity or heat production in residential and/or industrial environments. However, every conversion step leads to additional loss of energy which means that direct power or heat generation will likely happen only in case large amounts of surplus hydrogen is available. To illustrate the ongoing development on the Dutch hydrogen demand side, Figure 20 gives a geographic overview of projects.

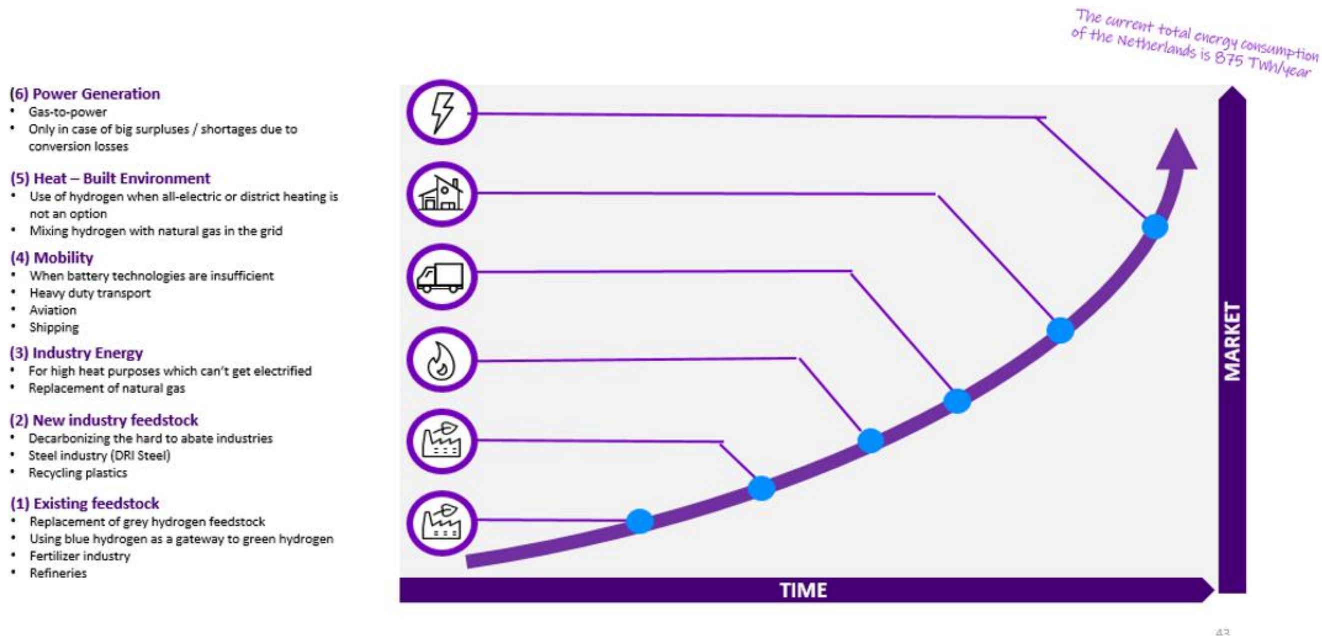


Figure 19: Expected demand development by application sectors (Accenture, 2021)

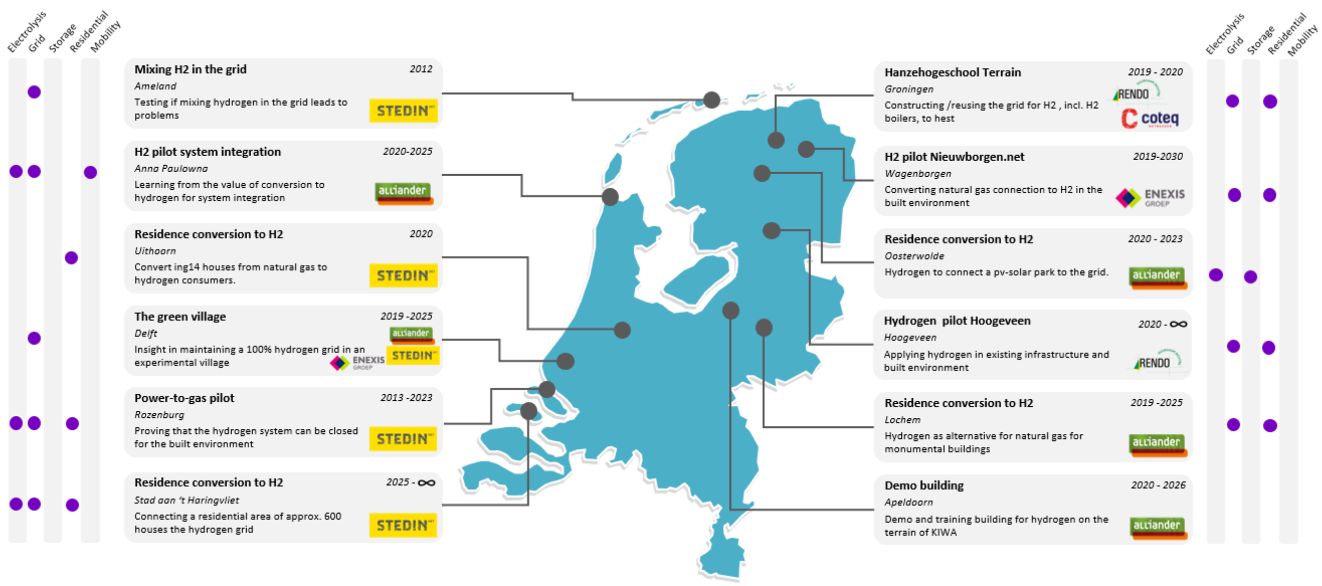


Figure 20: Overview of current and future hydrogen consumption initiatives in the Netherlands (Accenture, 2021)

4.4 TIS structural dimensions

The following paragraphs further examine the Dutch hydrogen supply chain by utilising the three structural dimensions of actors, networks and institutions from the TIS framework. They aim to act as a supplement to the more general stakeholder overview and supply chain analysis of the previous sections.

4.4.1 Actors

This section highlights the important actors concerning the hydrogen supply chain and, ultimately, the future hydrogen economy. As mentioned at the beginning of chapter 4, in the current situation, only a limited number of actors (and also networks and institutions) can be linked directly and exclusively to the hydrogen sector. As natural gas-based solutions still count as the status quo in the Dutch energy landscape, the corresponding entities are strongly represented in the following sections. However, most of the mentioned actors, networks and institutions already have or will have a strong influence on the slowly emerging hydrogen-based energy system in the Netherlands.

4.4.1.1 Governmental agencies

Industrial activities related to oil and gas extraction in the Netherlands fall under the auspices of the MINEZK. It is supported in this process by the troika of the Dutch state participant Energie Beheer Nederland (EBN), the State Supervision of Mines (SSM) and the Advisory Group of Economic Affairs. The latter is situated within the Netherlands Organization for Applied Scientific Research, known as TNO (EBN, 2018). This is relevant because every activity concerning the extraction of subsurface (gaseous) materials falls within the Ministries' circle of influence. Due to the predominantly grey hydrogen production, the Ministry and the SSM also strongly influence the downstream use of these substances.

The jurisdiction of SSM ranges through several different sectors, such as the gas networks, oil and gas extraction, underground storage and offshore wind energy. This multitude of roles gives SSM, an independent regulator for energy and mineral extraction, a major influencing power. Its main task is the supervision of compliance with regulations and laws especially concerning environmental protection and safety issues. This supervisory role is accomplished by regular visits to companies or construction sites. With this inside knowledge, SSM acts as an important advisor to the MINEZK. In case of incompliant behaviour from the supervised party, the SSM can take action against it in the form of warnings, penalties or even ordered shutdowns of certain installations. Ultimately, after informing the Ministry about the misbehaviour, permits can be withdrawn, and public prosecution can be initiated as the last step (SodM, 2021c).

Another government holding is Energie Beheer Nederland (EBN) which acts as a non-operating partner in most projects related to oil and gas in the Netherlands. Its main role is contributing know-how, capital, infrastructure and expertise towards a more sustainable gas value chain in the Netherlands. This should ensure a steady reduction of CO2 emissions and pave the way for a carbon-neutral Dutch energy system. Besides continuing with actions supporting natural gas extraction, EBN is also committed to developing storage opportunities for CO2 and hydrogen and green gas production. This is done as one of the strategic pillars and has led EBN to switch roles from being a silent partner to contributing knowledge, funding, and a professional network (EBN, 2021).

In terms of energy market regulation, the Netherlands Authority for Consumers and Markets (ACM) acts as the main independent regulator. Its goal is to represent consumers and businesses by championing their rights. The ACM also ensures a sector-specific regulation and the enforcement of consumer protection laws. Its aim is the creation of a level playing field where enterprises adhere to their rules and consumers can exercise their rights freely and in a well-informed way (ACM, 2021).

Furthermore, ACM also participates in the process of creating energy rules in Europe, concerning both the Dutch electricity and gas market. It strongly cooperates with other regulators such as the Agency for the Cooperation of Energy Regulators (ACER) and the Council of European Energy Regulators (CEER). In both organisations, ACM is part of different working groups and task forces concerning regional collaboration and knowledge exchange about creating effective regulatory policies for both the electricity and gas grids (ACM, 2021).

One of the central government agencies concerning entrepreneurial activity is the *Netherlands Enterprise Agency* (RVO), supervised by the MINEZK. Its role is threefold, namely providing support for financing, advising and networking. The networking can happen through an extensive international network, including embassies, trade offices and other regional cooperations between business developers and SMEs. RVO is also responsible for offering different subsidy and grant schemes to foster innovation outside the Netherlands. Within the Top Sector Energy, subsidy support can be requested for single (or a combination of) projects in the phases of industrial research, experimental development or demonstration. To be eligible for the support, they have to align with the CO2 and energy efficiency targets from the Dutch Climate Agreement. This can include the research areas of energy saving, energy flexibility, sustainable energy production and circular economy. Currently, projects related to TS Energy (including hydrogen) are subsidised with an annual amount of approximately € 130 million (RVO, 2021b).

Table 3: Influence of governmental organisations based on responsibilities

Government organisation	**Responsibility**	**Influenced supply chain phases**
Ministry of Economic Affairs and Climate Policy	Developing the Dutch environmental and energy policy	production/transportation/storage
State Supervision of Mines (SodM)	Independent regulator of mineral and energy extraction; safety/environmental issues in mining, gas network and offshore wind	transportation and storage
Energie Beheer Nederland (EBN)	State participant in exploration/production/storage/trading activities of natural gas from the subsurface; advisor to the Government; investing/facilitating/sharing of knowledge	production/transportation/storage
Authority for Consumers and Markets (ACM)	Independent energy market regulator; representation of consumers and businesses; sector specific regulation and ensuring consumer protection; cooperation with European energy regulators and policymakers	transportation (as commercial activity)

Netherlands Enterprise Agency (RVO)	Advising and networking tasks for entrepreneurial activities; fostering innovation by providing subsidies/grants;	production/transportation/storage

4.4.1.2 Knowledge and research institutes

The *Dutch Research Council* (NWO) acts as the main funding body for scientific research and innovation in the Netherlands, with an annual budget of approximately 1 billion Euro. The majority of this sum is dedicated directly to universities and research institutions as direct government funding through the Ministry of Education, Culture and Science. Based on recommendations by scientists and other national and international experts, NOW selects relevant research proposals for funding that are related to research infrastructure and societal challenges. This can happen by means of competition between the institutions to ensure that the most promising projects get enough funding (NWO, 2021).

