The effects of regional contextual structures on the development of green hydrogen in the Netherlands

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Abstract

As greenhouse gas emissions must decrease to avoid a climate disaster, energy systems must be transformed. One of the proposed solutions is green hydrogen, a non-emitting energy carrier. To study how technologies like green hydrogen develop and diffuse, the Technological Innovation Systems approach is often used. To incorporate the role of external factors as well as regional differences on technological development on a national scale, this research compares the contextual structures of the regions of the Northern Netherlands and Rotterdam-Moerdijk. The findings show that both regions have specific context conditions that influence the national green hydrogen Technological Innovation System in the Netherlands. The Northern Netherlands' existing natural gas infrastructure, proactive regional governments and geographical characteristics mean that initiatives along the entire green hydrogen value chain are developed. In Rotterdam-Moerdijk, large industrial actors, existing infrastructure and economic connections with other regions make it suitable for initial market creation and an important future green hydrogen transit region. Based on these findings, it is recommended that the influence of regional contextual structures on national technological innovation systems is strongly considered, both in academics and in policymaking.

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1. Introduction

Global energy-related CO_2 emissions reached 33 metric gigatons (Gt) in 2021 (IEA, 2021b). This is problematic as greenhouse gases such as CO_2 are a cause of climate change (IPCC, 2021). A growing global energy demand makes decarbonization of energy production even more essential to reduce greenhouse gas emissions (IEA, 2021b).

By emitting over 13 Gt of CO_2 in 2020, electricity production and heating are the largest source of energy-related CO_2 emissions, substantially more than the roughly 7 Gt resulting from transport, for example (IEA, 2021b). Renewable energy production is therefore essential in reducing greenhouse gas emissions. The share of global renewable electricity production grew by 8% in 2021, of which two-thirds can be attributed to a rise in solar and wind energy production (IEA, 2021a). A potential downside of these technologies is the intermittency of their production. Sunny and windy days may cause production to exceed consumption, while the opposite might be true for cloudy and windless days. To balance supply and demand, energy storage is needed but existing technologies are not deemed sufficient yet and require further development (Notton et al., 2018). Reduction of GHG emissions will not be achieved solely by decarbonizing electricity generation. Other high-emission activities, such as fertiliser or steel production and heavy-duty transport, require different solutions (Ericsson, 2017).

For many of the problems stated above, hydrogen is suggested as a potential solution. Hydrogen can be applied as fuel, as an energy carrier and as a chemical feedstock in industrial processes (Ishaq, Dincer & Crawford, 2022; Fan et al., 2021). However, most hydrogen is currently used as a chemical feedstock and produced from fossil fuels resulting in almost 900 Mt of CO_2 emissions in 2020 (IEA, 2021c). These fossil-fuel based forms of hydrogen production are known as grey hydrogen. To avoid GHG emissions, carbon capture and storage can be added to the production process. It is then referred to as blue hydrogen. To avoid the creation of the GHGs in production, green hydrogen is proposed as a solution.

Green hydrogen is produced from water using renewable electricity in a process called electrolysis (IEA, 2019). Using an electrolyser, water is split into hydrogen and oxygen. Currently, there are three main technologies for electrolysis: alkaline electrolysis, proton exchange membrane (PEM) electrolysis and solid oxide electrolysis cells (SOECs). These technologies differ in maturity, adoption, and costs (IEA, 2019). Current use of electrolysis is very limited and the production cost is significantly higher than its fossil fuel based counterpart (Nicita et al., 2020).

Increase in production is to be expected as national and international governmental bodies embrace green hydrogen as part of the energy transition. The EU, for example, has announced a hydrogen strategy to develop and scale-up the production of green hydrogen, aiming for at least 40 gigawatts (GW) of electrolysis capacity in 2030 (European Commission, 2020; European Commission, 2022). For reference, global electrolysis capacity in 2020 was only 300 megawatts (MW), less than 1% of the EU's 2030 goal (IEA, 2021d). Likewise, the

Dutch government aims to stimulate green hydrogen development and has released a national hydrogen strategy (Government of the Netherlands, 2020). These strategies, along with an already increasing number of green hydrogen projects, mean that momentum for the development of green hydrogen seems to be increasing (Topsector Energie, 2022).

The development of a technology, such as green hydrogen, has been studied using the theory of innovation systems, which assumes that innovation is dependent on the system in which it develops (Edquist, 1997; Manley, 2002; Nelson, 1993). A specific theory, Technological Innovation System (TIS), is used to understand the innovation system of a specific technology, such as green hydrogen (Bergek et al., 2008; Hekkert et al., 2007). Studies that have taken this approach as a basis have often chosen to analyse TISs on a national level, as a result of the importance of national institutions on technology development and driven by the ambition to contribute to national policy development (Wieczorek et al., 2015). Regional factors, however, can have a strong impact on the development of a technology (Rohe, 2020; Rohe & Chlebna, 2021; Rohe & Mattes, 2022). Regional legislation and market development, for example, have been considered as important drivers for early-stage technology development (Rohe and Mattes, 2022; Losacker & Liefner, 2020). Furthermore, there are external factors that influence a TIS, but are often not captured by a conventional TIS analysis (Bergek et al., 2008, 2015; Markard et al., 2015). External factors, in this situation, refer to factors that are external to the framework of the TIS, rather than being geographically or physically external. Factors can be geographically internal to a TIS but remain unrecognised by the TIS framework. Existing technologies and infrastructure within the geographical boundaries of a TIS, for example, can have a positive or negative impact on a TIS. To capture these contextual structures, the TIS-in-context framework is used (Bergek et al., 2008, 2015; Markard et al., 2015). Scholars have researched and compared these contextual structures and their effects on TISs on a national level (de Oliveira & Negro, 2019; van der Loos et al., 2021). However, while contextual structures can be region-specific, there have not been analyses that compared the influence of regional contextual structures within, and on, a national TIS. This research therefore aims to fill this gap by first performing an analysis of the national TIS, and subsequently comparing the contextual structures of green hydrogen in two regions to investigate the influence of these structures on the national green hydrogen TIS in the Netherlands. Regions, as used in this research, are also referred to as industrial clusters. The Netherlands has 5 main industrial clusters: Rotterdam-Moerdijk, North Sea Channel region, Chemelot, Zeeland and Northern Netherlands (Klimaatakkoord, 2020; Programma Verduurzaming Industrie, n.d.). For this research, the regions of Northern Netherlands and the Rotterdam-Moerdijk have been chosen since a large share of green hydrogen initiatives in the Netherlands is concentrated in these areas (Topsector Energie, 2021; RVO, 2021). At the same time, the regions have very different characteristics that might influence green hydrogen development. Rotterdam-Moerdijk houses Europe's largest seaport, is a consumer of grey hydrogen and a fossil-based energy hub (Port of Rotterdam, 2022; Port of Rotterdam 2020). The green hydrogen conditions in the Northern-Netherlands are shaped by its history of natural gas production and geological characteristics, such as salt caverns suitable for hydrogen storage (TNO, 2018; van Wijk, 2017). Considering the regions' different conditions and plans, it is important to understand how the regions and their context conditions can influence the development of green hydrogen in the Netherlands as a whole. Furthermore, the areas have very different characteristics and histories, making them suitable for comparison.

To achieve the research aim, the following research question was composed:

How do regional context conditions influence the emergence of the green hydrogen technological innovation system in the Netherlands?

The research uses semi-structured expert interviews as the main source of data. This source is complemented by academic literature and professional and public reports. The interviewees represent different stakeholders in the green hydrogen TIS that can range from enterprises of different sizes to networking organisations and government agencies.

By analysing the presence of regional contextual structures and their effects on the Dutch green hydrogen TIS, this research has both academic and societal relevance. Firstly, by investigating the influence of the contextual structures of two regions on a TIS, this research can expand the innovation systems literature. A better understanding of these contextual structures allows researchers to analyse how technological innovation systems develop more accurately.

From a social perspective, the analysis can help policymakers create effective policy, and businesses to make decisions on where and how to invest in green hydrogen, thereby adding to the development of hydrogen and thus the energy transition in the Netherlands. Since a rapid and successful energy transition is necessary to avoid further climate change, understanding how technological innovations such as green hydrogen can be developed is of great societal relevance.

