Identifying the Technical, Regulatory, and Market Barriers Inhibiting the Commercialization of an Integrated Hydrogen Economy in the Northern Netherland

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Abstract

Research problem and objective: The transition to a more sustainable energy system requires a tremendous shift in which hydrogen is likely to complement electricity as an important energy vector. Similar to renewable energy technologies, the commercialization of hydrogen technologies across the hydrogen supply chain may prove difficult, and only a few scholars have studied the subject in depth. This paper will address this gap by studying the technological, market, and regulatory barriers potentially inhibiting the development of an integrated hydrogen economy in the Northern Netherlands. The goal is to build a framework for the commercialization of a hydrogen economy. As this framework does not currently exist, it may be used as a blueprint to study other regions and work out a generalizable theory on developing hydrogen economies from scratch.

Method: 12 interviews have been conducted with managers, industry experts, and local governments in a single case study in the Northern Netherlands, where serious progress on developing a hydrogen economy is currently being made.

Results: 29 barriers were identified across the hydrogen supply chain, including both technology-specific and system-wide barriers. These barriers were highly interrelated and interdependent, indicating the complexity of developing a hydrogen economy. Besides, social acceptance barriers proved crucial to the commercialization of specific technologies. In addition, a roadmap with mitigation strategies is provided, which can help practitioners to understand better when and how the identified barriers should be addressed.

Conclusions: The results will help practitioners and academics better understand the implications of commercializing a hydrogen economy. The framework will also act as a blueprint on which future research can be based and which practitioners can use to better plan for the development of an integrated hydrogen economy.

1 Introduction

In the Paris Climate agreement, most of the world's countries have subjected themselves to the ambitious goal of collectively preventing the earth's average temperature to rise an additional 2 (preferably 1,5) degrees Celsius (United Nations, 2015). Nations across the world will have to decrease their Greenhouse gas emissions drastically to achieve this. In the EU, a revision in the European Green Deal aims for a reduction of 55% of CO2 emissions by 2030 and climate neutrality by 2050 (Europese Commissie, 2019). The potential for hydrogen (H_2) in the energy mix was already mentioned in the Green Deal and there's no doubt that H_2 will be an important part of the future energy mix (Abdin et al., 2020; Darmani et al., 2014; Hosseini & Wahid, 2016; IEA, 2019; IEA & CIEP, 2021; Rissman et al., 2020).

Most European countries have now made plans to incorporate hydrogen in their future energy strategy (IEA & CIEP, 2021) and so has the Dutch government who published their plans in the 'government strategy on hydrogen' (Rijksoverheid, 2020)[1]. The Northern Netherlands seems especially suitable for the development of an integrated hydrogen economy which lead the Fuel Cells and Hydrogen Joint Undertaking[2] (FCH JU) to dup this part of the Netherlands the 'hydrogen valley' of Europe (New Energy Coalition, 2020). Given its regional suitability, two consortia[3] of companies, governments, knowledge institutes, and NGOs have developed roadmaps to achieve a fully integrated hydrogen economy in the Northern Netherlands (New Energy Coalition, 2020; NIB, 2017) and there are currently 9 billion euro's worth of hydrogen projects in the pipeline (New Energy Coalition, 2020). Nonetheless, realizing a fully integrated hydrogen economy may prove very difficult to achieve.

It can be argued that the wide-scale diffusion of renewable energy (RE) technologies offers similar difficulties as the commercialization of a hydrogen economy. Both can be viewed from a supply chain perspective including production, storage distribution, and end-use (Abdin et al., 2020; Wee et al., 2012) in which the difference is in the specific technologies and the energy vector (electricity vs hydrogen) (Hosseini & Wahid, 2016; Jingzheng et al., 2015; Singh et al., 2015; Wee et al., 2012). The literature on RE technologies reviewed the many barriers potentially inhibiting its adoption (Sen & Ganguly, 2017; Wee et al., 2012; Yaqoot et al., 2016). The path-dependency of socio-technical regimes and the enormous scale of the transition resulting in the need for more holistic policy frameworks only add to this difficulty (Mowery et al., 2010; Steen & Weaver, 2017; Tsoutsos & Stamboulis, 2005). Therefore, Shakeel et al. (2017) extensively reviewed the commercialization literature and built a framework representing barriers and drivers addressing the issues of commercialization of RE technologies in Finland.

Nevertheless, no framework for the commercialization of an integrated hydrogen economy currently exists and especially not in the Dutch context. Some authors have analyzed the potential development of an integrated hydrogen economy in a country-specific context (Lu et al., 2013; Pudukudy et al., 2014; J. Ren et al., 2015; X. Ren et al., 2020) or reviewed the current state of hydrogen technologies across the supply chain and discussed barriers to its commercialization and development (Abdin et al., 2020; Hosseini & Wahid, 2016; Parra et al., 2019; Sharma & Ghoshal, 2015; Singh et al., 2015; Yue et al., 2021). In the Dutch context, recent hydrogen-related papers have been published concerning public views (Huijts, 2018), infrastructure project risks (Vasbinder et al., 2021) or specific parts of the

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[1] Is part of the Dutch Climate Agreement which was the Dutch response to the Paris Climate Agreement (Rijksoverheid, 2019)

[2] Part of the European committee

[3] New Energy Coalition and Northern Innovation Board

hydrogen supply chain (Chrysochoidis-Antsos et al., 2020; Frowijn & Sark, 2021; Honselaar et al., 2018; Juez-Larré et al., 2019). Moreover, many reports have been written concerning the application of hydrogen in the Dutch energy system (New Energy Coalition, 2020; NIB, 2017; PWC, 2021; RVO & EZK, 2019; TKI Nieuwgas, 2020; TNO, 2020b). But no framework for the commercialization of a hydrogen economy in the Northern Netherlands has been developed. This is important to study given the potential of hydrogen for the future energy mix, the plans set out by the EU, and the specific plans for developing an integrated hydrogen economy in the Northern Netherlands. Therefore, we will address this gap by studying the barriers inhibiting the commercialization of a fully integrated hydrogen economy in the Northern Netherlands. The methodology will be based on the paper of Shakeel et al. (2017). These authors found that the commercialization of RE technology is realized at the intersection of specific technical, market, and regulatory factors. Accordingly, the following research question will be answered:

What are the relevant technical, market, and regulatory barriers inhibiting the commercialization of a potential integrated hydrogen economy in the Northern Netherlands?

A single case study is conducted to help answer this question. In-depth semi-structured interviews with 12 different representatives from the local government, companies, and industry experts to help attain a thorough understanding of the technical, market, and regulatory barriers these stakeholders encounter in the commercialization of the technologies responsible for building the integrated hydrogen economy in the Northern Netherlands. Scientific literature and reports on the subject were used to complement the findings of the field research. In the resulting framework, various barriers and mitigation strategies were identified. Specifically, 29 barriers across the hydrogen supply chain proved problematic for the commercialization of the hydrogen economy. These did not only concern technical, market, or regulatory barriers, but also social acceptance barriers. Besides, the barriers did not only relate to specific technologies: some related to multiple technologies and others to the entire hydrogen economy. Moreover, many of these barriers proved highly interrelated and interdependent. In addition, mitigation strategies are suggested, and a roadmap is provided to help address these barriers.

This way, the results add to the scientific literature first by providing a framework that represents a comprehensive up-to-date overview of all relevant barriers that may inhibit the commercialization of an integrated hydrogen economy in the Northern Netherlands. This will help scholars to better understand the implications and complexities of the transition to hydrogen-based energy systems. It will also provide a blueprint that can be used in future research to realize a generalizable theory on hydrogen economy development. In doing so, this study lays the groundwork for theory building on this subject. Secondly, it will help (local) governments to better design policies by being well informed about the complexities of developing a hydrogen economy and what barriers should specifically be resolved. Lastly, it will aid managers in better navigating this developing market which will improve managerial decision making and increase the chances of (potential) hydrogen companies becoming successful. Consequently, the results may help to spur the commercialization of an integrated hydrogen economy and contribute to achieving the goals set out by the Paris Agreement, the Dutch climate agreement, and the European Green Deal (Europese Commissie, 2019; Rijksoverheid, 2019; United Nations, 2015).

The rest of the report is organized as follows. Section 2 reviews the literature on the subject and section 3 describes the methods used to conduct the study. Subsequently, section 4 reviews the results of the research. These are discussed in section 5 in which the framework is proposed as well. The report is concluded in section 6 where the limitations to this report are considered too.

2 Literature review

Before elaborating on the hydrogen economy, it is imperative to discuss the commercialization of renewable energy technologies first as this paves the way for a better understanding of what is required to develop an integrated hydrogen economy. Subsequently, the importance of hydrogen as a future energy carrier is discussed. In the last section, the focus is on developing a 'hydrogen economy' in the context of the Northern Netherlands and why a framework representing relevant barriers to its development is needed for its commercialization.

2.1 The challenge of commercializing RE technologies

2.1.1 The transition toward a sustainable world

The Paris Climate agreement clearly showed the world's ambition to transition the global energy system toward a more sustainable one (United Nations, 2015). The European Union on its turn even raised this ambition by setting emission reduction targets to 55% (from 45%) (Europese Commissie, 2019). Fossil fuels have been a reliable source of energy, but economic and environmental concerns are pushing government and policymakers towards a renewable energy transition (Wee et al., 2012; Yaqoot et al., 2016).

2.1.2 Barriers to RE adoption

However, full-scale commercialization of RE technologies is difficult to realize as many barriers may prevent its diffusion (Shakeel et al., 2017). Therefore, scholars have researched these barriers to help spur the commercialization of RE technologies. Wee et al. (2012) took a supply chain perspective and discussed barriers to the development of RE supply chains (to produce renewable electricity) and strategies to mitigate them. Yakoot et al., (2016) reviewed pertinent economic, institutional, technical, socio-cultural, and environmental barriers that may prevent the dissemination of decentralized RE technologies and they address these by providing remedial measures. Lastly, Sen and Ganguly (2017) show the opportunities and barriers to full-scale development of RE technologies and conclude by discussing global investment needs, investment strategies for the power sector, and actions to take to spur the global adoption of RE technologies.

Moreover, many scholars have researched potential barriers to the adoption of RE technologies in country-specific contexts (Ahmad et al., 2011; Al-Badi et al., 2009; Karatayev et al., 2016; Kelly, 2011; Kinab & Elkhoury, 2012; Sahir & Qureshi, 2008). Most of these studies help explain why specific RE technologies are best suitable for a given country and discuss how policy measures can be applied to increase the national uptake of RE technologies.

2.1.3 Socio-technical regimes

The adoption of full-scale RE technologies is not just about the development of technologies but concerns a complete system change that impacts the economic and social context (Tsoutsos & Stamboulis, 2005). Changing that system is hard as incumbent firms are part of a socio-technical regime that is path-dependent due to the *"embeddedness of existing technologies in production practices and routines, in consumption patterns, in organizational structures and cultural values, as well as in mental frameworks, beliefs and practices of engineers, managers, and scientists"* (Hoogma et al., 2005, p. 211). This means they are less likely to innovate as they pursue incremental change rather than radical innovation (Hoogma et al., 2005; Steen & Weaver, 2017). Shifting towards a new regime may therefore take decades (Steen & Weaver, 2017). Recognizing the system-wide implications of the sustainable transition, authors have investigated how such regime change can be achieved in the context of RE technology (Hoogma et al., 2005; Tsoutsos & Stamboulis, 2005).

2.1.4 New policy frameworks

Realizing the scale of change required to move to a more sustainable world, Mowery et al. (2010) called for the development of a policy framework encompassing a holistic system-wide view. Many researchers responded to this call. For instance, Darmani et al. (2014) found that the literature lacked an adequate framework representing drivers of RE adoption and proceeded to develop one within the TIS (technology innovation system) framework based on a comprehensive literature review. In an attempt to design the best policy mix Kivimaa and Kern (2016) determined that this would include both supporting policy measures helping to create the new technologies as well as policy measures aimed at ‘destroying’ the old. The authors provide a policy framework aimed at these goals and test the framework by applying it to the analysis of two countries. Lastly, Fagerberg (2018) discusses insights into innovation policies thoroughly and considers policies that may increase the uptake of RE technologies based on that. The author concludes by summarizing lessons based on his literature review in which ‘holistic policy making’ is considered an important factor.

2.1.5 Commercialization of RE technology

Ultimately, commercialization in general is a complex and difficult process and significant for the success or failure of a technology (Christensen & Bower, 1996; Easingwood & Harrington, 2002). Many innovation models aimed at helping practitioners have therefore been developed (Abernathy & Utterback, 1978; Balachandra et al., 2004; Easingwood & Harrington, 2002). Commercialization of RE technologies is even harder as attested by the many barriers observed in the literature, the path dependency of socio-technical regimes, and the system-wide implication of the transition requiring holistic policy frameworks.

Realizing the significance of commercialization and extensively reviewing the literature on this subject, Shakeel et al., (2017) stressed the importance of this process and determined that successful commercialization of RE technologies is the result of *“…the right mix of technical, market and regulatory factors''* (Shakeel et al., 2017, p. 4). These authors then proceed to identify relevant factors that may hamper the adoption of RE technologies in Finland and conclude by providing a framework representing important barriers and drivers to wide scale RE adoption. Such a framework may be very useful for practitioners as it aids them in navigating the complex road of RE commercialization. A similar case can be made for the development and commercialization of an integrated hydrogen economy which will be clarified in the subsequent section.

2.2 Hydrogen: the future energy carrier

2.2.1 Green, blue, and grey hydrogen

First, a clear distinction must be made between the three main types of hydrogen. This distinction is not made based on the end product but on the method of production and its resulting level of harmful greenhouse gas emissions. First, ‘grey’ hydrogen is produced using fossil fuel, and a relatively large amount of CO2 is emitted as a result (IEA, 2019; Yue et al., 2021). A wide range of feedstock is available for grey hydrogen production (e.g. coal, gas, oil), but natural gas constitutes the largest share 48% (Bareiß et al., 2019). Here, natural gas steam reforming (SMR) is the preferred production method for grey hydrogen (Abdin et al., 2020). Blue hydrogen is the next best alternative in terms of emissions. Here, hydrogen is produced using fossil fuels as well (either natural gas or coal-derived gas), but Carbon Capture and Storage (CCS) techniques are applied resulting in lower emission levels (Brändle et al., 2021; IEA, 2019; Yue et al., 2021). Lastly, green hydrogen is produced using renewable energy in a water-splitting process called ‘electrolysis’ resulting in zero emissions for the production process (Brändle et al., 2021; Hosseini & Wahid, 2016; IEA, 2019). Indeed, when considering the entire life cycle, CO2 emissions are also emitted for these production techniques due to e.g. construction of the plants (Al-Qahtani et al., 2021; Bareiß et al., 2019), but these are relatively low compared to traditional production methods.

2.2.2 Hydrogen demand in the industry

Today, refineries and the chemical industry consume most of the hydrogen produced worldwide (IEA, 2021b). Globally, 40 Mt and 50 Mt of hydrogen were consumed by oil refineries and the chemical industries respectively amounting to the usage of roughly 90 Mt in 2020 (20 kt was used for transporting resulting in just 0,02% of total usage) (IEA, 2021b). Substituting grey hydrogen currently used in these processes by green hydrogen can constitute the first steps toward creating green hydrogen demand (IEA, 2019) and will help improve the sustainability of these sectors (Abdin et al., 2020). One promising application in this regard is the hydrogen-based Direct Reduced Iron (DRI) production route (Rissman et al., 2020). 5 Mt of H_2 was used for this production method accounting for 7% of worldwide steel production (IEA, 2021b) (the 5 Mt is accounted for in the 40 Mt total consumption of the chemical industry in 2020). Although this production method is relatively novel and underutilized, it allows for sharp CO2 reduction in the process of steelmaking if green hydrogen is used as the feedstock (IEA, 2021b; Rissman et al., 2020). As steel production accounts for 7-9% in total world C02 emissions (World Steel Association, 2020), this is a very promising technology for achieving a net-zero economy (IEA, 2021c).

2.2.3 Hydrogen as a vital part of the energy mix

Beside potential future demand for H_2 in the industry, hydrogen is considered to be a potentially vital part of the future energy mix (Abdin et al., 2020; Darmani et al., 2014; Hosseini & Wahid, 2016; IEA, 2019; IEA & CIEP, 2021; Rissman et al., 2020). *"…its cleanness and flexibility to act as a fuel in various applications as well as energy storage"* make hydrogen especially suitable to help realize a net-zero future (Abdin et al., 2020, p. 4). Furthermore, there is a need for an additional renewable energy carrier besides electricity given its unsuitability for specific energy uses in industry, transportation, and storage. Hydrogen will serve that purpose (Rissman et al., 2020). H_2 can also be produced and stored in various ways allowing for enhanced flexibility in the energy system (Hassan et al., 2021; Nikolaidis & Poullikkas, 2017) and despite some specific safety concerns, hydrogen use as a fuel is safer than the use of conventional fossil fuels (Sharma & Ghoshal, 2015).

One major issue for the future energy system concerns energy storage. Due to the problem of intermittency seen in RE sources of electricity, there's a critical need for buffer supplies of energy (Aneke & Wang, 2016; Hadjipaschalis et al., 2009; He et al., 2021; Yue et al., 2021). Consequently, the storage of energy will be a significant factor in realizing the global shift toward a sustainable world (Aneke & Wang, 2016). While batteries may mitigate problems in daily energy fluctuation (Chowdhury et al., 2020), only H_2 seems a viable way to bridge seasonal storage and demand gaps (Reuß et al., 2017). Therefore, 'grid balancing' may become a serious application for green hydrogen (Buttler & Spliethoff, 2018; IEA, 2021c). Storage by hydrogen will also prevent energy curtailment by storing excess energy during times of overproduction (Parra et al., 2019).

2.2.4 FCEV

Another end-use is in Fuel Cell Electric Vehicles (FCEV) (Fayaz et al., 2012). Various car manufacturers have already marketed FCEVs, but wide-scale commercialization is yet to be realized as attested by the diffusion number of this technology (IEA, 2020c, 2021a) and the usage of H_2 for transport applications (IEA, 2021b). FCEVs may have a hard time competing with Battery Electric Vehicles (BEV) (Fayaz et al., 2012; IEA, 2019, 2021a), but fuel cells might be applied in the heavy-duty transport sector given the range limit of batteries for vehicles in those categories (Çabukoglu et al., 2019; IEA, 2019). Although further research is probably needed to determine the actual economic feasibility of heavy Duty FCEVs, (Forrest et al., 2020), many companies are planning to introduce these vehicles to the market in the coming years (IEA, 2021b, p. 84) and some are already operational (IEA, 2021b). Other hydrogen applications may also be found in the aviation, railway, and maritime sectors. Here, either hydrogen itself or hydrogen-based synthetic fuels could be used to help decarbonize these sectors (Abdin et al., 2020; IEA, 2021b).

2.2.5 Built environment

Energy use in buildings amounts to up to 28% of global energy-related CO2 emissions (IEA, 2019). So, decarbonizing this sector will significantly contribute to global CO2 reduction. Consequently, various studies have been conducted on how to realize net-zero buildings (Asaee et al., 2018; Feng et al., 2019; Stephan & Stephan, 2020; Wei & Skye, 2021; Zhou et al., 2016). Although many of these solutions are promising, given the potential role of hydrogen as 'the' future energy carrier (Abdin et al., 2020; IEA, 2019, 2021b; Rissman et al., 2020), researchers have begun to investigate the possibility of injecting hydrogen into the gas grid (de Vries et al., 2017; Quarton & Samsatli, 2020). Mixtures between natural gas and hydrogen, synthetic methane (production using hydrogen), pure hydrogen, and the use of fuel cells and co-generation might be possibilities for hydrogen use for heating in buildings (IEA, 2019). Mixtures have a relatively low impact on CO2 emission reduction (reaching a blend of 20% of H_2 (considered to be the maximum end-use applications will tolerate) and 80% natural gas results in only 7% reduction of CO2 emissions), but will strengthen the demand market in the short term as a steady demand for hydrogen in the built environment is created (IEA, 2021b).

The feasibility of mixing hydrogen was already shown in a Dutch project in Ameland back in 2007 (Kiwa, 2012) and has also been confirmed in the literature (de Vries et al., 2017). However, the high efficiency of electrical solutions for a building's energy compared to hydrogen will presumably result in low penetration of hydrogen in the residential sector in the future (IEA, 2021b). Nevertheless, there are many uncertainties in future equipment & infrastructure requirements and hydrogen prices. If these develop favorably, there might be a large potential market for hydrogen applications in buildings (IEA, 2021b).

2.3 Hydrogen economy in the Northern Netherlands

2.3.1 Defining the hydrogen economy

The term 'hydrogen economy' was first coined in the 1970s during the energy crises "to describe a national (or international) energy infrastructure based on hydrogen produced from non-fossil primary energy sources" (Tyndall, 2005, p. 10). Lui et al. (2012) described the hydrogen economy as *"… a proposed system where hydrogen is produced from carbon dioxide-free energy sources and is used as an alternative fuel for transportation".* Niaz et al. (2015) had a similar definition and defined a hydrogen economy as "…the infrastructure which is used to support the energy requirements of society, based on the use of hydrogen in place of fossil fuels". Nonetheless, no universally accepted definition exists (Balat & Kirtay, 2010) and many scholars use the term very loosely without defining it (Abdin et al., 2020; Hosseini & Wahid, 2016; Parra et al., 2019; J. Ren et al., 2015; Singh et al., 2015; Yue et al., 2021).

Nonetheless, in general, a hydrogen economy usually means an integrated hydrogen energy system or supply chain that includes hydrogen production, distribution, storage, and end-use applications (Abdin et al., 2020; X. Ren et al., 2020; Singh et al., 2015) where hydrogen can be considered the energy vector (Abdin et al., 2020). Therefore, the integrated hydrogen economy will be defined as *'an integrated energy infrastructure of production, distribution, storage and end-use application where hydrogen is the main energy vector'.*

2.3.2 The Northern Netherlands

Given the potential of hydrogen, most countries in Europe have devised plans for the development of a low-carbon hydrogen economy (IEA, 2021b). The Netherlands have done so as well in their 'Strategy on Hydrogen' (Rijksoverheid, 2020). This report is in line with the Dutch climate agreement (Rijksoverheid, 2019) and sees hydrogen as an indispensable part of the future energy mix (Rijksoverheid, 2019, 2020). Besides, in all future energy scenarios a national hydrogen transport network (including large-scale storage) connecting important demand and supply centers is considered indispensable (Netbeheer Nederland, 2021a). In addition, the Netherlands sees itself as the future hydrogen hub of Europe due to its access to the North sea (and therefore offshore wind) (IEA & CIEP, 2021), the large current demand for hydrogen in the industry (IEA & CIEP, 2021; Rijksoverheid, 2019), the existing gas infrastructure (and accompanied knowledge) (PWC, 2021; Rijksoverheid, 2019) and the availability of large underground hydrogen storage applications in salt caverns (HyUnder, 2014; IEA & CIEP, 2021; *Opslag in Zoutcavernes › HyStock*, n.d.).

Here, the Northern part of the Netherlands is considered especially suitable for the development of an integrated hydrogen economy and was dubbed 'the hydrogen valley of Europe' by the Fuel cells and Hydrogen Joint undertaking (FCH JU) – part of the European Committee (New Energy Coalition, n.d.). Table 1 was adopted from an investment plan by the New Energy Coalition[4] and shows why this part of the Netherlands has such large potential.

Enablers of hydrogen economy	**Explanation**	**Hydrogen related assets**	**Explanation**
Momentum of project pipeline	50 hydrogen projects currently in development in Northern Netherlands	Strategic electrolyzer locations	Sufficient space for large production installations in Delfzijl, Eemshaven, and Emmen
Private and public investments	Subsidies awarded by EU, national government, and local government	Parallel gas infrastructure	An extensive gas infrastructure already exists. This can be (partly) converted for hydrogen purposes
Regulatory mandates	Environmental policies, mobility initiatives, and special planning for hydrogen projects	Storage in salt caverns	Presence of large scale hydrogen storage capacity in Zuidwending (Groningen)
At-scale hydrogen collaborations	Government, private parties, and knowledge institutes are closely collaborating: the triple helix. Also, local governments are very committed (in capital and time)	Scalable offshore wind	The North Sea north of the Netherlands
Talent and knowledge institutes	Proven energy research hub including Gasunie, University of Groningen and vocational training centers. Also, existing knowledge on gas	Regional demand centers	Chemelot (NL)/North Rine-Westphalia/Delfzijl/ Rotterdam

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[4] Consortium of companies, knowledge institutes, (local) governments and NGO's aimed at spurring the transition towards a more sustainable energy transition (*Over Ons - New Energy Coalition*, n.d.)

	infrastructure, transportation, trading, and innovation. Moreover, innovation centers are quickly being developed by knowledge institutes		

Table 1: opportunities for an integrated hydrogen economy in the Northern Netherlands; adapted from New Energy Coalition (2020)

Some of these advantages had already been recognized by the Northern Innovation Board[5] which led to the development of a roadmap to achieve a fully integrated hydrogen economy (NIB, 2017). Moreover, an investment agenda was made by another consortium of local governments and businesses aimed at developing an integrated hydrogen economy in the Northern Netherlands (Collective of companies, 2019). According to the report, various regulatory measures, a certification system for green hydrogen, and financial aid are some of the important actions to be taken by the national government to help spur the development of the hydrogen economy in the Northern Netherlands. Building on this report, the New Energy Coalition devised a more elaborate roadmap for achieving this goal (New Energy Coalition, 2020). Similar to the NIB report, various policy measures that will aid in realizing the goals aimed for in the roadmap are discussed (New Energy Coalition, 2020)

Currently, 50 projects focusing on parts of the hydrogen supply chain (or the whole supply chain) are being executed and the total project pipeline amounts up to 9 billion euros in investments so far (New Energy Coalition, 2020). Project HEAVENN – the flagship project – was awarded subsidies of 20 million euros by the FCH JU which combined with an additional co-funding from public-private parties amount to up to 90 million euros in total subsidies (New Energy Coalition, n.d.). This project is a large-scale program aimed at the development of an integrated hydrogen supply chain by bringing together various subprojects. Its blueprint may be replicated to Europe and beyond after successful implementation (*Heavenn - About*, n.d.; New Energy Coalition, 2020). The scope of this project is smaller than the goal aimed for in the roadmap of the New Energy Coalition, but it constitutes an important milestone for achieving its end goal.