A central element for all knowledge transfer through public-private partnerships (PPP) in the Netherlands is the key sector (Topsectoren) innovation policy of the Dutch Government. These 9 key sectors were established to better link knowledge-/research institutes and the industry by setting up joint research projects. Although they are not knowledge institutions per se, a number of Top Consortia for Knowledge and Innovation (TKI) are used as binding links between the knowledge institutes and the government within each key sector. In the case of the energy key sector, a total of five TKIs are situated in it as sub-sectors (TU Eindhoven, 2019).

Hydrogen-related projects are mainly coordinated by TKI New Gas, which actively works together with more than 350 partners and collaborates with knowledge platforms such as the National LNG Platform, the National Hydrogen Platform (TKI Nieuw Gas, 2021b).

For example, one of the four Dutch technical universities, can propose a project to their respective TKI partner, which then submits an official application to the Netherlands Enterprise Agency (RVO) for financial support. By doing so, the PPP scheme is implemented on behalf of the government and the grant can be paid out from RVO to the TKI (TU Eindhoven, 2019).

As the countries' main natural science-related research organisation, the *Netherlands Organization for applied scientific research* (TNO) acts as a central element in the Dutch scientific landscape. As an independent organisation regulated by public law, it is not part of the government, knowledge institutions, or private companies. Research concerning the sustainable transition towards renewable energy supply has a key position within its nine focus areas. This Energy Transition expertise group is also home to the Advisory Group for Economic Affairs, as an in-house advisor for the MINEZK. The group focuses primarily on the use of subsurface areas in the Netherlands to support the implementation of the Mining Law and the efforts for the energy transition in this area. This includes exploring and storing hydrocarbons, geothermal heat, and the subsurface storage options for CO2 and other (e.g. hydrogen) substances. This deep subsurface is also expected to play a crucial role in reaching the formulated targets in emission reduction and as storage options for chemically bound energy (TNO, 2021).

The Energy Research Centre of the Netherlands (ECN) is a leading player in energy research for a sustainable Dutch energy transition. Since 2016 it operates under the responsibility of TNO and acts as an important point of contact for applied energy research. It acts as a strong collaboration platform where industrial, scientific and governmental parties can combine their expertise. ECN is also pursuing a wide range of joint projects on a European level concerning renewable energy and the reduction of greenhouse gases on a continuous basis (ECN, 2021).

Table 4: Functions of Dutch knowledge and research institutes

Knowledge and research institution	Function
Dutch Research Council (NWO)	The main funding body for scientific research and innovation
Top Sectors (Topsectoren)	Innovation policy of Dutch Government based on PPP structure
Netherlands Organisation for Applied Scientific Research (TNO)	Leading independent research organisation; renewable energy supply and transition one key topic; expertise group acting as in-house consultancy for MINEZK
Energy Research Centre of the Netherlands (ECN)	Collaboration platform for industrial, governmental and scientific actors in energy research; joint projects on EU level; operating under the responsibility of TNO

4.4.1.3 Industrial actors

In the Netherlands, both the transmission and (most of the) distribution system networks are in the hands of their respective network operator. Next to the gas infrastructure, this also includes the electricity network in that particular region (SodM, 2021b). As the countries' only gas transmission system operator and owner of the high-pressure natural gas pipeline network, Gasunie is the stakeholder with the strongest influence on the market for large-scale hydrogen transportation and storage. It is strongly involved in the only underground hydrogen storage project that is currently being pursued in the city of Zuidwending. On the lower pressure level of the network, seven different distribution system operators manage their distribution infrastructure which is connected to the transmission network of Gasunie Transport Services. They supply natural gas to small-scale commercial and residential users throughout the country (Gasunie Transport Services, 2021).

In the Netherlands, major industrial producers and consumers of hydrogen are usually grouped in integrated cluster regions. As mentioned in section 4.1, these are the areas around IJmond, Eemshaven, Maasdelta, Zeews-Flanderen and Limburg. They represent the backbone of the Dutch chemical industry ranging from petrochemical plants through base chemical manufacturing to fertiliser production. For the sake of simplicity, they can be seen as the five biggest producers and/or consumers of hydrogen in the country, with numerous individual companies operating within these industrial parks (Chemical Parks in Europe, 2021).

In terms of future green hydrogen production, the energy industry and specifically companies in the offshore wind sector will have major influence in providing the necessary electrical energy for the growing fleet of electrolysers. The Dutch Government is aiming for a 27 % share of renewable energy from the total energy usage in 2030 and therefore offshore wind parks have an important role in reaching that target (Government of the Netherlands, 2020).

Important actors of the renewable energy industry, especially concerning the large-scale production of green hydrogen, are the developing and operating firms of on- and offshore windfarms on Dutch territory. In terms of onshore wind production, the last evaluation from the Government in 2015 indicated a total number of over 2500 wind turbines with a combined capacity of 3000 MW, which is aquivalent to roughly 5 % of the total Dutch energy demand. By the end of 2020 the goal was to double this number to 6000 MW as previously agreed on in the Energy Agreement for Sustainable Growth (Government of the Netherlands, 2016).

Currently, seven active wind farm zones are operating off the Dutch coast with a combined capacity of 2.45 GW. They range from smaller scale innovation sites (19 MW, Borssele V) to large scale sites like Borssele I&II with a capacity of over 750 MW. The builders and operators of these wind parks represent some of the biggest energy companies in the Netherlands such as Royal Dutch Shell, Vattenfall, Eneco and several smaller enterprises. Besides the already operating zones, an additional seven wind farms are currently under construction or in preparation to bring the total installed capacity of offshore wind energy to 11 GW by the year 2030. This increase in capacity is expected to supply around 40% of the electricity demand in the country and represent 8.5 % of the total Dutch energy supply (Government of the Netherlands, 2020 and RVO, 2021a) Figure 20 gives an overview of the current and planned offshore wind farm zones in the Netherlands.

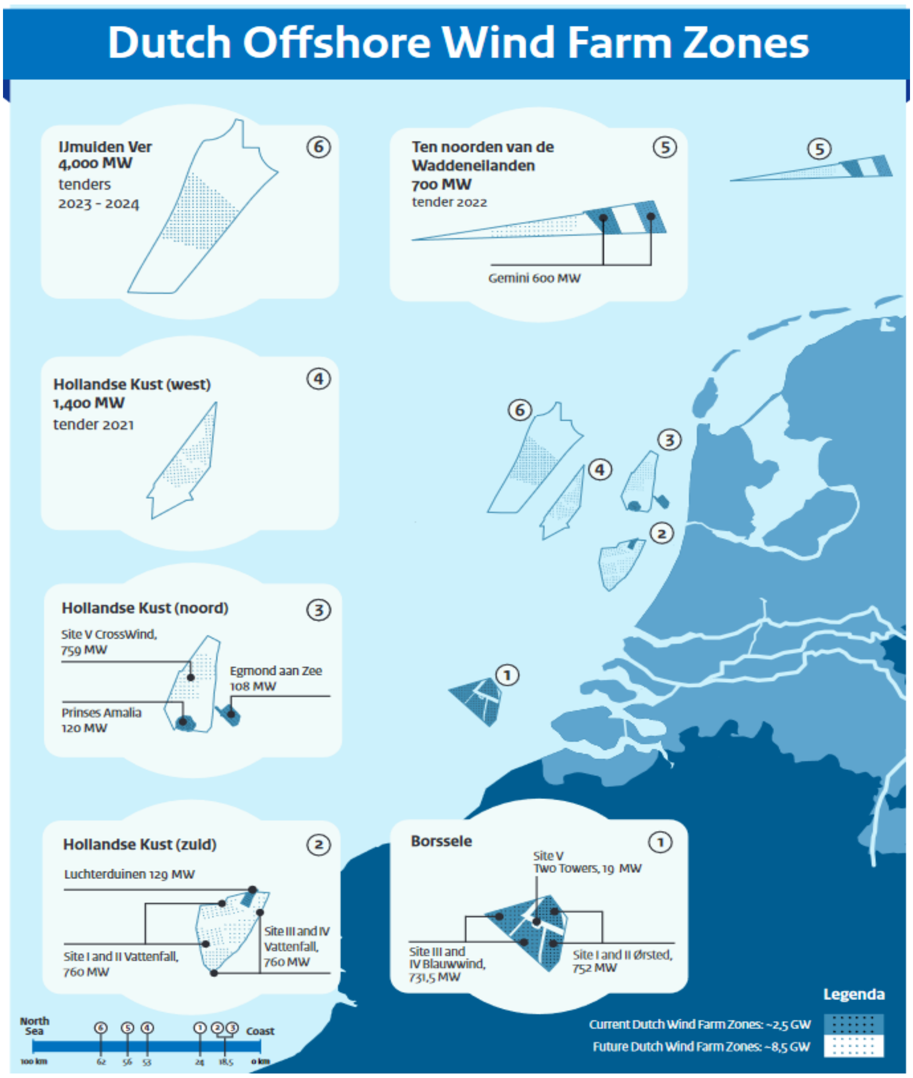


Figure 21: Dutch Offshore Wind Farm Zones (RVO, 2020a)

4.4.2 Networks

The following paragraphs describe the different types of networks that act as important connection points for actors in the hydrogen value chain. They are divided into two main groups. The focus of the first type of networks lies in providing a platform for information exchange between actors to accelerate research and development activities and further grow the body of knowledge. The second group of networks is more involved with providing help for economic cooperation and concrete support for project development. In addition, these interest groups can act as representatives for industry sectors, trade associations or international partnerships.

4.4.2.1 Knowledge developing networks

A vital knowledge network for companies and organisations was formed by creating the *H2 platform* in the Netherlands. Together with the Ministries of Economic Affairs and Climate and Infrastructure and Water, this platform aims to connect different parties to find solutions related to the different areas of hydrogen application. It is constantly growing and currently encompasses around 40 members. This includes solutions for the application within the sectors of energy, mobility and raw materials. Furthermore, it acts as a discussion panel for the government to stimulate and introduce new products and services related to hydrogen (H2 Platform, 2021).

Dutch academic research organisations that conduct Energy research have bundled their knowledge in the *Netherlands Energy Research Alliance* (NERA). It is a platform to share knowledge about research concerning the energy transition and, at the same time, increase the effectiveness of the different cooperations. It does not actively participate in formulating proposals and conducting research but instead acts as an informing and coordinating agency. The objective is the combination of interdisciplinary knowledge and assistance in finding the right priorities for research (NERA, 2021).

In terms of bringing together both medium and long-term research concerning the transition to a CO2 neutral industrial sector, the Electro-Chemical Conversion & Materials (ECCM) commission acts as an important advisor for the Dutch Government. The focus lies on the sustainable generation of energy, conversion and storage. Besides NOW and TNO, the commission is assisted by the three Top Sectors of Chemistry, Energy and HTSM, and the Ministries of Economic Affairs and Climate Policy and Education, Culture and Science. ECCM aims to incorporate the opportunities for system integration and cost reduction in the fields of hydrogen and electrochemistry. The emphasis lies in the fact that hydrogen can only continue to play a role in future energy systems when managed through an integrated approach combined with the electricity sector (ECCM, 2021).