2. Theory

2.1. Innovation Systems

Innovation has been defined in a broad way as 'new creations of economic significance' (Edquist, 1997, p. 3). Before the 1980s, innovation was generally considered to be a linear process (Manley, 2002). The science-push model and demand-pull model were used to explain this process, arguing that science and demand were drivers of research and development, resulting in the creation of new products and processes (Edquist, 1997; Mowery & Rosenberg, 1979). However, an increasing acknowledgement of the complexity of the innovation process led to the appearance of the innovation systems approach (Edquist, 1997; Manley, 2002; Nelson, 1993).

An innovation system has been defined as 'a heuristic attempt, developed to analyse all societal subsystems, actors, and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation' (Hekkert et al., 2007, p. 414). The theory is used to understand the influence of the system in which the development of an innovation occurs. Understanding the innovation system can help to influence the speed and direction of the innovation development, which can be important since innovation can lead to both economic and societal benefits as well as negative externalities (Hekkert et al., 2007). An innovation system consists of structural elements, specifically actors (e.g., private, or public parties, knowledge institutes, or NGOs), institutions (e.g., rules, regulations, norms or traditions), interactions (e.g., networks or social relationships) and infrastructure (in physical, knowledge or financial form) (Wieczorek & Hekkert, 2012). These elements often do not operate in coordination towards a shared goal. Instead, there are often tensions between different elements. The innovation system concept is used to understand the performance of the components that influence an innovation (Bergek et al., 2008).

Scholars have discussed several different perspectives of innovation systems. Examples are national innovation systems (Freeman, 2004; Godin, 2009; Lundvall, 2007), regional innovation systems (B. T. Asheim & Isaksen, 1997; Cooke et al., 1997) and sectoral innovation systems (Kubeczko et al., 2006; Malerba, 2002).

Innovation systems theories have been criticised for being unable to identify the dynamics of the innovation system (Bergek et al., 2008). Due to the dynamic nature of technological change, research into the process requires investigating the activities and interactions occurring in the innovation system (Hekkert et al., 2007).

2.2. Technological Innovation Systems

A fourth approach to innovation systems, technological innovation systems (TIS), aims to analyse a specific technology. A TIS can be defined as a system of actors, networks and institutions that contribute to the development and diffusion of a particular technology (Carlsson et al., 2002; Carlsson & Stankiewicz, 1991). The TIS theory studies the development and diffusion of a technology and can help to find barriers and institutional issues (Bergek et al., 2008). The theory is a popular approach in efforts to analyse the development of renewable energy technologies (Andersen, 2014; Andreasen & Sovacool, 2015; Tigabu et al., 2015).

As discussed in the previous section, structural elements are actors, institutions, interactions, and infrastructure. Furthermore, a TIS framework includes investigating the functioning of the system. The functioning of the system depends on key processes of the system, also known as the functions. These functions are dependent on the structural elements of the system and often interact, causing feedback loops (Bergek et al., 2008; Hekkert et al., 2007). An analysis of a TIS can highlight which processes are the cause for potential failure of the system and should be the focus of subsequent policy goals (Bergek et al., 2008). A TIS generally has seven functions as described in table 1 (Hekkert et al., 2007). These functions influence each other and can cause positive and negative feedback loops through their interactions.

Function	Description
F1 entrepreneurial activity	Activity of private actors related to the technology. Examples are new entrants to the technology, diversification activities of incumbent actors, experiments with the new technology.
F2 Knowledge development	Knowledge can be developed through 'learning by searching', in research institutes or R&D departments, or through 'learning by doing' in commercial activities.
F3 Knowledge diffusion through networks	Networks can exchange information. Interactions of actors can lead to 'learning by interacting' when actors collaborate, or 'learning by using' when users and producers interact.
F4 Guidance of the search	The focus of the government, industry, and market efforts to develop and diffuse the new technology.
F5 market formation	The formation of niche markets or comparative advantages to create a favourable market for the new technology.
F6 resources mobilisation	The allocation of financial and human resources, such as funds for research and testing, to the new technology.
F7 creation of legitimacy/counteract resistance to change	Acceptance of the new technology by private, public, and civil society actors. Actors can either resist or advocate the change by creating groups to lobby.

Table 1. Description of the seven TIS functions (Hekkert et al., 2007).

2.3. Regional aspects of technological innovation systems

While TIS analyses can be successful at investigating the development and diffusion of technologies, they are often conducted at the national level. Although TISs are global systems, research often focuses on the national level because of the large role that national institutions play in the development of a novel technology (Coenen, 2015; Wieczorek et al., 2015). However, regional particularities can often have a clear impact on the innovation system. These regional particularities are not always fully captured by the TIS. One alternative to TIS is the regional innovation systems (RIS) theory since it has a more regional focus. However, the RIS theory is not suitable for this research as it is used to study 'the institutional infrastructure supporting innovation within the productive structure of a region' (Asheim, 2008, p. 229). A RIS thus does not analyse a specific technology, but a region's ability to stimulate innovation in general.

Rohe and Mattes (2022) highlight two areas where regional factors can be crucial for a TIS. Firstly, regional factors can strongly influence knowledge creation. Certain types of knowledge, such as local customs and people, can increase chances of successful development of wind farms, for example. The second area is market formation. Especially in the early phase of a technology, but possibly in more mature stages as well, regional regulations, demand and technologies can play a large role in the development of a technology (Losacker & Liefner, 2020). Another factor dependent on regional context is legitimation (Mattes et al., 2014; Rohe, 2020). Legitimacy is an important function within TIS and sometimes overlooked. More particularly, the role regional decision makers play in legitimation of a technology is undervalued (Rohe & Chlebna, 2021).

Increased attention to regional factors can thus help make policy decisions that are more successful at development and diffusion of technological innovations (Rohe & Chlebna, 2021).

2.4. Technological innovation systems in context

Scholars have acknowledged shortcomings in the conventional TIS analysis (Bergek et al., 2008; Markard et al., 2015). Bergek et al. (2015) state that, while setting system boundaries is necessary for a TIS analysis, there are external factors that influence and interact with the innovation, also known as context structures. Conventional TIS analyses are therefore at risk of attributing too much weight to the functioning of the innovation system while partly ignoring the influence of the external factors. It is important to note here that external refers to the framework boundaries of a TIS, rather than the geographical or physical boundaries. Factors can be geographically internal to the TIS, while being external to the TIS framework. In this way, context structures can exist within the geographical boundaries of the studied TIS but be overlooked by a conventional TIS analysis. To incorporate the influence of context structures on the innovation system, an increasing number of publications use a TIS-in-context approach (de Oliveira & Negro, 2019; Hanson, 2017; van der Loos et al., 2021).

Bergek et al. (2015) highlight four context structures: technological, sectoral, geographical, and political.

The technological context structure encompasses other technological innovations systems, also referred to as TIS-TIS context. These technologies can both compete or enhance the selected TIS (Bergek et al., 2015). A technology can help another develop, for example if the legitimacy gained by a clean technology enables other clean technologies to be seen as legitimate as well. However, if technologies start to compete for limited resources, they might hinder each other's development. Two technologies that both require highly educated technicians, of which there is a limited supply, could be hindered in their growth due to this limited resource, for example. Since a TIS can thus be influenced by other TISs, it is important to take the TIS-TIS context into account (Bergek et al., 2015).

Sectoral industrial structures are existing firms, assets and infrastructure that can enable or hinder development of a technology (Mäkitie et al., 2018; Hanson, 2017). A positive interaction can occur in case the new technology can make use of existing resources or infrastructure. When the new technology competes with limited resources that are already in use by another sector, however, the sectoral context can be a limiting factor to development (Bergek et al., 2015). An example can be found in electric vehicle technology development. Charging infrastructure, incumbent car manufacturers and battery technology development are all sectoral context factors that heavily influence the development of electric vehicles. Taking these into account in the analysis of a TIS is therefore essential (Dong et al., 2020; Wesseling et al., 2015).

The third context structure relates to the impact of the specific conditions of the geographical location of the TIS (Bergek et al., 2015). The development of a TIS in a certain geographic location is strongly dependent on the context of the area. A country's institutions, for example, can create a favourable environment for the new technology. Similarly, the economic conditions under which the new technology must develop can allow benefits for emerging technologies. Influences do not only come from national conditions, though. In the same way that a TIS influences other TISs, a TIS in a certain geographical area is also influenced by international as well as regional conditions (Coenen et al., 2012).

Finally, the political context often strongly influences the development of the innovation system. The development of sustainable technologies is more likely when the energy transition is an important topic for many voters. Political support for a TIS can lead to increased availability of funds and increased legitimacy (Bergek et al., 2015).