2.3.3 Existing literature on the hydrogen economy

Nonetheless, a lot is unknown about how such an integrated hydrogen economy should be commercialized. Many authors have researched the potential for an integrated H_2 economy. For instance, Sharma et al. (2015) summarize the current state of hydrogen technology in production, distribution, and storage and provides three main technological barriers to full-scale adoption. In a more recent paper on the same subject Abdin et al., (2020) discuss all parts of the hydrogen supply chain in more detail and includes a comprehensive description of the (future) demand market. Hosseini et al., (2016) provide a similar analysis but mainly focus on RE technologies for the production of hydrogen. Likewise, Singh et al., (2015) discuss the whole hydrogen supply chain, although this paper focuses more on hydrogen as a fuel. Long-term storage for grid balancing is therefore not considered and the various kinds of RE production methods are left out too.

Moreover, Yue et al. (2021) critically review technologies, applications, and trends across the entire hydrogen value chain and link these to projects currently conducted across the world. They conclude by discussing the technical perspective of current hydrogen power systems and provide societal and political barriers to overcome. Alternatively, Para et al., (2019) review a more specific (but still system

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[5] Consortium of entrepreneurs, local government, and knowledge institutes aimed at speeding up economic development in the Northern Netherlands. It is currently mainly concerned with developing hydrogen power-based resources.

broad) part of the hydrogen economy by discussing four hydrogen systems that are currently already employed and may prove vital for the full transition to an integrated hydrogen economy. They concern Power-to-power (PtP), Power-to-gas (PtG), hydrogen refueling, and stationary fuel cell systems. The authors conclude by providing three main actions to take which would increase the uptake of these technologies.

In-country/region-specific context, Pudukudy et al. (2014) discuss some of the challenges and opportunities for hydrogen in Asia and conclude by providing some general recommendations which may spur the adoption of hydrogen technologies in that region. In China, Lu et al. (2013) review drivers, resources, and technologies that will help build a hydrogen economy and relate this to the suitability of the country's geography for hydrogen production, the available energy sources, and government policy and investments. Alternatively, Ren et al., (2020) focus more on the challenges of developing a hydrogen economy in China and concludes by providing recommendations to tackle these challenges. Lastly, Ren et al. (2015) applied a SWOT analysis to analyze the current status of the hydrogen economy (again in China) and used the multi-criteria-decision-method (MCDM) to prioritize strategies that help promote the hydrogen economy. These papers provide some valuable insights into the challenges governments and businesses might encounter in the development of a hydrogen economy, but these studies are either dated and/or do not consider the Dutch context.

In the Dutch context, some recent articles include the study of hydrogen infrastructure risks in the Netherlands which includes an integrated framework to predict prominent project risks (Vasbinder et al., 2021) and a case study on the consequence of the public's emotional responses to the development of hydrogen refueling stations (Huijts, 2018). There were also studies on specific hydrogen supply chain parts such as the risk assessment (in the context of permitting) for HRS (Honselaar et al., 2018), a study on the potential for underground hydrogen storage (Juez-Larré et al., 2019), a study on the technical potential of using on-site wind turbines to support hydrogen production facilities at HRS (Chrysochoidis-Antsos et al., 2020) and an analysis of using solar energy (photon driven) for the production of H_2 (Frowijn & Sark, 2021). Furthermore, many reports and roadmaps have been written or devised on the use of hydrogen across various sectors (PWC, 2021; RVO & EZK, 2019; TKI Nieuwgas, 2020; TNO, 2020b) and even specifically for the Northern Netherlands (Collective of companies, 2019; New Energy Coalition, 2020; NIB, 2017).

2.3.4 Framework for commercializing an integrated hydrogen economy

Ultimately, no framework for the commercialization of an integrated hydrogen economy currently exists. And certainly not for the Northern Netherlands. This is surprising given the potential for hydrogen as a future energy carrier, and the plans set out by the EU and the Netherlands for the development of such an economy. Similar to the Finland case (Shakeel et al., 2017), a framework will help identify the relevant market, regulatory and technical barriers potentially inhibiting the development and commercialization of an integrated hydrogen economy and will aid in tackling these barriers. Despite the author's focus on RE technologies instead of hydrogen, this paper argues that a similar framework will likely apply to the commercialization of an integrated hydrogen economy.

An integrated hydrogen economy can be considered a hydrogen supply chain where production is followed by storage, distribution, and end-use (Abdin et al., 2020; Hosseini & Wahid, 2016; Singh et al., 2015). This is similar to RE technologies, which can also be viewed from a supply chain perspective including the same elements (Wee et al., 2012). These supply chains partly overlap as RE sources are required for the production of green hydrogen (Brändle et al., 2021; Wee et al., 2012). Down the supply chain, the main difference is in the energy carrier (hydrogen vs electricity/another source to which electricity can be converted for storage purposes) and therefore the specific technologies for storage and distribution (Abdin et al., 2020; Wee et al., 2012). End-use may also differ, but as grid-balancing is likely to be an important purpose of H_2 in the hydrogen economy (Buttler & Spliethoff, 2018; IEA, 2021b), end-use purposes may again overlap (electricity supply to the grid). Indeed, the RE supply chain and the hydrogen economy are inextricably linked. Hydrogen technologies could even be considered to be part of the RE supply chain (Wee et al., 2012), and both concerning system-wide changes (Abdin et al., 2020; J. Ren et al., 2015; Singh et al., 2015; Tsoutsos & Stamboulis, 2005). Consequently, commercialization of the integrated hydrogen economy is expected to be spurred by a combination of the right mix of technical, regulatory, and market barriers (fig 1.) similar to RE technologies in Shakeel et al. (2017).

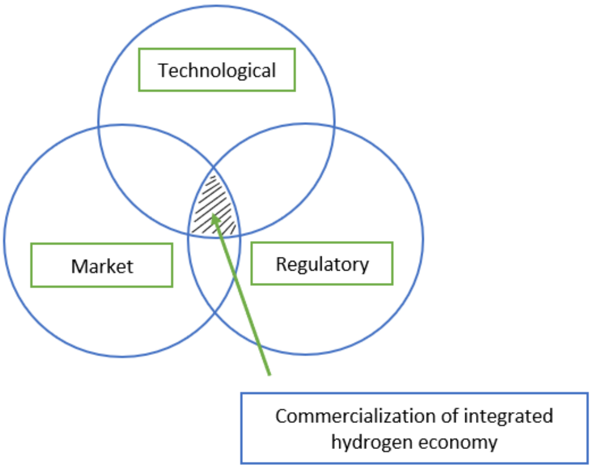

Figure 1: commercialization of integrated hydrogen economy; adapted from Shakeel et al. (2017)

To help narrow the scope of this report, the focus will be on specific technologies of a potential integrated hydrogen economy in the Northern Netherlands instead of all available technologies. Table 2 shows the technologies on which this report will focus and why the focus is on those specific parts. Appendix 1 elaborates more on the available hydrogen economy technologies and shows how this report relates to the roadmaps devised by the NIB and the NEC and the technological maturity of the hydrogen technologies. Figure 2 constitutes a visual representation of the hydrogen economy researched in this report. The main supply chain parts (production/distribution/storage/end-use) are represented by the colored boxes and the specific technologies[6] (elements) that will be researched in the study are included in those boxes. The relation between those technologies is visually represented by the blue/black arrows.

H_2 supply chain	**Technology**	**Explanation**
Production	Offshore wind electrolysis	Most promising for this part of the Netherlands as wind farms are being built in the North Sea which will partly be used for hydrogen production (New Energy Coalition, 2020; NIB, 2017; *Over NorthH2 - NorthH2 | Kickstarting the Green Hydrogen Economy*, n.d.; Rijksoverheid, 2020)
Storage	Compressed gas storage tank	Currently the most mature and straightforward short term storage method (Abdin et al., 2020; Hassan et al., 2021; Reuß et al., 2017) and therefore most likely to be an

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[6] Note that technologies are used in a broad sense and refer to the elements in figure 2. Therefore, a ‘specific’ technology encompasses all technologies for a given element (e.g., in the case of electrolysis, it concerns all types of electrolyzers and all auxiliary technology)

		important part of the hydrogen economy in the Northern Netherlands.
	Liquified hydrogen storage tank	Although liquified hydrogen will likely not be suitable for the distances found in the Netherlands (IEA, 2021b; Reuß et al., 2017), future FCEVs might use liquid hydrogen instead of compressed hydrogen in their fuel cells (IEA, 2021b) thus increasing the need for liquified H_2 storage. Besides, the Northern Netherlands may develop a liquid H_2 trading market, which combined with its ports will enable the region to become the hydrogen hub it aspires to be (New Energy Coalition, 2020)
	Salt caverns	Proven storage medium for large scale underground storage (Tarkowski, 2019) and permits are currently being arranged for the construction of this storage application in the Northern Netherlands (*Onze Planning › HyStock*, n.d.)
Distribution	Pipelines	Likely to be the most cost-effective distribution method given the distances in the Netherlands and the current existence of gas infrastructure (PWC, 2021; Reuß et al., 2017). Besides, Gasunie is planning to construct a hydrogen backbone in the Netherlands (largely using the existing infrastructure and partly building new infrastructure) with the aim of connecting the Dutch industrial clusters with each other and with Germany and Belgium (Gasunie, 2020)
	Liquified/compressed gas tank tube trailer	Supplying small amounts of hydrogen to e.g. refueling stations is most likely to be executed by compressed gas tube trailers (Reuß et al., 2017; Yue et al., 2021). However, there are various ongoing experiments with liquid hydrogen tanks in FCEV (IEA, 2021b) and future HRS may therefore need to supply liquid hydrogen instead. Moreover, the EU is targeting liquid H_2 HRS for every 450 km of roads (IEA, 2021b)
End-use	FCEV/Refuelling stations	FCEV potential was already stressed in the literature. It is also included in the plans of HEAVENN (*Heavenn - About*, n.d.) and in both the roadmap of the NIB and NEC (New Energy Coalition, 2020; NIB, 2017). Some HRS have already been constructed in the Northern Netherlands (*Pesse Voor Één Dag Waterstofmekka van Europa - Green Planet : Green Planet*, n.d.). To narrow the scope of the report, the focus will be on passenger vehicles (heavy-duty transport/trucks are not included)
	Chemical industry	The importance of substituting grey hydrogen by green hydrogen in the chemical industry was already stressed in the Literature. The Northern Netherlands has a chemical industry to which this could apply as well (New Energy Coalition, 2020; NIB, 2017). The focus will be on methanol production given its global importance (globally the second-largest end-user of H_2 in the industry (IEA, 2021b)) and given the existing methanol producing industry in the Northern Netherlands (New Energy Coalition, n.d.). The first consumer of hydrogen (ammonia production (IEA, 2021b))

		is not considered as there are no ammonia production plants in this region.
	Grid-balancing	Given the access to long term storage in salt caverns (*Opslag in Zoutcavernes › HyStock*, n.d.) and the significance and the role hydrogen can play in grid-balancing (Buttler & Spliethoff, 2018; IEA, 2021c), this application is likely to be part of the future hydrogen economy in the Northern Netherlands. It is also included in both the roadmap of the NIB and the NEC (New Energy Coalition, 2020; NIB, 2017).
	Built environment	Various projects will be testing the viability of using hydrogen for heating in buildings in the Northern Netherlands (*Heavenn - Storage & Built Environment*, n.d.; New Energy Coalition, 2020). There's high uncertainty about its feasibility (IEA, 2021b), but there's certainly potential for its integration into the hydrogen economy of the Northern Netherlands if these projects prove successful. Although partial injection of hydrogen for the built environment is a potential scenario in the context of the Netherlands (TNO, 2020b), it is excluded to narrow the scope of this report. The focus will be on injecting pure hydrogen into the built environment.

Table 2: parts of a potential integrated hydrogen economy in the Northern Netherlands

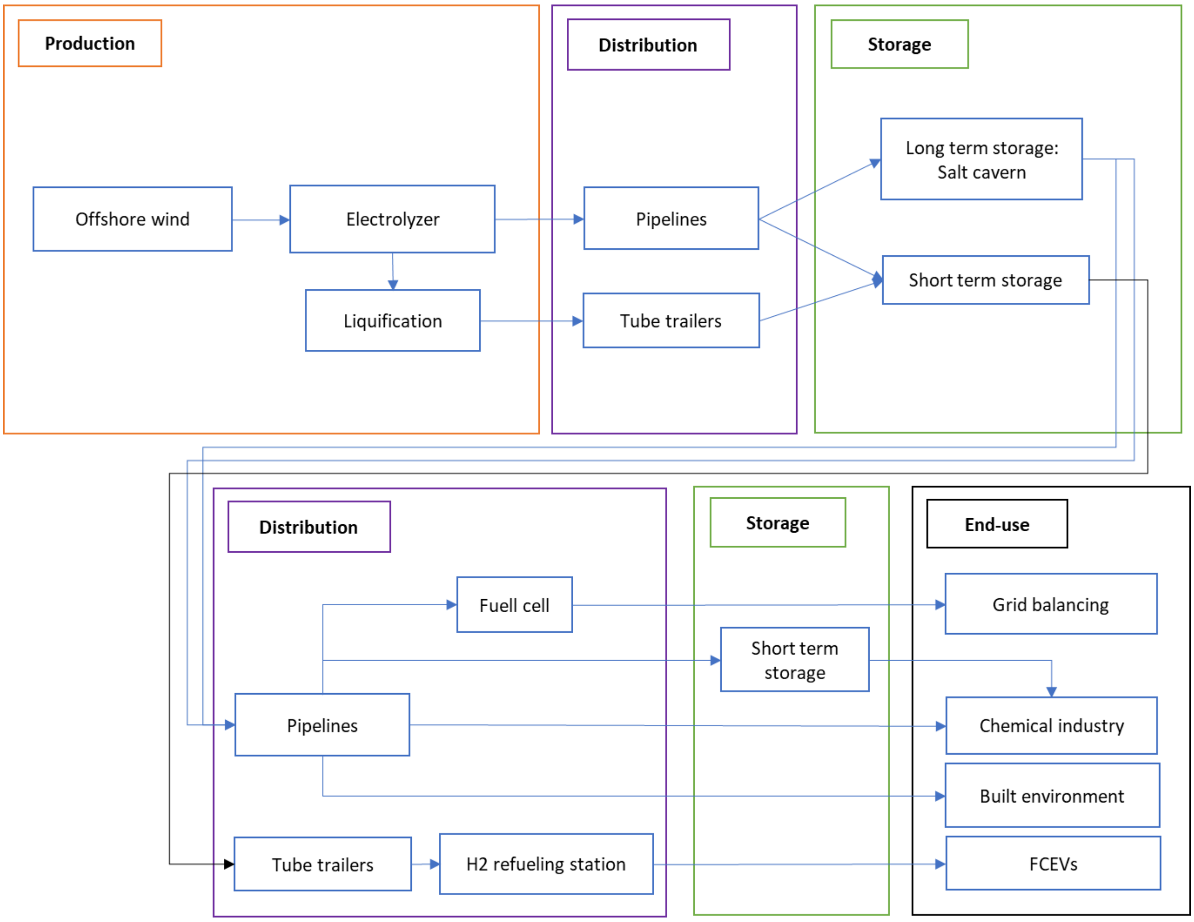

Figure 2: the integrated hydrogen economy in the Northern Netherlands[7]

2.3.5 Contribution

This study will contribute to the existing literature by developing a framework for the commercialization of an integrated hydrogen economy in the context of the Northern Netherlands. This framework will help academics to better understand how addressing technological, market, and regulatory barriers will help commercialize an integrated hydrogen economy and what the implications of developing such an integrated energy system are. The framework may then be used to research the development of hydrogen economies in other contexts to help identify differences and similarities in order to advance the field of hydrogen. Practitioners can use the framework to better plan for the development of an integrated hydrogen economy as it will help them identify potential problems early on and address these issues accordingly.

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[7] Note: the schematic overview only shows the technologies researched in this report and not the most likely setup of those technologies. This especially concerns liquefaction after electrolysis as this seems an extremely inefficient use of energy due to the efficiency losses seen in both electrolysis and the process of liquefaction.

3 Methodology

3.1 Research design

This research will build an overview of all relevant technical, regulatory, and market barriers potentially inhibiting the development of an integrated hydrogen economy in the Northern Netherlands. The case for the Northern Netherlands is extremely favorable for the development of an integrated hydrogen economy compared to other potential locations across the globe and there are already 9 billion euros worth of projects in the pipeline (New Energy Coalition, 2020). It can therefore be considered a unique case. Besides, the theoretical background showed that no framework of relevant barriers for the commercialization of an integrated hydrogen economy currently exists. Especially not in the context of the Northern Netherlands. Moreover, such a concept has not yet been developed in reality either, so there is no practical experience to account for it. Given the novelty of the concept and the small theoretical basis, this study will be exploratory in nature (Karlsson, 2016). As the goal is to develop a framework for the commercialization of an integrated hydrogen economy, this paper attempts to build a theory, which can be tested and refined in future research (Karlsson, 2016).

This report will apply the same method as Shakeel et al. (2017) who studied the commercialization of RE technologies (in this study hydrogen technologies) in the context of Finland (in this study the Northern Netherlands). Similar to their paper, this study will apply an in-depth case study method. This method is considered to be suitable as the phenomenon studied enjoys only a small theoretical basis, and the aim is to build theory (Eisenhardt, 1989; Eisenhardt & Graebner, 2007; Siggelkow, 2007). Besides, the study focuses on a contemporary event, making the case methodology especially suitable (Benbasat et al., 1987).

As the phenomenon is studied in its natural setting, this approach also increases the validity for the practitioner who can be considered 'the ultimate user of research' in operations management research (Karlsson, 2016). Although multiple case studies provide a better grounded more generalizable theory (Eisenhardt & Graebner, 2007; Karlsson, 2016), a single case study allows for a more in-depth exploration of the phenomenon (Karlsson, 2016). Given the uniqueness of the case – no similar case currently exists – and the highly exploratory nature, a single case study is considered to be the best approach (Benbasat et al., 1987; Eisenhardt & Graebner, 2007; Yin, 1984).

Shakeel et al. (2017) determined that confining their study *"to a single unit of analysis increased the probability of leading to biased and less accurate results"* (Shakeel et al., 2017, p.4). As Yin (1984) explains, multiple units of analysis may be applied to case study research. Similar to the paper of Shakeel et al. (2017), this study will apply multiple units of analysis (technology-specific and system broad) to acquire a more comprehensive understanding of how the technical, regulatory, and market barriers inhibit the development of an integrated hydrogen economy making the research an embedded single case study (Yin, 1984).

Interviews will be conducted with company representatives and local governments who can be considered experts on the subject as they apply business expertise to develop parts of the hydrogen supply chain or have specific knowledge on regulatory issues (in the case of local governments) Additionally, the scientific literature and reports on the subject were studied to complement these findings.

3.2 Case and interviewee selection

3.2.1 Case selection

A unique situation exists in the Northern Netherlands where governments, companies, knowledge institutes, and NGOs are working together to develop an integrated hydrogen economy. Therefore –

as previously explained – this part of the Netherlands was dubbed 'the hydrogen valley of Europe' by the Fuel cells and Hydrogen Joint undertaking (FCH JU). As case selection in single case studies can be based on the unique research opportunities (Yin, 1984), the distinctive situation in the Northern Netherlands is exploited for this research. Hence, the hydrogen valley in the Northern Netherlands is the subject of this single case study.

3.2.2 Interviewee selection

For the selection of interviewees, it is important to consider that the collected field data has information on all parts of the hydrogen supply chain from the overview in appendix 1. The road map of the New Energy Coalition (2020, p. 38) provides an extensive overview of all companies and government agencies that are involved in (future) hydrogen projects. Based on this a selection was made that covers all parts of the hydrogen supply chain (see table 3). Note that company 'I' was added only after its importance for the hydrogen economy became clear in the interviews.

Organization/ Academic	**Core business**	**(potential) expertise in hydrogen technologies**	**Expected expertise based on**
Company A	Building and managing large-scale transportation of natural gas. It will (partly) shift to hydrogen and green gas in the near future.	● Building pipelines for hydrogen transportation ● Repurposing existing pipelines for hydrogen use ● Short term hydrogen storage applications. ● Long term hydrogen storage	Company will distribute hydrogen in its network in the future and will adjust its infrastructure accordingly. It is also codeveloping several hydrogen projects concerned with the production distribution and storage of hydrogen.
Company B	Company producing essential chemicals for all sorts of end products	● Electrolyser technology	Company will build a 20 MW electrolyzer to produce green hydrogen
Company C	Builds HRS and produces clean fuels	● HRS	Will built HRS in Drenthe in 2021
Company D	Owner and commercial operator of the Harbours in the Northern Netherlands.	● Wind energy + electrolysis ● Electrolyser technology	Company is co-developing a hydrogen project aimed at producing green H2 using wind energy.
Company E	Operates and develops next-generation gas storage facilities for energy companies	● Long term hydrogen storage in salt caverns	Company is testing the viability of using underground salt caverns as storage facilities for hydrogen in the Northern Netherlands
Company F	Supplier of energy (services)	● Wind energy + electrolysis ● Electrolyzer technology	Company plans to construct a large green hydrogen production facility in the Northern NetherlandsN-t

Company G	Network operator	- Built environment - Partial injection of hydrogen into gas grid - Full injection of hydrogen into gas grid	Involved in projects aimed at converting the built environment to the use of hydrogen
Company H	Network operator	- FCEV - Fuel cells	Company itself is not involved in FCEVs and fuel cells. The interviewee of interest is an expert in fuel cell technology
Company I	Coordinating agency	- Economic integration - System coordination	Responsible for coordinating the development of the hydrogen economy in the Northern Netherlands
Company J	Network operator	- Grid balancing - System broad issues	Not directly involved in the Northern Netherlands. Person of interest is an energy expert
Municipality K	Municipality	- HRS - FCEV	Taking part in several mobility initiatives including HRS and FCEVs

Table 3: selection of organizations and academia for research

3.3 Data collection

Data collection consisted of two parts. First, semi-structured interviews were conducted in November and December of 2021. The semi-structured interviews help to systematically collect information while still allowing for the exploration of new issues when they arise (Wilson, 2014). In this case, the structured part of the interview is related to the technical, economic, and market barriers for a specific hydrogen technology. The flexibility that semi-structured interviews allowed, gave the chance to pursue specific topics that arose during the interviews which helped to uncover new concepts (Gioia et al., 2013). Interviews were conducted with employees in various hydrogen-related businesses across the hydrogen supply chain, and a government agency related to a number of hydrogen projects. These participants were mostly managers, but an R&D engineer and a part-time researcher (electrical engineering) also participated. These diverse viewpoints helped to limit bias as this mitigates the problem of informants engaging in *"convergent retrospective sensemaking/or impression management"* (Eisenhardt & Graebner, 2007, p.4). This also improves the triangulation of data and enhances the validity of the study (Karlsson, 2016).

Reliability and validity were further enhanced by developing an interview protocol (Yin, 1984). The protocol is based on Jacob and Furgerson (2012) and was developed using existing literature, the main barriers suggested by Shakeel et al. (2017), and the research question (see appendix 2). 12 protocols were developed as these had to be tailored to the specific company or government agency. The interview questions were sent to the interviewees in advance of the interview. Afterwards, a structured summary was sent to the interviewees to ensure no misunderstanding had occurred (see appendix 5), thus improving the accuracy of documentation (Karlsson, 2016). As the analysis was done simultaneously with conducting the field research, protocols were adjusted according to new findings focussing more on the concepts discovered in those interviews (Gioia et al., 2013). The interviews were transcribed soon after the interview took place to ensure a fresh memory of the interview and allow for quick follow ups when necessary (Gioia et al., 2013; Karlsson, 2016).

Secondly, the scientific literature and reports were researched to complement the findings from the field research. These concern the latest scientific articles on hydrogen technologies related to the hydrogen supply chain parts of this study and reports on hydrogen in the context of the Netherlands or the Northern Netherlands by various kinds of stakeholders. This secondary source of data added additional richness to the findings of the case study (Yin, 1984) and helped ensure the triangulation of data as well, again improving the validity of the study (Eisenhardt, 1989; Karlsson, 2016).