On a continental level, the biggest public-private partnership in Europe is currently the *Fuel Cells and Hydrogen Joint Undertaking* (FCH-JU), which aims to support research, development and demonstrations projects related to hydrogen and fuel cell technologies. The objective is to facilitate a successful market introduction of these products and services, achieve economic development, and reduce dependency on hydrocarbons. Its three members are the European Commission, Hydrogen Europe as an industry representative and Hydrogen Europe Research as a representative for the research community. This allows many stakeholders such as utility companies, regional authorities, universities, etc., to actively participate in decision-finding processes regarding the newest innovative hydrogen solutions. This Joint Undertaking is not limited to production technologies only and should therefore stand symbolically for all research projects related to hydrogen (FCH-JU, 2021).

4.4.2.2 Interest groups

The Employers Organisation for the Technological Industry (FME) is the largest network organisation for the technology sector in the Netherlands. It represents over 2000 enterprises of various sizes from the metal, electronics and plastic sector. It aims to connect the members to key stakeholders such as governmental organisations, knowledge institutes and other companies from the private sector. To further strengthen the competitiveness of Dutch technology firms, FME aims for a comprehensive transition process in technology, society, and the labour market (FME, 2021).

The Dutch interest group of all network operators is *Netbeheer Nederland* (NBN). It also acts as a trade association and allows dialogue on national and European level with governments, market players and non-governmental organisations about issues relating to the energy transition. To fulfil its mission, NBN strongly promotes cooperation between the different network operators and makes proposals on behalf of them to achieve the desired changes regarding legal codes, conducts and the network tariffs' structure (Netbeheer Nederland, 2021).

Gas Storage Nederland acts as the main representative organisation for Dutch gas storage developers and operators. It also functions as a cross-border platform between Germany and the Netherlands to voice the intentions and needs of actors from both sides of the border. It aims to ensure that regulations, a level playing field and procedures concerning licensing are placed on the agenda of national governments and regulatory authorities of the European Union. In the Netherlands, discussions are held with the MINEZK and the Authority for Consumers and Markets (ACM) as the two main regulatory bodies responsible for issues concerning the energy transition (Gas Storage Nederland,2021).

The *International Partnership for Hydrogen in the Economy (IPHE) is a network of 22 countries to connect governments around the world for* efficient progress in hydrogen and fuel cell technologies. By doing so it aims to accelerate the transition to sustainable mobility and energy systems by utilising fuel cell and hydrogen applications across several sectors. Its mission is to provide information to broad stakeholder groups, including the general public, policymakers, and the private sector. By accelerating market penetration of new technologies, sharing knowledge and expertise among participating initiatives and monitoring worldwide developments, it plays an important bridging role for governmental, non-governmental and commercial actors (IPHE, 2020b).

WaterstofNet is currently the biggest collaboration platform for hydrogen projects in the Benelux region. It aims to contribute knowledge and networks of expertise to achieve carbon-neutral hydrogen solutions in the Netherlands and Flanders. It is based on the 4 organisational pillars of network organisation, knowledge centre, Government advisor and projects. This allows WaterstofNet to unite the industry in both countries and act as a contact point for companies, governments and the general public. By doing so, knowledge and expertise from different actors can be conveniently merged to realise new projects and keep the Dutch-Flemish region in a leading position in hydrogen-related research and application. This already leads to the formation of a hydrogen industry cluster with more than 60 members from across the whole hydrogen value chain who are collaborating with authorities and knowledge institutions in the region (WaterstofNet, 2021).

4.4.3 Institutions

Institutions are grouped based on their financial or legislative steering capacity. The first group of institutions consists of different national and European funding mechanisms essential for a successful development (and sometimes even operation) phase of a hydrogen project. The subsidy and grant sums depend on the technology readiness level of the proposal and how they can be situated within the structure and objective of a particular scheme. The second group of institutions includes relevant regulatory instruments, such as acts, laws, directives etc. They function as the legal background for developing and operating physical infrastructure and providing services to end-users. Their task is to ensure that economic, environmental and social aspects are considered during every project phase.

4.4.3.1 Financial institutions

Several different support schemes are currently available for hydrogen-related research and development projects in the Netherlands. They cover the spectrum from fundamental research up to demonstration projects. Within the field of sustainable energy storage and conversion, a total amount of € 25.7 M was granted to pursue research by four different initiatives. The Dutch Research centre (NOW) announced a call for projects with a technological readiness level (TRL) 1 to 3. As part of the National Research Agenda (NWA), additional calls for projects have been made concerning storage and conversion technologies with TRL 1 to 3. For the production of green hydrogen through electrolysis, the Faraday Lab Programme from TNO in Petten and the HydroHub Megawatt Test Center from the Institute for Sustainable Process Technology (ISPT) in Groningen stand out. (IPHE, 2020a).

As of 2020, the *Mission-Oriented Research, Development and Innovation* scheme (MOOI) allows funding of projects related to offshore wind, renewable energy on land, industry and built environment, with a total budget of € 65 Mio. These research topics can all be applied to hydrogen technologies. It is aimed at large projects and consortia where a minimum number of participant and budget size is required. For hydrogen projects with a higher technology readiness level, the *Demonstration Energy and Climate Innovation* grant scheme (DEI+) is an essential financial mechanism to reach final deployment. There are currently € 40 Mio reserved for hydrogen projects with a maximum cost coverage of 45 % or € 15 Mio per projects. (IPHE, 2020a). The third crucial national subsidy scheme is the Demonstration of *Climate Technologies and Innovations in Transport* (DKTI) scheme. It aims to stimulate a wide range of sustainable transport projects, where innovation has not reached the market yet or has only done so recently (Gigler,2021).

The currently biggest single RVO subsidy program (total budget of 5 billion Euro) concerning renewable energy and CO2-reducing technologies is the *Stimulation of sustainable energy production and climate transition* (SDE++) scheme. This scheme acts as the backbone for the Dutch renewable energy transition efforts and is the follow up of the SDE+ scheme, supporting large-scale projects in the areas of renewable energy production and reduction of greenhouse gas emissions. This subsidy scheme is aimed at the operating period of certain projects. It compensates for any difference between the cost price of the applied technology and the (potential) revenue of the applying organisation. With a minimum hydrogen production capacity of 0.5 MW, projects related to hydrogen are situated in the "low-CO2 production category, together with the carbon capture and storage (CCS) subcategory. However, the number of full-load hours for SDE++ subsidised electrolyser projects is currently still limited due to insufficient supply of green electricity for a full-time operation.

In this case, unused annual production capacities (max. 100 % per annum) can be carried over to the following years with a forward banking mechanism (RVO, 2020b).

In April 2021, an additional funding amount of 338 million Euro from the National Growth Fund was announced to support the scale-up of hydrogen and green electrons in the manufacturing industry. This "green power" (Groenvermogen) proposal is aimed primarily at the chemical industry, as currently the biggest producer and consumer of hydrogen in the Netherlands. Until the closing of the investment program in 2028, the Top Sectors of Energy, Chemistry and High Tech will strongly collaborate through the commission for Electro-Chemical Conversion and Materials to reach the targets formulated in the Climate Agreement. (Government of the Netherlands (2021) and ChemistryNL (2021))

On a European level, the major hydrogen-related financial stimulation program and public-private-partnership is the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) with a total budget of 700 million euros. A new programming period is currently being set up, as the last period of 2014-2020 ended recently. The new period is expected to be made available soon, with a substantial budget to fulfil the ambitions announced as part of the "Clean Hydrogen Alliance" strategy of the European Commission. From the perspective of the FCH-JU, numerous other subsidy options and funding instruments are available. Figure 22 shows the types and sources of financial instruments available (Topsector Energie, 2020)

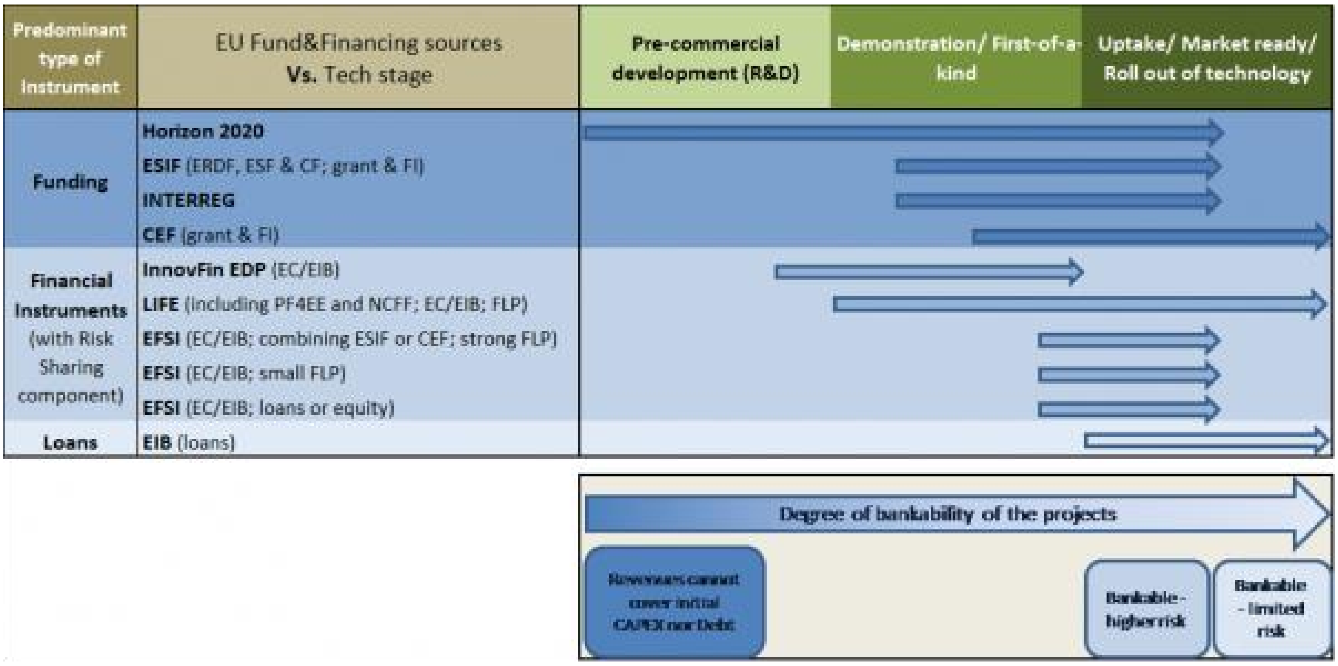


Figure 22: Overview of EU financing instruments
(Source: Topsector Energie, 2020)
Horizon 2020: 7th EU Framework Programme for Research and Innovation; ESIF: European Structural and Investment Fund; ERDF: European Regional Development Fund; ESF: European Social Fund; CF: Cohesion Fund; INTERREG: Interregional cooperation projects; CEF: Connecting Europe Facility; EIB: European Investment Bank; FLP: First-Loss Piece; EFSI: European Fund for Strategic Investments; EDP: Energy Demonstration Projects

4.4.3.2 Laws and regulation

Currently, the most prominent and up to date EU energy legislation is the recast of the Renewable Energy Directive, which entered into force at the end of 2018. It aims to help the EU in reaching its ambitious emission reduction targets and secure the continent a leading role in developing and using renewable energy solutions. Besides the need to draft national energy and climate plans, member countries must transpose the other elements of the directive by 30 June 2021. This recast should also ensure that the overarching EU climate ambitions are achieved by supporting the integration of energy systems and formulating a specific hydrogen strategy (European Commission, 2014).