These four contextual structures often overlap and interact with each other, and while a TIS is influenced by its contextual structures, the contextual structures are also impacted by a TIS.

2.5. Regional technological innovation systems in context

As discussed in the previous section, a TIS-in-context attempts to capture the influence of external factors on a technological innovation. It allows for comparison of context conditions between geographic areas and periods of time.

However, as discussed in section 2.3., there are often regional aspects that are overlooked in a TIS analysis. Crucial factors, such as market formation and legitimacy, can be heavily dependent on regional aspects. In turn, these regional factors are subject to influence from contextual structures. The political context on a regional level, for example, can impact regional availability of funds and legitimacy. Existing industries in a region can have a large impact on the development of a new technology as well, since it can hinder or stimulate new local initiatives. It is therefore important to investigate how regional contextual structures influence a TIS on a regional level. Once these regional influences are clear, the effects of the regional context structures on national TIS development can be investigated.

Analysis of the influence of regional contextual structures can be especially interesting when different regions are compared. Potentially, such an analysis provides insights into why the emergence of a technology has been more successful in one region than the other. These insights can then be used to determine instruments that can stimulate the development of the technology in other regions too, ultimately contributing to the development of the TIS on national or global levels.

While scholars have compared TISs and their context conditions in different nations and over time (de Oliveira & Negro, 2019; van der Loos et al., 2021), comparing context conditions between regions within a nation is unprecedented. This research thus contributes to the literature on TIS, TIS-in-context and geographical and regional aspects of these theories.

3. Methodology

Building on the theory discussed in the previous section, this section discusses the research design, data collection, and data measurement.

3.1. Research Design

This research aims to investigate the Dutch green hydrogen TIS and the effects of contextual structures of two regions on the national TIS. To do so, the structures of the green hydrogen TIS on the national level will be mapped, complemented by an analysis of the contextual structures of the two regions and their respective influence on the national TIS. This approach is shown in figure 1.

The framework is based on work by de Oliveira & Negro (2019), where an adapted version of the framework by Wieczorek & Hekkert (2012) was used. The framework is adapted to be able to make a comparison between the two regions.

In step 1, the structural dimensions of the nationally delineated TIS are researched, to gain a general understanding of the Dutch green hydrogen TIS. Step 2 consists of mapping the contextual structures for both regions and investigating the effects of the development of green hydrogen. Finally, in step 3, the effects of the contextual structures are compared between the regions, as well as their potential influence on the national TIS. This will reveal which regional contextual structures are most influential for development of the green hydrogen technology in the Netherlands.

While the focus of the analysis is on the contextual structures and their effects, mapping the structural dimensions of the national TIS (step 1) is important for the latter steps. Ultimately, to establish how regional context structures affect a national TIS, one must have an understanding of the national TIS. Each step is described in section 3.3.

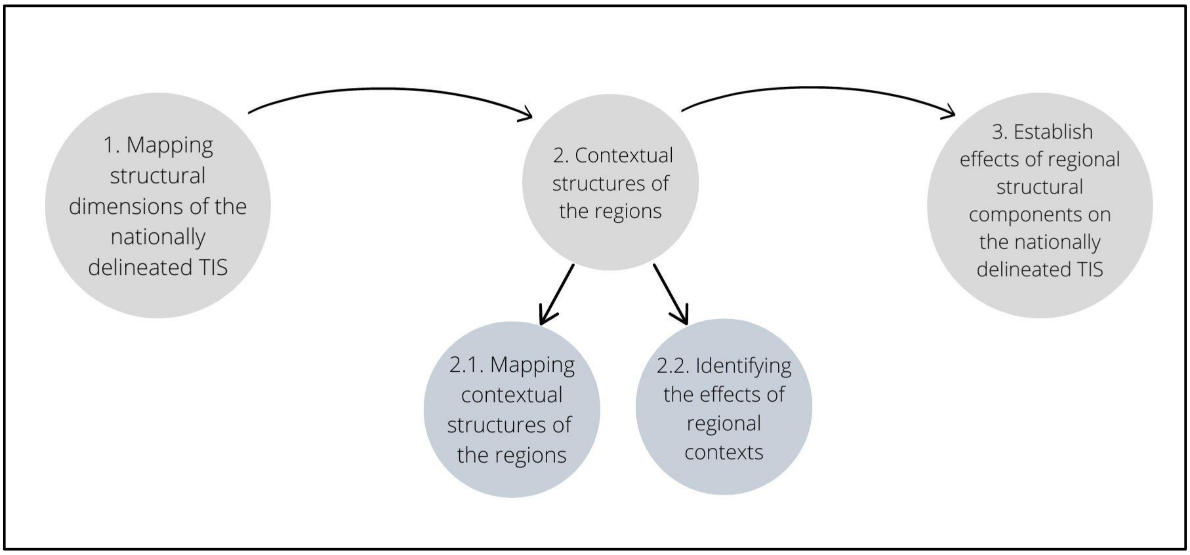

Figure 1. Research steps.

3.2. Data collection

The required data is mainly sourced from semi-structured expert interviews, complemented by academic literature and professional and public reports. Scientific literature is found using Scopus and Google Scholar, while grey literature is found using the Google search engine.

Preparation of the interviews consisted of finding and contacting interviewees and the creation of an interview guide (appendix A). Purposive sampling was used to find interviewees that represent key stakeholders in the Dutch green hydrogen TIS. While conducting interviews, the interviewees are asked to recommend additional interviewees, a strategy known as snowballing sampling (Bryman, 2012). In total, 15 interviews were conducted. To be able to map the contextual structures of the regions, most interviewees were expected to have region-specific knowledge. The interviewees are representatives of businesses of different sizes, networking organisations, knowledge institutes, and government agencies. In two instances, government representatives recently changed positions. However, both are still active in the Dutch green hydrogen environment and were able to provide insight into the regional aspects and the influence on regional development. Table 2 provides an overview of the interviewees and the sectors they represent. Given the variety of the interviewees, some questions were more applicable to some interviewees than to others. Several interviewees had specific knowledge on one region, while being less informed on the other region or factors on the national level. These interviews are still valuable to the research since they provide information on region-specific factors. Interview guides followed a general outline but were adapted per interviewee, based on their backgrounds. Interview questions are based on previous TIS (-in-context) analyses (Bergek et al., 2008; de Oliveira & Negro, 2019; Hekkert et al., 2011; Hekkert et al., 2007) and designed to match the outline of this research. All interviews were held online and in Dutch. When quotes were extracted from the interviews, these were translated from Dutch to English. An overview of the original Dutch quotes can be found in Appendix B.

The interviewees were asked permission to have the audio recorded and transcribed. The interviewees were also asked to fill out the informed consent form to allow the data from the interview to be used in this research. Here, interviewees can also indicate to what extent their details can be disclosed. Information retrieved from the interviews is anonymized. For example, an interviewee can be referred to as ‘government official 1’. Interview data is stored on the researcher’s private online storage.

The interviews are coded using NVIVO to attribute remarks by interviewees to characteristics such as the TIS functions, the presence or absence of contextual structures, and the impact of contextual structures on TIS functioning.

NUMBER	ORGANISATION TYPE	IN-TEXT ABBREVIATION
1	Government - National	G1
2	Government - Regional	G2
3	Government - Regional	G3
4	Business - Large company	B1
5	Business - Large company	B2
6	Business - Large company	B3
7	Business - Large company	B4
8	Business - Large company	B5
9	Business - SME	B6
10	Knowledge institute	K1
11	Knowledge institute	K2
12	Knowledge institute	K3
13	Network organisation	N1
14	Network organisation	N2
15	Network organisation	N3

Table 2. Overview of interviewees.

3.3. Data measurement

As explained in section 3.1, the analysis of the TIS and its contextual structures includes several stages. This section will explain for each stage how the collected data will be collected to be able to draw conclusions.