Interviewee identification code	Company
A.1	Operator of gas infrastructure
B.1	Chemicals company
C.1	Producer of high-pressure technology (designs and constructs technology for HRS)
K.1	Large municipality (involved in several hydrogen projects)
D.1	Harbour operator (involved in large hydrogen production project)
A.2	Operator of gas infrastructure
E.1	Provider of fast-cycle gas storage services
F.1	Supplier of energy (services)
G.1	Network operator (involved in projects aimed at converting the built environment to the use of hydrogen)
H.1	Network operator
I.1	Coordinating agency (responsible for coordinating the development of the hydrogen economy in the Northern Netherlands)
J.1	Network operator (not directly involved in the Northern Netherlands)

3.4 Data analysis

The interviews were transcribed in Microsoft Word (see appendix 4 for transcripts) and coded using Atlas.ti software. Given the theory-building approach of this research, codes were based on both theory and data (Karlsson, 2016). Here, pre-defined codes were based on the hydrogen technologies included in this research and the theory of Shakeel et al. (2017). So, the predefined codes were mainly a combination of a barrier (technical/market/regulatory) and a specific hydrogen technology (e.g., technical barriers electrolyzers). Next, additional codes were added to capture emerging themes (Karlsson, 2016).

Data reduction is key in the practice of qualitative data analysis (Miles & Huberman, 1984). Hence, codes were assigned only to concepts and data that were deemed relevant to this research. This judgement was based on the relevance of data to hydrogen technology and/or to the entire hydrogen economy. Consequently, all data related to hydrogen technologies or to hydrogen economy-related subjects were coded. The predefined codes and the emerging codes resulted in a total of 53 distinct codes. Table 5 provides an overview of these:

Predefined codes (40)	Emerging codes (13)

Technical barriers wind farm	Blue hydrogen production barriers
Regulatory barriers wind farm	Blue hydrogen production opportunities
Market barriers hydrogen production	Hydrogen production opportunities
Regulatory barriers hydrogen production	Hydrogen production barriers
Technical barriers electrolyzers	Hydrogen pipeline distribution
Regulatory barriers electrolyzers	Chicken-egg problem
Technical barriers hydrogen pipeline distribution	Social acceptance issues
Market barriers hydrogen pipeline distribution	Storage in general
Regulatory barriers hydrogen pipeline distribution	General grid balancing
Technical barrier HRS	General barriers
Market barrier HRS	General technical barriers
Regulatory barrier HRS	General market barriers
Regulatory barriers hydrogen storage	General regulatory barriers
Technical barriers hydrogen storage	
Market barriers hydrogen storage	
General short-term storage	
Liquid hydrogen opportunity	
Liquid hydrogen barriers	
Technical barrier chemical industry	
Market barrier chemical industry	
Regulatory barrier chemical industry	
Technical barrier FCEV	
Market barrier FCEV	
Regulatory barrier FCEV	
Technological barriers grid balancing	
Market barriers grid balancing	

Table 5: overview of pre-defined and emerging codes

Subsequently, these first-order codes were grouped into second-order codes (the hydrogen technology which they are part of). In the last step, these were aggregated into themes (namely, the hydrogen supply chain part these technologies are part of) which resulted in a coding tree (see appendix 3). Table 6 provides an excerpt of this coding tree. Next, this data was exported to excel to allow a better visual representation; all data related to a specific technology and supply chain part was now easily accessible. The goal was to establish a clear overview of all interview data related to a specific subject. Here, all relevant interview quotes related to a particular subject were combined with scientific literature and reports on the subject to realize a complete overview of all information on a specific topic. This enabled an exhaustive review of all potential barriers related to the selected technologies in this study and of the entire integrated hydrogen economy in the Northern Netherlands.

First-order code	**Second-order code**	**Theme**	**Is part of**
Hydrogen pipeline distribution	Pipelines	Hydrogen distribution	Barriers inhibiting H2 economy Northern Netherlands
Technical barriers hydrogen pipelines distribution			
Market barriers hydrogen pipelines distribution			

Regulatory barriers hydrogen pipelines distribution			
Technical barriers HRS	HRS		
Market barriers HRS			
Regulatory barriers HRS			
Technical barriers hydrogen storage	Long term hydrogen storage barriers	Hydrogen storage	
Market barriers hydrogen storage			
Regulatory barriers hydrogen storage			
Storage in general	Long term hydrogen storage barriers & Short-term hydrogen storage and liquid hydrogen		
General short term storage barrier	Short-term hydrogen storage and liquid hydrogen		
Liquid hydrogen opportunity			
Liquid hydrogen barriers			

Table 6: excerpt of coding tree

4 Results

4.1 Hydrogen production

4.1.1 Windfarm

Technical barriers

The results reveal that although no technical barriers were identified for the construction of wind farms, a shortage of materials may constitute a barrier to windfarm development in relation to hydrogen production.

First, the technological readiness of offshore wind farms is 9/11 which means it is considered *"…commercial and competitive, but needs evolutionary improvement to stay competitive"* (IEA, 2020a, p.1). Although the technology is not yet competitive with grey alternatives (IEA, 2020a), no technical barriers were identified to its use.

Secondly, a shortage of materials may prove problematic. According to the manager (A.1):

"…there is a huge demand for offshore wind all over the world, and not just for the wind farms themselves, but also for the cables and the converter stations which are needed. That's going to be very tense…"

In a letter to the House of Representatives, the Ministry of Economic Affairs stated that the Netherlands has had to adjust its goals concerning the construction of offshore wind farms by 2030 partly due to supply restrictions (EZK, 2021). This is especially problematic given the huge scale of wind farms required to attain sufficient capacity to produce the quantities of hydrogen needed. The manager of a harbor operator (D.1) stated this more clearly:

"It's not something you just roll out. Uhm, a large, very large power plant has a capacity of 2.4 gigawatts, so it's really a huge power plant that has to be installed at sea."

Besides, only 11,1% of all electricity consumed in the Netherlands was from RE sources in 2020 (CBS, 2021). For the country to achieve its climate goals, it has to increase its green electricity share and aims to construct more wind farms to this end (EZK, 2018; Rijksoverheid, 2019). Moreover, the use of electricity will only increase as electrification is an essential part of the government's strategy to achieve climate neutrality (Rijksoverheid, 2019). Consequently, more demand for construction materials is expected, increasing the difficulty for hydrogen production projects to construct wind farms in time.

Regulatory barriers

The results reveal three key regulatory barriers for wind farm construction in relation to hydrogen production. These concern (1) the acquisition of suitable lots for wind farms, (2) the long permitting procedures for these projects and (3) difficulties in the national law requiring TenneT to connect windfarms to the onshore grid, but not to an electrolyzer.

First, the acquisition of lots. Lots are locations for wind farms at sea which parties can acquire after participating in a government tender. Electrolyzers can only be constructed at specific locations (the footprint of an electrolyzer facility is large and can only be located at specific industrial areas with sufficient space). Consequently, wind farms need to be constructed at specific locations (close to the electrolyzer). The manager (A.1) stated:

"But hey, we're looking at pretty big electrolyzers. That may be clear. But there aren't that many places in the Netherlands where you can put that thing. So, what we actually need is a very specific wind block[8]*, which is what we are now looking for. Of course, that is just not possible"*

Here, competition can prove problematic as a potential hydrogen producer is bidding against other parties whom the producer may lose to in bidding for the lot. Hence – given the importance of these lots – if no specific regulations are designed that makes it easier for hydrogen production parties to acquire suitable lots, these projects may stand before having started. According to the same source (A.1), laws and regulations are now being devised to mitigate this problem. But currently, these regulations potentially slow down the development of hydrogen production facilities. The significance of access to green electricity for a hydrogen production plant cannot be underestimated according to the manager (D.1):

"If that does not accelerate[9]*, then the plans for large-scale green hydrogen production may develop, but that is where it stops. If green electricity is not available, the whole chain will be stranded."*

Secondly, the permitting procedures are time-consuming and can cause significant delays for offshore wind farm projects. A letter by the Ministry of Economic Affairs to the House of Representatives indicated that (besides issues in the supply chain) the extensive permitting trajectories were responsible for the inability of the Netherlands to adhere to its previous plans of realizing 10 GW of offshore wind capacity by 2030 (EZK, 2021). These extensive procedures can also significantly delay hydrogen production projects according to multiple sources (A.1; B.1).

Lastly, according to national law, TenneT[10] is obliged to connect wind farms to the onshore grid. This saves significant costs to the wind farm operator as this is a very capital-intensive procedure according to the manager (A.1). These costs are passed on to TenneT and therefore socialized (although the costs are incorporated in the transport rate in this case). However, TenneT is not yet obliged to connect wind farms to an electrolyzer. So, hydrogen production parties may need to bear the full cost of connecting the wind farm to the electrolyzer. The extent to which this constitutes a barrier to windfarm development in relation to hydrogen production depends on the situation.

According to the manager (F.1) involved in a large hydrogen production project, this will not be an issue as their production facility will be connected to the national grid instead of directly to an electrolyzer. Conversely, the manager (A.1) of different hydrogen production projects stated that the severity of this issue depends on the total package of available regulatory instruments. According to her, the connection can be incorporated into the hydrogen price and if the hydrogen sales are subsidized by an OPEX (Operational Expenditure) subsidy, the connection does not disproportionally impacts the business case of the project.

This means that the extent to which the regulatory obstacle constitutes an actual barrier depends on the type of project (electrolyzer directly connected to a wind farm or not) and future developments in regulatory instruments.

4.1.2 Electrolyzer

Technical barriers

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[8] A lot a meant here

[9] Concerns the construction of wind farms

[10] Dutch high voltage grid operator

No technical barriers were identified for the construction of electrolyzers. There are technical obstacles that must be mitigated, but these are not considered barriers that will significantly delay the projects.

The scale of future hydrogen production plants is significantly bigger than compared to existing plants. Scaleups are needed in electricity connections, compression, and the supply of demineralized water. It is also not clear whether PEM or Alkaline will be used in some instances. As to the construction of a large electrolyzer plant, the manager (F.1) explained:

"But I know from my experience in the energy world, we also had a similar phenomenon in the 1990s when scaling gas turbines. Generally, that went well, but it also went by trial and error. And there was also a phase where people had problems with certain materials in those gas turbines themselves leading to damage when they built the power plant."

However, the obstacles are surmountable and will not limit or significantly slow down the development of those facilities according to the managers involved in hydrogen production projects (A.1; B.1; F.1).

Lastly, it is important to note that despite the low electrolyzer efficiency currently seen in this technology[11], this is not considered to be a significant barrier. Indeed, the technology is expected to improve (Brändle et al., 2021; IEA, 2019), but as hydrogen prices are largely determined by green electricity prices (Hosseini & Wahid, 2016; Nikolaidis & Poullikkas, 2017), scale-up of windfarms in the North Sea is expected to significantly contribute to lowering the cost of green hydrogen according to the manager (I.1).

Market barriers

Two market barriers were identified. These concern (1) a chicken-and-egg problem for supply and demand parties and (2) the cost price of producing green hydrogen. Note that the market barriers concern both wind farms and electrolyzer plants. Therefore, wind farms and electrolyzers are jointly considered here (for that reason, no market barrier section is included in section 4.1.1. Wind Farms).

The first barrier concerns the chicken-and-egg problem. Before organizations make the investment decision to construct a large hydrogen production facility, they need to have some commitment from demand parties that they will purchase the hydrogen produced. These parties on their turn may not be willing to adjust their production processes for the use of green hydrogen because they have no certainty that supply parties can deliver the right amount of green hydrogen reliably when the adjustment is completed. As it is hard to gain commitment from end-users, the business case for large hydrogen production facilities becomes less attractive. This also relates to market maturity. No hydrogen trading market currently exists. The manager (D.1) explained:

"There is no mature market and that means that you don't have an economic price mechanism. If you want to buy hydrogen from someone and you can't agree on the conditions, the price, continuity, and quality, you don't have the alternative of switching somewhere, so the platform that allows you to determine economically whether a certain intake of a certain amount of hydrogen fits into your business model is not there."

Consequently, demand parties will be hesitant to include green hydrogen in their production processes, and the business case for a hydrogen production facility is further diminished.

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[11] 20-30% conversion losses according to the manager (J.1).

The second market barrier relates to the price of producing a kilogram of hydrogen. Currently, steam methane reforming using natural gas (SMR) offers the most cost-competitive way to produce hydrogen (Nikolaidis & Poulikkas, 2017). Production costs range between €1,2 and €1,6/KgH2 (in Europe), while green hydrogen production costs range between €2,7 to €7 (IEA & CIEP, 2021). These cost are expected to drop significantly due to scaling (Brändle et al., 2021; Hydrogen Council, 2021; IEA & CIEP, 2021), but when price parity (to grey hydrogen) will be reached, remains uncertain[12]. Many demand parties will not be willing to acquire green hydrogen if the prices are too high compared to grey or blue alternatives. Indeed, the production of green hydrogen will likely allow for the use of a so-called green tag (certificate proving the product is sustainable) which will enable production parties to pass on (part of) the additional cost to end-users who value the green product differently according to the manager (D.1). However, this is certainly not the case in all instances, especially if these parties must compete globally. The manager (A.1) explained:

"In any case, something will be needed on the purchase side to make it (green hydrogen) *competitive with grey, so to speak. This is what they are doing in Germany, for example, where the government is temporarily bridging the value gap. These kinds of instruments will have to be in place for the time being if this step is to be taken. There is no other way."*

Regulatory barriers

Two regulatory barriers were identified. These concern the (1) European Renewable Energy Directive II (REDII) and (2) the inadequate SDE++ subsidy. Hydrogen certification is not considered a regulatory barrier but will be discussed as well.

First, the REDII. This European directive on the use of electricity to produce renewable liquid and gaseous transport fuels states in article 27 that the source of electricity for the production plant should:

(1) *"come into operation after, or at the same time as, the installation producing the renewable liquid and gaseous transport fuels of non-biological origin"* (European Parliament, 2018, p.47)

And that it:

(2) *"is not connected to the grid or is connected to the grid but evidence can be provided that the electricity concerned has been supplied without taking electricity from the grid"* (European Parliament, 2018, p. 47)

These directives are meant to prevent double subsidy requests and greenwashing according to the manager (I.1)[13]. It potentially has a number of consequences: (1) for every hydrogen production

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[12] The Hydrogen Council estimates that price parity might be attained by 2030 at optimal locations. However, north-western Europe is not an optimal location (optimal locations are locations with high potential of combined RE sources (wind and solar). These include Saudi Arabia, Chile, and Australia) and it might take until 2050 until price parity is reached here (Hydrogen Council, 2021). But no specific RE source is mentioned (so, this does not specifically concern offshore wind). Brändle et al. (2021) estimate that by 2050, offshore wind hydrogen production will cost between 1,7 and 2,2 USD/kg of H_2 (optimistic cost range). The exact price of grey hydrogen (using SMR) in 2050 is unclear. According to the Global Hydrogen Review report by the IEA, this price will range between 1,1 and 2,1 USD/kg of H_2 (IEA, 2021b). But in their Energy Technology Perspectives report, the IEA estimated the price of grey hydrogen (using SMR) to be above 2 USD (and surpassing 3 USD in some instances) in 2050 due to increased gas prices (IEA, 2020b). How exactly gas prices and hydrogen technology will develop remains unclear. Consequently, it remains uncertain when price parity to grey hydrogen will be attained (if ever).

[13] According to the manager (I.1), double subsidy requests relate to the potential practice in which subsidies are requested for both the green electricity production from the RE source and for green hydrogen production at the electrolyzer facility. In this case, subsidies are granted for two energy applications (electricity supply for direct use and for hydrogen production), while the energy can only be used once. Greenwashing is about the waterbed

project, an additional renewable source has to be constructed equal in capacity to the production plant (taking into account efficiency losses of the electrolyzer), (2), the electrolyzer has to run according to the production profile of the renewable energy source (3) and exceptional planning is required by hydrogen production parties to realize the completion of both the wind farm and the hydrogen production facility in time, to meet the first additionality requirement.

These consequences can prove problematic for a hydrogen production project. First, (in the context of the Northern Netherlands) it may not be possible for some hydrogen production projects to realise additional wind farm capacity at sea, either due to the financial impact of those projects or due to the limited availability of suitable lots (discussed in the previous section). Secondly, if the production profile is to be followed, the electrolyzer produces irregularly, resulting in various kinds of potential issues. For instance, an electrolyzer may require a constant supply of energy to run efficiently[14] or else, its business case is negatively impacted. Moreover, demand parties may require a constant supply of hydrogen. This is not possible when adherence to the concerned law is required (except when countermeasures are taken to mitigate this issue, e.g., batteries/hydrogen storage). Lastly, a lot of additional complexity is added to production projects because of the second requirement of the additionality principle. The manager (B.1) explained this clearly:

"They're both mega projects and those projects tend to run late sometimes. If they diverge too much… How are you going to link them, matching the development of renewable energy with the development of sustainable solutions of this kind?"

Given its potential impact on the business case of hydrogen production projects the Senior Policy Advisor of Hydrogen Europe stated that the principle of additionality is *"…the single highest regulatory barrier holding back renewable hydrogen deployment in Europe today"* (European Commission, 2021, p. 68). Moreover, the manager (I.1), the hydrogen production projects in the Northern Netherlands will not continue if this law is not adjusted.

Conversely, the potential dramatic impact of the additionality principle is viewed differently by the managers directly involved in hydrogen production projects in the Northern Netherlands. First, the manager (F.1), the manager (A.1), and the manager (B.1) all assumed wind profile had to be followed for the project and this is not considered a significant issue in their business case. Secondly, requirement to complete the windfarm shortly after completing the production plant was considered an obstacle by these managers (A.1; F.1)[15], but not a significant barrier either.

These statements seem contradictory. But an additional enquiry into the subject showed that the expected severity of the impact of REDII depends on the situation. The manager of the project (B.1) stated:

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effect in which hydrogen production based on green electricity will cause the use of more grey electricity at another location. This way, hydrogen is sold as green but essentially it is not as it causes increased use of fossil fuel-based energy elsewhere.

[14] A higher utilization rate will reduce the capital cost of the electrolyzer per kg of hydrogen (Brändle et al., 2021; HyUnder, 2014). Intermittent supply of energy may also make PEM electrolyzers more suitable for operations than Alkaline, given their flexibility (its startup cold start-up time is quicker in the case of PEM; when both are on operating temperature, the start-up time is similar (< 1 second)) (Buttler & Spliethoff, 2018). As PEM electrolyzers are more capital intensive (Buttler & Spliethoff, 2018), this may also affect the business case of the project.

[15] The project in which participant B.1 is involved will source the electricity from a third party and will not construct its own wind farm. Consequently, this issue is of no concern for this party.

“Depending on how RED will be implemented in the end per country and the availability of renewable energy, will determine how big this barrier will be”.

According to her, it is not yet clear how the Netherlands will enforce REDII. Hence, if the country does not fully implement REDII its effect is less severe. Besides, if a lot of wind energy is produced, the impact of the additionality principle will likely be less severe as it might be easier for hydrogen production projects to acquire green energy. However, if electrolyzers are directly linked to wind farms significant complexity is added to the project.

Company A and F will have a direct link between electrolyzer and windfarm, unlike company B. According to the manager (A.1), REDII adds complexity to the project, but it will not completely prevent its realization. However, she is in favour of a less strict additionality regime, especially during the start-up phase of these projects. The manager (F.1) stated that his company might be able to adhere to REDII, but he does welcome a transitioning period as well. Besides, he (F.1) stated that some specific hydrogen production projects cannot succeed due to the additionality requirement as it will be hard to acquire suitable lots, or the financial impact is too significant.

These statements show that the projects included in this study will likely be realized while still being able to adhere to REDII. However, these regulations add significant complexity to the projects and a transitioning period during which REDII is not enforced is welcomed. Besides, some projects outside the scope of this study may not be able to develop at all due to the additionality principle. Although REDII might be adjusted in the near future (European Commission, 2021), it is considered a barrier given the significant complexity it adds to hydrogen production projects and the fact that hydrogen production projects might not be realized in the case of its full implementation in the Netherlands.

The second barrier concerns the SDE++ subsidy instrument which is not suitable for hydrogen yet. This barrier is strongly related to the high cost of producing hydrogen. Due to its high cost, it is necessary to subsidize the use of green hydrogen at the start to compensate for the ‘unprofitable top’. Therefore, the NIB[16] called for the idea of a well-designed incentives structures to increase the early use of green hydrogen in the Northern Netherlands (NIB, 2017) and a collective of companies in the Northern Netherlands explained in their report that an SDE+[17] like subsidy should be developed to this end (Collective of companies, 2019). According to the manager (I.1), the SDE++[18] subsidy is meant to help invest in RE technologies that help to reduce CO2 emissions. Here, technologies that have a relatively high impact on emission reduction are favored over technologies that have less impact. As hydrogen production is not a mature technology yet, its impact on CO_2-emission reduction is relatively small. Consequently, H_2 cannot compete with other renewable technologies when applying for SDE++ OPEX subsidies as explained by the manager (I.1). Hydrogen production parties do expect such a subsidy instrument to be offered (this could mean a revision of the current subsidy instrument) in the future, but it is currently not guaranteed, and production parties cannot start building their hydrogen production facilities until that moment. This is a significant regulatory barrier inhibiting the development of hydrogen production facilities.

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[16] Northern Innovation Board: consortium of companies, governments, knowledge institutes and NGO’s.

[17] Existing government exploitation subsidy aimed at covering the ‘unprofitable top’ in cases where companies want to start producing green energy or want to reduce CO2 emissions (Rijksdienst voor Ondernemend Nederland, 2021).

[18] SDE++ is an improved version of the formerly used SDE+ subsidy (it is still essentially a OPEX subsidy for RE use and production) (Indienergy, n.d.)

Certification of hydrogen was considered as well. Currently, there is no certification for green, blue and grey hydrogen yet (IEA, 2021b). Consequently, production parties are not guaranteed that their hydrogen can be labelled ‘green’ after the factory has been constructed and this is crucial for the development of a hydrogen market: *“For a low-carbon premium market to function effectively, however, it must be founded on a dedicated and reliable system of certificates and labels to provide certainty to consumers about the low-carbon attributes of products they are acquiring”* (IEA, 2021b, p.213).

The lack of certification for hydrogen was mentioned as an obstacle by multiple participants (K.1;D.1;G.1). But it is not considered a significant barrier. CertifHy (an EU subsidized organisation) is currently devising a hydrogen certification scheme (CertifHy, n.d.) and Vertogas (independent institute mandated by the Ministry of Economic Affairs and Climate) is working on a similar scheme for the Netherlands (Vertogas, 2021). Both schemes have not yet been completed, but the manager (A.1) expects this regulatory issue to be tackled before the final investment decision is made. Alternatively, the manager (F.1) stated that the market is now currently looking at the compliance criteria for green hydrogen that are described in REDII. His company will aim to comply with these criteria. Therefore, he does not expect that certification will influence their FID (F.1). Lastly, the manager(B.1) stated that the issue of certification depends on the type of project. She explained that certification will be less of an issue if the hydrogen is directly supplied to the customer (its green origin is easy to prove). But if it is first injected into the gas grid, certification becomes more important.

Based on these statements, certification is not deemed a significant barrier. It is important to realize a certification scheme in most instances, but this is expected to be realized in time.

4.2 Hydrogen storage

4.2.1 Long term hydrogen storage

Technical barriers

No technical barriers were identified for long-term storage. However, a lack of long-term storage capacity may prove problematic in the future.

The manager (E.1) concerned with long-term storage in salt caverns in the Northern Netherlands stated that he expects no significant technical barriers to the development of the salt caverns. Indeed, salt caverns are a proven storage medium as these underground storages have already been used for the chemical industry in the US and UK for decades (Tarkowski, 2019). Besides, many authors in the scientific literature and reports by the IEA and HyUnder (project aimed at assessing large scale underground hydrogen storage in Europe) have claimed salt cavern to be a viable technical solution to long-term hydrogen storage (Carneiro et al., 2019; HyUnder, 2014; IEA, 2019; IEA & CIEP, 2021; Reuß et al., 2017). Moreover, the technology is almost mature: the technological readiness level is 10/11, which means it is considered *“commercial and competitive, but needs further integration effort”* (IEA, 2020a, p.1). The manager (E.1) explained that the demonstration project has so far been successful[19], and no major complications are expected in the future.

There are concerns about the lack of space for long-term hydrogen storage. According to the manager, in the short term, the 4 salt caverns that are scheduled to be constructed by 2030 will provide sufficient

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[19] The salt cavern at Zuidwending was filled with hydrogen in September 2021 to conduct some tests. In the winter of 2021/2022 full-scale testing of the hydrogen-filled cavern will be done by filling it completely with H_2 and monitoring it for leaks during this period. No complications are expected.

long-term storage capacity for the hydrogen economy in the Netherlands[20] (especially when the linepack of the hydrogen backbone in the Netherlands is used[21]). However, if the hydrogen economy accelerates, a significant increase in storage capacity is required for which salt caverns will not suffice.

50 salt caverns[22] could be needed according to the manager, but the Netherlands likely does not have sufficient space for the development of this number of salt caverns. If hydrogen becomes the preferred method for energy flexibility, the lack of underground storage will seriously impede this application of hydrogen (TNO, 2021).

Market barriers

No significant market barriers for long-term hydrogen storage in salt caverns were found. There is uncertainty concerning the economic viability of the early construction and development of salt caverns in the Northern Netherlands. This relates to the uncertainty of when hydrogen will be produced at scale: there may be a large gap in time between the completion of the salt caverns and the first large green hydrogen production facilities. However, the company has faith in the national hydrogen strategy and is willing to take the risk.