The EU Hydrogen Strategy document addresses the necessary economic, regulatory and research steps towards integrating hydrogen as an energy carrier into our energy system on a large scale. The central element is the supply of clean (green) hydrogen, produced with renewable energy, which will be introduced by using a gradual approach through different phases. Until 2030 the goal is to reach a total electrolyser capacity of 40 GW with the possibility to produce up to 10 million tonnes of green hydrogen. The share of the Netherlands is expected to be between 3 and 4 GW installed capacity by 2030, as laid out in the National Climate Agreement (European Commission, 2020)

Activities concerning the research and extraction of minerals and underground storage of substances are regulated by law through the Dutch Mining Act (Mijnbouwwet). This legal document is supplemented by the Mining Decree (Mijnbouwbesluit) in the form of a collection of rules for implementing the Mining Act. An additional form of mining-related supervision is warranted by the Mining Regulation (Mijnbouwregeling), an agreement between several Dutch Ministries to combat the risk of pollution by oil and other substances in the North Sea (Overheid, 2021).

The underground storage of substances is additionally controlled by the *State Supervision of Mines* (Staatstoezicht op de Mijnen) through the Major Risks and Accidents Decree (Besluit risicos's zware ongevallen), which functions as the implementation of the SEVESO III EU directive. The role of SSM lies in reviewing and approving storage plans as an advisor for the MINEZK. This aims to ensure safe underground storage of different substances which is also controlled on an annual basis through inspections according to guidelines of the Decree. The vital interest of this Decree and SSM is to ensure that seismic activity, through the storage and re-extraction processes, is prevented, which has caused significant damage in recent years around the Groningen gas field (SodM, 2021a).

The spatial planning aspect of projects concerning the physical living environment in the Netherlands is considered in the permitting procedure of the General provisions environmental legislation Act (WABO). As current legislation does not differentiate between large-scale centralised and small-scale localised hydrogen production, the permitting requirements are subject to procedures concerning health and safety, risk assessment, environmental impact assessment and integrated environmental obligations. This means that smaller regional production through electrolysers follows the same type and order of permitting as large centralised production, such as on big industrial sites. Additionally, due to land use planning regulation, production activity would only be permitted within a designated industrial area or occasionally in a special commercial area. However, the currently used WABO regulation for spatial planning will be replaced by the more extensive Environmental Act (Omgevingswet), which will come into force on 1 January 2022 (HyLAW National Policy Paper Netherlands, 2019).

The usage of the Dutch electricity grid, for example, by electrolysers, is regulated through the Electricity Act 1998 (Elektriciteitswet 1998). Although there is no distinction made between connecting an electrolyser or other electrical equipment to the grid, the TSO and DSOs are legally not allowed to store electrical power, for example, through the power to gas technologies. Besides that, trading and producing energy falls outside their scope, which acts as a barrier to forming an integrated energy system with storing and converting power to gas or vice versa when necessary (HyLAW National Policy Paper Netherlands, 2019).

The main regulatory instrument for gas transmission and distribution in the Netherlands is the Dutch Gas Act (Gaswet). Natural gas is currently defined as a gaseous substance with a methane content of more than 50 % or gas from a renewable source with the same parameters, which meets the requirements of the Ministerial Decree Gas quality. This regulation has the effect that the Authority for Consumers and Market (ACM) can only set tariffs for gases that meet the requirements mentioned above. Therefore, there is currently no legal basis to determine prices for hydrogen by the ACM. Furthermore, the injection of hydrogen into the natural gas grid is currently strongly limited both on the TSO and DSO levels. In the high-pressure TSO grid, a maximum amount of 0.2 mol-% of hydrogen is allowed for injection, while for the regional grids of the DSOs, this value is 0.5 mol-%. Amending the Gas Act to enable gas transportation with less than 50 % methane concentration could be a solution to this issue but is seen as a very time-consuming process. To avoid this lengthy process, the Ministerial Decree on Gas quality could be amended by the MINEZK towards allowing the injection of hydrogen below 50 % to secure a share in natural gas of over 50% (HyLAW National Policy Paper Netherlands, 2019).

The alternative for transporting hydrogen through a pipeline is its distribution in tanks via roads and railways. The former will be particularly important for securing a steady supply of hydrogen to the anticipated refuelling infrastructure for cars and heavy-duty vehicles. Current restrictions in the Netherlands concern transportation and short-term storage through bridges, tunnels, and parking spaces. Transnational transportation of hazardous materials in Europe is governed by the ADR treaty and is implemented in the Netherlands through the Transport on hazardous substances law (Wet Vervoer gevaarlijke stoffen). As a consequence of this law, tanks containing hydrogen can only be transported through 5 specific tunnels in the country. This precautionary measure is aimed at securing the critical tunnel infrastructure, especially the ones located under or near waterways, from unwanted damage and exorbitant repairing costs in case of accidents. Since the transport of dangerous substances has been standardised throughout partner countries of the ADR treaty, future production sites for mobility hydrogen will have to be chosen carefully regarding the transportation infrastructure to avoid unnecessary logistical problems (HyLAW National Policy Paper Netherlands, 2019).

Table 5: Dutch regulatory instruments concerning hydrogen

Regulatory instrument	Scope	Influenced supply chain phase(s)
Mining Act/Mining Decree/Mining Regulation	Extraction of gaseous substances from and storage in the subsurface areas	production (grey hydrogen), storage
EU Renewable Energy Directive	Policy instrument for promoting and producing renewable energy in the EU	Production (green hydrogen)
Major risks and accidents decree (BRZO)	Underground storage of gas	storage

General provisions environmental legislation Act (Wet Algemene Bepalingen Omgevingswet)	Various physical aspects of construction projects	production/transportation/storage
Electricity (Electriciteitswet)	Grid connection to TSO and DSO network levels	production (green hydrogen)
Gas Act (Gaswet)	Transmission/distribution, quality parameters and tariffs for natural gas	transportation (with economic aspect)
Transport on hazardous substances law (based on ADR) (Wet Vervoer gevaarlijke stiffen)	Routes for road transport of pressurised tanks	transportation

5. Challenges and drivers along the hydrogen supply chain

The following chapter explains the different types of challenges and barriers that are currently affecting the hydrogen supply chain and aims to answer the second sub-question. Interview respondents were selected based on their involvement in the different parts of the supply chain and the previously conducted stakeholder overview in section 4.1. Based on the responses of the interviewees and the previous literature review, a summary of the important challenges and drivers is provided in Tables x and y. The negatively or positively affected phases of the Dutch hydrogen supply chain are mentioned in each table. An explanation of each challenge and driver is given in the section below.

Table 6: Challenges and negatively affected supply chain phases

Challenges	Negatively affected supply chain phases
Regulation and political circumstances	Production, transportation, storage, consumption
Public acceptance	Production (mainly renewable energy capacity), storage, consumption
Hydrogen market	Transportation, storage, consumption
Economic and financial aspects	Production, consumption
Workforce	Production, transportation
Consumer demand	Production, transportation, storage
Electricity generation capacity	Production

Table 7: Drivers and positively affected supply chain phases

Drivers	Positively affected supply chain phases
Geographic conditions	Production, storage
Entrepreneurship and innovation	Production, transportation, storage, demand
Infrastructure	Transportation, storage
Expertise	Production (grey hydrogen), transportation, storage
Industrial clusters	Production, transportation, demand

5.1 Challenges

The following paragraphs provide an overview of the different key challenges mentioned by the interview respondents. According to the received feedback, these are the national and international regulatory and political circumstances, the issue of public acceptance, the situation on the hydrogen market, the financial background of project development, the amount of needed workforce and the demand articulation.

5.1.1 Regulation and political circumstances

Based on the feedback from multiple interview partners, missing or unclear regulation can be seen as one of the major challenges that various supply chain actors currently have to face. This can even be the case for the government itself when it is not entirely clear for a ministry or agency which types of hydrogen can be classified and financially supported as renewable hydrogen. Another regulatory dilemma can be seen between designing policy instruments with the highest cost-efficiency versus catering to the specific local preferences of particular projects. Developing projects and markets with the lowest sum of subsidies is often contrary to considering specific regional or local needs *(Policy Advisor L).*

According to *Project Engineer C,* similar issues are also seen in certain projects with a unique character, like large-scale blue hydrogen production. In this case, missing previous examples act as a barrier to developing the best suitable regulatory framework for a new project. *Asset Manager D* mentioned that difficult circumstances arise for the development of projects when a regulatory instrument does not allow any deviation from a given situation. This is the case for the Dutch distribution system operators (DSO), which are, at this moment, legally not allowed to transport hydrogen to customers through their existing pipeline network. Additionally, it is also forbidden for the DSOs to engage in any hydrogen-related activity directly with households as their end customers.

Unclear policies concerning hydrogen also pose the danger of indirectly supporting the build-up of grey areas within the legislation. This makes it particularly difficult for regulators to exercise their intended supervisory power, both on the supply and demand side of the chain. An uncertain situation like this can have severe consequences in the crucial areas of public safety. Therefore, a revision of policy documents is needed to allow a responsible form of supervision for safety-related issues *(Senior Advisor O).*

A mainly short-term oriented form of policymaking can lead to losing the focus on the bigger picture, such as long-term emission targets and climate goals in general. This political dilemma can also be seen in the Netherlands, where climate policies mainly focus on the current decade to reach the previously determined targets for 2030. The aim here is to accomplish these goals and targets in the fastest and (more importantly) most cost-efficient way possible. This rather short-sighted approach can also be detected in the structure of specific major subsidy schemes for climate- and energy-related projects, such as the SDE++ scheme *(Policy Advisor L).*

5.1.2 Public acceptance

According to *Senior expert G* and *Senior Advisor O*, public participation and acceptance are critical factors for energy-related project developments in the Netherlands. On the one hand, there is a general reluctance in supporting large-scale infrastructure projects that bear the possibility of altering the aesthetic appearance of a neighbourhood or landscape. This “not in my backyard” (NIMBY) mentality is powerful in highly developed western European countries like the Netherlands or Germany. The NIMBY approach can be observed, even though the majority of people is usually aware of the ultimately positive impact on their environment and energy system from these projects.