3.3.1. Mapping of the nationally delineated TIS

As described in section 2.2, in conventional TIS analyses, analysing the structural elements and the functions is the main focus of the research. In this research, however, the focus lies on the regional context structures and their impact on the national TIS. Therefore, only a basic understanding of the structural elements and functioning of the national TIS is needed. This stage of the analysis is conducted by first mapping structural elements of the nationally delineated TIS: actors, institutions, interactions, and infrastructure (Wieczorek & Hekkert, 2012). By consulting academic and grey literature, the structural elements were mapped before the expert interviews were conducted. Next to the structural elements found in the literature, however, interviewees were also able to provide additional elements. For example, some interviewees possessed specific knowledge on the development of regulation that was not found in the literature yet. Having a clear image of the structural components in advance of the interviews also allowed for more region-specific interview questions. To understand the basic functioning of the structural elements that were mapped, grey literature was used, and interviewees were also asked for several key processes in the green hydrogen national TIS. To ultimately determine the effect of regional context structures, it is important to have this understanding. Findings from (grey) literature and a few interview questions suffice to create this basic understanding. The questions followed the TIS functions as described by Hekkert et al (2007), an overview of the functions and example questions is provided in table 3. An interview question on function 2, knowledge development, for example, could have been: 'which parties are responsible for innovation in green hydrogen and in which part of the value chain are innovations currently most needed?'. These interview questions are based on the indicators and previous analyses of functions in TIS research (Bergek et al., 2008; de Oliveira & Negro, 2019; Hekkert et al., 2011; Hekkert et al., 2007). Discussing the structural elements and basic functioning on the national level in interviews was kept brief to allow focus on the regional context structures.

Function	**Example question**
F1 entrepreneurial activity	How have green hydrogen initiatives and plans developed in recent years? Do you see many new parties entering the industry?
F2 Knowledge development	Which parties are responsible for innovation in green hydrogen and in which part of the value chain are innovations currently most needed?
F3 Knowledge diffusion through networks	How is new knowledge distributed, and do you find diffusion is sufficient for further development of green hydrogen?
F4 Guidance of the search	What role has government policy played for the development of green hydrogen, and is current policy aligned with business agendas in the green hydrogen industry?
F5 market formation	How is demand for green hydrogen developing? Do you think this is sufficient for further development of green hydrogen supply?
F6 resources mobilisation	Do important players in the green hydrogen industry have sufficient access to physical, human, and financial resources? If not, how does this hinder green hydrogen development?
F7 creation of legitimacy/counteract resistance to change	How, in your opinion, is green hydrogen perceived by the general public? Do you expect that resistance to green hydrogen initiatives can be a limiting factor to development?

Table 3. The seven system functions and example questions (Hekkert et al., 2007; Negro & Hekkert, 2008).

3.3.2.1. Mapping contextual structures of the regions

After identifying the structural elements and basic functioning of the nationally delineated TIS, the contextual structures for both regions were sourced from the interviews. Before conducting the interviews, research using academic and grey literature provided an idea of the contextual structures in both regions. The interviewees were asked for their view on the technological, sectoral, geographical, and political context of green hydrogen in each region. Table 4 shows indicators for the presence of context structures. Interviewees were asked to explain in what shape or form the context structure is present.

To research the sectoral context structures, for example, interviewees were asked about the presence of existing infrastructure in the Northern Netherlands region. Some interviewees did not have specific knowledge on certain context structures, or on one of the regions. In that case, interviewees indicated that they did not know. Next to the interviews, these insights were also gathered from academic and grey literature.

Context structure	**Indicator**
Technological	The presence of other related technologies that influence the development of green hydrogen activities in the region.
Sectoral	The presence of existing firms, assets and infrastructure that can interact with green hydrogen activities in the region.
Geographical	The presence of geographic characteristics that can influence development of green hydrogen activities in the region, such as neighbouring countries or regions that support a green hydrogen market or favourable environmental conditions.
Political	The presence of political interest in green hydrogen activities or areas that affect green hydrogen activities in the region.

Table 4. Context structures and indicators (Bergek et al., 2015).

3.3.2.2. Identifying the effects of regional contextual structures

Once the contextual structures of the regions were discovered, interviewees were requested to explain how the regional contextual structures affect development of green hydrogen activities in the regions. Table 5 and the interview guide show example questions for each contextual structure. In this part of the interview, there was a lot of room for discussion, since answering these questions requires specific knowledge. When interviewing a regional government official, for example, it is interesting to dive deeper into the political context structure. Interviewees were also asked how differences between the regions could impact green hydrogen development on the national level.

Context structure	**Example questions**
Technological	How do the identified related technologies affect the development of green hydrogen initiatives in [region]?
Sectoral	What is the impact of these existing firms, assets and infrastructure that can interact with green hydrogen activities in [region]?
Geographical	What is the effect of the geographical characteristics identified in the previous question on development of green hydrogen activities in [region]?
Political	What is the influence of the presence/absence of political interest on development of green hydrogen activities in [region]?

Table 5. Context structures and example questions.

3.3.3. Comparison of regional context effects on the nationally delineated TIS

Once the effects of the contextual structures in each region had been identified, it was possible to highlight the differences. After listing all effects for both regions, commonalities and differences became clear. Firstly, this provided valuable insights since it made clear if and how regions can develop using their own characteristics. Secondly, together with the direct answers from interviewees on how the region's different development paths impact the national green hydrogen TIS, this made it possible to determine the influence of region's context conditions on the national TIS. These insights were then compared to the findings of the basic functioning of the national TIS as discussed in section 3.1.1. This ultimately made it possible to answer the research question.

4. Results

4.1. The nationally delineated TIS

Hydrogen technology is not new. As described in the introduction, the global hydrogen industry is a well-developed one (IEA, 2021c). This leads to extensive experience in handling hydrogen. Green hydrogen, however, is only produced on a small scale compared to the grey hydrogen industry and compared to the volumes for green hydrogen that are suggested in, for example, EU plans for the coming years (European Commission, 2020; European Commission, 2022). Green hydrogen technology therefore has large challenges in upscaling ahead.

Following the Dutch National Hydrogen Programme, the hydrogen value chain can be divided into three stages. The first is production and import, then there's domestic transport and storage, and finally use and export (Nationaal Waterstof Programma, 2021).

Production of green hydrogen starts with renewable electricity as the basis for electrolysis. For the Netherlands, that will mean mostly offshore wind energy, as captured in the National Climate Agreement (Rijksoverheid, 2019). Recently, plans for offshore wind were doubled to a capacity of at least 21 gigawatts (GW) in 2030, equal to approximately 75% of the current Dutch electricity use (Rijksoverheid, 2022). Further growth may amount up to 70 GW in 2050 (Rijksoverheid, 2022). Major players in this part of the value chain are large utilities and energy companies such as Eneco, Shell, Ørsted, van Oord and Siemens. TenneT is the grid operator and responsible for connecting offshore windparks to the mainland.

Once renewable electricity is generated, it is used for electrolysis to split water into hydrogen and oxygen. The target set for electrolyser capacity by the Dutch government is at least 3-4 GW by 2030 (Rijksoverheid, 2022). Recently, there have been announcements of initiatives for green hydrogen production. These initiatives mainly come from major energy companies such as Shell, BP, Vattenfall, Engie and Uniper, in cooperation with large hydrogen consumers such as Air Liquide and Yara and consortia such as HyCC (Nationaal Waterstof Programma, 2022; Topsector Energie, 2022).

Considering the limited amount of free space and environmental conditions of the Netherlands, imports from other international regions, better suited for hydrogen production, is expected to be necessary (Rijksoverheid, 2021; Port of Rotterdam, 2020; van Wijk & Hellinga, 2018). Additionally, neighbouring countries are counting on importing green hydrogen through Dutch ports. This is further stimulated by European plans to import half of Europe's green hydrogen use by 2030 (European Commission, 2022). Important actors for this import are Port authorities, Gasunie, which is responsible for the Dutch gas infrastructure, and companies such as Vopak and HES international (Topsector Energie, 2022).

The next step in the green hydrogen value chain is transport and storage. A reason often named for development of green hydrogen activities in the Netherlands is the extensive existing natural gas transport infrastructure connecting domestic parties as well as neighbouring countries (Nationaal Waterstof Programma, 2021). A large share of these pipelines can be refitted for hydrogen transport, reducing the investment needed to adopt green hydrogen on a large scale (PwC, 2021). GasUnie is the Dutch gas network operator and is involved in most infrastructure projects. Transport infrastructure projects will aim to connect large industrial clusters, such as Rotterdam, Zeeland, and Northern Netherlands, as well as more local users and large industrial areas across the border, such as the Ruhr-area (Nationaal Waterstof Programma, 2021). Next to Gasunie, there is an important role to play for the national and regional governments in creating the legislation needed for hydrogen pipeline construction and use, and for the industrial clusters. The Delta Corridor for example, is a pipeline project connecting the Rotterdam-Moerdijk cluster with the Chemelot cluster and the German North Rhine-Westphalia area. This project is initiated by the Port of Rotterdam and Chemelot cluster along with industrial partners, showing that initiative can come from these parties as well.