Besides, the HyUnder report stated: *"Although a cavern requires a significant upfront investment, it has a relatively small contribution to the total specific hydrogen costs of <0.5 €/kg."* (HyUnder, 2014, p. 13). The manager (E.1) explained:

"…we think that for the storage just like for the natural gas storage caverns that I have now, they turn out to be very profitable"[23]

Regulatory barriers

No significant regulatory barriers were found. Although hydrogen has different chemical properties than natural gas, the manager (E.1) explained permitting may prove less problematic than obtaining permits for natural gas storage. Permits mostly concern potential heat radiation and noise. The heat radiation range for hydrogen is lower than for natural gas (TNO, 2020a). Noise relates to pressure and as hydrogen will be stored at the same level of pressure as natural gas (80-180 bar), no additional noise issues are expected. The manager explained:

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[20] According to scenario studies by TNO, between 42 and 475 GWh of UHS in salt caverns capacity is required by 2030 for which the current salt extraction sites at Zuidwending and Heiligerlee (Groningen) are likely to prove sufficient (TNO, 2021).

[21] Linepack refers to the storage capacity available in de gas infrastructure based on possible pressure adjustment in the pipelines (Quarton & Samsatli, 2020). Linepack flexibility (difference in volume between a maximally pressured pipeline and the required minimum of pressure in the pipeline) is significantly lower for hydrogen given the lower energy density and lower compressibility of H_2, but it is still usable (Quarton & Samsatli, 2020).

[22] According to scenario studies by TNO, actual required capacity varies greatly across multiple scenarios between 2030 and 2050. If hydrogen becomes the preferred method for large scale energy flexibility (and in case of an extreme weather scenario), the resulting needed storage capacity can reach 32,9 TWh, requiring >200 salt caverns (in case of normal weather, the required capacity is 15-26 TWh). However, if other flexibility options are utilized (and the weather is ideal), 1,3-4,3 TWh of storage capacity is needed, amounting to up to 17-34 salt caverns. These constitute the upper (32,9) and lower (1,3,-4,3) limits of required storage capacity (TNO, 2021) (scenario studies by Netbeheer Nederland indicate a required capacity of 10-47 TWh (Netbeheer Nederland, 2021b)). As the available storage capacity in salt caverns in the Netherlands is 15 TWh (TNO, 2021), the need for additional storage capacity outside the Netherlands or in depleted fields is dependent on developments in the energy system.

[23] Note that the gas storage manager does realize the company is taking a financial risk and that he is not certain the caverns will be profitable in the future.

"I am a little less concerned about this than I was with the natural gas permits we had and that is partly because hydrogen is much more fleeting, hydrogen has a completely different heat radiation range. If hydrogen catches fire, you shouldn't stand above it, you'll be gone. In the middle of the flame, it is about two thousand degrees (…). Up there (referring to right above the flame) *it is 2000 degrees but half a meter to a meter away from the flame you can stand perfectly well and with natural gas flames you really have to stand tens of meters away otherwise you feel very hot."*

4.2.2 Short term hydrogen storage and liquified hydrogen

Short term storage

Short-term storage is not expected to be an integral part of the hydrogen economy in the Northern Netherlands. Linepack (see footnote 14 p. 26) in the hydrogen gas infrastructure and the salt caverns will constitute the storage options in the future economy, although short term storage in compressed gas tanks may be used by the industry to act as a buffer according to the manager (E.1). But no significant barriers were identified for compressed hydrogen tanks. Storage in compressed hydrogen tanks is the most straightforward route for short term hydrogen storage (Abdin et al., 2020; Hassan et al., 2021; Reuß et al., 2017) and it is a mature technology (IEA, 2020a).

Liquified hydrogen

Two market barriers and two technical barriers were identified for liquid hydrogen. The market barriers concern (1) competition with other carrier substances (ammonia/LOHC) and (2) national and international policy and market developments. The technical barriers concern (1) the boil-off losses and (2) the conversion losses. However, the results are unclear about the (future) use and relevance of liquid hydrogen in the hydrogen economy in the Northern Netherlands. This section will address this accordingly.

First, there are few, or no end-use cases for liquid hydrogen[24] in the built environment, FCEVs[25], the chemical industry or grid balancing. Liquid hydrogen might be an appropriate way to transport hydrogen due to its higher energy density (Abdin et al., 2020; Arcadis & Berenschot, 2021; Hydrogen Council, 2021). However, according to the IEA, transportation through pipelines (up to 1000 km)[26] is the most economical method to transport hydrogen. Especially if these concerns retrofitted pipelines (IEA, 2019), which is the case for the Northern Netherlands (and the Netherlands) (PWC, 2021).

Nonetheless, liquid hydrogen is one of three[27] main carriers of H_2 gaining traction for long distance hydrogen transport (Hydrogen Council, 2021), so there's a future scenario in which liquid hydrogen is imported through one of the Northern harbours to be subsequently transhipped, transformed to gaseous hydrogen or locally stored (Arcadis & Berenschot, 2021)[28]. When comparing the three main

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[24] Main end use is as a fuel in space technology (Abdin et al., 2020).

[25] Several car manufacturers have tried applying liquified hydrogen in passenger cars in combination with combustion engines, but these prototypes were considered 'inefficient' (Arcadis & Berenschot, 2021). The expert (C.1) explained that there will not be an application for liquid hydrogen as a fuel in passenger vehicles due to boil-off losses. There is ongoing research into liquified hydrogen for heavy-duty trucks (IEA, 2021b), so these vehicles might end up being end-use cases for LH_2. Here boil-off losses have a lower impact due to more constant use of the vehicle according to the expert (C.1).

[26] Above a 1000 km, transport by ship using liquid hydrogen, LCOH, or ammonia is the most suitable transport method (Arcadis & Berenschot, 2021; IEA, 2021b).

[27] The other two are ammonia and LCOH (Hydrogen Council, 2021).

[28] This report referred to the possibility of future hydrogen import through ports in the Netherlands, not specifically ports in the Northern Netherlands. The New Energy Coalition considers the northern harbors (Eemshaven/Delfzijl) to be suitable for hydrogen import and export (New Energy Coalition, 2020).

carriers, the Hydrogen Council stated: "*The cost-optimal solution depends on the targeted end-use, with deciding factors including central versus distributed fuelling, the need for reconversion, and purity requirements.*" (Hydrogen Council, 2021, p.5)[29]. Moreover, actual hydrogen imports will also depend on national and European policy regarding the development of the hydrogen economy as well as the development of the worldwide hydrogen market (Netbeheer Nederland, 2021a). Additionally, the manager (A.2) project related to the potential use of liquid hydrogen in the Northern Netherlands by stating that it depends on how the cards are shuffled, how the technology develops, how safety aspects are judged and how choices by the market are made.

The main concerns for liquid hydrogen are conversion losses due to liquefaction (25-35% in conversion losses (IEA, 2019)) and boil-off losses (resulting in substantial energy losses during storage) (Abdin et al., 2020; Hydrogen Council, 2021). So, technological developments will also impact the possible usage of liquid hydrogen[30]. The manager (E.1) explained:

"Look, yes, if, perhaps in 10 years' time, the technology will be so good that you will achieve 95% efficiency or close to it, so that's quite a difference from the current 30% that you lose in conversion now."

Ultimately, further research is required into the use of liquid hydrogen (IEA, 2021b), but its potential usage is mainly as a carrier and possibly as a fuel for trucks. The extent to which the barriers potentially blocking the usage of liquid hydrogen inhibits the development of the hydrogen economy in the Northern Netherlands remains unclear. The potential applications for LH_2 are limited, but the manager (J.1) stated that hydrogen imports might help to accelerate the development of the hydrogen economy in the Netherlands. According to him, liquid hydrogen imports can increase the supply of hydrogen for the country which can help increase its usage in the Netherlands[31] and accelerate the development of the hydrogen economy. But – as stated – the extent to which liquid hydrogen imports will be relevant for the development of the hydrogen economy in the Northern Netherlands will be based on the national energy policy and developments in the (national) energy market (Netbeheer Nederland, 2021a), technology developments, market choices and judgement of safety aspects. Consequently, there is a lot of uncertainty about the importance of LH_2 for the (Northern) Netherlands despite the potential benefits of liquid hydrogen imports.

4.3 Hydrogen distribution

4.3.1 Pipelines

Technical barriers

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[29] If the targeted end-use is ammonia, transportation using ammonia as a carrier may be most cost-efficient. If the targeted end-use is high purity hydrogen, liquid hydrogen may be the most cost-efficient (Hydrogen Council, 2021).

[30] According to the IEA, a reduction of conversion losses of 18% is possible. Increased production plant efficiency and improvement in boil-off management will help to achieve this. Competition with ammonia and LOCH does have to be considered: technological improvement will also improve the potential of these carrier substances (IEA, 2019).

[31] The manager (J.1) explained that there is limited availability of space for renewable electricity production technologies suitable for hydrogen production in the Netherlands. So, hydrogen imports (possibly in liquid form) can compensate for this and accelerate H_2 usage in the Netherlands (and therefore the Northern Netherlands).

No significant technical barriers were identified for the use of pipelines in hydrogen distribution. According to the HyWay 27 report[32]existing natural gas pipelines in the Netherlands will be suitable for the transportation of hydrogen after making several technical adjustments (PWC, 2021). The manager (A.2) did not identify any major barriers to the repurposing of existing natural gas pipelines either. The future hydrogen infrastructure will partly include new pipeline infrastructure specifically suitable for hydrogen transportation. Laying new pipelines is more capital intensive (IEA, 2021b; PWC, 2021), but it is a mature technology (IEA, 2020a) and no significant barriers are expected here either.

Market barriers

No significant market barriers were identified for the main hydrogen infrastructure[33]. The repurposing of the gas infrastructure will be very capital intensive, but the national government has granted a significant subsidy. This partly mitigates the loading risk[34]. The manager (A.2) expects his company to proceed with the construction/repurposing of the gas infrastructure despite the loading risk that is still present after partial subsidization[35].

A point of concern is the lack of commitment from the national government that the gas infrastructure company will be the future operator of the hydrogen infrastructure (just like it now is the operator of the natural gas infrastructure). This can prove problematic as more commercially oriented companies may be able to acquire the most profitable parts of the hydrogen infrastructure, leaving the company with the least profitable parts of the gas infrastructure. Consequently, it cannot capitalize on the profitable parts of the hydrogen infrastructure to compensate for the least profitable parts. Although the company expects the government to assign them the task of the operator, the national government should provide direction and do so quickly. This is not considered a significant barrier as it is expected that this will happen.

Regulatory barriers

Two regulatory barriers were identified for hydrogen transportation through pipelines. These concern (1) the assessment framework for permits and (2) the duration of permitting procedures.

First, there is no assessment framework for permits in terms of safety regulations and spatial integration[36]. The manager of a hydrogen infrastructure project stated:

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[32] Report written by Price Waterhouse Coopers in conjunction with government ministries, network operators, and various other stakeholders on the feasibility of repurposing existing gas infrastructure for the use of hydrogen (PWC, 2021).

[33] A distinction between the main hydrogen infrastructure that includes parallel pipelines and the regional infrastructure which concerns single pipelines. Regional hydrogen infrastructure barriers are considered in 4.4.2 (built environment) and 4.4.4 (chemical industry).

[34] Risk of infrastructure not being fully used when the repurposing/construction is completed resulting in a suboptimal or negative return on investment according to the manager (A.2).

[35] According to the IEA, the two main drawbacks of pipelines are high investment cost and the need to acquire rights of way. Therefore, the certainty of demand and government support is needed (IEA, 2019). The former issue is addressed by the government subsidy which partly mitigates the loading risk (i.e., the uncertainty of demand). The latter issue is of lesser concern as the project is largely about repurposing existing natural gas infrastructure (instead of new infrastructure being constructed, for which rights of way must be acquired).

[36] Relates to guidelines on how deep the pipelines must be in the ground, and the statistical chance of accidents happening and several types of safety measures to be taken according to the manager (A.2).

“They are also working on that at the moment, so I hope that, every time I think that it will be ready next week, it turns out that something else has come up. So, the assessment framework is still to be drawn up for the permit.”

If this is not settled in time, the hydrogen infrastructure project will be delayed.

The second barrier concerns the permitting process. This process takes 2,5 to 3 years according to the manager (A.2). Given its duration, the development of the hydrogen economy will be delayed when a quick deployment of hydrogen infrastructure is required by the market (at specific locations).

Both barriers can impact the overall development of the hydrogen economy. According to the HyWay27 report *“A pipeline-based hydrogen transmission network can also boost the development of the hydrogen market”* (PWC, 2021, p.6). The potential market will be greater when more consumers and producers are connected by the transmission network increasing the liquidity of the market (PWC, 2021). And a more liquid market will help spur the development of the hydrogen economy. The manager (I.1) explained:

“That is also what you want to have in a hydrogen market because what is fatal for a hydrogen market is if there is no liquidity and therefore if you need hydrogen for your production and you can't get it, then your production will come to a standstill and that means, as a company, that you run very big risks and you don't want that”

So, a delay in the development of the hydrogen transmission network will also delay the development of hydrogen end-use applications and possibly hydrogen production facilities.

4.3.2 Hydrogen Refuelling Stations

Technical barriers

No significant technical barriers were identified for hydrogen refuelling stations (HRS) in the Northern Netherlands. The technological readiness level is 9/11 which means it is considered *“…commercial and competitive, but needs evolutionary improvement to stay competitive”* (IEA, 2020a, p.1)[37]. Given its technological readiness level, there are technical challenges to overcome. But according to the expert (C.1) of a high-pressure technology firm involved in the development of HRSs, no significant technical barriers are expected to delay the roll-out of HRS in the Northern Netherlands. He did state that improvement is required concerning the lack of unified standards[38] in FCEV design. However, a lack of standardization is considered an obstacle and not a significant barrier to the rollout of HRSs in the Northern Netherlands. The expert (C.1) stated that a European committee is now working on it and expects that the required standardization will be included in legislation soon. Moreover, the lack of standardization is mostly problematic for buses and trucks, not for passenger FCEVs.[39]

Market barriers

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[37] Note that the maturity level of the technology depends on the type of HRS operation: a 35 MPa HRS has a maturity level of ‘9/11’. High throughput of 70 MPa HRS has a maturity level of ‘3/11’, which means only small prototypes exists and additional research is required (IEA, 2021b). Here, only regular (9/11) HRSs are considered.

[38] The lack of standardization refers to the standardization in the design and development of FCEVs according to the expert. Due to the lack of standardization among vehicle manufacturers, problems may occur during refueling (e.g., the tank is not fully refilled as the system cannot identify the type of vehicle and how the FCEV should be filled according to filling protocol).

[39] According to the expert some level of standardization has already been achieved in FCEVs due to cooperative efforts among Japanese firms. It is mainly that manufacturers of buses and trucks have not agreed upon standards yet.

Two market barriers for HRSs were identified. These concern (1) the capital expenditure of HRSs and (2) the chicken-and-egg problems for HRSs and FCEVs.

First, the capital expenditure of HRS is extremely high. The IEA estimates HRS investment costs between 0,6 and 2 million for 700 bar HRSs and 0,15 and 1,6 million for 350 bar HRSs (IEA, 2019). Apostolou and Xydis (2019) did a literature review on the subject and found similar results (although the lower end is higher). Depending on the type of HRS[40], the average cost ranges between 1.2 and 2 million euros (Apostolou & Xydis, 2019). The expert (C.1) confirmed these price ranges (1-2 million euros)[41]. Xu et al. (2020) found this to be the main issue when investing in HRSs[42] and the IEA considered the high investment cost to be the main factor limiting the market share of HRSs (and FCEVs) in the transportation sector (IEA, 2021b). According to the expert (C.1), this constitutes a major barrier for potential hydrogen station owners as the payback period is extensive[43]. Moreover, capital cost is not expected to decline significantly. The expert (C.1) indicated that due to the high technological nature of the high-pressure technology, only a marginal reduction of the capital cost is expected to be realised in the future. The IEA also indicated that prices are not expected to drop as only a few suppliers can deliver HRS components (IEA, 2021b) and Apostolou et al. (2019) only expect a marginal decline of capital cost by 2030 based on their literature study[44].

The second market barrier concerns the chicken-and-egg problem between FCEVs and HRSs. Potential HRS owners are not willing to invest in HRS if their potential market is small (which is exacerbated by the high capital costs of HRS). Consumers and companies are less willing to invest in FCEVs if the refuelling infrastructure is not present. This constitutes a chicken-and-egg problem which is well recognized in the literature (Bai & Zhang, 2020; IEA, 2019, 2021a; Li et al., 2018; RVO & EZK, 2019; Xu et al., 2020). In this light, the expert (C.1) explained that the HRSs they are currently building are either fleet owner stations (H_2 refuelling stations for companies that own their own fleet of vehicles) or commercial stations aimed for usage by trucks and buses[45]. It is not yet economically viable to build HRSs just for hydrogen passenger vehicles as the FCEV market is so small. He stated:

"All the gas stations (HRS is meant here) *that have been constructed so far are all paid for with subsidies (…). The question is, when will the tipping point come that companies themselves can say, I'm going to get so much market, I dare to erect one* (an HRS) *myself."*

Regulatory barriers

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[40] Cost difference is based on the type of hydrogen (liquid vs gaseous), its origin (onsite production vs offsite production) and the capacity (kg H_2 dispensable per day) (Apostolou & Xydis, 2019).

[41] The CAPEX of a petrol station is around 150.000 euros according to the expert (C.1). This is about 10 times lower than the investment costs for HRS.

[42] Note that Xu et al. (2020) research critical barriers to the development of HRS in China, but the financing barrier is considered to be applicable to the Dutch context as well.

[43] This can be exacerbated by the lack of financing from banks and subsidy options from the government (Xu et al., 2020). Data collection efforts in this research were not sufficient to confirm whether this is the case for the Northern Netherlands as well.

[44] Actually, the average cost of HRS is first expected to increase in the early 2020s as more high capacity HRSs are constructed (which are more capital intensive) and more onsite hydrogen production HRSs are built (also more capital intensive than their offsite production counterparts). Cost decline in later years is caused by advantages in economies of scale in building high capacity HRSs and by constructing more offsite hydrogen production HRSs (Apostolou & Xydis, 2019)

[45] It is a good first step to deploy HRSs for captive fleets as this will help support the initial construction of HRSs according to the IEA (IEA & CIEP, 2021), but this is likely not sufficient to mitigate the chicken-and-egg problem.

No significant regulatory barriers were identified for HRSs. A Dutch study did identify the need to provide guidance for authorities on how to evaluate qualitative risk assessment (QRA)[46] documents as many inconsistencies were identified in how these evaluations were performed (Honselaar et al., 2018). Although inconsistencies may still exist in QRA-evaluations[47]guidelines now exist for HRS permitting according to the manager (K.1). The expert (C.1) confirmed this and noted that there is little experience with permitting authorities concerning the evaluation of permitting requests for HRS, but this did not significantly influence the length of the procedure and it is therefore not considered a barrier to HRSs development in the Northern Netherlands.

4.3.3 Tube trailers

No barriers were found for the use of tube trailers to supply hydrogen refueling stations. The expert (C.1) stated that improvements might be realized in the amount of gaseous hydrogen that can be transported (by increasing pressure), but no technical issues are expected. It is also a mature technology according to the IEA (2021b). The expert (C.1) explained that most hydrogen refueling stations in the Northern Netherlands will likely be supplied by gaseous tube trailers. Alternatively, in the case of large-scale H_2 refueling stations close to the hydrogen gas infrastructure might be supplied by pipelines. But no significant barriers are expected in the case of H_2 supply by gaseous tube trailers.[48]

4.4 Hydrogen end use

4.4.1 FCEV adoption

Technical barriers

No significant technical barriers were identified for FCEVs[49]. The technology readiness level is 9/11, so it is considered "*… commercially available, needs evolutionary improvement to stay competitive*" (IEA, 2020a, p.1). The literature also identified various technical obstacles to overcome (IEA, 2021b; İnci et al., 2021; Wang et al., 2021)[50]. However, the manager (H.1), no technical challenges will prove problematic for wide scale FCEV adoption. Besides, he stated that most of these barriers will be mitigated when manufacturers start scaling FCEV production.

Market barriers

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[46] The QRA-document is an important document that *"assesses the risks of the HRS associated to people and buildings in the vicinity of the HRS."* (Honselaar et al., 2018, p.2)

[47] The Dutch study on QRA of HRS recommended guidelines for permitting authorities based on discovered inconsistencies in QRA evaluations (Honselaar et al., 2018). It is beyond the scope of this report to research whether this is still the case or not as it was not considered a barrier by the participants, nor was it mentioned as a barrier in the articles and reports reviewed for this report.

[48] A study into potential safety issues around hydrogen transport in the Netherlands also did not find any major issues concerning hydrogen road transport. It stated: "*Hydrogen is currently counted as a GF0 category in the Manual for Risk Analysis in Transport (…). This means that arithmetically speaking, it is not a risk-relevant substance and is not included in the risk calculations"* (Arcadis & Berenschot, 2021, p.48). The report explained that additional hydrogen transport (on top of current flammable liquids transport) can increase risk potential, but this is not likely. Besides, if hydrogen transports start substituting fossil fuel liquids transport, the risk potential will actually decrease (Arcadis & Berenschot, 2021).

[49] Note that passenger vehicles are meant here. Heavy-duty vehicles (trucks) are not considered in this study as it is beyond the scope of this report.

[50] An elaborate discussion of these challenges is beyond the scope of this paper as these are not considered significant barriers. They are also not mentioned here given the wide range of technical challenges seen in FCEVs and their fuel cells and their highly technical nature.

Two market barriers were identified for FCEV adoption. These concern (1) the lack of HRS infrastructure and (2) the chicken-and-egg problem for FCEVs and HRSs.

First, the lack of HRS infrastructure. This barrier is widely mentioned in the literature (Brey et al., 2018; Hwang et al., 2021; IEA, 2019, 2021b; Xu et al., 2020) and was recognized in the context of the Netherlands as well (RVO & EZK, 2019). it was already discussed in the context of HRS in the previous section and will therefore only be shortly considered. In the Northern Netherlands, this chicken-and-egg problem was recognized by an expert (C.1) and the manager (H.1). An engineer stated:

"And this is of course an issue with hydrogen. If the hydrogen refueling stations in Groningen fail, you can go to Delfzijl for half a refill for trucks. Or else, you must go to Pesse. Those are considerable distances."[51]

Consequently, potential FCEV buyers are not willing to purchase FCEVs as they cannot conveniently refuel their cars. As previously stated, this makes a potential gas station operator hesitant to invest in HRS infrastructure.

Secondly, the high cost of purchasing an FCEV is considered a barrier to FCEV adoption (Apostolou & Xydis, 2019; IEA, 2019; Wang et al., 2021). An expert (C.1) stated:

"Uhm, yes well the cars are very expensive. The Nexo is at EUR 90.000 and the Mirai at EUR 70.000[52]*. Of course, these are considerable amounts of money for the consumer."*

According to the IEA, these costs are mainly attributed to the fuel cell cost and the cost of on-board storage (IEA, 2019). These costs can be reduced by research-based technology improvements (IEA, 2019; Wang et al., 2021) and by scaling production (IEA, 2019, 2021b). The manager (H.1) also explained that all cost issues will be mitigated when manufacturers start scaling. It is just a matter of time before this will happen according to him.

As previously stated, the worldwide diffusion numbers of FCEVs are negligible (IEA, 2020c, 2021b) and the Northern Netherlands is no different in this regard[53]. It is important to note that the use of FCEVs is very promising despite potential competition with BEVs. Its advantage is in faster refueling and a higher potential range compared to BEVs (IEA, 2019). The expert (C.1) stated that diesel drivers are likely to be the future FCEV drivers and gasoline drivers are likely to be the future BEV drivers. The manager (H.1) agreed with this statement and explained that hydrogen will likely replace diesel, kerosine, and natural gas. This way, BEVs and FCEVs will complement each other by suiting different needs from different kinds of consumers (IEA, 2019). Given its potential demand, the plans by many companies to either introduce or buy FCEVs, and the commitment of many nations to support FCEV adoption (IEA, 2021b), scaling will happen and prices will drop. Consequently, the cost price barrier is likely to diminish in the future, but it is now a significant barrier to FCEV adoption in general and in the Northern Netherlands.

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[51] Delfzijl, Groningen, and Pesse are all cities in the province of Groningen, situated in the Northern Netherlands. The distance between Pesse and Groningen is 57,8km. Between Delfzijl and Groningen, it is 35km and between Delfzijl and Pesse it is 84,3km.

[52] The Hyundai Nexo and the Toyota Mirai

[53] The number of FCEVs registered in the Netherlands was 442 passengers by 30-09-2021 (Nederland Elektrisch, 2021). There is no specific data on the Northern Netherlands, but even if these registrations were fully concentrated in the Northern Netherlands, FCEV adoption could still be considered negligible. For comparison, the number of BEVs registered by 30-09-2021 was 208.564 (Nederland Elektrisch, 2021)

Regulatory barriers

No regulatory barriers were identified for FCEV adoption. Indeed, supporting measuring will stimulate FCEV adoption and help attain zero-emission vehicle deployment goals (Hwang et al., 2021; IEA, 2019). For instance, subsidies could help lower the purchase price of FCEVs or decrease the refueling cost (H. Lee et al., 2021). But there are no specific rules and regulations inhibiting FCEV adoption in the Northern Netherlands.