On the other hand, there were certain incidents in the Netherlands which have a strong negative impact on gaining back the trust and support of the public. These are mainly linked to the oil and gas extraction activities in and around the Groningen gas field. The following earthquakes and property damages have led to a massive loss of trust from residents and the general public towards any gas- or subsurface-related activities in the Netherlands. This mistrust towards such projects even includes government agencies that have the task to supervise and regulate these projects according to safety standards. People often require nearly zero risks in exchange for their trust and support. As short- and long-term storage of hydrogen in the subsurface areas is expected to play a key role in supporting the Dutch hydrogen economy, such societal tensions can pose a great threat for further development of these projects *(Senior Advisor O).*

5.1.3 Hydrogen market

The previously mentioned missing regulation can also impede the build-up of a competition-based market structure in a different way. This prolonged uncertainty is especially dangerous for receiving a clear demand articulation by the prospective users of hydrogen. Without knowing the amount of needed hydrogen gas, both supply and demand-side will keep waiting for the other party to make the first significant steps, which will strongly hinder the formation of a hydrogen market. Gas suppliers and transmission/distribution companies need long-term certainty to strategically plan their pipeline network's costly development and operation *(Gas TSO expert A).*

A growing number of announced projects for green hydrogen production will make a unitary system for quality standards and guarantees of origin inevitable for a functioning national (and international) hydrogen market. But when it comes to concretely and legally defining the different types of hydrogen (grey, blue, green) and their origin, there are currently no policy instruments to do so. As a result, hydrogen users who want to (or even have to) present the environmentally relevant impacts about their energy intake to customers and shareholders have no legally binding instrument to do that. This leads to additional uncertainty pointing from the consumers towards the producers and distributors *(Government Advisor K).*

5.1.4 Economic and financial aspects

Financial instruments such as subsidies and grants provide temporary support for new or currently cost-inefficient technologies and services. In the European Union (and the Netherlands as a member country), a combination of an insufficient number of subsidy schemes and amounts and complicated tendering processes hamper the effective subsidization of projects. *(Energy Consultant N)*

As a result, bridging the funding gap for costly projects is not working adequately. At first sight, the ambitious European Green New Deal initiative has brought many new subsidy schemes on the market. However, due to a high number of applicants and intense competition between different technologies, the current amounts are still insufficient. This is one reason why most large-scale green hydrogen projects across Europe have not taken their final investment decision (FID) and are expected to only do so in the next 1 to 2 years *(Energy Consultant N).*

Politically predetermined directions for financial support mechanisms already hinder subsidising the most efficient alternatives for renewable energy technologies. On the one hand, the Dutch government aims to realise carbon neutrality through various technologies and other approaches by the middle of this century. In contrast to that attempt stands the sometimes very specific and limited approach to providing subsidies for energy-related projects. For example, the simple fact of having an electrolyser project funded with a subsidy scheme is often more important than realising the same emission reduction through other ways, like blue hydrogen. Therefore, favouring one specific solution over another does not seem to fit the logic of reaching the ambitious goals and targets of the Dutch and European Parliament. Moreover, with still largely insufficient capacity available for renewable energy production, this form of forced financing can lead not only to an artificial increase in prices for green electricity but can also hinder the funding and ultimately the dispersion of alternative energy technologies, such as modern heat pumps or electric vehicles *(Energy economist H).*

By aggressively promoting and subsidizing (almost) exclusively green hydrogen through water electrolysis, alternative technologies with more advanced business cases (e.g. blue hydrogen) are at risk of being ignored by politicians and investors. This also has the risk of wasting their potential for immediately reducing large amounts of carbon emissions. This prioritization of specific solutions can even prolong the period of cost reduction for specific technologies, compared to more competition-based forms of financing *(Energy economist H).*

5.1.5 Workforce

Technologies like electrolysers have been used for many decades before the current hype about green hydrogen. However, it can now be seen that due to a missing demand from the industrial sector, they were gradually withdrawn from the scientific world until the recent turnaround. The niche market for electrochemistry did not prove strong enough to secure the needed scientific and financial support for large-scale development. This drawn-out period of reduced research activity is now being felt in the form of missing academic and non-academic workforce with the necessary know-how. In the Netherlands, the sudden demand for research work about hydrogen, electrochemistry etc., could not be met, as there were (and still are) not enough people with the suitable academic background to fill the positions. This also means that major enterprises' research and development departments often employ people with more practical knowledge than universities or national research institutes. Such misalignment between the practitioners' side of the industry and academia's more theoretical side has to balance out to include the essential research and education part into the hydrogen value chain *(Professor for Energy Systems I).*

Next to the missing scientific workforce at universities and research facilities, there is also a lack of employees with specific knowledge in the private sector. This is evident when looking at the expected high demand of physical on-site workers for developing and maintaining the prospective hydrogen infrastructure. The limited number of people currently working in hydrogen and the ones working with natural gas will not be enough to facilitate a safe and reliable hydrogen economy. Knowledge about natural gas can be seen as a valuable asset in the Netherlands, but there is a strong need for the redeployment of staff to hydrogen-related works. Besides that, the customer- and account managers, mainly within the DSOs, also need to be trained to deal with new types of questions, complaints or other operational challenges. They have to give municipalities and customers an understanding of what can be done and why certain projects are done or not done *(Asset Manager D).*

Due to its strong multidisciplinary character, knowledge transfer between actors of a hydrogen economy is crucial throughout the development and operational phase of the whole value chain. These highly complex and dynamic fields of expertise do not allow single actors to overlook all technical, economic, legal and social aspects of their activity at the same time. Here, a generalist form of thinking is required to connect the different actors and stakeholders who all represent different needs and intentions. Therefore, more highly skilled consultants need to be involved both at a governmental and non-governmental level throughout the research and development process of new technologies and services concerning hydrogen *(Energy consultant N).*

5.1.6 Consumer demand

The production side is waiting for a clear demand articulation, which is vital to support further research and funding for that first element of the hydrogen supply chain. However, to formulate those needs by the different end-use sectors, extensive research is needed within their operating areas, which is often not the case. When it comes to hydrogen, in the Netherlands, there is currently limited research and innovation activity happening in the sectors of the built environment and heavy-duty transport. This is incomparable with the numerous large-scale production- and infrastructure-focused (multi)national projects currently being prepared. One potential reason for this discrepancy is a strong suspicion that a lot of practical, demand-sided research and development is still happening behind closed doors of large companies. This usually has to do with important strategic goals of different firms but hinders other market players and the supply side in seeing their true intentions *(Energy Advisor M).*

Speeding up development on the demand side is also crucial because tailoring the given product or service to a specific need from customers bears many opportunities in terms of innovation and scale-up. This holds especially for end-use sectors like mobility, built environment (heating) or electricity production. For example, there are numerous possibilities in the gas turbine industry, such as mixing oxygen with hydrogen for better combustion results, reducing NOx emissions, etc. Currently, this is not being pursued sufficiently fast and therefore acts as an additional barrier to bringing together the different building blocks of the hydrogen value chain in the Netherlands *(Project Engineer C).*

5.1.7 Electricity generation capacity

Multiple gigawatts of extra wind and solar energy capacity has to be installed to replace grey and ultimately blue hydrogen with green hydrogen. According to Business Development Manager F, this development is further hindered by the fact that the ambitious targets for offshore wind energy in the Netherlands are still mainly aimed at replacing the currently operating coal- and gas-fired power plants *(Business Development Manager F).*

Given the conditions for energy production in the Netherlands, large-scale renewable electricity generation for green hydrogen will only be possible by using extensive amounts of offshore wind power. In this case, there is a strong connection to the financial aspect of renewable energy. Costs for renewable energy in the Netherlands, especially offshore wind, are still too high compared to other parts of the world. Therefore, the missing capacity for green electricity is paired with financial pressure to develop those national capacities and competition from countries with much lower production costs for renewable energy *(Professor for Energy Systems I).*

5.2 Summary of challenges

After concluding the data analysis, concerning the different challenges that hinder the build-up of the Dutch hydrogen supply chain, regulatory barriers can be seen as a central element affecting all parts of the chain in a more or less direct way. Missing, unclear or overly strict regulatory instruments can cause a kind of chain reaction throughout all areas of the hydrogen sector, which mutually impedes the different phases of the supply chain. Regulatory uncertainty also unsettles potential market participants and the general public. This is negatively complemented by financial problems such as missing or insufficient subsidy schemes that can strongly slow down the formation of a competition-based market economy. Another disadvantage is considered as the “chicken or egg” dilemma, stakeholders of the different supply chain phases are mutually waiting for the other side to engage in financial or development tasks. While the production side requires concrete demand articulation for scale-up, consumers need to be sure about receiving the required amount and quality of hydrogen. Even if regulatory and financial circumstances were entirely beneficial for project developments, the problem of insufficient numbers of researchers, physical workers and multidisciplinary experts would currently still not allow a smooth transition towards a functioning hydrogen economy. Finally, the “chicken and egg” problem of waiting for the other side, between demand articulation and supply offering from the production side, poses another threat to increasing the speed of development.

5.3 Drivers

The sections below present the most important drivers that were identified during the data collection process. They are seen as the greatest opportunities to further develop the phases of the supply chain into a fully functional hydrogen value chain. The selected points are linked to the geographical conditions of the Netherlands, the level of expertise in gas technology, the structure of the industrial sites, the existing infrastructure and the Dutch entrepreneurial and innovation activity.

5.3.1 Geographical conditions

The preconditions for producing large amounts of renewable energy for green hydrogen production are generally good in the Netherlands. Even though many densely populated areas limit the onshore areas for wind or solar farms, the offshore area available in the North Sea is extensive for European standards. Large parts of the North Sea off the Dutch coast are relatively shallow, allowing easier construction, mainly for wind parks and floating solar farms. As costs for offshore development increase with the distance to the mainland, these closer and shallower areas will be critical to reaching the necessary electricity production capacity *(Energy Advisor M).*

Good geographic preconditions for energy and hydrogen production prove to successfully secure important support from national and supranational governments. In the case of the Netherlands, this means the setup of a Hydrogen Valley as a designated area with the recognition and strong support of the European Commission. Out of all Hydrogen Valley locations worldwide, the Netherlands has the highest number (5) of separate projects, which shows the strong level of influence that geographical conditions can have *(Government advisor K).*

5.3.2 Level of expertise

The long history of natural gas usage in the Netherlands is an essential advantage for developing and maintaining infrastructure and services related to hydrogen. As a country with one of the highest shares in residential natural gas use in Europe, both the assets in installations and the human workforce are crucial for building up the hydrogen economy. The previously mentioned insufficient workforce is partially compensated by a high level of expert knowledge from the people currently working in the gas industry. This expertise also includes the market structures that are now used for natural gas in the Netherlands. It is a virtual market and seen as one of the most effective and liquid markets available. The Dutch gas market acts as a global benchmark for trading gaseous energy carriers and is expected to play an important role in setting up trading and certification mechanisms for the anticipated hydrogen market *(Energy Economist H).*

Hydrogen projects often incorporate a whole chain of different technologies and development phases with a strong multidisciplinary character. Especially at the beginning, when entire supply chains have to be established with a greenfield strategy, the knowledge and expertise of, for example, large energy firms or integrated oil and gas companies in the Netherlands can be vital for successful project development. This experience includes technical, economic and regulatory knowledge for building up a complex integrated value chain on a large scale. Furthermore, the simultaneous interaction with key stakeholders such as lawmakers, regulators, investors and contractors is a skill that only a few firms possess. Therefore, it is vital to utilize such knowledge *(Concept Engineer B).*