Both a challenge and an opportunity of green hydrogen production is that production volumes will vary over time, since production is connected to offshore wind electricity production. If green hydrogen is to fulfil a role in balancing the electricity network, storage capacity is crucial (Nationaal Waterstof Programma, 2021; PwC, 2021). In the short term, the majority of initiatives is aimed at storage in salt caverns in the Northern Netherlands, where pilots are conducted by Gasunie. Salt caverns and abandoned natural gas fields below the North Sea are also considered for future storage (Nationaal Waterstof Programma, 2021).

In the final stage of the value chain, green hydrogen is either used or exported. In the use phase, green hydrogen can be applied in various ways (Ishaq, Dincer & Crawford, 2022; Fan et al., 2021). Since green hydrogen supply will be limited in the foreseeable future and some heavy industry processes are unlikely to be electrified, this is where most green hydrogen use will occur initially (Nationaal Waterstof Programma, 2021). Firstly, grey hydrogen can be replaced by green hydrogen. An example can be found in Shell's plans for Holland Hydrogen 1 in the Port of Rotterdam, a green hydrogen production facility that will replace some of Shell's grey hydrogen use in its refineries in Pernis. In Zeeland, Yara aims to replace grey hydrogen in its fertiliser plant (Topsector Energie, 2022). Aside from the replacement of grey hydrogen use, green hydrogen can also be used for industrial processes that currently run directly on fossil fuels. This is what TATA Steel aims to do in cooperation with the Port of Amsterdam and HyCC. By replacing fossil fuel use in the steel production process with green hydrogen, it aims to reduce its carbon footprint (Topsector Energie, 2022).

Although a large share of initial hydrogen supply might be used for the heavy industry, there are plenty of other initiatives too. In the mobility sector, for example, there are plans for hydrogen buses in multiple provinces, plans for hydrogen inland shipping vessels and trains (Topsector Energie, 2022; Nationaal Waterstof Programma 2021). In the built environment, multiple projects are in progress to use green hydrogen as a substitute of natural gas in heating. Plans and pilot projects are underway in different municipalities (Topsector Energie, 2022).

Finally, a share of hydrogen supply, produced and imported, will be exported. According to the Dutch National Hydrogen Programme (2021), Germany has indicated it aims to import large volumes of green hydrogen as soon as 2030. As described in the transport and storage section, the existing natural gas network will play an important role in transporting produced and imported natural gas to neighbouring countries. The most important player here is GasUnie.

Several actors are of importance throughout the entire green hydrogen value chain. The ministry responsible for Dutch environmental and energy policy is that of Economic Affairs and Climate Policy (MINEZK). This body has been, and is, essential in the creation of legislature, regulation and in providing funding for pilot projects. In some cases, it will cooperate with the Ministry of Infrastructure and Water Management (MINIenW).

4.2. Regional contextual structures and their effects

After describing the structure of the nationally delineated TIS for green hydrogen in the Netherlands, this section investigates the regional characteristics that shape the green hydrogen TIS in the Northern Netherlands and Rotterdam-Moerdijk. This is done per region, by first describing the present context conditions and subsequently determining the effect of these conditions on the national development of green hydrogen.

4.2.1. Northern Netherlands

4.2.1.1. Technological context conditions

An important technological context condition in the Northern Netherlands is renewable electricity. As discussed in section 4.1, electrolysis for green hydrogen production requires renewable electricity. As multiple interviewees have mentioned, the past years have seen a sharp increase in renewable electricity production while its price declined sharply (B1, K1, K2). The interviewees found this to be an important development, as a low price for this green hydrogen production factor brings down green hydrogen production costs, making its business case more attractive (B1, K1, K2). This required renewable electricity is expected to originate mostly from offshore wind energy (Klimaatakkoord, 2020).

Sufficient availability and low prices do not, however, automatically lead to ideal circumstances for large-scale electrolysis. A network organisation noted that one of the important promises of green hydrogen use is to prevent further strain on the overstretched Dutch electricity grid, for which extensions are very costly (N1). Therefore, it is most efficient to connect large-scale electrolysers directly to local or regional renewable electricity sources.

The Dutch government assigned areas off the coast of the Northern Netherlands to be developed into offshore wind farms. Although there currently is one offshore wind farm, Gemini, its 600MW capacity is insufficient for planned large-scale electrolysis initiatives and dwarfed by the 4,7 GW capacity that the future offshore wind farms in this area are expected to produce (Rijksoverheid, 2022). This regional development of large-scale renewable electricity was regarded by multiple interviewees as a positive influence on green hydrogen development in the Northern Netherlands as it can be used to power large-scale electrolysis (K2, B3, B5, N1).

Development of these wind parks will take several years, however. In the meantime, as multiple interviewees noted, the existing international electricity cables that come ashore in Eemshaven could provide a solution (B5, K2, N2). These are existing connections between the Netherlands and Norway, and the Netherlands and Denmark, in the form of the power cables NorNed and COBRA. These cables can supply electrolysers in the Northern Netherlands with renewable electricity immediately, while renewable electricity from other sources is still under development (van Wijk, 2017).

This regional context condition has an impact on the national green hydrogen TIS. It shows that sufficient regional availability of renewable electricity is necessary to develop large-scale green hydrogen production. If this factor is not taken into account in deciding how and where renewable electricity production is developed, green hydrogen production will be hindered. The availability of renewable electricity from international power cables and future large-scale offshore wind parks mean that the Northern Netherlands can become a contributor to Dutch green hydrogen production.

4.2.1.2. Sectoral context conditions

The most prominent regional context condition for the Northern Netherlands is its history in natural gas production. In the sectoral context, this means that a large amount of natural gas related infrastructure, business and knowledge is present in the region. With reducing and eventually disappearing production of natural gas, these assets become available for different use. This is relevant for development of green hydrogen activities since there are many similarities with natural gas. Existing natural gas pipelines only need minor adjustments to be suitable for hydrogen transportation, although some interviewees noted that the possibility of hydrogen leaks still must be investigated (B4, K1). Gasunie, the gas grid operator, was a frontrunner in the investigation of hydrogen development after realising that natural gas activities were declining (K2, N2). Additionally, there is a positive effect of the presence of knowledge-developing actors such as the university of Groningen and the Hanze university of applied sciences (B5). As a business actor noted:

> "Originally, there is a lot of natural gas infrastructure here because the natural gas was found here, of course. So, we can use that. The knowledge is available in the North, with knowledge institutes but Gasunie is here as well." (B5)

Another sectoral context condition is the presence of industrial actors in the Northern Netherlands. Multiple interviewees noted that the presence of chemical industries, mainly in the Eemshaven and Delfzijl ports, are important for green hydrogen development in this region as they can provide demand for green hydrogen for fuel and feedstock, thereby stimulating suppliers to develop green hydrogen production sites (B5, N3). These ports are united under Groningen Seaports, which is playing an active role in coordinating regional efforts in green hydrogen development, for example by being a frontrunner in HyNorth, a network organisation in the Northern Netherlands (B3, B5).

Next to chemical industry players, the ports house multiple large power plants. While these currently run on fossil fuels, a government actor explained that these parties are considering to (partly) switch to green hydrogen as a fuel (G1).

Linking these regional factors to the national green hydrogen TIS, the existing industrial actors are important in market formation for green hydrogen in the Northern Netherlands. However, multiple interviewees were critical of the impact these actors would have on the national level, as they are small in size, compared to other Dutch and European ports such as the Port of Rotterdam (B2, B3).

The impact of the existing natural gas pipeline infrastructure on national development is important too. With slight adjustments this infrastructure can become available for hydrogen use, greatly reducing the development cost and time of green hydrogen activities.

4.2.1.3. Geographical context conditions

There are several geographical context conditions that impact green hydrogen development in the Northern Netherlands.