4.4.2 Built environment

Technical barriers

No technical barriers were identified to the use of pure hydrogen in the built environment in the Northern Netherlands. The technological maturity level of an H_2 boiler is 9/11 which means it is *"…commercially available, needs evolutionary improvement to stay competitive"* (IEA, 2020a, p.1)[54]. The technology is not fully mature, but according to the manager (G.1) involved in a project aimed at converting a residential area to the use of hydrogen in the Northern Netherlands, no major technical barriers are expected. He stated that the house pressure regulatory, the gas meter, the indoor piping, and the boiler must be either replaced or adjusted. But this is technologically achievable[55]. There is a small technical challenge in making sure that the hydrogen built up caused by leakage can never exceed 10% in closed-off spaces as this can prove dangerous. Nevertheless, there are already various ways to mitigate this issue, and this is not a significant barrier either.

Market barriers

Two market barriers were identified to the use of pure hydrogen in the built environment. These concern (1) the lack of hydrogen supply and (2) the potential high OPEX cost for consumers.

According to the manager (K.1) will pose a barrier to the application of pure H_2 in the built environment. She explained that it does not make sense to start using hydrogen in the built environment when there are enough good alternatives to make the built environment sustainable and given the limited supply of hydrogen at first. Especially as some parts of the industry cannot reduce their emissions without the use of green hydrogen. This relates to the so-called 'Hydrogen Ladder' devised by Nature and Environment (a Dutch environmental organisation) (Natuur en Milieu, n.d.). According to this organisation, the use of green hydrogen for an end-use application should be determined based on three questions. Table 7 gives an overview of the questions and subsequently relates them to the built environment.

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[54] TNO (2020b) stated that there are two possible technological options for using pure hydrogen for residential use. First is the H_2 boiler, which is discussed in this section. Secondly, a hybrid heat pump uses electricity to produce heat using a heat pump (for baseload coverage) and an H_2 boiler to cover peak demand. The latter technology can help reduce energy demand as direct electrification omits the need for energy conversion and reconversion (TNO, 2020b). However, a discussion of this technology is beyond the scope of this report.

[55] It is important to note that some end-use applications in the building are not suitable for the use of pure hydrogen (de Vries et al., 2017; TNO, 2020b), so the stove and other old equipment using natural gas will have to be replaced as well. The stove will likely be electric. According to the manager(G.1), there are hydrogen stoves on the market, but electric stoves will be installed in the houses converted to hydrogen in the Northern Netherlands. This is due to (1) the maturity of the market for electric stoves (technological readiness level is higher compared to hydrogen stoves), (2) the fact that hydrogen use will be decreased (H_2 is mainly to be used to cover peak times in energy usage) and (3) because of safety issues (the fire brigade is in general against open fires in houses). The houses will also need additional insulation to decrease their hydrogen demand according to the manager (G.1). This again poses no significant technological barriers.

Question	Explanation	Relation to built environment
(1) Is there a more sustainable solution?	If there already is a suitable solution to improve sustainability for a specific end-use application, then hydrogen can be better applied to another end-use application that cannot easily reduce its emissions without green hydrogen.	District heating, electric heat pumps, and better insulation are suitable solutions to reduce emissions in the built environment (IEA, 2021b)
(2) Is there a more energy-efficient solution?	If a solution for a specific end-use application is more energy-efficient than that solution should be applied	Electric heat pumps (combined with insulation) are more energy-efficient (IEA, 2021b).
(3) Is there a societally more cost-effective solution?	All costs throughout the whole hydrogen production chain should be compared with the alternative solution.	The best option for emission reduction in an economic sense depends on the specific location according to the IEA (IEA, 2021c) and the manager (G.1)

Table 7: the hydrogen ladder and its relation to the built environment; adapted from (Natuur en Milieu, n.d.)

As no alternatives (besides green hydrogen) are available to reduce emissions in (part of) the industry, the scarce supply of green hydrogen should be used to help this sector become more sustainable, not the built environment (Natuur en Milieu, n.d.). Besides, direct electrification of the built environment is more energy efficient (IEA, 2021b). Therefore the use of hydrogen in the built environment likely remains limited (IEA, 2021b). In addition, the IEA stated in its Net Zero by 2050 report *"Energy efficiency and electrification are the two main drivers of decarbonization of the buildings sector in the NZE* (Net Zero Emission).*"*[56] (IEA, 2021c, p. 141). Moreover, in its report on the use of green hydrogen for the existing built environment in the Netherlands, TNO stated that even if hydrogen is used in the built environment, insulation efforts to reduce energy demand and investing in electrification remain crucial (TNO, 2020b).

Conversely, both the manager (H.1) and the manager (J.1) stated that in an economic sense, the hydrogen ladder is reversed. They both explained that the consumers in the built environment pay a relatively high price for natural gas compared to the industry. Hence, there is a better business case for the use of hydrogen in the built environment than for the industry. The relatively expensive hydrogen could first be used to help make the built environment more sustainable, increasing the demand for hydrogen resulting in improved economies of scale (after which hydrogen could be used to reduce emissions in the industry as well). Besides, in specific contexts, the IEA did state that hydrogen can be the best option to achieve NZE. According to the organization *"District energy networks and low-carbon gases, including hydrogen-based fuels, remain significant in 2050 in regions with high heating needs, dense urban populations and existing gas or district heat networks"* (IEA, 2021c, p. 142)[57]. The Netherlands has a well-developed existing gas infrastructure which can be used (after repurposing) to distribute the hydrogen (PWC, 2021).

Consequently, the manager (G.1) stated that the best economic solution for NZE built environment depends on the location:

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[56] Energy efficiency relates to improved design features of the building, energy efficient appliances and adjusted consumer behavior (IEA, 2021c).

[57] Note that the expected use of hydrogen in the built environment remains marginal compared to electrification and other renewables in the NZE scenarios despite this statement (IEA, 2021c).

“*But if I look at the area in which we operate, which is predominantly rural and slightly urban. The various studies that have been carried out show that green gas* (either biogas or green hydrogen) *in combination with a hybrid heat source is the most cost-effective option for people.”*

In addition, full electrification of the built environment may not be realistic. According to the manager (G.1), the materials and technical manpower needed to strengthen the electricity network puts enormous strain on available resources. He explained:

“Yea and then we start noticing the excavation problem to strengthen the electricity network, which is a huge challenge. If residential areas start doing this (transitioning to full electric)*, then this means that every residential area and every street must be excavated to strengthen the network. If you look at the cost and the manpower that is required, of which there are already shortages, never mind the required raw materials to make the cables. There are a lot of elements of which we say, we should look at all the options to see which is best per residential area.”*

Social acceptance issues also favor hydrogen over electrification according to the manager (J.1) and the manager (G.1). The adjustments that must be made for electrification in the houses are significant compared to what is necessary to make the houses suitable for green hydrogen use. There is little willingness among residents to accept such a large interference, the manager (G.1) explained. TNO also stated that although insulation efforts will be needed in case of conversion to hydrogen, homes must be insulated from day one in case of full electrification (TNO, 2020b). According to the organization, in case of conversion to hydrogen *“…insulation can take place at its own speed. This can be crucial for creating a support base for the changes that are necessary to get rid of natural gas”* (TNO, 2020b, p.14).

So, there are some suitable applications for green hydrogen in the built environment in the Netherlands. In some locations, hydrogen is economically the best green alternative. In other cases, the social acceptance issues in full-scale electrification efforts can favor hydrogen over this option. Nevertheless, hydrogen will be first supplied to the industry in the Northern Netherlands according to the manager (I.1). Based on the limited availability of H_2 in the beginning (around 2030)[58], a lack of hydrogen supply can significantly delay its application in the built environment. The extent to which this barrier will be relevant depends on national policy. If the government chooses to electrify all (or most) buildings (or realize district heating networks) instead of using hydrogen, this barrier will not prove relevant as hydrogen will not be applied in the built environment.

The second barrier concerns the economic feasibility of applying hydrogen in the built environment. As previously stated, in some locations H_2 is economically the best green alternative. Nonetheless, the OPEX costs are too high compared to natural gas. The manager (G.1) stated:

“… if you look at the OPEX costs, the cost for which we buy hydrogen, it bears no relation to what people now pay for natural gas.”

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[58] Any plans to convert (part) of the building environment on a large scale will likely happen after 2030 (TNO, 2020b). Before this year, increasingly larger (pilot) projects will help in gaining experience allowing for potential conversion of the built environment (TNO, 2020b). This is also the year around which large-scale hydrogen production projects in the Northern Netherlands are scheduled to be completed (or are in an advanced stage of development) (New Energy Coalition, 2020). If the hydrogen supply constraint barrier poses a problem for the conversion of the built environment to hydrogen, this effect will be noticeable only after 2030.

The company (G) now covers these additional costs to help persuade residents to agree to participate[59], but in the long run, this is not a viable business strategy. The cost of hydrogen was already discussed in a previous section (4.1 Hydrogen production) and will not be discussed in depth here[60]. It is important to note that CAPEX costs will be of less concern according to the manager (G.1). He stated that costs for the adjustments in the houses and the one-time cost of converting the gas infrastructure are not an obstacle. In the current project, CAPEX costs are not economically justifiable. But if future residential areas are connected to the national hydrogen backbone, CAPEX cost will become negligible.

Regulatory barriers

Two regulatory barriers were identified. These concern (1) the ODE and energy tax that must currently be paid by consumers and (3) the Dutch gas law that currently prohibits network operators to transport hydrogen through the gas infrastructure. Hydrogen certification in relation to the built environment is also discussed, but it is not considered a barrier.

First, ODE[61] and energy tax must still be paid for green hydrogen applications in the built environment. Both increase the energy price for the consumer, which is already comparatively high as discussed in the market barrier section. Moreover, the fact that ODE must be paid for green hydrogen use in the built environment is surprising: ODE is a tax on fossil fuel based energy aimed at subsidizing green energy use (Rijksoverheid, n.d.). According to the manager (G.1), this constitutes a major barrier to the rollout of hydrogen use in the built environment both in the current pilot phase and (especially) for a potential nationwide rollout of hydrogen in the built environment. It is possible that this law is adjusted by 2030 (after which a potential nationwide rollout of hydrogen use in the built environment is possible), but the manager (G.1) finds it hard to estimate whether this barrier will be mitigated by then or not. If not, the price increase of H_2 due to both ODE and energy tax will make a large-scale rollout of hydrogen use in the built environment ‘unlikely’.

Secondly, the Dutch gas law currently dictates that network operators cannot transport hydrogen through the gas infrastructure[62]. According to the manager (G.1), a change in this law will be realized by 2023 in the earliest scenario. This can significantly delay pilot projects and diminish investment momentum in these projects. Conversely, the Authority for Consumer and Markets (ACM) is investigating a possible framework of tolerance that could allow hydrogen transportation through the gas infrastructure for test purposes. Besides, delays in pilot projects do not necessarily delay the roll-out of hydrogen use in the built environment after 2030. According to the manager (G.1), in an optimistic scenario, the impact will be minimal. So, the extent to which this issue constitutes an actual barrier remains unclear. In a pessimistic scenario, pilot projects incur serious delays and investment momentum is lost which can result in serious delays for eventual roll-out after 2030. In an optimistic scenario, the impact is considered ‘minimal’.

Hydrogen certification was also considered. According to the manager (G.1), the absence of a certification system for hydrogen poses a problem to the current project: residents expect a

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[59] Note that this is a pilot project where the aim is to gain experience and test the viability of using green hydrogen in a residential area. The goal is not to achieve an economically feasible business model.

[60] As stated in this section, scaling of H_2 production will result in lower cost for green hydrogen. Besides, SDE++ like subsidies are needed. If these are granted, the cost of hydrogen is further reduced. It remains unclear how this will affect the hydrogen cost price exactly. But if these remain relatively high, its costs pose a barrier to its application in the built environment as explained.

[61] ODE stands for ‘Opslag Duurzame Energie’ (Dutch) which translates to Surtax Sustainable Energy.

[62] Mixing of hydrogen into natural gas up to 0,5% is by law possible for low calorific networks of regional network operators (TNO, 2020b). This is far from the required 100%.

‘sustainable solution’, but the ‘sustainability’ label is not yet guaranteed by a certification system. However, as discussed in section 4.1.2. Electrolyzer (p. 24)certification is not considered a barrier because this system will be arranged on a European and national level soon.

4.4.3 Grid balancing

The results show it remains unclear how grid balancing, and energy balancing will be organized in the future and what role hydrogen will exactly fulfil in this system. Hence, no barriers were identified. But possible scenarios and some potential barriers will be discussed. Here, a distinction must be made between grid balancing and energy balancing according to the manager (J.1). Grid balancing refers to power balancing which concerns second to second balancing of the electricity grid making sure demand always matches supply. Energy balancing refers to balancing the supply and demand of electricity for longer periods (seasonality differences).

Grid balancing

Current power balancing is realized by scaling up or down the electricity production in gas powered electricity production plants. As these plants will be scaled down there is increasing interest in the possibility of a demand side response mechanism (DMS)[63] for power balancing according to the manager (J.1). Batteries can also help mitigate daily and hourly fluctuation in the energy grid as explained by this participant (J.1) and the literature (Chowdhury et al., 2020; IEA, 2021c; Netbeheer Nederland, 2021a). It is not likely that hydrogen will serve this purpose as batteries and DMS mechanisms are cheaper options to realize power balancing according to the manager (J.1).

Energy balancing

Hydrogen will play a vital role in the energy balancing of the future energy system. H_2 is indispensable in covering future seasonality differences in demand and supply of electricity (IEA, 2021c; Netbeheer Nederland, 2021b; Reuß et al., 2017). An electrolyzer will be used to convert the green electricity to hydrogen during times of overproduction (mostly in the summer)[64]. These electrolyzers can be best (centrally) located close to the source of production as this will prevent the need to construct additional electrical infrastructure to supply the electrolyzers (Netbeheer Nederland, 2021b). Conversely, the manager (J.1) stated that a decentralized placement of the electrolyzers is the best alternative. According to this participant, the residual heat constitutes a major loss of energy in electrolysis (efficiency losses of the electrolyzer amount up to 20-30%, which is lost in heat). A decentralized approach would allow for the residual heat to be reused in the regional industry, built environment or other end use purposes. This would not be possible in the case of a centralized approach. An expert stated:

“If you start thinking centrally, then you have quite a problem, because if you locate a gigawatt electrolyzer at a central location, then you have a heat generation capacity of more than 200 megawatts, which is really huge.”

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[63] *“DSM is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility’s load shape”* (Gellings, 1985, p.1). For instance, the industry could be incentivised to decrease production (and thereby reduce the electricity use) during moments of peak demand according to the manager (J.1).

[64] Both PEM and Alkaline electrolyzers are considered to be suitable for this purpose given their response time of <1 second (when they are at operating temperature) (Buttler & Spliethoff, 2018). The technological maturity level of both PEM and Alkaline Electrolyzers is 9/11 (IEA, 2021b). So, technological maturity has not yet been attained in electrolyzers, but no major technological barriers are expected for these technologies as discussed in section 4.1.2 Elektrolyzer (p. 24).

So, in the case of centralized placement, there is too much residual heat for a region to absorb. A smaller decentralized electrolyzer across multiple regions will help a specific region to better absorb the residual heat for end use purposes. This would increase energy efficiency significantly.

The produced hydrogen will be stored in the salt caverns located in the Northern Netherlands. All issues related to long term hydrogen storage were discussed in section 4.2.1. Long-term hydrogen storage (p. 29) and will not be considered here.

Reconversion of H_2 to electricity will likely be executed by hydrogen-fired gas turbines. According to the manager (J.1), H2-fired gas turbines will allow for the use of the current gas infrastructure (e.g., existing power plants can be converted to hydrogen usage instead of natural gas). Existing gas turbines can be used for hydrogen firing with some adjustments[65] according to the manager(J.1)[66]. In the scenario studies by Netbeheer Nederland (2021b), long-lasting peak demand was also covered by power plants based on sustainable gasses (possibly hydrogen). In the same study, the likely placement of these power plants would be close to potential demand centers as this would relieve the electricity grid as much as possible (Netbeheer Nederland, 2021b).

The future of grid balancing and energy balancing

Nonetheless, what the future energy balancing (and grid balancing) system will exactly look like remains unclear. The manager (J.1) stated that the answer to that question has not fully crystallized yet. Moreover, Netbeheer Nederland stated in their report: *"since the performed analysis results in relatively few operating hours for electrolyzers and to a lesser extent for batteries and electricity production, additional economic analysis is needed to determine a suitable quantity and commitment of flexibility resources"* (Netbeheer Nederland, 2021b, p.23). So, additional economic analysis is required the determine the best grid balancing setup. Besides, the design of the future energy system is dependent on the development of the international energy market and the national energy policy (Netbeheer Nederland, 2021b). Consequently, it remains unclear how extensive the electrification of all end-use applications will be and how much hydrogen will be produced locally (Netbeheer Nederland, 2021a). Therefore, it is unclear what grid balancing options will be applied (DMS/batteries/hydrogen), what the specific setup of these technologies will be, and how these will operate in relation to each other according to the manager (J.1).

In any case, it will take many years before hydrogen will be used for energy balancing (or grid balancing) purposes. The manager (E.1) stated that there are currently no plans for energy balancing (or grid balancing) using large scale underground hydrogen storage[67]. According to him (E), natural gas will

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[65] The IEA stated that the technological readiness of pure H_2 fired gas turbines is 7/11 (IEA, 2021b). So, technological improvements are required before this technology can be deployed.

[66] Fuel cells can be used for this operation as well (IEA, 2021b; Kotowicz et al., 2018; Quarton & Samsatli, 2020). However, the required H_2 purity for a PEM fuel cell (the straightforward technology for this type of operation) is 99,99% which is considered a large drawback of PEM fuel cells (Kotowicz et al., 2018). Hydrogen purity in the Dutch gas grid will be at least above 98%, but actual purity levels will depend on the level of cleaning performed on the existing gas infrastructure and future rules and regulations (PWC, 2021). Nonetheless, it will be hard to attain purity levels of 99,99%. According to the manager (J.1), the relatively low impurity levels of the hydrogen transported through the gas grid may pose a problem for future fuel cell operations in a grid balancing setup.

[67] The large-scale underground hydrogen storage facilities (in salt caverns) that are expected to be finished by 2030 will serve as a buffer between H_2 production facilities and end-use applications such as the industry according to the manager (E.1).

likely keep playing a role in energy balancing (and grid balancing) for the next 50 years and If hydrogen is used to this end, it will be deployed in a phased approach[68].

4.4.4 Chemical industry[69]

Technical barriers

No technical barriers were identified for the use of green H_2 in future methanol production in the Northern Netherlands[70]. Basically, the molecule used for the production process stays the same according to the manager (B.1). There might be some challenges in scaling production using green hydrogen, but most technology is considered mature or almost mature. The manager (D.1) also stated there are no major technical challenges in replacing the grey hydrogen with green hydrogen in the methanol producing industry. Moreover, a report on hydrogen use in the industry in the Netherlands stated that *"technology wise, everything is possible…"* (RVO & EZK, 2019, p.3). Consequently, no major technical barriers are expected.

Market barriers

Three market barriers were identified. These concern (1) the cost of hydrogen, (2) the chicken-and-egg problem for supply and demand parties, and (3) the cost of hydrogen infrastructure.

First, the cost of hydrogen is too high according to the manager (B.1). Methanol producing companies will not be able to compete in global markets based on current green H_2 prices[71]. The cost price of hydrogen will have to drop before methanol producing companies can become sustainable.

As discussed in section 4.1.2. 'Electrolyzer', this price is expected to drop. However, the exact cost price for the future is unknown, and this is problematic for determining the business case for transitioning to green hydrogen. The manager (A.2) stated:

"…as soon as the industry does not know where it stands in terms of the price of hydrogen, it cannot calculate it (referring to the investment decision). *So, it will be hard to make an investment decision."*

The second barrier relates to the chicken-and-egg problem already discussed in 4.1.2. 'Electrolyzer'. Methanol manufacturers will be hesitant to invest in converting their processes for the use of green hydrogen if they are uncertain that they will be able to receive a reliable volume of this gas when the transition (of their production processes) has been completed. On their turn, potential production parties want some guarantee that the hydrogen they produce can be sold. However, it is hard to get this commitment from potential demand parties since they (the production parties) cannot guarantee that the hydrogen can be delivered in the right quantities by the time their production processes have been completed (e.g., large production projects may be delayed). Consequently, both supply and

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[68] A phased approach means that hydrogen will play an increasingly larger role in grid balancing while the role of natural gas slowly decreases. Moreover, a mixed solution could be applied at first. Mixing hydrogen with natural gas in a gas fired turbine is a relatively mature technology (9/11) (IEA, 2021b) and according to the manager (F.1), most gas turbines in Europe and the Netherlands can handle hydrogen-natural gas mixes of 20% to 25%.

[69] Note that the results in this section are not directly based on data from methanol producing companies in the Northern Netherlands. There are also no specific reports on green H_2 use in these companies in the Northern Netherlands either. Consequently, it remains unclear if these barriers directly apply to these companies. This limitation will be addressed in the discussion (p. 68).

[70] As explained in section 2.3.4. 'Framework for commercializing an integrated hydrogen economy', the focus is on methanol producing industry (see p. 15)

[71] As explained in section 4.1.2 (Electrolyzer, p. 26), the use of a green tag (certificate proving the product is sustainable) can allow a producer to pass on part of the higher cost to its customers. However, this is not always the case, especially if parties must compete globally.

demand parties cannot realize a viable business case. Therefore, methanol producing companies will delay their participation in the hydrogen economy.

This also relates to the lack of market maturity. The manager (D.1) stated:

"The market is not yet mature. This is all very well for pilot projects, which can be solved with subsidies and, um, risk-sharing agreements. But when it comes to the baseload for the purchase of raw materials for your factory, that's a very vulnerable situation on which your economic survival is dependent."

Moreover, the manager (I.1) explained:

"So, you want to make sure that if you are going to invest and use hydrogen, that it is available in sufficient quantities and that you can get it. If you create a market and allow a lot of parties to enter, you can ensure that those volumes will be created, that people will start to trust it, and that eventually the risks surrounding the use of energy and raw materials can be hedged"

As there is no mature hydrogen trading market yet, there is no economic price mechanism to determine whether there is a viable business case for using green hydrogen in their production process or not. Besides, there are no good alternatives to switch to either (in case the supplier breaches the contract). This uncertainty and level of dependence results in a bad business case for methanol producing companies.

The third is the cost of hydrogen infrastructure. According to the manager (A.2), issues may arise when the regionally located industry needs to be connected to the hydrogen infrastructure. These locations are connected to the country's main infrastructure with single pipelines (instead of parallel pipelines). Consequently, a choice between delivering pure hydrogen, a mixture of hydrogen & natural gas or only natural gas must be made. In some instances, not all end-use applications in a regional area will need pure hydrogen. Therefore, a 100% hydrogen delivery through (the single) pipeline is not likely, despite the pure hydrogen requirements of some local industries. The company (A) can build separate pipelines to some of these factories if their potential buying volume is large enough.[72] However, this will not be the case for a significant number of factories. As a result, some of these companies must delay their transition to the use of green hydrogen in their production processes.

Regulatory barriers

No regulatory barriers were found for green H_2 use in the methanol producing industry. The consequence of RED II for methanol production was considered: the production process requires a steady inflow of hydrogen and as RED II requires hydrogen production facilities to follow wind profile, it may be difficult to ensure a steady supply of green hydrogen. The manager (B.1) stated that this issue may add complexity to the project: these companies will need to ensure a steady supply in a different way according to her (E.g., by ensuring a buffer supply (for which the salt caverns may prove useful), ensuring different sources of H_2 supply or purchasing more baseload energy). However, she (B.1) stated that despite the added complexity, this issue will not constitute a barrier that will significantly delay hydrogen use in the methanol producing industry. Besides – as previously explained – RED II might be adjusted soon (European Commission, 2021).

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[72] The cost of building the infrastructure will be included in the transport tariff for H_2. If the company's buying volume is large enough, this could be economically justifiable. In the case of relatively low volume, it will not be. Therefore, the choice to transition to the use of hydrogen depends on the business case (for the factory) for this connection according to the manager (A.2).

H_2 certification was considered as well. Here again, this will not constitute a serious barrier for methanol producing companies as certification will be settled by either Vertogas or CertifHy soon. This was confirmed by the manager (B.1)

4.5 Additional findings

4.5.1 Blue hydrogen

Blue hydrogen was not included in this research. But it will be discussed as it was mentioned by several participants. According to some participants, blue hydrogen can help to transition to a hydrogen economy (A.1 ;B.1; K. 1; D.1). The manager (D.1) explained:

"In order to break the chicken-and-egg problem in building up the chain, with the dot on the horizon of everything becoming greener, of course, blue hydrogen would have a role to play in developing that chain, in developing that market."