5.3.3 Industrial clusters

Industrial clusters play an important role in the economic activity of the Netherlands. This concentrated demand for energy and raw materials acts as a strong driver towards developing the Dutch hydrogen economy. The clusters are strategically oriented on inland and along the Dutch coastline. They are mostly already connected to high pressure and high voltage transmission systems for gas and electricity, which is an additional advantage for future hydrogen use. As these consortia of enterprises are usually located close to waterways and ports, they give hydrogen an excellent opportunity to kickstart with market development and price reduction in sight. As the Port of Rotterdam, major deep-water ports serve as important transfer and trading hubs for all kinds of materials and energy carriers required by different industry sectors *(Business Development Manager F).*

Besides the opportunity to import and export energy carriers through the port infrastructure of the Netherlands, these areas also provide a strong chance for directly introducing new technologies on a (usually) more economic large-scale. This holds especially true for hydrogen, where customers from the petrochemical or steel industry are often located close to the waterways. The Dutch port areas are equipped with a tightly interwoven network of transport and storage infrastructure, such as pipelines, storage tanks etc. At the same time, they can also allow smaller firms located in or around the industrial cluster to use hydrogen for their processes on a smaller scale while enjoying the benefits of a highly developed infrastructure network *(Business Development Manager F).*

5.3.4 Infrastructure

As a longtime producer and user of natural gas, the Netherlands is home to one of the largest networks of gas pipelines in Europe. This allows a comprehensive repurposing of these strategically important infrastructure elements for future hydrogen transmission and distribution services and is considered as the national hydrogen backbone. Besides the dense national network, the Netherlands is also internationally well connected with Scandinavia through the North Sea and North Africa through countries like Italy and Spain. The connections to areas with high solar and wind energy potential are expected to play a vital role in providing the remaining amount of green hydrogen, which cannot be produced on Dutch soil or coastal areas. An average high-pressure gas pipeline can transport around ten times more energy than the equivalent of a high-voltage cable for a significantly lower price. This is considered as the strongest argument for maintaining and repurposing the existing pipelines in the Netherlands and throughout the European continent *(Professor for Energy Systems I).*

5.3.5 Entrepreneurship and innovation

A strong entrepreneurial mindset and adequately funded national research and development programs are the backbones of the Dutch innovation policy. As indicated in various reports by different organisations, Dutch companies are generally seen as active in the hydrogen scene. As indicated under 5.1.4 and 5.1.6, there are still areas where improvement is needed. Besides the national programs, the Netherlands is also part of different regional collaborations for research and knowledge exchange, for example, in a pentalateral energy forum between Germany, France, Switzerland, Austria and the Benelux countries. By participating in these forums and associations, the Netherlands acknowledges international cooperation's importance to strengthen their leading position on a European and global level *(Government advisor K).*

5.4 Summary of drivers

Looking at the different drivers that are expected to support the emergence of the Dutch hydrogen economy strongly, geographical conditions take a central role. Beneficial topographic circumstances on land and in offshore areas have a positive impact indirectly on other drivers too. This can be seen in the case of the cluster formations of large industrial corporations in the Netherlands, which are mostly located close to waterways and ports. This opportunity to provide supply and demand simultaneously on a large scale is particularly interesting for developing the anticipated Dutch hydrogen backbone network. Combined with a high level of expert knowledge in the (natural) gas sector, solid external recognition from the EU and an already extensive natural gas pipeline network, the favourable preconditions for hydrogen development in the Netherlands are above average.

6. Results

The following chapter discusses the results from the interviews of the previous chapter and further literature. By reflecting on challenges and drivers, ideas for improvement can be given which helps answering the third sub-question. This chapter also provides a theoretical reflection to highlight how findings can be linked to the literature review in chapter 2.

6.1 Necessary developments for the Dutch hydrogen supply chain

The following subsections discuss how to further develop the Dutch hydrogen supply chain, based on the discovered challenges and drivers from the previous chapter. This also helps answering the third sub-question. Additional findings of the interviews and other literature are included as a supplement.

6.1.1 Electricity generation capacity

One of the most important prerequisites for building up a hydrogen supply chain, of mainly green hydrogen, is developing a reliable electricity supply based on renewable energy production. Multiple interview respondents mentioned this requirement as crucial for reaching the goals and targets set out for 2030 and 2050. As *Project Engineer C* pointed out, trends and developments like increasing electric heating, battery electric vehicles or electrification of industrial processes are often overlooked next to the general excitement concerning green hydrogen. However, as the costs for producing renewable energy on a large scale in the Netherlands are still too high, the risk of lagging behind with the development is given. According to *Professor for Energy Systems I*, the Netherlands can only accomplish these targets when the costs for offshore wind energy can be further reduced from currently around €0.05/kWh to €0.02-0.03/kWh. This will support the continuous development of green electricity supply, considering that 60 % to 80 % of total costs for producing green hydrogen are linked to the energy costs for powering the electrolyzer.

If we look at the general goal of realising a fast and substantial decarbonisation of large greenhouse gas emitters, expanding the electricity grid and production capacities for green electricity can also lead to large-scale electrification of processes that are currently still powered with fossil fuels. According to *Government advisor K*, directly utilizing renewable electricity will always be more efficient than other technologies that require intermediate steps for energy conversion.

Combining the production of renewable energy through solar and wind power with hydrogen production also has the advantage of relieving capacity constraints in the electricity grid. Using, for example, solar energy production and converting it into hydrogen for storage and grid stabilization purposes, the share of produced hydrogen can be increased while grid congestions can be avoided. By doing so, even less cost-efficient renewables, like onshore solar energy, can be integrated into the energy system while also preventing congestion of the grid *(Professor for Energy Systems I)*.

6.1.2 Systemic approach

Thinking about hydrogen more systemically and holistically can have various aspects. For example, this can mean developing a stronger consortia structure where "first movers" with stronger financial background and risk tolerance are taking the lead to reduce the inherent risk and uncertainty for other stakeholders. Furthermore, this more effective way of joining forces along the hydrogen value chain can positively impact the collaborative work of such projects (Ball & Weeda, 2015).

Revaluating the intentions of policymaking for hydrogen can also severely impact developing a hydrogen value chain. Currently, there is a powerful focus on scaling up the capacity for green hydrogen production. In contrast, the previously mentioned problem of insufficient green electricity capacity is often disregarded in the discussion. According *to Business Development Manager F*, the transition period before establishing the green hydrogen economy needs to be given a lot more attention. Instead of debating whether green or blue hydrogen is the better solution, the respondent strongly supports both, to begin with large-scale decarbonisation of the industrial sectors as soon as possible. For the Netherlands, this can mean that large amounts of continuously produced process gases, such as refinery gases from (synthetic) fuel production, can be utilised to start decarbonisation through blue hydrogen on an industrial scale. Additionally, the trend towards biofuels can accelerate this process, leading to negative emissions by storing the CO2, which was previously captured by biogenic material, underground (*Business Development Manager F).*

A positive side effect can also be the utilization of sustainable byproducts, for example, green CO2, that are generated during the usage of biofuels for hydrogen production *(Professor for Energy Systems I)*.

Endeavours of unprecedented scale, such as comprehensive decarbonisation, require a more inclusive way of thinking that leaves space for alternative solutions along the way. Several research and development programs are underway, for example, exploring methane pyrolysis or autothermal reforming. These technologies are still in their earlier phase of development. Still, they can quickly transform into promising solutions if unexpected technological barriers arise in the way of green hydrogen or changes in (geo)political circumstances happen. As *Professor for Energy Systems I* explains, a process like methane pyrolysis has the significant advantage of not releasing any CO2 emissions and instead, captures the carbon content of natural- or biogas in a solid form. Whatever conversion process is used, in the end, the dominating factor is always the price for the input energy needed to power that process. Therefore, it is not always about renewables but more about a seamless transition towards green electricity and hydrogen in the longer term, which will ultimately become the most cost-efficient solutions. These thoughts are in line with the statement of *Government advisor K,* who underlines the importance and power of innovation. To facilitate this systemic and holistic way of thinking, the potential of technological development must not be underestimated at any times. This is important because even solutions that currently get less attention can suddenly gain popularity if a few breakthroughs are achieved. Technologies that are not taken into account can become the gamechanger or even the symbolic black swan for already established solutions. Therefore, engaging in an active discourse with other regions and countries while pushing the technological frontier research and development programs is of utmost importance *(Government advisor K).*

6.1.3 Regulation and policymaking

The issue of regulatory barriers to the development of hydrogen and its related services spans through the whole value- and supply chain. Looking at the hydrogen supply chain as a complex and highly interdependent structure, Brandon & Kurban (2017) discuss challenges from a more holistic perspective. A high number of stakeholders have to be simultaneously involved in creating the desired hydrogen economy. This can only be achieved when the full supply chain is addressed, and sufficient policy support is given. As mentioned under section 5.1.1, missing or unclear regulation is considered as one of the most challenging factors in planning and developing the next steps of the hydrogen economy, both in the Netherlands and beyond.

From the governmental side, policymaking's temporal focus is always oscillating between short-term "visible" goals (e.g. the year 2030) and long-term strategic thinking. In the case of the Netherlands, this means that current short-term policy and financial support for fast and cost-effective carbon reduction needs to be reevaluated by keeping in mind the end goal of 2050. According to *Policy Advisor L*, this discrepancy between realising fast and cost-efficient decarbonisation on the short run and reaching the goals of 2050 for complete climate neutrality has to be taken seriously. It means that the timing of certain developments and policies needs to be handled carefully because the long-term goals of 2050 cannot be put on the agenda only after reaching the first batch of goals in 2030. On the other hand, policymaking is also strongly intertwined with gaining the general public's trust and securing their commitment by providing information and allowing public participation. Ultimately, the goal of every law or policy instrument is controlling the risks associated with a certain product or service, such as hydrogen, and securing the safety of the public. Therefore, regulations have to be designed around the fact that, besides an objective safety concern of the government, people also need to feel subjective, personal safety regarding large infrastructure investments in their surrounding environment. For a highly flammable and pressurized gas like hydrogen, this is even more important. This policymaking approach needs to be intensified for securing and keeping the public's trust in the long term (*Policy Advisor L).*

Creating adequate policy instruments related to hydrogen does not necessarily mean that entirely new laws and regulations are needed in every case. According to *Senior expert G,* basic legislation in the Netherlands is often already suitable for hydrogen technologies and services, but the common knowledge and standardisation needs to be improved. For example, unlike hydrogen transport above ground, the storage and transportation of hydrogen from underground reservoirs through wells do not have ISO standards yet. Like the previous development of a well design for geothermal installations, such design standards are also needed in caverns, reservoirs and wells for hydrogen. Complementing or altering the current legislation, for example, the Dutch Mining Act, would also support the work of supervisory agencies to better evaluate their safety testing procedure for hydrogen-related undertakings. Independent regulators and agencies have an essential role in assessing risks and opportunities that lead to the formulation of new laws and regulations.