Firstly, the region has many salt caverns, as well as empty natural gas fields. Many interviewees stated that the storage potential in the Northern Netherlands, specifically at Zuidwending, will play a crucial role in the development of green hydrogen activities (G3, B4, B5, K3, N1). The existing regional and national gas infrastructure, complemented by new hydrogen infrastructure, can make it possible to use these areas as storage locations to provide a balancing function for the Dutch hydrogen network. A business actor discussed this:

> "You can invest in storage in this way, and I'm calling this storage as in a salt cavern to be able to store larger quantities, and thus also be able to fulfil the balancing function of a system."(B4)

Although these projects for hydrogen storage are very promising, a knowledge institute representative stressed that the projects are still in the development phase:

> "Everyone is quick to say: we will store hydrogen underground. But there are only a handful of pilot projects. In salt caverns and gas fields. It has been shown to be possible. But it has to develop further. So the maturity is not sufficient yet, and especially for the gasfields."(K1)

The region's proximity to Northern Germany is another factor of influence. Northern Germany can develop in a future market for green hydrogen produced in or transported through the Northern Netherlands (van Wijk, 2017). Several interviewees regarded this future demand as an incentive for green hydrogen activities to be developed in the Northern Netherlands (B3, N2).

Finally, the region's access to the North Sea is an important feature. Not only due to the factors that were discussed earlier, such as landing offshore wind energy, international power cables and the presence of the Groningen Seaports, but also because this means that the region is included in discussions with the provinces of Zeeland, South-holland and North-holland to join forces as a North Sea region, after this region was appointed as one of the main hydrogen corridors in the recent RePowerEU plan (G3; European Commission, 2022).

The Northern Netherlands geographical context conditions will have a large impact on the national development of green hydrogen. Its salt caverns can provide an important balancing function between supply and demand for green hydrogen as well as the electricity grid.

4.2.1.4. Political context conditions

The fourth context condition concerns the political context in which a new technology develops. For the Northern Netherlands, this context condition has been very influential. Many interviewees regarded this as a key reason for the high number of green hydrogen related activities in the region (G3, B4, B5, B6, K1, K2, N1). The declining natural gas production means a significant share of economic activities will disappear. This has led to demand for new economic activity in the regions, for which green hydrogen seemed a suitable option. A networking organisation representative emphasised the impact of reduced natural gas activities on the region:

> "But because the government has said: we will reduce that [natural gas production] to zero, that also means that you have to look at, what are the consequences, economically? For the region this means that the regional economic product will decline by 8-10, or maybe more, percent. That is dramatic for a region, if you receive 12 percent less income."(N1)

This urgency has led to a strong political interest in development of green hydrogen initiatives and participation of regional and local governments in initiatives such as the New Energy Coalition. An interviewee explained that regional governments, for example the Province of Groningen, are involved in multiple ways (B5). The province provides permits but is also involved in the creation of infrastructure and expansion of the ports, for example. The Provinces of Groningen, Friesland and Drenthe also play a role in initiatives such as the NOM, an organisation aimed at stimulation of economic investments and development of the Northern Netherlands, including green hydrogen projects. Multiple interviewees stated that in this way, regional governments in the Northern Netherlands play a major role in attracting and developing green hydrogen initiatives (B5, B6, G1, K2).

This political interest is also shown on the national and European level. The national government has created the National Programme Groningen, and the European Just Transition Fund has allocated funds to help the Northern Netherlands in their transition from fossil fuels. A share of both funds is allocated to green hydrogen initiatives, a factor seen as crucial for green hydrogen development by several network organisations (N1, N2).

This involvement of regional and local governments has led to an approach to green hydrogen development, where the whole value chain is the target of development, and all stakeholders are included. This concept is known as a hydrogen valley:

> "The hydrogen valley is basically a defined area where all elements of the value chain are present: hydrogen production, logistics, start up usage in industry, mobility, the built environment. That is what we have achieved in the Northern Netherlands and that is why we have become the first hydrogen valley of Europe."(N1)

In interviews, this was regarded as one of the key characteristics of green hydrogen development in the Northern Netherlands (K2, K3, N2).

Development of green hydrogen as a result of these political context conditions can impact national development of green hydrogen strongly. The region's need for new economic activity as a result of diminishing natural gas activities leads policymakers to take an active role in developing a green hydrogen economy, resulting in many initiatives along the green hydrogen value chain. These initiatives create innovation and explore how green hydrogen can be implemented, not only in large-scale industrial use, but also in mobility and homes, for example. In order to develop the green hydrogen TIS on the national level, this experience will be valuable.

4.2.2. Rotterdam-Moerdijk

4.2.2.1. Technological context conditions

The large majority of offshore wind capacity to be developed in the coming years is assigned to the western coast of the Netherlands, where the Rotterdam-Moerdijk cluster is situated (Rijksoverheid, 2022). Part of this electricity will come ashore in the Port of Rotterdam, creating an opportunity for large-scale electrolysis. The importance of these plans is underscored by multiple interviewees (G1, K1, N1, N2).

Another related technology that might impact green hydrogen production in the Rotterdam-Moerdijk region is blue hydrogen. Blue hydrogen initiatives can have a positive impact on green hydrogen development, as it might help increase and mature the use of hydrogen in general, especially while sufficient renewable energy capacity is still under development (G3, B2). However, it is important to prevent lock-in. Initial demand for hydrogen might be large enough to justify both blue and green hydrogen, but blue hydrogen projects should be developed for this transition period only, and long-term vision should focus on green hydrogen. Otherwise, the two technologies might compete for available funds and infrastructure. This tension was explained by a government representative:

> "I get the idea that blue hydrogen is unavoidable in the transition phase. That you need it in the transition phase, but you have to be aware of lock-in. So you don't hold on to blue hydrogen until the end of time. So then you will have to say in advance: we will do this for x amount of years and we will stop after that and switch to green entirely."

Like the Northern Netherlands in section 4.2.1.1., regional availability of renewable electricity from offshore wind farms is an important enabler for large-scale green hydrogen in the Rotterdam-Moerdijk area and thus for development of the national green hydrogen TIS. Blue hydrogen initiatives have both enabling and hindering potential for the national green hydrogen TIS. Blue hydrogen can help to satisfy and develop short term hydrogen demand in a low-carbon manner while green hydrogen production is under development. Simultaneously, if blue hydrogen projects are developed without planning for a switch to green hydrogen, blue hydrogen can slow down development of the green hydrogen national TIS.

4.2.2.2. Sectoral context conditions

An influential factor for the development of green hydrogen in the Rotterdam-Moerdijk cluster is the existing use of grey hydrogen by industrial actors, for multiple reasons.
Firstly, this use can be easily replaced by green hydrogen, once available, creating demand for the first production initiatives as industrial actors are required by the EU to increasingly replace grey hydrogen with its green counterpart (European Commission, 2022). Several business actors regarded this EU legislation to be a strong enabling factor for green hydrogen development in the Rotterdam-Moerdijk area (B1, B2, B3, B5). As discussed in section 4.1, green hydrogen can be used, for example, in the refineries located in the Rotterdam-Moerdijk area.

> "In Rotterdam, of course there is, let's name the most obvious, Shell and BP, two very large refineries, Air Liquide and Air Products who both currently produce grey hydrogen for those refineries, among others, but also all kinds of chemical industry and biomass refineries that need it."(K2)

Secondly, some infrastructure for hydrogen transport is already present in this area, reducing the investments needed for green hydrogen use. Finally, business actors noted that a large amount of knowledge on how to handle hydrogen and develop large-scale projects is present in the industrial actors, businesses and authorities (B1, B4).

Next to existing grey hydrogen use by industrial parties in the region, there are also industrial actors that do not use hydrogen yet but might do so in the future. Industrial processes that are hard to electrify or that can use hydrogen as a chemical feedstock were also named in interviews as potential green hydrogen consumers (G2, K2). This provides an even larger demand for green hydrogen in coming years.

The Rotterdam-Moerdijk cluster has pipeline connections to the rest of the Netherlands as well as German industrial areas. The existing natural gas grid can be used for future green hydrogen transport. This requires adjustments to the grid, but Gasunie is already developing these projects along with new pipeline projects. This grid will make it possible to transport produced and imported green hydrogen throughout the Netherlands and to Germany, particularly the German Ruhr area (B1, B5, K1, N2). Many interviewees regarded import as necessary since domestic green hydrogen production will not be sufficient to satisfy demand, especially when considering demand from across the border (G3, B1, B2, K1, K2, N1). The cluster's potential role as a green hydrogen transit hub is also planned through the use of tube trailer trucks between Rotterdam, Antwerp and the Ruhr area, for example (K2).