Blue hydrogen can mitigate the chicken-and-egg problem of hydrogen production by ensuring a reliable supply of hydrogen according to the manager (D.1). This will push demand parties to adjust their processes for the use of hydrogen and therefore spur hydrogen production parties to start investing in green hydrogen production facilities. In the Government Strategy on Hydrogen, blue hydrogen was mentioned as a an important stepping stone to develop the hydrogen economy in the Netherlands, and plans are incorporated to include it in the SDE++ subsidy scheme (Rijksoverheid, 2020). Besides, the IEA recommends investing in Carbon Capture and Storage technologies for the production of blue hydrogen to help accelerate the development of the hydrogen economy (IEA, 2021b). Moreover, both TNO[73] and the EU mentioned the importance of blue hydrogen as an intermediate step towards the development of a hydrogen economy (ECEEE, 2020; TNO, 2020b). But social acceptance issues may slow down its uptake. The manager (D.1) explained that people do not find it acceptable to keep supporting using fossil fuels and storing CO_2 underground which may prevent companies from investing in it. He stated:

"So, actually you see that the first route to break through the chicken-and-egg problem is being somewhat delayed socially by this discussion."

Nevertheless, it remains unclear how important blue hydrogen will be for the development of the hydrogen economy in the Northern Netherlands and what specific barriers potentially slow down its uptake as an exhaustive review of this subject is beyond the scope of this report.

4.5.2 Social acceptance barriers

Although social acceptance issues cannot be categorized as regulatory, technical, or market barriers, the results show they do prove to be problematic for various parts of the hydrogen economy. This section discusses clear social acceptance barriers and cases where uncertainty remains in whether social acceptance issues may prove to be barriers or not.

Wind farm

The results show that social acceptance constitutes a significant barrier to windfarm development in relation to hydrogen production. When discussing the need to lay electricity cables across the North Sea and the Wadden Sea to connect the windfarm to the electrolyzer, the manager (D.1) stated:

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[73] Independent Dutch organization for applied scientific research whose aim is to support governments and companies with knowlegde and data based on research (*Onze Organisatie | TNO*, n.d.)

"Well, as you say, technically that may not be the biggest challenge. We also lay sea cables between the UK and the Netherlands, between America and the UK, and between Norway, so that's all well and good, but the challenge lies in how to make it socially acceptable to lay those cables. That is the big bottleneck."

These issues relate to both horizon pollution (the wind farms will be visible from the Wadden Islands), but also to the construction of cables across the seabed. These cables will have to be drawn across a nature reserve (*Waddenzee | Natura 2000*, n.d.) and this can potentially constitute a significant bottleneck. The same manager (D.1) explained:

"And sometimes you can't avoid disturbing nature and then a decision will have to be taken from above, from the government with a mandate of, well, we know that it's not according to the agreement, but we'll do it. Then everyone in the Netherlands will have the opportunity to raise an objection up to the Council of State, and then eventually a ruling will be given, and the cable will be built after all, but that's seven years down the road."

Hydrogen storage in salt caverns

Permitting trajectories were not considered to be regulatory barriers to salt cavern development. However, according to the manager, permitting trajectories can potentially take a long time because local governments consider potential social resistance before granting permission to develop the caverns. The manager explained that this will likely not be an issue as residents are welcoming the hydrogen developments in the area. The manager:

"…but I think that the regulations (referring to permitting authorities who consider social acceptance before granting the permits) *are certainly a challenge, but in the end, it will be alright."*

This is due to the problematic issues concerning gas from Groningen[74] causing residents to favour future hydrogen usage and associated hydrogen technologies such as the salt caverns at Zuidwending. However, if additional caverns or depleted fields are used in future scenarios, permitting issues related to social resistance might prove problematic for the accelerated development of the hydrogen economy in the Northern Netherlands. TNO also stressed the need to consider the societal playing field before each underground storage project. According to the organization *"…the level of participation must not be determined from legal frameworks, but from the societal playing field, and in relation to the overall project strategy."* (TNO, 2020a, p.8)

Hydrogen refuelling stations

It remains unclear to what extent social acceptance issues will influence the development of HRS networks in the Northern Netherlands. The literature does indicate the relevance of social acceptance issues in relations to HRS construction (Hienuki et al., 2021; Y. Lee et al., 2021; Xu et al., 2020). These mainly relate to the perceived danger of the station which may result in local protest (Hienuki et al., 2021; H. Lee et al., 2021; Xu et al., 2020). But according to the expert (C.1), social acceptance issues have not stopped or delayed any HRS projects so far. However, he stated that the absence of any protests may be because current HRS are located outside residential areas. Given the relevance of social acceptance issues in the literature, these issues might become problematic when the future HRS infrastructure continues to develop and starts entering residential areas. To what extent this will

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[74] Concerns the earthquakes caused by natural gas extraction in Groningen resulting in damages to buildings and the (mental) wellbeing of residents (*Gronings Gas – Sociale Vraagstukken*, n.d.)

constitute a barrier by that time remains unclear as there is no specific data for the Northern Netherlands on this subject.

FCEV adoption

According to the manager (H.1), there is ignorance among some consumers regarding FCEVs and this mostly relates to safety issues. He stated that some consumers judge FCEVs to be hazardous due to the danger of a potential explosion when the vehicle catches fire. He stated:

"We have rules and regulations that prescribe labels, those diamond shaped labels. If it is explosive, flammable, highly inflammable, it is a red diamond with a black flame in it. Well, that applies to gasoline, natural gas, diesel, and that exact same emblem is applicable to hydrogen. But for some reason, the media always says hydrogen is explosive. That is strange…"

FCEVs are not more dangerous than internal combustion engine (ICE) vehicles are, but the public perception is distorted according to the manager (H.1). However, to what extent this influences FCEV adoption remains unclear. The literature on FCEV adoption mainly considers FCEV cost price, lack of HRS infrastructure, and H2 refueling cost[75] as barriers inhibiting FCEV adoption (Hwang et al., 2021; IEA, 2019, 2021b, 2021a; H. Lee et al., 2021). Social acceptance is generally not mentioned. Consequently, social acceptance is not expected to be a significant barrier to FCEV adoption in the Northern Netherlands either, but the results lack a definitive answer.

Built environment

One significant social acceptance barrier was identified for converting the built environment to the use of green hydrogen. This concerns potential resistance among residents. According to Netbeheer Nederland, individual households will not be allowed to choose the renewable heating solution of their liking as this is considered *"economically and practically unfeasible"* (Netbeheer Nederland, 2021a, p.35). Consequently, entire neighbourhoods or multiple neighbourhoods must transition to hydrogen simultaneously if hydrogen is applied for heating in the built environment[76] (Netbeheer Nederland, 2021a). The manager (G.1) stated:

"But look, they (referring to residents) *can just take the attitude of not cooperating with a sustainable alternative. And just as I said, that also applies to the district heating network and all-electricity*[77]*. If someone wants to stay on the gas grid, they have every right to do so. And then the question is, imagine that's only 1% of the entire neighbourhood, and the others say they do, and they want a sustainable alternative. How do you deal with that? In principle, you would then have to maintain the entire network for that one percent."*

This shows that resistance among a few residents can lead to the complete cancellation of the project that covers an entire neighbourhood. But social acceptance issues can be more subtle as well. According to the manager (G.1), many residents have questions about how the conversion of their

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[75] H_2 refueling cost is not considered a significant barrier in this study. According to the expert (C.1), if the cost of gasoline is around €1,50 per liter, the cost per kilometer of an FCEV is already comparable to an ICE vehicle. Current gasoline prices are around 2 euros (Brandstof-zoeker.nl, n.d.), making FCEV driving costs even more competitive.

[76] This is also the case for all other transitioning options such as all electric and district heating (Netbeheer Nederland, 2021a)

[77] As previously discussed, social acceptance issues are more problematic when pursuing an electrification strategy. Despite this fact, social acceptance issues are a significant barrier to the conversion of the built environment to hydrogen as well.

homes to hydrogen will impact them. Some have only a few questions and soon comply. Others are more hesitant. This requires a different communication strategy for every household which can cause serious delays.

So, social acceptance issues can either lead to the complete cancellation of the project or result in serious delays. This social acceptance barrier should not be underestimated. According to the manager (G.1), this constitutes the biggest barrier to transitioning to hydrogen in the built environment.

4.5.3 System broad barriers

Lack of technical manpower

A lack of technical manpower is considered a significant barrier to the development of the hydrogen economy in the Netherlands and the Northern Netherlands. Given the requirements for building an entirely new energy system in case of hydrogen use, the IEA recommended starting introducing training programs to make sure there is a skilled workforce to help develop the hydrogen economy (IEA, 2021b). However, there is currently a shortage of technical manpower in the labor market in the Netherlands and this is expected to be the case in the near future as well (ROA, 2019).[78] Consequently, the manager (A.2) stated:

"…there is still a great deal of work to be done, and I am talking particularly about the transport part (referring to the work needed to repurpose the existing gas infrastructure for the use of hydrogen), *but you can imagine when it comes to storage, electrolyzers, when it comes to importing terminals, when it comes to converting the industry, there is a great deal of work involved. So where do you get those people from?"*

Hence, a lack of technical manpower can slow down the entire hydrogen economy in the Northern Netherlands. Besides, this barrier can be exacerbated by a wait and see attitude in the installation industry. The manager (G.1) explained that few parties in the installation industry are willing to train hydrogen specialized installers as there is no demand for their services in the industry yet. Consequently, a lack of hydrogen certified installers can be expected when the development of the hydrogen economy in the Northern Netherlands starts to accelerate.

Policy development and uncertainty

Many hydrogen projects are being developed in order to test the viability of various hydrogen technologies and how they would interact in a hydrogen economy in the Northern Netherlands (New Energy Coalition, 2020). However, many uncertainties and interacting factors make it difficult to design government policies correctly and allocate investments efficiently. The manager (K.1) stated:

"Uhm, yes, you can actually see that on all fronts, including in your scheme (relating to the overview of hydrogen technologies: p.15)*, everyone is encountering start-up problems. Yes, that's actually a thing across the board."*

These start-up problems originate from a lack of coordination and from a high level of uncertainty in the future development of the hydrogen economy in the Northern Netherlands. After an investment plan for the Northern Netherlands was made,[79] It quickly showed that many of the local projects would

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[78] This report includes forecasts until 2024. There is no data available on labor market shortages after this date. Note that the data concerns technical manpower across all sectors, not necessarily the technical manpower required to build hydrogen infrastructure (ROA, 2019).

[79] Investment plan made by McKinsey & Company in conjunction with various local organizations to support the development of the hydrogen economy in the Northern Netherlands by providing requirements, an implementation plan and a roadmap (New Energy Coalition, 2020)

not be able to develop on their own given their mutual dependence. To mitigate this problem, a foundation was founded with the aim of coordinating all the hydrogen projects in the Northern Netherlands. The manager (I.1) stated:

"No one can do it alone, there is no one who can set up the whole chain by himself and scale it up so that means that you need all those parties together, they are dependent on each other, you have to coordinate them to ensure that they can all take the steps and make the investments at the same time. If that is not possible then nothing will come of it"

To some extent this coordination agency mitigates the coordination problem, but the significance of this agency for the development of the hydrogen economy in the Northern Netherlands is an indication of the difficulty for many companies and projects to get started. This difficulty is exacerbated by a lot of uncertainty in the future development of this economy. Although it is clear that hydrogen will constitute an important energy carrier for the future energy system in the Netherlands (Rijksoverheid, 2019, 2020), what role it will play exactly remains unclear as this is dependent on the development of the international energy system and national policy (Netbeheer Nederland, 2021b; TNO, 2021). However, the developments of the international energy system are unpredictable, and there is no exact national policy yet either. According to the manager (I.1), national policy is currently being formed:

"Political discussions are now taking place to see how all this should be done. The policy is just not there yet. And that's not a delay or anything like that, it's more like… it's part of the fact that the policy is being formed at this stage in parallel with the development of the project. And they are still learning from each other"

In addition, the manager (J.1) stated that a focused policy by the government is not yet possible. He explained:

"I think that there are still too many options with no clear winner to start targeting policies. There is still a great chance that you are betting on the wrong horse, so you should not put all your money on one horse just yet. But you do have to make sure that you can scale up quickly enough when you have a clear idea of which horse is going to win. Maybe it is a bit symbolic but that is the phase we are in."

Moreover, the (Northern) Netherlands is also dependent on European policy developments, increasing the complexity of the playing field for designing hydrogen-related policies as explained by the manager (I.1).

According to the IEA "*Transitioning quickly to a liquid market that supports scale-up and widespread hydrogen adoption will require timely development of hydrogen-specific infrastructure, which implies adequate planning and mobilization of sufficient investment"* (IEA, 2021b, p.210). But as stated, the level of mutual dependence (of hydrogen projects), the uncertainty in future developments in hydrogen technology, future European legislation, and future energy systems all limit the ability to plan adequately and allocate investment efficiently (either by limiting the ability of government to design focused policies or by affecting the business case for hydrogen projects adversely). Therefore, the development of the hydrogen economy in the Northern Netherlands incurs delays. It is important to note that many of these delays are unavoidable given the described uncertainties. The manager of the Coordination agency stated:

"Look, if there is a well-regulated policy, and you have to assume that it does the right thing, that gives certainty and that parties will invest more easily because they know where they stand, so of course,

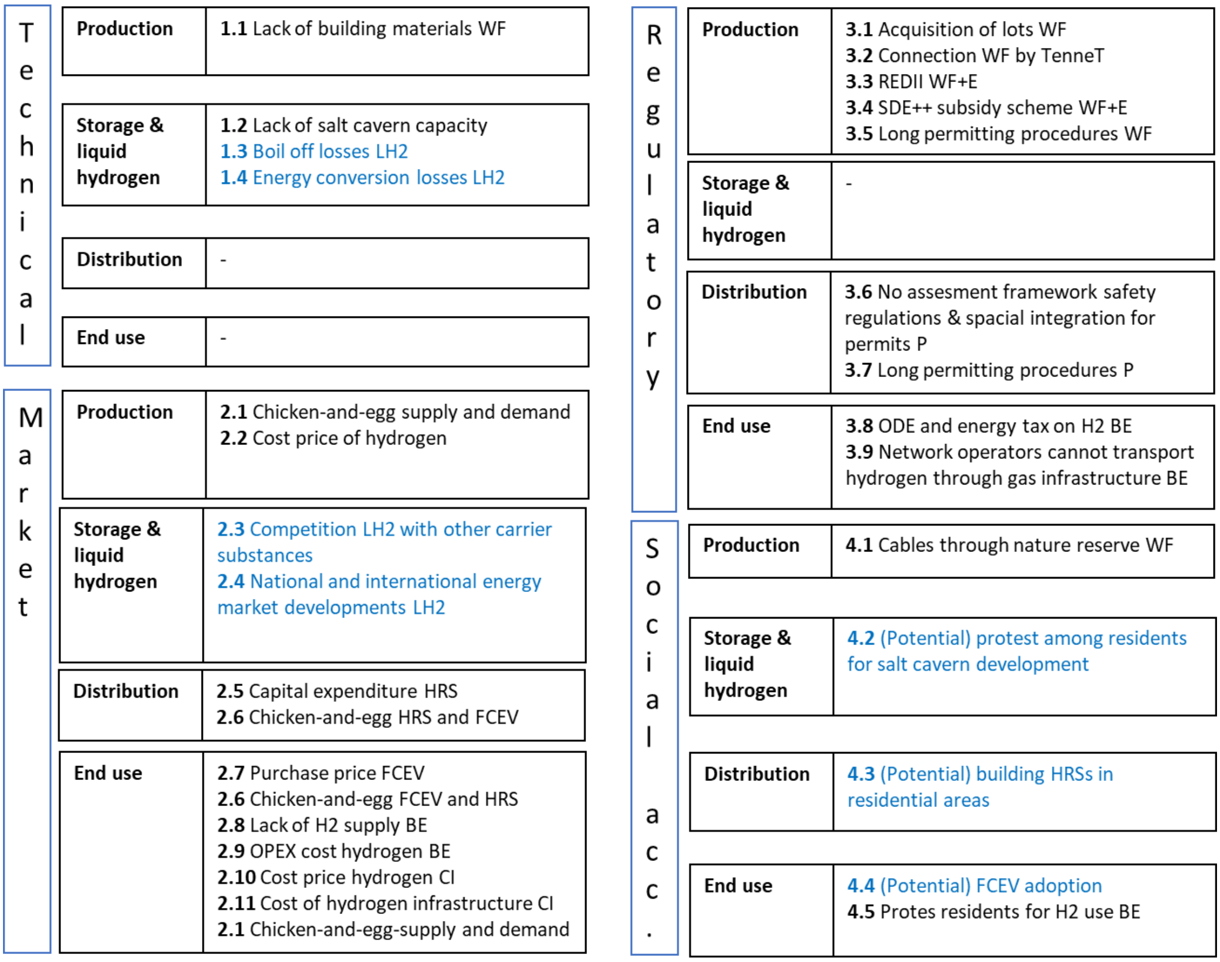
that will help. But making policy on something of which you don't know what it will look like is very complicated. There is a reason that the policy is not there yet.”

5 Discussion

5.1 Interpretation of barriers

5.1.1 Technical barriers

Figure 3 provides an overview of the barriers identified in the results section. First, it stands out that technical barriers are not likely to inhibit the development and commercialization of the hydrogen economy in the Northern Netherlands. A lack of building materials may delay the construction of wind farms, but this is a supply issue rather than an actual technical barrier. Technical barriers were identified for the use of LH_2, but its initial use will be limited given its narrow range of applications. LH_2 can potentially help accelerate the development of the hydrogen economy in later stages, but it remains unclear what its impact will be.



Technical	
Production	**1.1** Lack of building materials WF
Storage & liquid hydrogen	**1.2** Lack of salt cavern capacity **1.3** Boil off losses LH2 **1.4** Energy conversion losses LH2
Distribution	-
End use	-

Market	
Production	**2.1** Chicken-and-egg supply and demand **2.2** Cost price of hydrogen
Storage & liquid hydrogen	**2.3** Competition LH2 with other carrier substances **2.4** National and international energy market developments LH2
Distribution	**2.5** Capital expenditure HRS **2.6** Chicken-and-egg HRS and FCEV
End use	**2.7** Purchase price FCEV **2.6** Chicken-and-egg FCEV and HRS **2.8** Lack of H2 supply BE **2.9** OPEX cost hydrogen BE **2.10** Cost price hydrogen CI **2.11** Cost of hydrogen infrastructure CI **2.1** Chicken-and-egg-supply and demand

Regulatory	
Production	**3.1** Acquisition of lots WF **3.2** Connection WF by TenneT **3.3** REDII WF+E **3.4** SDE++ subsidy scheme WF+E **3.5** Long permitting procedures WF
Storage & liquid hydrogen	-
Distribution	**3.6** No assesment framework safety regulations & spacial integration for permits P **3.7** Long permitting procedures P
End use	**3.8** ODE and energy tax on H2 BE **3.9** Network operators cannot transport hydrogen through gas infrastructure BE

Social acc.	
Production	**4.1** Cables through nature reserve WF
Storage & liquid hydrogen	**4.2** (Potential) protest among residents for salt cavern development
Distribution	**4.3** (Potential) building HRSs in residential areas
End use	**4.4** (Potential) FCEV adoption **4.5** Protes residents for H2 use BE

Figure 3: an overview of barriers inhibiting the development of the hydrogen economy in the Northern Netherlands; blue barriers are either potential barriers or barriers related to a technology whose practical application is debatable (in this case LH_2); WF = Wind Farms; BE = Built environment; CI = Chemical industry; P = Pipeline; E = Electrolyzer; FCEV = fuel cell electric vehicle; HRS = Hydrogen refueling station.

The fact that technical barriers will not impede the development and commercialization of these technologies is not surprising. The technologies chosen for this study were included because of their relatively high technological maturity (see table 8). Consequently, most technologies were in their final developmental stages and were already available for commercial usage.

Technologies	Readiness level
Offshore wind farm	9/11
Electrolyzer (PEM and Alkaline)	9/11

Hydrogen salt cavern storage (long term storage)	10/11
Compressed hydrogen tank (short term storage)	11/11
Hydrogen pipeline transport	11/11
Tank tube trailer transport	11/11
Hydrogen refueling station (35 MPa) HRS	9/11
Passenger FCEV	9/11
H_2 boiler	9/11
Methanol industry	Technology readiness high (according to participant B.1)

Table 8: overview technological readiness hydrogen (related) technologies; based on (IEA, 2020a, 2021b).

In some cases, technical challenges must be resolved to achieve full technological maturity, but in all cases, the results indicate that these challenges do not constitute barriers that will inhibit the commercialization of the technology.

5.1.2 Market barriers

Market barriers are more pervasive and are mainly attributed to cost price barriers and chicken-and-egg problems. Moreover, these barriers are highly related and, in some cases, interdependent. The high cost of green hydrogen is the main market barrier in the hydrogen economy in the Northern Netherlands. Its high cost-price results in an unsatisfactory business case for end-use applications in the built environment and the chemical industry. Consequently, demand parties are less inclined to switch to the use of green hydrogen. This in turn affects the business case for supply parties as they require some commitment from end-users that the hydrogen they produce will be purchased. This is highly related to the absence of a mature liquid hydrogen trading market which normally provides certainty to parties about the demand, supply, and price of a commodity. The lack of a price mechanism to determine the business case for green hydrogen use, and the absence of the ability to switch to other supplying partners is problematic for end-users and exacerbates the chicken-and-egg problem already observed. Moreover, the system's broad barrier of coordination and uncertainty diminishes the ability to quickly develop a hydrogen economy in the Netherlands further.

Given the difficulty of the chicken-and-egg problem observed for supply and demand parties (which partly relates to the high cost of green hydrogen production), a well-designed policy scheme by the (local) governments could help the economy to get started by efficient investment allocation and targeted regulations. But designing effective policies is not possible in this early stage of technological development: the technological maturity of most hydrogen technologies is relatively high, but what the best setup of those technologies is and what end-use application should be part of the hydrogen economy in the initial stages remains unclear. This is dependent on technology developments, the development of the national & international energy markets, and national & European policy developments.

Despite this uncertainty, the likelihood of hydrogen use for the built environment in the early stages of the development of the hydrogen economy in the Northern Netherlands is low. Due to the relatively small quantities of green hydrogen available in the initial stages of the hydrogen economy (beginning of 2030), most of the available green H_2 will be allocated to the industry. This is a good strategy according to the IEA which stated that governments are confronted with the challenge of balancing hydrogen infrastructure development too slow (with the risk of impeding the development of the hydrogen economy) and deploying it too quickly, with the risk of initial underutilization and associated costs. This latter issue can be partly mitigated if the industry is first decarbonized using green H_2 as demand for hydrogen is more certain in industrial hubs than for other end-use applications (IEA, 2021b). However, it will make transitioning the built environment to NZE more difficult as full-scale electrification can prove challenging. Moreover, it will impede the development of the hydrogen economy by limiting hydrogen usage in this end use application.

Lastly, the chicken-and-egg problem observed between FCEVs and HRSs is problematic, and this barrier is exacerbated by the high capital cost of both FCEVs and HRSs. HRS investment costs are roughly ten times higher than for regular petrol stations and as the addressable market is small (few FCEV are on the road), its business case is further diminished. Potential FCEV owners are not likely to purchase an FCEV as there is little or no refuelling infrastructure. Moreover, they are less inclined to acquire an FCEV given its high purchasing price. Therefore, it is no surprise that only 3 refuelling stations are installed in the Northern Netherlands and only 422 passenger FCEVs[80] are registered in the whole country despite its range and refuelling advantage over BEVs. FCEV prices may drop due to scaling, but this is outside the control of parties within the Netherlands as previously explained. Conversely, the price of HRS will not significantly drop, and the chicken-and-egg problem will not suddenly disappear. Consequently, a quick roll-out of HRSs and a large-scale adoption of FCEVs in the Northern Netherlands is not likely without policy intervention.

Nonetheless, the market situation for the development of the hydrogen economy in the Northern Netherlands appears favorable. As stated, a well-developed hydrogen transport system can improve hydrogen market liquidity and spur the development of the hydrogen economy. However, to ensure a reliable supply of hydrogen to end-users, large-scale hydrogen storage is necessary. The 'linepack' in the future hydrogen grid can cover part of the flexibility needs, but salt caverns will be required to ensure sufficient storage capacity. Consequently, the fact that no market barriers were identified for both long-term hydrogen storage in salt caverns and hydrogen transportation in pipelines is extremely beneficial for the development of the hydrogen economy in the Northern Netherlands.

The absence of significant market barriers is highly region-specific and turns out favorable for the Northern Netherlands. First, no market barriers are found for hydrogen pipelines as there is a clear direction by the national government to transition to the use of hydrogen for parts of the energy system (sufficiently clear for this investment decision). Therefore, company (A) can invest in the hydrogen transportation infrastructure with confidence. Moreover, its well-developed natural gas infrastructure allows for a relatively low-cost transition to hydrogen infrastructure. According to the HyWay27 report, in the case of a completely new construction of hydrogen gas infrastructure, the project would incur four times the current projected cost (PWC, 2021).

Consequently, it would be significantly more difficult to develop a hydrogen transportation infrastructure from scratch. According to the manager (A.2), in the case of laying new pipelines, companies are likely to choose smaller diameters for their pipelines to improve their business case. However, when future developments in the hydrogen economy result in increased hydrogen demand, the gas infrastructure will not be able to supply given its limited capacity. Besides, the business case might be negative, and no infrastructure is built at all. Lastly, the loading risk for the investment is partly mitigated by a significant government subsidy, reducing the needed investment cost by half. The financial risks still present are acceptable, so no market barriers will delay its deployment. The government policy, the subsidy and, especially the presence of a well-developed gas infrastructure are all region-specific and favor the Northern Netherlands significantly: it is expected that in a different regional context, market barriers could significantly delay the deployment of hydrogen pipelines infrastructure when these factors are absent.