These kinds of unclear or missing policy instruments also bear the risk of supporting the emergence of legal grey areas where neither the operating company nor the regulator knows what is legally allowed or enforceable. This is especially disadvantageous in the case of the Netherlands, where, due to previous seismic activity caused by underground gas storage, the society is generally more sceptical towards any gas-related development projects. This already causes delays or even cancellations of certain projects due to a lack of trust and public opposition *(Senior Advisor O).* This strongly influences hydrogen because a lot of parallels can be drawn with natural gas. Existing laws concerning the storage and transport of gases or liquids can help set up new regulations. Still, they need to be urgently amended to be useful in the new regulatory environment.

6.1.4 Market structure for hydrogen

Multiple experts have underlined the challenge of creating a new market structure for hydrogen trading during the interviews. According to *Professor for Energy Systems I*, there is a strong need for coordinated action on both the national and EU level, where member countries align their different views and intentions. In the (renewable) electricity market, financial incentives like CO2 taxes or more cost-efficient technologies were a big help for market development. However, this is not sufficient for hydrogen because now, technological development, infrastructure development, and establishing a whole new market structure have to happen simultaneously on a large scale (*Professor for Energy Systems I).*

Interview respondents also pointed out the connection between regulation and market structures. Essential future instruments in this regard are different standards that determine tradable hydrogen's exact physical and chemical composition. As *Government Advisor K* points out: “there needs to be decision making on what purity of hydrogen we are going to transport through those repurposed gas pipelines”. Besides eliminating uncertainty among customers of hydrogen, standards are also closely linked to safety-related issues. To make use of an extensive hydrogen market, standards and guarantees for the required quality need to be in place to ensure the safety of the end-users. This is especially important when hydrogen applications are expected to cover large areas of use in direct proximity to humans, such as hydrogen vehicles, fuel stations or heating appliances in homes (*Government Advisor K).*

Even though there exists a market for hydrogen in the Netherlands, it cannot be counted as one of the usual energy markets. According to *Energy Economist H*, there is no transparency due to mostly bilateral agreements between a limited number of producers and consumers. Furthermore, due to a missing national hydrogen pipeline, distribution systems are sometimes also owned by producers, which doesn´t allow a switch between distributors. This form of limited competition and general opacity needs to be resolved with the help of market instruments. *Government Advisor K* mentions certification schemes and guarantees (GO) of origin as the most urgently required instruments. Certificates are generally used to serve some form of national supporting scheme, while guarantees of origin act as an electronic tracking instrument that shows end consumers that a specific share of renewable energy was used in a process, such as hydrogen production (GreenPower,2014). A promising development is the European hydrogen environmental guarantee of origin scheme CertifHy, proving that a registered plant produced a specific quantity of hydrogen with a specific method and quality (CertifHy, 2019).

On the road towards making hydrogen a tradable commodity in the EU and European Economic Area (EEA), the recent report of Stratas Advisors (2021) points out that several different GO schemes currently exist across the continent. However, they are still inconsistent in their scope, the references and thresholds they use or their definition of green hydrogen. In this situation, the call for a unified legislation can be made once again, which needs to ensure a clear and explicit definition for green hydrogen across the continent. Additionally, there is also a need to establish an interface between the European Energy Certificate System (EECS) and GO schemes like CertifHy. Electrolysers connected to a national grid inevitably use the energy mix of all regional grids of the EU. By producing hydrogen through partially non-renewable energy sources and transporting it with vehicles to their designated end-user, additional GHG emissions are added to the supply chain. Even though the same platform is used by CertifHy and the EECS for managing and organizing their certification products, their systems are not directly connected. This means that with a growing number of “green” hydrogen production facilities, these certificates will play an even more important role in determining what is actually green hydrogen. The European RED II directive needs to be amended to include fossil-free electricity from nuclear power plants into the certification system. This needs to happen in a way that- besides wind, solar and hydropower- EECS certificates can also be supplemented by nuclear-based electricity for free trade of hydrogen certificates (Stratas Advisors, 2021).

6.1.5 Financial incentives

Energy Economist H points out that new forms of financial incentives can act as a strong motivating force for initiating a switch towards more sustainable energy use conditions. In a country like the Netherlands, where large amounts of natural gas are used, this is particularly important to provide a reason for end-users to replace their current natural gas-powered appliances. However, small-scale residential users still pay a lot more for gas than large consumers. This means that the relative tax burden for households is a lot more than the amount paid by large-scale consumers with much higher GHG emissions. Therefore, if fossil fuels like natural gas should be phased out permanently, their tax burden has to increase, especially for users who enjoyed highly beneficial price structures over long periods (*Energy Economist H).*

Multiple interview partners pointed out that adapting the currently available funding instruments, such as subsidies, grants etc., is crucial for securing a continuous flow of new projects and ultimately reaching the desired scale-up in production-, storage- and transportation capacity. A good example was given by *Professor for Energy Systems I*, who mentioned that Capital Expenditure (CAPEX) for green hydrogen would primarily come down through massively scaling up the production of electrolysers and not through research and innovation, as often assumed. This, however, can only be achieved if some form of financial support is provided during this start-up phase of development.

As previously mentioned, the aggressive subsidizing of one specific technology or solution can distract policymakers and investors from seeing the bigger picture with the reduction of GHG as the general goal. *Energy Economist H* suggested a new theoretical approach, where different technologies are left to compete with each other for a specific subsidy scheme in a recurring way to support the one(s) with the highest emissions cuts and the lowest costs. This form of approach was confirmed by *Policy Advisor L*, who pointed out that the Dutch government is aiming to provide yearly tenders, for example, for electrolyzer projects, where different applicants compete with each other for the subsidy amount. By doing so, the focus lies directly on driving down costs in the most efficient way possible (Rijksoverheid, 2020).

The currently high price for producing green hydrogen makes national and European subsidy schemes important for realising projects. According to *Project Engineer C*, the Dutch SDE++ scheme still needs to be broadened to allow financing of the complete hydrogen value chain. He also mentioned the idea of establishing a similar scheme on an EU level in the form of a carbon contract for difference. Besides creating new national and European schemes, *Energy Consultant N* mentioned that it is not enough to simply increase the number of subsidies without providing the necessary financial background for them. On an EU level, there is already a seemingly high number of subsidy schemes -linked to the efforts of the European Green Deal- that are suitable for hydrogen-related projects.

Nonetheless, funding budgets need to be made available in a more generous way, due to the increasing number of competing projects throughout Europe. Another area where development is necessary is the procedure by which applicants can get funding. As mentioned previously, competition can be a valuable tool for selecting the most suitable project for funding. Still, it can also turn into a burden when too much of it is present. *Energy Consultant N* also mentioned the rigorous and complicated tendering method, which needs to be overthought for improving funding processes in the future.

Energy Economist H pointed out that modifying the timing of certain financial support instruments can positively affect the development curve of technologies. Here, the intense focus on the currently still costly green hydrogen production in the Netherlands can be mentioned as an example. By time-delayed support for blue hydrogen, as a fast way of emission reduction through a more developed (SMR+CCUS) technology, green hydrogen can be given the needed time to develop further and decrease its costs. Once there is a mechanism in place, which regulates that blue hydrogen is less subsidised from a certain date onwards, green hydrogen can gradually become more competitive and phase out blue hydrogen in a controlled way.

6.1.6 Demand side

Several respondents have mentioned the need to shift the focus away from hydrogen production and involve the future end-users more in the process. These necessary demand-sided developments can happen in different ways. *Energy Advisor M* mentioned that in the Netherlands, the number of ongoing research projects on the demand and application side is strongly lagging behind the numerous projects for hydrogen production. In the built environment and mobility areas, the focus is more on risks and safety-related issues and getting the new infrastructure accepted by the public. This makes the actual implementation and dissemination of application technologies complicated. Such a mismatch in the value chain between the production and consumption sides needs to be balanced out as soon as possible.

The “chicken and egg” problem of mutually waiting for the other side to make a move can be solved if stakeholders decide to take that first important step for investing and developing. *Gas TSO expert A* mentioned that it is crucial for transmission system operators to have transport capacity booked both on the entry and exit side of the pipeline network. The Dutch gas TSO is gradually becoming more confident about an increase in hydrogen demand. Therefore, it is seen as a valid option to start building the hydrogen backbone before demand has materialized itself in the form of contracts. This, however, can only happen if strong support from the government and shareholders (in this case, the Dutch Ministry of Finance) is secured (*Gas TSO expert A).* Through this form of risk-taking and early investment, hydrogen users on the demand side can indirectly be influenced positively by reducing uncertainties and providing an environment for safe demand articulation.

7. Theoretical reflection

The approach of the TIS framework has repeatedly been used in recent years to examine the development and dynamics of emerging innovations which are often based on certain technologies (Markard et al., 2015). It is specifically aimed at investigating the systemic problems that act as challenges and barriers to the development of the system and formulates recommendations in policy support mechanisms (Wieczorek & Hekkert, 2012). The case of the Dutch hydrogen economy, together with its supply chain, is an example of a different and broader approach towards an innovation system that is strongly based on technological, economic and social factors. Moving away from a strictly technological viewpoint allows a more holistic observation of interrelations between the pillars of the triple bottom line. Coenen (2015) underlines the necessity of applying a more situational approach by identifying structures empirically on a case-by-case basis. Such a delineation enables a better tracing of influences instead of defining boundaries in an ad hoc way through prefabricated templates. This missing contextual thinking was previously also mentioned as a critique point by other innovation scholars (Markard et al., 2015). During the recent years, the approach of the framework was extended and aligned more with this call for clearer context. The aim of this research project was also to use this kind of approach. The process of qualitative data gathering was aligned with the seven functions (Hekkert et al., 2007) of innovation systems and interview questions for experts were formulated based on indicators (Wieczorek, 2012) for each function. This allowed the identifications of both challenges and driving forces along the Dutch hydrogen supply chain after previously mapping the present state of development through the structural dimensions of actors, networks and institutions. Using the functional approach, the phenomenon of cumulative causation could be discovered, where different functions can interact or interfere with each other to either accelerate or slow down the TIS development (Suurs et al., 2009). The goal was to show how certain aspects have an influence on the technological, environmental and social context of hydrogen. By combining the qualitative research of literature review and interviews about sustainable- and hydrogen supply chains, similarities in certain challenges and drivers could be detected between the Netherlands and other regions.

In the early days of research about sustainable supply chain management, scholars were more involved in understanding certain technical and operational circumstances concerning production planning, managing inventory and organizing reverse logistics for collecting and remanufacturing the returned products (Gupta & Palsule-Desai, 2011). As (Linton et al., 2007) point out, sustainable thinking has shifted from one specific organization and its products and services towards the whole supply chain in the last decades. This allows sustainability to be adopted and developed more broadly by considering the whole life-cycle of a product or service. Acknowledging this strong interdisciplinary character is rooted both in natural and social sciences (Linton et al., 2007). The analysis of a supply chain - such as the one necessary to establish the Dutch hydrogen economy- through the TIS framework's comprehensive structural and functional approach can underline this strong interconnection between the triple bottom line's economic, environmental and social dimensions (Elkington, 1998). Natural sciences help us understand what effects certain activities can have on the environment for current and future generations. On the other hand, social sciences are important to discover how groups of people interpret vague definitions like sustainability through cultural norms, governmental actions or community activity (Linton et al., 2007). The present research project has shown this particularly strong social aspect, which is often overlooked but has to be seriously taken into consideration in the Netherlands and beyond.