The Rotterdam-Moerdijk area's existing grey hydrogen use, and large industrial players mean that green hydrogen use can be developed in this area on a large scale. This initial demand is crucial for market creation and integration of green hydrogen into the energy system, stimulating the development of the national green hydrogen TIS. Additionally, the area's strong economic and infrastructural connection with Germany's Ruhr area will quickly develop a green hydrogen transit function for the Rotterdam-Moerdijk area. This is important for the development of the national green hydrogen TIS since the Netherlands will have to import green hydrogen for domestic use.

4.2.2.3. Geographical context conditions

Geographically, the Rotterdam-Moerdijk cluster has an interesting position through its access to the North Sea. The North Sea region seems to become a hotspot for green hydrogen activity in Europe, which means that the Rotterdam-Moerdijk can benefit from its proximity (G2, K2). One interviewee described that there is cooperation between port authorities, exchanging experiences on topics such as certification and safety (B1). A governmental representative underscored that in the REpowerEU, the North sea was assigned as one of the main areas for green hydrogen development, and that this leads to cooperation between regions with North-sea ports (G2).

> "That was a reason for us to search for an improved connection with our colleagues from the Northern Netherlands, Zeeland and North-Holland. We just had our first conversation on this topic to discuss: how can we, also towards Europe, get the North Sea in the picture as well as possible?"(G2).

This proximity to, and cooperation with, other regions along the North Sea coast can be an important enabling factor in the Dutch green hydrogen TIS. Thinking in terms of TIS functions, this cooperation enhances knowledge diffusion, resource mobilisation and guidance of the search by focusing development efforts.

4.2.2.4. Political context conditions

With increased attention for reduction of fossil fuel use, the Rotterdam-Moerdijk cluster saw an increased risk of reduction in business in fossil fuels, too. This took shape, for example, in European carbon pricing for industry and more recently in requirements for greening a share of grey hydrogen use in 2030 (G1, B1, B2; European Commission, 2022). These developments also alerted regional policymakers, who started to cooperate with the port authority and nearby municipalities. Although a large part of green hydrogen initiatives are driven by large industrial actors and the Port of Rotterdam, the regional government has played a role in supporting initiatives in the industrial cluster, by lobbying at the national and EU level and by coordinating other green hydrogen activities in the province of South-Holland (G2, G3).

This regional context condition shows that regional governments can influence green hydrogen in multiple ways. Next to standard responsibilities, such as permitting, regional governments can play a role in being a facilitator and connector. Very importantly, regional government actors can increase resource mobilisation for the technology through lobbying on the international level. This ultimately benefits national green hydrogen development.

4.3. Comparison of regional context effects on the nationally delineated TIS

This section discusses the main differences and similarities of the impact of the context conditions between the Northern Netherlands and Rotterdam Moerdijk.

4.3.1. Technological context conditions

The regions are alike in the importance of generation of renewable electricity as an important factor in green hydrogen development. With the majority of future offshore wind production planned along the western coast, Rotterdam-Moerdijk seems to have a good position for large-scale green hydrogen production. The Northern Netherlands, however, will also be able to produce significant amounts of green hydrogen from future offshore wind parks near its coast. Potential shortcomings in renewable electricity can be drawn from its power connections with Denmark and Norway.

This context condition shows that in order to develop the green hydrogen TIS on the national level, regional availability of renewable electricity is crucial. Once sufficient renewable electricity is available for electrolysis, both regions can become responsible for a significant share in national production of green hydrogen.

4.3.2. Sectoral context conditions

Sectoral context conditions play an important role in both regions.

Both regions have existing knowledge, actors and infrastructure that will be of use in the development of green hydrogen activities, although these factors differ between the regions. Rotterdam-Moerdijk can benefit from its current grey hydrogen use for green hydrogen demand, existing hydrogen infrastructure and hydrogen-specific knowledge present with industrial actors and authorities. The Northern Netherlands can make adjustments to its extensive existing infrastructure for natural gas to create a hydrogen infrastructure relatively quickly and cheaply.

In the Rotterdam-Moerdijk area, mostly large-scale green hydrogen production projects are developed, aiming to supply large industrial actors. Additionally, the Rotterdam-Moerdijk area aims to become a large green hydrogen transport hub, importing and distributing green hydrogen throughout the Netherlands and neighbouring countries. In the Northern Netherlands, initiatives are spread widely and differ in size, which is partly a result of the hydrogen valley approach that involves many actors in this region.

This shows how regional context conditions can create different development paths while both contributing to the national green hydrogen TIS. Large-scale green hydrogen production for industrial use in the Rotterdam-Moerdijk area can help overcome the technological and regulatory challenges that currently exist and bring down production cost through economies of scale. It can help to develop a market for green hydrogen, paving the way for more players to enter, and it can become a transit hub to supply the Netherlands with green hydrogen. The Northern Netherlands can also do this on a smaller scale but will also be important due to its extensive pipeline infrastructure.

4.3.3. Geographical context conditions

In terms of geographical context conditions, the main difference between the regions is the availability of large-scale storage in salt caverns in the Northern Netherlands. This storage can provide an important balancing function between hydrogen supply and demand, and in the electric power grid. Due to the presence of salt caverns in Zuidwending and their proximity to the existing natural gas grid, this region is the focus of green hydrogen storage plans in the Northern Netherlands.

The access to the North Sea for both regions and the resulting cooperation with similar regions appears a valuable factor too. Knowledge exchange, cooperation for resource mobilisation and alignment of efforts are all benefits that enhance development of the national green hydrogen TIS.

4.3.4. Political context conditions

The political context shows important differences between the regions. In the Northern Netherlands, regional and local governments are important drivers for green hydrogen initiatives. The region's need for new economic activity as a result of diminishing natural gas activities leads policymakers to take an active role in developing a green hydrogen economy. This, in turn, has led to green hydrogen initiatives being spread across all parts of the value chain in this region. In order to use green hydrogen to decarbonize activities from heavy transport to heating in the built environment and electricity grid balancing, the insights provided by the Northern Netherlands hydrogen valley approach may prove crucial. When successful, the hydrogen valley concept can be applied in other regions too, reaching homes, businesses, and industry outside of the large industrial clusters.

Rotterdam-Moerdijk's green hydrogen developments are driven less by regional and local governments, and more by large industrial actors. Regional and local policymakers definitely still play a role in green hydrogen development in the region, but in a less prominent manner than in the Northern Netherlands. Its industrial actors may be motivated by the prospect of declining fossil fuel business and regulation requirements but are crucial in developing a new technology.

The political context condition shows that, although not a prerequisite, regional and local policy can strongly influence regional development of a technology.

5. Discussion

The results have shown that regional context conditions are of importance to the development of the green hydrogen technological innovation system in the Netherlands. This is in line with findings from literature.

Market formation, for example, has been found to be one of the main areas where regional context conditions can be of influence on a TIS (Rohe and Mattes, 2022; Losacker & Liefner, 2020). This research affirms this, finding that Rotterdam-Moerdijk's industrial players will be important actors in the creation of an initial market. The Northern Netherlands also have a role here, as regional regulation is important for market creation (Losacker & Liefner, 2020). The strong supportive stance of the regional governments will therefore enhance market creation for green hydrogen.

Another reason why support from regional policymakers in the Northern Netherlands can be influential, is that regional decision makers can strongly impact legitimisation of a new technology (Rohe & Chlebna, 2021).

As Bergek et al. (2015) found, technological context conditions can be both enhancing or competing factors in new technology development. In this research, this was reaffirmed as the availability of sufficient renewable electricity and the development of blue hydrogen were seen as both potential enabling and restraining factors.

Existing sectoral structures are also seen as both potentially hindering and enabling factors for a TIS (Hanson, 2017). In the case of green hydrogen in the Netherlands, sectoral context conditions were found to be strongly influential for the national TIS. The availability of existing resources and infrastructure can be an important enabler for green hydrogen development. The potential negative effects found in literature, such as resistance from incumbents, were not found to be of strong effect (Bergek et al.,2015).

In summary, all four regional context conditions are of profound importance to the development of the national green hydrogen TIS. This research therefore supports arguments that describe the importance of regional features for TISs and inclusion of context conditions (Bergek et al., 2015; Coenen et al., 2012, Rohe and Mattes, 2022; Losacker & Liefner, 2020, Hanson, 2017). The regional perspective on a TIS-in-context is thus valuable in order to understand the development of a TIS on the national level, even more so when multiple regions are included since this can show how regions have different distinctive features that can impact a TIS on the national level. This is relevant, not only for academics but also for policymakers since national policymakers can be more effective in national development of a technology when taking into account the regional features that influence it. Future research, comparing the effects of regional context structures for multiple regions on a nationally delineated TIS, is therefore certainly recommended.