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[80] Note that FCEV relates to passenger FCEV in this study.

The same is the case for hydrogen storage. The company (E) has faith in the government's hydrogen strategy. Hence, it is willing to invest in large-scale underground hydrogen storage in salt caverns. Moreover, the fact that this company already exploits salt caverns for natural gas storage, makes the step towards its application for hydrogen storage easier (based on its experience). Especially as the exploitation of underground natural gas storage is highly profitable, allowing the company to finance its hydrogen storage experiments. Besides, not all regions have suitable salt cavern capacity – if at all (HyUnder, 2014).

5.1.3 Regulatory barriers

Regulatory barriers are generally not interlinked and interdependent like market barriers are. But unlike technical barriers, they are highly relevant. Here, it stands out that the regulatory barriers are concentrated in hydrogen production, pipelines, and the built environment. A plausible explanation is that these are large scale projects that have a (potential) significant impact on their environment. And as current legislation is not yet designed to accommodate the development of a hydrogen economy, these supply chain parts are the first and foremost subjects to encounter regulatory resistance.

5.1.4 Social acceptance barriers

Social acceptance barriers were initially not included in this study as it was not included in Shakeel et al. (2017). Their article considered the right mix of technical regulatory and market barriers to allow for the commercialization of RE technologies. Public awareness was mentioned in this study, but this only related to the price premium that must be paid by the public for RE technologies (Shakeel et al., 2017). This is surprising as the scientific literature has widely covered social acceptance issues related to the construction of offshore wind farms (Gonyo et al., 2021; Haggett, 2011; Hall et al., 2013; Kim et al., 2019), which is a RE technology. The fact that no specific location was considered for this study (just the country of Finland) could be an explanation for the exclusion of social acceptance issues: the public is generally in favor of RE technologies, but not when these are constructed at places where people are emotionally attached to the land (van der Horst, 2007). Consequently, local residents protest despite considering RE technologies beneficial for the society in general (van der Horst, 2007). This practice is regularly referred to as 'Not In My Backyard' (NIMBY) behavior (van der Horst, 2007).

This study did consider specific locations for hydrogen technologies and associated RE technologies (e.g., wind farms at the North Sea and HRSs in residential areas). Consequently, social acceptance issues proved problematic for the commercialization of H_2 technologies and in some cases, these were considered the bottleneck barriers. This was the case for the construction of wind farms and the application of hydrogen in the built environment were social acceptance issues either lead to potential significant delays (windfarm construction; H_2 in the built environment) or even a complete cancellation of the project (H_2 in the built environment). Besides these immediate threats to the commercialization and roll-out of hydrogen technologies, social acceptance issues could also adversely impact other parts of the hydrogen supply chain. This is the case for HRSs and salt cavern development which currently encounter no social acceptance issues but might start experiencing these issues when the hydrogen economy starts to accelerate.

5.2 Timeline for the Northern Netherlands

Although it is beyond the scope of this report to provide specific remedial measures to mitigate the barriers identified, this study did find that some barriers should be resolved sooner than others. Besides, the results do include suggestions to help resolve or mitigate some of the barriers. Moreover, in some cases the solution to a barrier is obvious. To provide a clear overview of when what barriers should be resolved, table 9 shows a timeline of three main periods in which the barriers identified should be tackled. This section will discuss why these barriers should be resolved within those timeframes and provide suggestions on how these could be resolved. Table 10 (p. 66) gives an overview of suggested remedial measures and constitutes the framework for the commercialization of the integrated hydrogen economy in the Northern Netherlands.

	Barrier	**Supply Chain part**	**2022-2025**	**2025-2030**	**2030-2050**
1.1	Lack of building materials	Windfarm	🟥	🟥	🟥
1.2	Lack of capacity	Salt cavern			
1.3	Boil off losses	LH_2			
1.4	Energy conversion losses	LH_2			🟥
2.1	Chicken-and-egg supply and demand	Electrolyzer + Windfarm/chemical industry	🟥	🟥	🟥
2.2	Cost price of hydrogen	Electrolyzer + Windfarm		🟥	🟥
2.3	Competition with other carrier substances	LH_2			
2.4	National and international market developments	LH_2			
2.5	Capital expenditure	HRS	🟧	🟥	🟥
2.6	Chicken-and-egg	FCEV and HRS	🟧	🟥	🟥
2.7	Purchase price	FCEV	🟧	🟥	🟥
2.8	Lack of H_2 supply	Built environment	🟧	🟧	🟥
2.9	OPEX Cost H_2	Built environment			🟥
2.10	Cost price hydrogen	Chemical industry	🟥	🟥	🟥
2.11	Cost of hydrogen transportation infrastructure	Chemical industry			🟥
3.1	Acquisition of lots	Windfarm	🟥	🟥	🟥
3.2	Connection by TenneT	Windfarm	🟥	🟥	🟥
3.3	RED II	Electrolyzer	🟥	🟥	🟥
3.4	SDE++ subsidy HP	Electrolyzer + wind farm	🟥	🟥	🟥
3.5	Long permitting procedures	Windfarm	🟥	🟥	🟥
3.6	No assessment framework	Pipeline	🟥	🟥	🟥
3.7	Long permitting procedure	Pipeline			🟥
3.8	ODE and energy tax H_2 BE	Built environment			🟥
3.9	Transportation H_2 by network operators	Built environment	🟥	🟥	🟥
4.1	Violation of nature reserve	Windfarm	🟥	🟥	🟥
4.2	Protest among residents	Salt cavern			🟥

4.3	Protest among residents	HRS		🟧	🟥
4.4	Safety concerns potential users	FCEV adoption	🟧	🟥	🟥
4.5	Protest residents for H2 use	Built environment	🟧	🟥	🟥
5.1	Lack of technical manpower	Whole supply chain	🟥	🟥	🟥
5.2	Lack of adequate government policy	Whole supply chain	🟥	🟥	🟥

Table 9: timeline for mitigation of barriers inhibiting the development of the hydrogen economy. Red colour indicates the need to immediately address the barrier in the related timeframe; orange colour indicates doubt about the need to address the barrier in the related timeframe.

Hydrogen production, the chemical industry, and hydrogen pipeline

Without an adequate supply of green hydrogen, the hydrogen economy cannot develop. Therefore, it is imperative to mitigate barriers related to hydrogen production promptly. These are also the projects where the FID will be taken in the next few years. These concern the lack of building materials (1.1), the chicken-and-egg problem (2.1), rules and regulations concerning the acquisition of lots (3.1), connection of windfarms to the shore by TenneT[81] (3.2), RED II (3.3), the long permitting procedures for wind farms (3.5) and the social acceptance barrier concerning the nature reserve (4.1). How 1.1 should be resolved is unclear and it will be hard to mitigate this barrier (given the expected acceleration of wind farm construction worldwide (IEA, 2020b)), but government policy could be designed to prioritize allocating building materials for hydrogen projects instead of regular wind farms.

The chicken-and-egg problem is also hard to abate. Reducing the cost price of hydrogen (2.2, 2.10) could help mitigate this problem by ensuring a better business case for end users, thereby ensuring better commitment by end-users that the hydrogen produced (by production parties) will be consumed. Hence, the business case for hydrogen production parties is improved as well. Cost price reduction will be realized (partly) by scaling green H_2 production in 2030. However, tackling the SDE++ subsidy barrier (3.4) will likely be indispensable in mitigating the chicken-and-egg problem for supply and demand parties by ensuring a relatively low-cost price of hydrogen in the initial stages of hydrogen economy development. Tackling this barrier (3.4) will require an adjustment in national law to make the SDE++ subsidy suitable for hydrogen production. This could be done by allocating part of the SDE++ subsidy budget specifically for hydrogen application according to the manager (I.1). This is necessary because potential CO_2 reduction caused by hydrogen production is relatively low due to the relatively low technological immaturity of hydrogen technologies.[82] Here again, the SDE++ subsidy would only have to be working correctly by 2030, but the promise that this barrier will be resolved by 2030 must be made now. Hence, this barrier should be addressed promptly. Note that the importance of resolving

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[81] Dutch high voltage grid operator

[82] As stated in the results section, SDE++ subsidy is allocated to RE technologies that have the largest impact on CO_2 reduction. As hydrogen technologies are relatively immature, their impact on CO_2 reduction is low compared to other more mature technologies. Therefore, SDE++ subsidy is not granted to hydrogen projects in most cases. Some policy instruments are being developed to help make the SDE++ subsidy more suitable for hydrogen technologies. However, according to the manager (I.1), the requirements for hydrogen projects in this potential adjusted policy for the SDE++ subsidy would still be highly unfavorable (e.g., the number of operating hours for the elektrolyzer must be very low making the business case economically unjustifiable)

this barrier was already stressed by a large group of companies in the Northern Netherlands and TKI Nieuwgas (Collective of companies, 2019; TKI Nieuwgas, 2020).[83]

Besides, (1) government mandates for hydrogen use by end-users, (2) government funds, (3) partial injection of hydrogen into the natural gas grid, (4), (potentially) blue hydrogen, and (5) tailor-made support for the 'hydrogen valley' can help mitigate chicken-and-egg problem. Mandates will improve the business case of production parties by ensuring commitment by end-users that the hydrogen produced will be consumed as they (end users) are bound by law to do so (IEA, 2021b) and government funds help de-risk hydrogen projects by reducing their investment cost, thereby improving the business case for both demand and supply parties (New Energy Coalition, 2020). Consequently, they are more inclined to invest and investment from one side will induce investment from the other side. Alternatively, partial injection of hydrogen into the gas grid could help mitigate the chicken-and-egg problem for supply and demand parties by ensuring an outlet for hydrogen producers (IEA, 2021b; Quarton & Samsatli, 2020). This will improve the business case of potential hydrogen producers and their resulting commitment to producing hydrogen will likely induce demand parties to commit to hydrogen usage.[84]

Additionally, blue hydrogen could help mitigate the chicken-and-egg problem by ensuring a reliable supply of hydrogen in the initial stages of hydrogen economy development. A reliable supply of hydrogen will provide assurance to demand parties that sufficient quantities of hydrogen will be reliably available when they have adjusted their processes for the use of hydrogen. Consequently, these parties will be more likely to commit to (green/blue) hydrogen use, and this commitment drastically improves the business case for supplying parties. Hence, the chicken-and-egg problem is mitigated. Note that the results do not provide an extensive review of the role of blue hydrogen for the mitigation of the chicken-and-egg problem, so a definitive answer to its potential use for the development of the hydrogen economy in the Northern Netherlands is absent. However, it is clear that the Dutch national government, the European Union and the IEA all consider blue hydrogen to be an important stepping stone to developing a hydrogen economy (ECEEE, 2020; IEA, 2021b; Rijksoverheid, 2020).

Furthermore, the Northern Netherlands as a 'hydrogen valley' should be considered in relation to the chicken-and-egg problem. According to the IEA *"Providing tailor-made support for selected, shovel-ready flagship projects through grants, loans and tax breaks (ensuring due diligence to guarantee fair competition), while establishing the support schemes and regulations that will be needed later, can kick-start low carbon hydrogen expansion"* (IEA, 2021b, p. 210). The hydrogen valley in the Northern Netherlands can be considered such a flagship project (*H2Valleys | Mission Innovation Hydrogen Valley Platform*, n.d.; New Energy Coalition, n.d.). Here, an ecosystem of projects exist that are closely working together – coordinated by coordination agency (I) – were the aim is (partially) to test the

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[83] TKI Nieuwgas is a consortium for knowledge and innovation in the Dutch energy sector. Participants include representatives from knowledge institutes, government agencies and the (gas) industry (*Wie Zijn Wij? | Topsector Energie*, n.d.)

[84] Note that the possibility of hydrogen blending is limited due to multiple factors such as the tolerance of end use appliances (de Vries et al., 2017) (20% is an estimation of the maximum that end use appliances will tolerate (TNO, 2020b) depending the composition of the natural gas (de Vries et al., 2017) and the age of the appliances (TNO, 2020b)), its effect on metering operations (IEA, 2021b; TNO, 2020b) and hydrogen purity requirements by end users (IEA, 2021b). Moreover, an extensive check in houses and other end-users of such a mixture will be needed (TNO, 2020b). Also note that its effect on CO_2-emission reduction is negligible: a 30% mix scenario will result in CO_2-emission reduction of 10% (IEA, 2021b). Hence, blending should be mainly aimed at mitigating the chicken-and-egg problem for supply and demand parties instead of CO_2-emission reduction.

viability of hydrogen technologies and investigate how an integrated hydrogen supply chain can best be realized. In this situation, tailor-made support could be applied to accelerate the development of the hydrogen economy (which can help accelerate the hydrogen economy for the Netherlands and possibly Europe). Although an extensive review of the extent to which tailor-made support is already available is beyond the scope of this research, it is clear that significant improvements can be made as attested by the many regulatory barriers (3.1;3.2;3.3;3.4;3.5;3.8;3.9) and some market barriers (2.5;2.7) were governments could intervene with tailor made support.

Lastly – as previously explained – an adequate government policy on hydrogen would help to provide certainty to the market regarding investments in hydrogen technologies. However, uncertainty in future developments in hydrogen technology, future European legislation and future energy systems all limit the ability to plan adequately and allocate investment efficiently. Consequently, how government policy can best be designed to help accelerate the development of the hydrogen economy is still being debated. Hence, mitigating barrier 5.2 (lack of adequate government policy) is extremely difficult. Nonetheless, there are strategies available. According to the manager (J.1), the best strategy in this stage of development is to allow for as much experimentation as possible. He stated:

"…the question is how much room for experimentation do governments, grid operators and market participants get over the next 3 years, 3 to 5 years. How much money do you put into exploring those horses (referring to hydrogen technologies) *and how much freedom do you provide in regulation."*

This will allow parties to quickly discover which hydrogen technologies are best suited for the hydrogen economy in the Northern Netherlands as explained by the manager (I.1). In the next phase, better policies can be designed based on the outcomes of these experiments. The policy barrier 5.2 can thus be addressed immediately. However, to what extent additional room for experimentation is necessary and how such policies should be best designed remains unclear and is beyond the scope of this study. Nonetheless, there is room for improvement as attested by barrier 3.9 which currently makes it difficult for network operators to experiment with hydrogen use in the built environment.

Resolving barrier 3.1 (acquisition of lots), barrier 3.2 (connection by TenneT) and the REDII barrier (3.3) seem straight forward. First, 3.1 could be tackled by allocating lots specifically to wind farms for hydrogen production projects and it should do so promptly given the long lead times (New Energy Coalition, 2020). Secondly, 3.2 could be addressed by adjusting the law, requiring TenneT to also connect the wind farm to an electrolyzer. Lastly, RED II could be mitigated by a temporary exemption from REDII according to the manager (A.1) and the NEC (New Energy Coalition, 2020). Resolving this barrier will also help mitigate barrier 3.1: if the need to ensure additional electricity is (temporally) not required, hydrogen production parties will not have to (directly) acquire lots anymore.

The results are unclear about how barrier 3.5 (long permitting procedures wind farms) can be best mitigated. Here, a possible mitigation strategy is to review the procedure closely at a governmental level and look for possible ways to reduce its length for hydrogen production projects.

The social acceptance barrier concerning the need to lay electricity cables across the Wadden Sea (4.1) will be more difficult to mitigate. The literature has considered multiple strategies for mitigating social resistance among residents for offshore windfarm construction. For instance, Hall et al. (2013) reviewed 7 case studies and found four recurring themes: (1) the need for trust between residents and the windfarm developer, (2) the need for distributional justice, (3) the need for procedural justice and (4) place attachment. Based on this, these authors found that (1) ensuring honesty and transparency by the wind farm developer (2), a compensation plan for residents, (3) providing full and unbiased information (4) and ensuring an early assessment of regional compatibility with the wind farm project to be sound mitigation strategies for the four respective themes. Moreover, Hagget (2011) found some of the same recurring themes (lack of tangible benefits; place attachment; role of planning and decisions-making systems; visual impact) and concluded that strong participation of residents (1) in the decision making process and (2) assigning them a key role in the process are imperative for successful realization of an offshore wind farm project. However, social acceptance in this case mainly concerns the need to lay sea cables across a nature reserve. Consequently, the suggested strategies can help mitigate this barrier to some extent (by persuading local residents), but these will likely not prove sufficient. Especially as a violation of the nature reserve can result in protest on a national level (not only local residents) both by citizens in the Netherlands and environmental protection organizations who will object (in principle) to projects that violate the environment. Hence, it remains unclear what the best mitigation strategy is.

Hydrogen pipeline transport

Barriers inhibiting the development of hydrogen pipelines infrastructure must be tackled within the same timeframe as the hydrogen production barriers (starting in 2022). This mainly concerns the assessment framework (3.6) which is required for repurposing the existing natural gas grid for hydrogen transportation. As this project will start soon (Gasunie, n.d.)[85] and given its importance for the development of the hydrogen economy, this barrier should be tackled promptly. However, the results are unclear about the extent to which it is possible to mitigate this barrier. The second pipeline related barrier concerns the long permitting procedures (3.6) which will prove problematic only when a quick expansion of the network is needed at specific locations. Therefore, this barrier (3.6) will be relevant only after 2030 when the hydrogen economy starts to accelerate, and hydrogen is required beyond the industry clusters that will be connected by the national hydrogen backbone. The New Energy Coalition has suggested an accelerated right-of-way approval (New Energy Coalition, 2020), but it remains unclear how this could be achieved and – consequently – how the current length of the permitting procedure (2,5-3 years) can be reduced.

Liquid hydrogen

The results on liquid hydrogen show that its potential use is mainly as a carrier and possibly as a fuel for trucks. However, multiple technical and market barriers may prevent its eventual usage in the Northern Netherlands. These are the boil off losses (1.2), energy conversion losses (1.3), competition with other carrier substances (2.3) and national and international market developments (2.4). How these barriers should be resolved remains unclear, but these may not need to be resolved in the end. The technical barriers (1.2;1.3) might be mitigated by investing (either on a national level or in the Northern Netherlands) in R&D for liquid hydrogen, but the results are unclear about how this could best be achieved. Besides, the market barriers (2.3;2.4) may render its usage obsolete due to competition with other carrier substances (2.3) and/or due to national and international market developments which may lead to little or no hydrogen imports (2.4). Consequently, it remains unclear if these barriers should be mitigated and how they should be mitigated exactly. Hence, these are excluded in table 10 which shows the mitigation strategies per barrier. For the same reason these barriers are not assigned a specific timeline for mitigation in table 9.

FCEVs and HRSs

The results are unclear about the need to swiftly address the barriers concerning FCEVs and HRSs. Although there is still a limited supply of hydrogen, measures could already be taken to start expanding

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[85] Regional backbone development will be realized by 2026. Up forward from 20206, the industrial cluster in the Netherlands will be connected by the national backbone (Gasunie, n.d.)

the refuelling infrastructure for FCEVs to enable a widescale adoption of these vehicles after 2030. To enable this, solutions must be found to mitigate the high capital expenditure of HRSs (2.5), the cost price of FCEVs (2.7)[86] and possibly the low adoption rate of FCEVs because of its perceived danger (4.4)[87]. These will likely mitigate the chicken-and-egg issues observed for FCEVs and HRSs (2.6). Mitigation strategies for barriers 2.5 and 2.6 are straight forward to some extent. As explained in the results section, the capital cost of HRSs is not likely to decrease significantly despite some expected technological improvements. Consequently, policy intervention could be aimed at improving the business case for HRSs by providing extensive subsidies and/or by ensuring appealing financing options.

In case of FCEVs, it is important to note technological challenges cannot be resolved in the Northern Netherlands or Netherlands. The Netherlands do not have any passenger FCEV manufacturers (New Energy Coalition, 2020). Moreover, this is not likely to happen in the (Northern) Netherlands either (RVO & EZK, 2019)[88]. Consequently, technical challenges (and scaling production) cannot be mitigated by interventions within the Northern Netherlands and must be resolved by passenger FCEV manufacturers outside the (Northern) Netherlands. So, a straightforward measure in the (Northern) Netherlands would be a one-time subsidy reducing the purchase price of the vehicle. This subsidy already exists for electric vehicles (RVO, 2022a), but a similar subsidy for passenger FCEVs is only available for company cars, not for private purchases (RVO, 2022b). Therefore, this subsidy could be made available for passenger FCEVs as well. Besides, a clear roadmap could be designed (either at a national level or specifically for the Northern Netherlands) that includes clear goals on the number of FCEVs that should be adopted by a given year (IEA, 2021b) These statistics should be tracked closely to help assess the progress made (IEA, 2021b) and allow for adequate policy intervention when necessary. This roadmap would be useful to help accelerate roll-out of HRSs as well (IEA, 2021b).

Nonetheless, there is no immediate need to address these barriers as a large supply of hydrogen will only become available after 2030. Therefore, these barriers could also be addressed between 2025-2030 to enable wide scale adoption of (passenger) FCEVs after 2030. Here, the protest for HRS diffusion (4.3) can become problematic only after 2025 as HRSs start to enter residential areas. However, it remains uncertain how fast HRSs will roll-out across the Northern Netherlands, so this could become problematic after 2030 as well. Besides, this study did not find a final answer about the extent to which this barrier will prove problematic at all. In any case – if this barrier proves problematic – the fact that social acceptance issues concerning HRSs are highly related to their perceived danger (Hienuki et al., 2021; H. Lee et al., 2021; Xu et al., 2020) indicates that a straightforward mitigation strategy could be to clearly communicate safety facts with local residents before HRS construction in residential areas.

Built environment

As explained, large scale hydrogen use in the built environment will only be realised after 2030 (if at all). Before this date, various experiments will be conducted in the built environment to test the

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[86] Note that this barrier can only be mitigated by government subsidies and/or tax benefits for customers as the Netherlands do not have a passenger FCEV industry. So, scaling production to mitigate these barriers is beyond the control of national authorities.

[87] No definitive answers concerning the impact of this barrier were found. Future research should study the extent to which this social acceptance barrier impedes FCEV adoption. If the impact of this barrier is significant, it should be mitigated promptly.

[88] This report investigated the opportunities for the Dutch industry concerning hydrogen. With regard to the development of passenger FCEVs and delivery vans, it stated that no such industry currently exists in the Netherlands and it is highly unlikely that these will be produced in the Netherlands in the future neither given the high entry barrier and the lack of a Dutch OEM (RVO & EZK, 2019).

feasibility of a large-scale roll-out. To enable this, the regulatory barrier concerning the transportation of hydrogen by the network operator should be resolved promptly (3.8). An adjustment in the law allowing for hydrogen transportation through the existing gas infrastructure in case of pilot projects seems a straightforward solution for this. By 2030 – when a potential roll-out of hydrogen in the built environment is possible – the ODE and energy tax barrier (3.7), the high OPEX cost for H_2 (2.9), the lack of hydrogen supply (2.8) and the social acceptance barrier concerning protest among residents (4.5) should be resolved. Here, it is important to note that the high OPEX cost (2.9) is strongly related to the cost of producing hydrogen (2.2), which is expected to drop due to scaling (e.g., when the cost of producing green H_2 drops, OPEX cost for green H_2 for consumers drop as well). It is also strongly related to the SDE++ OPEX subsidy arrangement (3.4) which could help lower the cost of producing green hydrogen. So, the extent to which this barrier should be addressed remains unclear as mitigating these other barriers (2.2/3.4) could automatically resolve the OPEX barrier in the built environment (3.7). If these do not prove sufficient, the national government could compensate residents for their hydrogen usage. However, a study by Netbeheer Nederland (2021b) shows that in all future energy scenarios (also where hydrogen is used in the built environment), the energy cost price for the consumer will increase. Hence, clear communication regarding the distribution of the cost of the energy transition will be imperative for creating a support base for the transition (Netbeheer Nederland, 2021b).

Like mitigating barrier 3.8, an adjustment in the law could help resolve the ODE and energy tax barrier (3.7): for instance by removing the ODE for hydrogen usage and removing (or reducing) the energy tax. This will make the cost of H_2 more acceptable for the consumer. The lack of hydrogen for the built environment (2.8) will be more difficult to mitigate as an initial limited supply of green hydrogen is likely. Blue hydrogen and hydrogen imports could increase the total supply of hydrogen and thereby allow for its use in the built environment early on. So, the national government could pursue a strategy of investing in blue hydrogen, investing in importing infrastructure and closing contracts with international parties for hydrogen imports. If it chooses to pursue this strategy, it should start to do so soon as this infrastructure should be completed by 2030. However, it is beyond the scope of this report to extensively review this.

Lastly, a specific strategy for mitigating the social acceptance barrier (4.5) remains unclear. Clear communication to residents is a straightforward approach for limiting their resistance. However, the results have shown that residents might protest despite being well-informed. And as individual protests might lead to a complete cancellation of the project, a more effective measure is necessary. Hence, the manager (G.1) has suggested making an adjustment in the law allowing the (local) government to force residents to comply to the use of hydrogen for heating in their homes (a similar law could force residents to comply to other sustainability measures such as heat pumps and district heating were necessary). How this law should specifically be designed, and what needs to be considered remains unclear, but it is obvious that such a law is likely to be needed.