8. Conclusion

The research project aimed to investigate which preconditions have to be fulfilled for developing the hydrogen supply chain for the Dutch hydrogen economy. This led to the formulation of the main research question: *"How can a functioning Dutch hydrogen economy be established from a supply chain perspective?"*. The main research question is supplemented by three sub-questions which were answered consecutively. Recommendations for future research are presented at the end of the chapter.

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8.1 Present state of hydrogen supply chain

By utilizing a literature review and the structural dimension of the TIS framework, four phases (production, transportation, storage and demand-side) of the current Dutch hydrogen supply chain were mapped and analysed. All phases showed a strong connection to natural gas, which is still the dominant force in the Dutch energy system. The production part revealed a leading role of the Netherlands, as currently the second-largest producer of hydrogen in Europe. The Dutch producers supply almost exclusively grey hydrogen to a limited number of large-scale consumers, mainly situated in the petrochemical sectors, like oil refineries or fertilizer producers. Green and blue hydrogen production is still in its infancy with a slowly increasing number of projects but still minimal supply on a commercial scale. The country's extensive natural gas pipeline network is a major advantage in the race towards kickstarting a hydrogen economy. Therefore, both national and cross-border transport to neighbouring countries will be possible, with numerous large-scale industrial hydrogen consumers conveniently located close to the (anticipated) high-pressure hydrogen backbone network. In June 2021, the MINEZK officially declared, based on the conclusion of the HyWay 27 report, that the development of the hydrogen backbone is safe, cost-efficient and feasible (Rijksoverheid, 2021). As a natural gas producing country, projects targeting the large-scale storage of hydrogen can rely on a high level of expertise in gas technology. In the Netherlands, the most promising options of large-scale storage facilities (depleted gas fields and salt caverns) are available and mainly located in the country's northern half. Facilities for medium-scale storage of liquid and gaseous fuels and energy carriers are also available, primarily close to ports and strategic waterways. On the demand side of the supply chain, the above-mentioned industrial sectors are playing the leading role. Several promising application areas have been identified, but research and development activity is still lagging behind, compared to a much higher number of hydrogen production projects. Projects for hydrogen and fuel-cell vehicles and solutions for the built environment are currently being pursued the most on the demand side. In summary, the infrastructural and geographic conditions in the Netherlands are promising for the further development of an extensive hydrogen economy.

8.2 Challenges and drivers

Based on the interviews with experts, a number of challenges drivers were identified as essential for developing the hydrogen supply chain. Interview questions were formulated according to the previously defined indicators for each TIS function. This approach allowed the examination of challenges and drivers, both from a developmental and operational point of view and aimed to give an understanding of how they can influence hydrogen-related projects in different phases. Looking at the challenges, the most frequent answer was the limited or not existing regulatory and legislative background that is needed to succeed with such projects. This includes standards for applications and constructional elements, certifications, guarantees of origin and laws. Besides that, social aspects like the NIMBY mentality and strong public participation and opposition were mentioned as disadvantageous for developing and operating plants for energy production or storage. The economic aspect was articulated in the form of missing market structure and trading mechanisms for cross-border hydrogen dealing. Finally, insufficient renewable energy production capacities were mentioned as an often overlooked but crucial factor for kickstarting the large-scale production of a green hydrogen economy. While certain challenges had an immediate negative effect on individual phases of the supply chain, others could be linked to multiple phases, or even the whole supply chain. On the side of the drivers, mainly advantageous preconditions in the Netherlands were identified. General geographic conditions such as the shallow parts in the North Sea off the Dutch coast or the close proximity to waterways for the import or export of fuels and energy carriers are strong drivers. Additionally, the structure of Dutch industrial clusters and the well-established supply infrastructure (gas, electricity, steam) can be valuable opportunities for further development. The long history in gas extraction and downstream processes leads to a high level of expertise in the (natural) gas technology sector, which will be of great help once hydrogen is introduced on a larger scale into the energy system.

8.3 Mastering challenges and leveraging drivers

To overcome the currently existing barriers for a hydrogen economy in the Netherlands, several different recommendations were given by interview respondents. The production phase of the hydrogen supply chain needs urgent development of renewable energy production capacity to meet the targets of a large-scale green hydrogen supply. This electrification process can also lead to faster decarbonisation of other industrial processes, thereby supporting hydrogen to reduce GHG emissions. However, a strong systemic approach is considered to be inevitable for succeeding in this endeavour. Combining the benefits of different hydrogen types is especially important in the early phase of development, where solutions for the transition period towards a fully green hydrogen economy are needed. The importance of continuous support for alternative technologies with a currently lower level of attention was underlined by different respondents. Reevaluating regulations and modifying the policymaking approach was seen as the factor with the most significant influence on the short term. In the case of the Netherlands, solving the mismatch between short-term goals for 2030 and long-term strategies for 2050 was mentioned. Securing long-term public trust and support for these projects is vital for staying on track with goals and targets. The creation of these necessary policy instruments can either happen through amending or modifying existing legislation or creating new laws aimed explicitly at hydrogen. New design standards (e.g. ISO) for hydrogen-related applications or complementing major Dutch laws, like the Mining Act, were noted by respondents. Establishing a comprehensive hydrogen economy also requires strong market structures for national and cross-border trade. Precise standards for assuring physical and chemical quality and guarantees of origin for certifying low-carbon production techniques are the two most important instruments for a hydrogen market. Besides establishing such standards and GOOs, an interface between them and the European Energy Certificate System (EECS) is needed for managing and organising such products. An essential tool for supporting hydrogen projects is the expansion of financial instruments, such as subsidy schemes or grants. Funding of research and development activities in the Netherlands is already well-established, but adapting these instruments for more efficient use in the hydrogen sector is urgently needed. Turning away from promoting specific technologies and solutions aggressively and including the whole supply chain more competitively was mentioned as a desired outcome. Besides creating new funding opportunities, subsidy budgets must be increased both on a national and EU level. Increasing the amounts of funding needs to go hand-in-hand with overthinking the rigorous and complicated tendering methods currently in place.

Additionally, time-delayed support mechanisms were mentioned as a helpful way of providing transitional funding while simultaneously allowing other solutions to co-evolve in a more controlled way. This can enable the phase-out of subsidies for transitional solutions (e.g. blue hydrogen) sooner and allow full support on desired solutions (e.g. green hydrogen) in the longer term. Finally, the often overlooked demand side of the supply chain has to be involved a lot more in the debate about a hydrogen economy. The mismatch between the production and consumption side has to be balanced out by initiating more research and development projects on the application side and involving these stakeholders more directly in the discussion. This kind of “chicken or egg” problem has to be solved by securing strong governmental and stakeholder support to limit risks and uncertainty among investors and constructors. By doing so, the so-called “first movers” with higher risk tolerance and financial power can take the initial steps towards developing crucial parts of the hydrogen supply chain.

8.4 Recommendations and future research

This thesis project identified several factors that act as either a challenge or driver for implementing a hydrogen economy in the Netherlands. Due to the strong interdependency between these factors, it is recommended that participating stakeholders address more potential problems and barriers simultaneously, than they currently do. This is especially true for the social impacts when making such groundbreaking changes in a countrys´ energy system. Conducting further research about the relation between public acceptance/support and success in project development is therefore recommended. Additionally, restructuring and expanding funding instruments is already seen as an urgent need and therefore also a strong recommendation can be formulated for the governmental side. The limitations in terms of the temporal scope of this thesis, make additional longitudinal research about the interaction of TIS functions or challenges and drivers an attractive possibility. Finally, some of the currently less addressed aspects – such as limited workforce or technologies for consumer demand- of introducing a hydrogen economy, give great opportunities for increased research and policymaking activity.

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Appendix

Appendix A – Interview questions

TIS Function	Indicators	Questions
Entrepreneurial activities	Number of entrepreneurs/start-ups, new market entrants, experimentation activity, level of uncertainty	- How would you describe the entrepreneurial activity for hydrogen technologies in the Netherlands? - What tools/methods can be utilized to reduce uncertainty among entrepreneurs/investors? - Is there a specific strategy to align the number and size of players within the research areas of the different supply chain phases?
Knowledge development and diffusion	Size/number/type of R&D projects, availability of publications/reports and prototypes	- What are the biggest opportunities and strongest drivers for including the lower pressure gas network into the hydrogen economy? - Which element of the supply chain do you see as most promising in terms of research activity and which one is lagging behind?
Guidance of the search	Targets/goals/visions/expectations of government and industries,	- How clearly are the different visions and expectations of the government being communicated to the public and the industry? - What are the short and longer term expectations regarding the introduction of the hydrogen economy and further R&D activity in the Netherlands? - What are the preconditions for a clear demand articulation for hydrogen from customers?
Market formation	Niche markets, tax incentives, environmental certificates/standards	- What are the barriers to the formation of an extensive hydrogen market in the NL/EU? - How can the market for hydrogen be supported and developed? - Would you consider the supply-push or the demand-pull as more defining and why?
Resource mobilisation	Physical resources: infrastructure, natural resources	- What role do you expect for the DSOs to play in bridging the supply and demand side of hydrogen?
	Human resources: know-how, education, training programs	- What form of additional education or training is necessary for the development and operation of a Dutch hydrogen economy? - What type of short/long term knowledge development is necessary in the H2 sector?

		- What form of mismatch do you see between the scientific research knowledge and the practicioners side when it comes to solutions for the hydrogen economy?
	Financial resources: private investment, government funds, venture capital	- What financial aspects are currently seen as obstructive for large-scale investments into hydrogen technologies? - Which financial instruments do you see as essential for securing a profitable construction and operation? - What financial and regulatory changes do you see as crucial for the build-up of a hydrogen market?
Creation of legitimacy	Public opinion and acceptance	- How do you see the current and future level of public acceptance for hydrogen related technologies and services?
	Size of technology networks	- How can the knowledge and information exchange be improved within the hydrogen network?
	Size and influence of interest/lobby groups	- What is the current influencing and lobbying force of the stakeholders and how can it be strengthened?

Appendix B – List of interviewees

Interviewee	Function	Sector	Interview type
A	Gas TSO expert	Transportation/Storage	Online (MS Teams)
B	Concept Engineer	Production	Online (MS Teams)
C	Project Engineer	Production	Online (MS Teams)
D	Asset Manager	Distribution	Online (MS Teams)
E	Business developer hydrogen	Production	Online (MS Teams)
F	Business Development Manager	Production/Storage	Online (MS Teams)
G	Senior expert	Storage/Government	Online (MS Teams)
H	Energy Economist	Energy markets	Online (MS Teams)
I	Professor for Energy Systems	Academia/Research	Online (MS Teams)
J	Manager Energy and Fuels	Research	Online (MS Teams)
K	Government Advisor	Production/Storage/Transportation	Online (MS Teams)
L	Policy Advisor	Government	Online (MS Teams)
M	Energy Advisor	Production/Storage/Transportation	Online (MS Teams)
N	Energy Consultant	Production/Storage/Transportation	Online (MS Teams)
O	Senior Advisor	Storage/Government	Online (MS Teams)