Salt caverns and chemical industry

Less urgent are barriers concerning salt caverns capacity (1.2), protests for salt cavern development (4.2) and the cost of hydrogen transportation infrastructure for the chemical industry (2.11). The first two are highly related. The results show that the four salt caverns – which are planned to be in operation by 2030 – will provide sufficient storage capacity. It is between 2030-2050 that the national need for hydrogen storage capacity exceeds this capacity and additional salt caverns are needed (possibly beyond what is available in the Netherlands, which constitutes the core issue of this barrier). A potential mitigation strategy could be to use salt caverns across the border in Germany as this country has more capacity (HyUnder, 2014). Besides, depleted fields[89] could serve as a long-term storage method for hydrogen. However, this is an immature technology (IEA, 2020a; Tarkowski, 2019) and there's ongoing research into its potential use (IEA, 2021b; Tarkowski, 2019). In this case, technical barriers must be mitigated to allow for its use (Netbeheer Nederland, 2021a; TNO, 2020a). These barriers are not considered as this is beyond the scope of this report. As explained in the results, this barrier (1.2) only becomes problematic when hydrogen becomes the preferred energy flexibility method. If not, the available storage capacity in the Netherlands will prove sufficient for hydrogen storage needs across the country (and thereby for the Northern Netherlands as well) (TNO, 2021).

As explained, protest for salt cavern development for hydrogen usage is currently not considered a barrier, but the development of additional caverns (especially outside the current region at Zuidwending) might encounter protest. In this case, protest for salt cavern development (4.2) should be addressed adequately, but this will be after 2030. A straightforward strategy would be to transparently communicate all relevant information concerning the salt caverns to residents. This is now also being done for the salt caverns at Zuidwending according to the manager (E.1). However, how this potential barrier should specifically be addressed remains unclear.

Barrier 2.11 will be relevant after 2030 as the green hydrogen supply will only become available after this date. Hence, the fact that some industrial companies may choose not to start using hydrogen due to the disproportionally large hydrogen transportation cost can only occur after 2030. As this is a financial complication, a potential mitigation strategy could be to financially compensate these companies. Another possibility is local 'un-blending' of the a (natural gas mixed with hydrogen) that is delivered to these companies according to the manager (A.2). In this scenario, a company that requires pure hydrogen can still be connected to the grid that is supplying a blend, increasing its chances of being supplied hydrogen against an economically justifiable price. However, the technological readiness of this technology is not yet mature according to the manager (A.2).

Technical manpower

The lack of technical manpower (5.1) must be addressed promptly as it will take time to train enough people to help build the hydrogen economy. Especially as there is already a short supply of technical manpower on the labour market (ROA, 2019). Reskilling employees currently employed in the gas industry in the Northern Netherlands was suggested by the manager (K.1) of a large municipality. The New Energy Coalition suggested this strategy as well in their investment plan (New Energy Coalition, 2020). Alternatively, Netbeheer Nederland (2021b) called for the building sector, the installation industry and network operators to work together on making an action plan on how to ensure a greater inflow of technical manpower. However, given the current short supply of technical manpower, it may be difficult to mitigate this barrier at all. Especially as efforts to tackle this problem are ongoing and date back to 2013 (EZK, 2020; Techniekpact, n.d.).

Grid balancing

No barriers were identified for grid balancing as it remains unclear how grid balancing, and energy balancing will be organized in the future. Hence, these barriers cannot be addressed. It is clear though that additional analyses are needed to determine economically the best setup of flexibility options (e.g., salt caverns/batteries/DMS) (Netbeheer Nederland, 2021b). Besides, Netbeheer Nederland

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[89] (oil/gas) deposits, aquifers and underground mine workings (IEA, 2021b; Reuß et al., 2017)

(2021b) has suggested to urgently create incentives to make sure enough investments are allocated to the required flexibility options by the time this is needed.

		Barrier	**Supply chain part**	**Timeline**	**Suggested mitigation strategies**
Hydrogen production	1.1	Lack of building materials	Wind farm	Starting 2022	- *Allocating* building materials specifically for wind farms related to hydrogen production projects (**possibly**)
	2.1	Chicken-and-egg supply and demand	Hydrogen production/chemical industry	Starting 2022	- *Resolving* barrier 3.4 (SDE++ subsidy - *Government* mandates for hydrogen use by end users - *Government* funds for hydrogen projects - *Partial* injection H2 into gas grid - Investing in blue hydrogen (potentially) - *Government* policy aimed at sufficient room for experimentation - *Tailor* made support hydrogen valley
	2.2	Cost price of hydrogen	Hydrogen production	Starting 2022	- *Resolving* barrier 3.4 (SDE++ subsidy
	3.1	Acquisition of lots	Wind farm	Starting 2022	- *Allocating* sufficient lots specifically for hydrogen production (**possibly**)
	3.2	Connection by TenneT	Wind farm	Starting 2022	- *Adjustment* of law requiring TenneT to connect wind farms to Electrolyzers (**possibly**)
	3.3	RED II	Hydrogen production	Starting 2022	- *Temporal* exemption REDII
	3.4	SDE++ subsidy HP	Hydrogen production	Starting 2022	- *Adjusting* subsidy scheme for hydrogen
	3.5	Long permitting procedures	Wind farm	Starting 2022	- *Review* of procedures to look for (tailor-made)

					options to reduce its length (**possibly**)
	4.1	Violation of nature reserve	Wind farm	Starting 2022	- *Suitable* mitigation strategy remains unknown
Hydrogen storage	1.2	Lack of salt cavern capacity	Salt Cavern	After 2030	- *Research* in suitability of depleted fields - *Enquiring* for potential use of salt cavern in Germany
	4.2	(Potential) Protest among residents	Salt Cavern	After 2030	- *Informing* residents (**possibly**)
Hydrogen distribution	3.5	No assessment framework	H_2 Pipeline	Starting 2022	- *Suitable* mitigation strategy remains unknown
	3.6	Long permitting procedure	H_2 Pipeline	After 2030	- Accelerated rights-of-way (**possibly**)
	2.5	Capital expenditure	HRS	Starting 2022 or after 2025	- Government subsidy (**possibly**) - Ensuring appealing financing options (**possibly**)
	2.6	Chicken-and-egg	HRS/FCEV	Starting 2022 or after 2025	- *Mitigating* barrier 2.7 (cost price FCEV) - *Mitigating* barrier 2.5 (capital expenditure HRS) - *Mitigating* barrier 4.4 ((potential) safety concerns end users)
	4.3	Protest among residents	HRS	After 2025 or after 2030	- Informing residents about actual safety hazards HRSs (**possibly**)
End use	2.7	Cost price	FCEV	Starting 2022 or after 2025	- Cost price reducing subsidies for private use FCEV
	4.4	(Potential) Safety concerns end users	FCEV	Starting 2022 or after 2025	- Informing the public about acutal safety hazards FCEVs (**possibly**)
	2.10	Cost price hydrogen	Chemical industry	Starting 2022	- *Resolving* barrier 3.4 (SDE++ subsidy

	2.11	Cost of hydrogen transportation infrastructure	Chemical industry	After 2030	- Financial compensation for hydrogen use by the government (**possibly**) - Local un-blending of H_2/natural gas mix (Technology not yet mature)
	3.7	ODE and energy tax H_2 BE	Built Environment	After 2030	- Removing ODE and removing/reducing energy tax (**possibly**)
	3.8	Transportation H_2 by network operators	Built environment	Starting 2022	- Adjusting the law allowing hydrogen transport for pilot projects (**possibly**)
	2.8	Lack of H_2 supply	Built environment	After 2030	- Investing in blue hydrogen and hydrogen imports (**possibly**)
	2.9	OPEX Cost H_2	Built environment	After 2030	- Resolving barrier 3.4 (SDE++ subsidy) - Resolving barrier 2.2 (cost price barrier) - Compensation of residents for hydrogen usage (**possibly**) - Informing the public about distribution of cost of energy transition
	4.5	Protest residents	Built environment	After 2030	- Adjustment in rules and regulation allowing a forced transitioning of a residence to hydrogen
System broad	5.1	Lack of technical manpower		Starting 2022	- Strong cooperation between network operators, the building sector and the installation industry (However, it remains unknown if this barrier can be mitigated at all given the existing efforts)
	5.2	Lack of adequate government policy		Starting 2022	- Providing sufficient room for experimentation

Table 10: framework for commercializing the integrated hydrogen economy in the Northern Netherlands. 'Possibly' is assigned to mitigation strategies that were logically inferred from the data, but not backed by either the literature or the interviews.

5.3 Study implications

5.3.1 Theoretical implications

The results have shown that many barriers are linked and interdependent and that some will have to be addressed sooner than others. Moreover, not only the barriers, but the parties involved in developing the hydrogen economy are highly dependent on each other as well. Hence, this study adds to the scientific literature by providing a more comprehensive understanding of the complexities of developing a hydrogen economy from scratch.

Secondly, by developing a framework for the commercialization of an integrated hydrogen economy (table 10) a blueprint for developing an integrated hydrogen economy is provided which can be refined and generalized in future research. This way, this study helps to lay the groundwork for theory building in future research on hydrogen economies.

Lastly, this report extends the theory of Shakeel et al. (2017) by showing that social acceptance barriers are highly important in the commercialization process of hydrogen technologies when specific locations are considered. Here, social acceptance does not concern cost for the consumer compared to conventional technologies (which was considered in their paper). Rather, it concerns resistance due to the perceived danger of technologies, the visual pollution it causes or due to the violation of the surrounding nature. Consequently, future research should include this factor from the start. Figure 4 shows its implication:

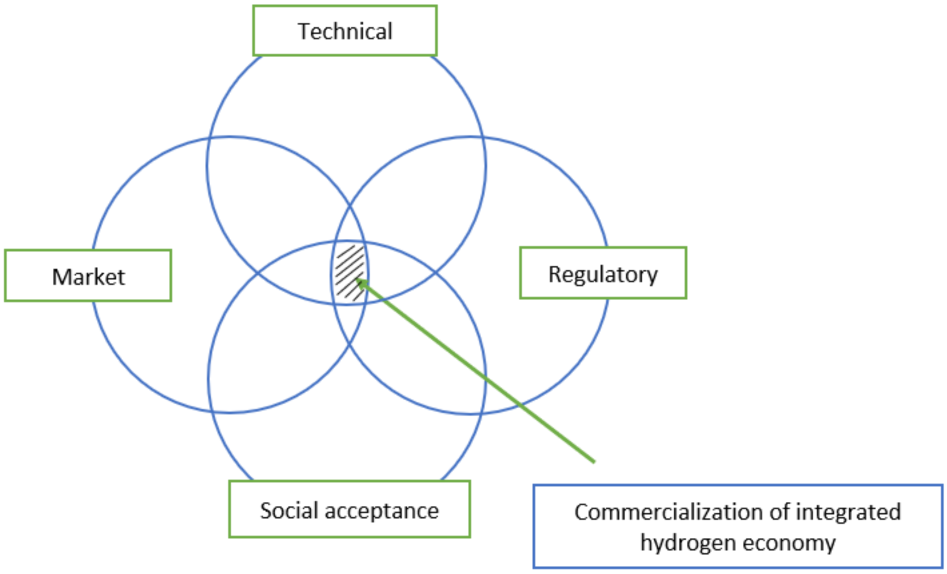

Figure 4: commercialization of an integrated hydrogen economy; adapted from (Shakeel et al., 2017)

5.3.2 Practical implications

The results provide an extensive overview of barriers identified for the development of an integrated hydrogen economy in the Northern Netherlands. Additionally, the discussion suggests several mitigation strategies which can help to mitigate or resolve these barriers. Here, some practical implications can be derived for practitioners. First, being knowledgeable of all barriers related to hydrogen technologies can help (local) governments to ensure a smooth commercialization of these technologies in the Northern Netherlands by allowing them to address these in time. At first this means creating sufficient room for experimentation which will ultimately help accelerate the development of the integrated hydrogen economy in this part of the Netherlands. This means resolving barrier 3.8 (barrier now preventing hydrogen transportation through pipelines by network operators) but ultimately all other regulatory barriers that now impede its development as well. Besides, the (local) government should assess (in collaboration with private parties) whether there is sufficient room for experimentation or not (which relates to 5.2: designing effective government policies).

Addressing the market barriers is likely to prove more difficult as these will not be resolved by simply adjusting rules and regulations. But the results do show that (local) governments can help mitigate the market barriers by various policy measures. For instance, government subsidies will (partially) help mitigate various barriers such as 2.1 (chicken-and-egg problem supply and demand), 2.2 (hydrogen cost price) 2.7 (FCEV purchase price), 2.5 (capital expenditure HRS), 2.11 (cost of hydrogen transportation infrastructure). Besides, specific policies can address the chicken-and-egg problem for supply and demand parties (e.g., partial injection of H_2 into the gas grid; government mandates; government funds; (potential) investment in blue hydrogen)

Secondly, the results help create a sense of urgency for resolving specific barriers by providing a roadmap for addressing these. For instance, as it is imperative to ensure a reliable supply of hydrogen in the early stages of hydrogen economy development, government policy should first aim to resolve 1.1 (lack of building materials), 2.1 (chicken-and-egg problem supply and demand), 3.1 (acquisition of lots, 3.4 (connection of windfarms to the shore by TenneT), 3.3 (REDII), 3.4 (SDE+ subsidy barrier), 4. 1 (social acceptance barrier concerning the nature reserve), and the 3.6 (assessment framework pipeline). Next, barriers concerning FCEVs and HRSs could be addressed and in later stages focus can shift to the built environment (2.8;3.9;4.5) and various specific barriers (2.9;3.7;3.8;4.2;2.11).

Thirdly, this study has shown that many barriers are linked and interdependent. Therefore, addressing one barrier can affect others. This will help (local) governments understand the implications of their policies better and will aid them in formulating improved rules and regulations. For example, resolving barrier (3.4) SDE++ subsidy barrier will help resolve barrier 2.2 (cost price H_2) which on its turn affects 2.1 (chicken-and-egg problem) 2.9 (high OPEX cost H_2 built environment) and 2.10. (cost price hydrogen chemical industry). Another example is barrier 2.5: addressing 2.5 (capital expenditure HRS), 2.7 (purchase price FCEV) and 4.4 ((potential) safety concerns end users) will help mitigate the chicken-and-egg problem for FCEVs and HRSs. And addressing barrier 3.3 (REDII) will help mitigate barrier 3.1 (allocation of lots for wind farms). Moreover, as demand parties are mostly dependent on the development of hydrogen production facilities, tackling all barriers related to hydrogen production (1.1;2.1;3.1;3.2;3.3;4.1) is crucial to enable H_2 use for end use parties. Hence, these barriers apply to end use parties to some extent as well.

Lastly, the results help managers understand the business environment of their organization better by being knowledgeable of which barriers are currently inhibiting the hydrogen economy in the Northern Netherlands. This will allow them to make better strategic business decisions for their respective hydrogen companies. For instance, being informed about all the barriers that hydrogen production parties experience can help managers at end use parties better estimate the business case for transitioning to hydrogen.

5.4 Limitations and future research

Several limitations must be considered in this study. First, it is hard to prove theoretical saturation for parts of the data. For instance, it remains unclear if additional interviews with experts on FCEVs would yield more valuable information or that its contribution would be marginal and negligible. This is the case for all parts of the hydrogen supply chain that were covered by only one interview (e.g., the built environment and hydrogen pipelines). Additionally, specific data was missing in case of HRSs (role of (lack of) financing and subsidies), the chemical industry, short term storage and tube trailers (no interviews with directly involved participants were conducted). Indeed, the scientific literature and reports helped ensure triangulation of data by providing additional richness to the findings (Eisenhardt, 1989; Karlsson, 2016; Yin, 1984) but theoretical saturation was not achieved in some cases and cannot be proved in others and this can impact this study's reliability (Aguinis & Solarino, 2019). So, future research could study these technologies more extensively to ensure theoretical saturation. To this end, a grounded theory method could be applied (Gioia et al., 2013).

Secondly, this study covered various hydrogen technologies across the supply chain, but it did not review all possible technologies. For instance, onshore wind and solar PV were not considered for hydrogen production, heavy-duty vehicles were not considered for FCEVs and many industry applications for green hydrogen were not included in this study (e.g., DRI steel production and ammonia production). Hence, future research could focus on these subjects in more depth to identify the relevant barriers inhibiting their commercialization.

Thirdly, although it was beyond the scope of this report to extensively review possible remedial measures to the barriers identified, this report does suggest some mitigation strategies. However, some have been logically inferred from the results and are not backed by either the literature or statements from participants. Moreover, as an extensive review of remedial measures is lacking, even mitigation strategies that are backed by literature and statements from participants may prove insufficiently adequate. Therefore, future research should focus on identifying all possible remedial measures for their respective barriers and when these should be implemented to allow for its mitigating effect to be realized in time.

Lastly, this study only covered the Northern Netherlands and is a single case study. Although some barriers are likely to apply to the national (or even international) context as well, this study's results do not readily apply to a different regional context. Therefore, the results are not generalizable (Karlsson, 2016). Hence, future research could extend this report by studying the relevant barriers inhibiting the development of an integrated hydrogen economy in a different regional context. This will also help establish a universal framework for barriers inhibiting an integrated hydrogen economy whose blueprint can be used for various hydrogen projects across the globe. This will also contribute to the scientific literature by providing a more comprehensive understanding of the complexities of developing an integrated hydrogen economy.

6 Conclusion

As the world is transitioning to a more sustainable energy system, it has become clear that green hydrogen will constitute an important vector in future energy systems. Like many nations, the Netherlands aims to include H_2 in their energy strategy. The Northern region of this country is more ambitious and is already actively trying to develop an integrated hydrogen economy. However, no framework for the commercialization of the technologies in this economy currently exists. To this end, this study aimed to identify the technical, market and regulatory barriers inhibiting the commercialization of a potential integrated hydrogen economy in the Northern Netherlands.

This report identified 29 barriers across the hydrogen supply chain that can inhibit its developments by slowing down the (full-scale) commercialization of the technologies that make up the supply chain. Here, few technical barriers (4) were identified as the technological readiness of many technologies reviewed for this study were relatively high. Market barriers (11) were more pervasive and ubiquitous and were identified for most hydrogen technologies across the hydrogen supply chain. Fewer regulatory barriers (9) were identified compared to market barriers and these were concentrated in hydrogen pipelines, hydrogen production and the built environment. Besides, the identified barriers did not only concern technical, market or regulatory barriers. Social acceptance (5) also proved relevant to the commercialization of the hydrogen economy and crucial to some specific technologies. Additionally, the barriers do not only relate to specific hydrogen technologies as attested by the two system wide barriers identified in this study, whose significance cannot be underestimated. Here, especially a lack of technical manpower can slow down the development of the entire hydrogen economy. Lastly, in showing that many barriers are highly interlinked and interdependent, additional insights into the complexities of developing a hydrogen economy from scratch is provided. This way, the first steps towards creating a universally applicable framework for developing and commercializing a hydrogen economy have been taken.

For addressing the barriers, this study has provided a roadmap to indicate when what barriers should be resolved to enable a smooth commercialization and development of the hydrogen economy in the Northern Netherlands. This timeline showed the importance of first addressing barriers related to the construction of essential hydrogen infrastructure (pipelines/hydrogen supply) and in subsequent stages focus on less important supply chain parts such as HRSs, the built environment and FCEVs. Additionally, this report has suggested some mitigation strategies to help resolve the identified barriers. Although potential remedial measures have not been extensively reviewed, (local) governments are provided with some tools to help address these barriers. Here, '(local) governments' is a key word as nearly all barriers should be mitigated in some way by government policy. Hence, it is no surprise that most practical implications are policy related.

7 Appendices

7.1 Appendix 1: overview of hydrogen supply chain technologies

	NIB road map	NEC road map	This report	Maturity level[90]	Covered by
Production[91][92]					
Onshore wind + electrolysis	x	x		10+9	
Offshore wind + electrolysis			x	9+9	A/C/D/F
Solar + electrolysis[93]	x			10+9	
Hydropower + electrolysis				11+9	
Geothermal + electrolysis				11+9	
Nuclear + electrolysis				11+9	
Biomass gasification	x			5	
Storage[94]					

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[90] Scale 1-11. Based on (IEA, 2020a, 2021b). This refers to the hydrogen technologies. In case of production, the RE technology maturity is given by the first number. The second refers to the maturity level of the electrolysis process.

Small prototype
1-4
Large prototype
4-6
Demonstration
6-8
Market update
8-10
Mature
11

[91] The production of green hydrogen is either performed by water splitting processes or using biomass. The former one can then be subdivided into Electrolysis, Thermolysis and Photolysis. The biomass process can be subdivided in biological processes and thermological processes which on their turn are subdivided into specific methods for producing green hydrogen (totaling 7) (Nikolaidis & Poullikkas, 2017). The feedstock for electrolysis in case of green hydrogen production is green electricity from renewable energy sources (Hosseini & Wahid, 2016). The combination of both the method and the RE source are provided in the table to allow for a clear overview of the technologies available for integration in a hydrogen economy. This relates to the most mature technology (water splitting electrolysis).

[92] The four main electrolyzer technologies currently on the market are Proton Exchange Membrane Electrolysis (PEMEL), Alkaline Electrolysis (AEL), Solid Oxide Electrolysis (SOEL) and Anion Exchange Membrane (AEM) electrolysis of which the former two are the most mature technologies (Buttler & Spliethoff, 2018; IEA, 2020b).

[93] Solar PV is mentioned in the report by the NEC, but it is not incorporated into their roadmap (New Energy Coalition, 2020)

[94] Actual storage methods for hydrogen are numerous. The four main ways to store hydrogen are by compressions, liquification, physisorption and chemisorption, which can be subdivided in roughly 33 specific methods (Abdin et al., 2020; Hassan et al., 2021). These methods concern the state in which hydrogen is stored and not the vessel in which it is stored. Many of these storage methods are either economically infeasible, technologically immature or both. To provide a clear overview of what value chain parts are included in this

Salt caverns (compressed hydrogen)	**x**	**x**	**x**	**9**	A/E
Other underground hydrogen storage applications[95]				**2**	
Compressed hydrogen tank	**x**	**x**	**x**	**11**	A/C/D
Liquid cryogenic tank			**x**	**11**	
Compressed cooled hydrogen tank				**11**	
Material-based (chemical) storage				**4**	
Distribution					
Pipelines (compressed gas)	**x**	**x**	**x**	**11**	A/G
Tank tube trailer (compressed gas)	**x**	**x**	**x**	**11**	C
Tank tube trailer (liquified hydrogen)			**x**	**11**	C
Ship transport (liquified hydrogen)				**7**	
Ship transport (LOCH)[96]				**5**	
Ship transport (Ammonia)				**11**	
H_2 refuelling stations (compressed gas)[97]	**x**	**x**	**x**	**3-9**	C
Fuel cell (for grid balancing)	**x**	**x**	**x**	**8**	J
End use					
FCEV[98]	**x**	**x**	**x**	**8-9**	C/H

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paper, the storage methods in the table show a combination of the state in which the hydrogen is stored and the vessels in which it is kept. This again relates to the most mature technologies. To allows for an integral overview, all storage methods besides the ones mentioned are included under one denominator: material-based (chemical) storage.

[95] These concern depleted hydrocarbon (oil/gas) deposits, aquifers and underground mine workings (IEA, 2021b; Reuß et al., 2017)

[96] Liquid Organic Hydrogen Carrier: concerns hydrogen stored in unsaturated organic compounds which allows for its storage at ambient conditions (Niaz et al., 2015; Reuß et al., 2017)

[97] This refers to HRS for light duty transport (9), heavy duty 35MPa (9) and heavy duty 70MPa high throughput (3).

[98] Fuel Cell Electric Vehicles is a very broad term. It can mean heavy duty trucks, light duty passenger vehicles and everything in between (Forrest et al., 2020). For this research, only passenger vehicles are considered. The rating is based on light-duty/passenger vehicles (9) and heavy-duty (8).

Other heavy-duty transport[99]	x	x		**3-8**	
Built environment[100]	x	x	x	**6-11**	G/K
Grid balancing[101]	x	x	x	**4-9**	J
Chemical industry	x	x	x	**7-9**	B/D
Steel industry[102]		x		**4-7**	
Refinery		x		**7-9**	

Based on (Abdin et al., 2020; Forrest et al., 2020; Hassan et al., 2021; Hosseini & Wahid, 2016; IEA, 2020a, 2021b; New Energy Coalition, 2020; Niaz et al., 2015; NIB, 2017; Nikolaidis & Poullikkas, 2017; Reuß et al., 2017

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[99] Aviation (6 for small aircraft, 3 for medium aircraft), shipping (5-7 depending on technology used), and train (8).

[100] This concerns hydrogen for heating, which can be subdivided in 4 main methods: injecting a mixture between natural gas and hydrogen (6/9 – relates to injecting a mixture of H_2 and natural gas into the grid (6) and the H_2 enriched natural gas pump (9)), injecting synthetic menthane (produced using hydrogen) (6/9 – relates to production of synthetic methane (6) and the synthetic CH_4 heat pump (9)), injecting pure hydrogen (9 – H_2 boiler) and using fuel cells & co-generation (9) (IEA, 2019, 2020a). Note that this study focusses on injecting pure hydrogen and includes the use of a pure H_2 boiler and a hybrid heat pump.

[101] Rating based on the use of an anomia turbines (4), ammonia blending in coal plants (5), hybrid fuel cell gas turbine systems (6), pure H_2 gas turbines (7), a high temperature fuel cell (8), and H_2 blending in natural gas turbines (9). This study focuses on the latter three technologies given its relative technological maturity.

[102] Rating based on hydrogen technology used for steel production. H_2 blending in DRI process is the most mature (7).

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