This research has encountered multiple limitations. To start, a limited sample of interviewees was found. Although the interviewee group was balanced between representatives from different levels of government, business actors, knowledge institutes and network organisations, a larger sample would likely have given additional insights. While attempts to increase the number of interviews were made, many invites remained unanswered. The reduced validity that resulted from this limitation is partly covered by the desk research into grey literature. While it is difficult to gain the same insights that additional expert interviews might have provided, grey literature provided a means of triangulation by gaining information from additional data sources.

A second limitation can be found in the scoping of the research. Incorporating the entire green hydrogen value chain, and researching both the national and regional level, sometimes made it difficult to get into detail. While an interviewee, for example, might have extensive knowledge on the technical aspects of the electrolysers for green hydrogen production, these details were beyond the scope of this research, since production was only a part of the value chain. For future research, it might therefore be interesting to investigate effects of regional context structures on a more specific part of the green hydrogen value chain.

While the aim of this research was to compare two regions, inclusion of other regions could have provided additional insights. The included regions were chosen for a reason, as initial research indicated the regions had very different characteristics, but both saw a large concentration of green hydrogen initiatives. There are, of course, other regions in the Netherlands that provide interesting research cases as well. Including these might have resulted in the identification of additional effects of regional context structures on the green hydrogen TIS in the Netherlands. However, considering the already limited number of interviewees and time, this might have resulted in a more superficial analysis of all regions. While this research found that regional context conditions impact a national TIS, these results can hardly be extrapolated given only two regions were studied.

6. Conclusion

This research investigated the effects of regional context conditions on the emergence of the green hydrogen technological innovation system in the Netherlands. Two regions were identified, the Northern Netherlands and Rotterdam-Moerdijk, as these regions both harbour a large number of green hydrogen initiatives but have very different characteristics, making them interesting to compare. Building on innovation systems theories, a TIS-in-Context approach was combined with a regional scope. By comparing the context conditions of both regions using literature and expert interviews, multiple effects on the Dutch green hydrogen TIS were identified. It was found that both regions play an important role the green hydrogen development. The Northern Netherlands, stimulated by regional and local government initiative, is building on its extensive natural gas infrastructure and knowledge. Green hydrogen initiatives are developed across the entire green hydrogen value chain, and its salt cavern storage capacity will perform an important balancing function in national green hydrogen development. Rotterdam-Moerdijk's green hydrogen development shows a different path. Here, initiative from large industrial actors drive green hydrogen development. Existing hydrogen use, knowledge, infrastructure, and potential demand mean that Rotterdam-Moerdijk can be an important region in upscaling of production and market creation. Additionally, Rotterdam-Moerdijk aims to become a leading importer, helping to satisfy future Dutch green hydrogen demand.

These findings show how regional context conditions can have significant impact on the development of a nationally delineated TIS. In TIS-related research, this is an important factor to keep in mind. Policymakers, seeking to support the development of a new technology, should also take regional context conditions into consideration.

References

Andersen, A. D. (2014). No transition without transmission: HVDC electricity infrastructure as an enabler for renewable energy? *Environmental Innovation and Societal Transitions*, *13*, 75–95. https://doi.org/10.1016/J.EIST.2014.09.004

Andreasen, K. P., & Sovacool, B. K. (2015). Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development. *Journal of Cleaner Production*, *94*, 359–368. https://doi.org/10.1016/J.JCLEPRO.2015.01.056

Asheim, B. (2008). Differentiated knowledge bases and varieties of regional innovation systems. *Innovation*, *20*(3), 223–241. https://doi.org/10.1080/13511610701722846

Asheim, B. T., & Isaksen, A. (1997). Location, agglomeration and innovation: Towards regional innovation systems in Norway. *European Planning Studies*, *5*(3), 299–330.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions*, *16*, 51–64. https://doi.org/10.1016/j.eist.2015.07.003

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, *37*, 407–429. https://doi.org/10.1016/j.respol.2007.12.003

Bryman, Alan (2012), Social Research Methods. *Oxford University Press*

Carlsson, B., Jacobsson, S., Holmén, M., & Rickne, A. (2002). Innovation systems: analytical and methodological issues. *Research Policy*, *31*, 233–245.

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. In *J Evol Econ* (Vol. 1).

Coenen, L. (2015). Engaging with changing spatial realities in TIS research. *Environmental Innovation and Societal Transitions*, *16*, 70–72. https://doi.org/10.1016/j.eist.2015.07.008

Coenen, L., Benneworth, P., & Truffer, B. (2012). Toward a spatial perspective on sustainability transitions. *Research Policy*, *41*, 968–979. https://doi.org/10.1016/j.respol.2012.02.014

Cooke, P., Gomez Uranga, M., & Etxebarria, G. (1997). Regional innovation systems: Institutional and organisational dimensions. *Research Policy ELSEVIER Research Policy*, *26*, 475–491.

de Oliveira, L. G. S., & Negro, S. O. (2019). *Contextual structures and interaction dynamics in the Brazilian Biogas Innovation System*. https://doi.org/10.1016/j.rser.2019.02.030

Dong, J., Wu, X., Liu, C., Lin, Z., & Hu, L. (2020). The impact of reliable range estimation on battery electric vehicle feasibility. *International Journal of Sustainable Transportation*, *14*(11), 833–842. https://doi.org/10.1080/15568318.2019.1639085

Edquist, C. (1997). Systems of Innovation Approaches-Their Emergence and Characteristics. In *Systems of innovation: Technologies, institutions and organizations* (pp. 1–35). https://www.researchgate.net/publication/272396959

Ericsson, K. (2017). Biogenic carbon dioxide as feedstock for production of chemicals and fuels A techno-economic assessment with a European perspective. *Miljö-Och Energisystem, LTH, Lunds Universitet*.

European Commission. (2020). *A hydrogen strategy for a climate-neutral Europe*. Retrieved from https://www.eu2018.at/calendar-events/political-events/BMNT-

European Commission. (2022). Repower EU. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

Fan, Z., Ochu, E., Braverman, S., Lou, Y., Smith, G., Bhardwaj, A., ... & Friedmann, J. (2021). Green hydrogen in a circular carbon economy: Opportunities and limits. *Columbia Center for Global Energy Policy*.

Freeman, C. (2004). Technological infrastructure and international competitiveness. *Industrial and Corporate Change*, *13*(3), 541–569.

Godin, B. (2009). National Innovation System: The System Approach in Historical Perspective. *Science, Technology, & Human Values*, *34*(4), 476–501. https://doi.org/10.1177/0162243908329187

Government of the Netherlands. (2020). *Government Strategy on Hydrogen*.

Hanson, J. (2017). *Established industries as foundations for emerging technological innovation systems: The case of solar photovoltaics in Norway*. https://doi.org/10.1016/j.eist.2017.06.001

Hekkert, M., Negro, S., Heimeriks, G., & Harmsen, R. (2011). *TIS a manual for analysts*. Retrieved from https://beeldbank.rws.nl

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, *74*(4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

IEA. (2019). *The Future of Hydrogen*. Retrieved from https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

IEA. (2021a). *World Energy Outlook 2021*. Retrieved from www.iea.org/weo.

IEA. (2021b). *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. Retrieved from www.iea.org/t&c/

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Ishaq, H., Dincer, I., & Crawford, C. (2022). A review on hydrogen production and utilization: Challenges and opportunities. *International Journal of Hydrogen Energy*, *47*(62), 26238-26264.

Kubeczko, K., Rametsteiner, E., & Weiss, G. (2006). The role of sectoral and regional innovation systems in supporting innovations in forestry. *Forest Policy and Economics*, *8*, 704–715. https://doi.org/10.1016/j.forpol.2005.06.011

Klimaatakkoord. (2020). Industriële Clusters Publiceren Plannen 2030-2050. Retrieved from https://www.klimaatakkoord.nl/actueel/nieuws/2020/10/22/industriele-clusters-publiceren-plannen-2030-2050

Losacker, S., & Liefner, I. (2020). Regional lead markets for environmental innovation. *Environmental Innovation and Societal Transitions*, *37*, 120–139. https://doi.org/10.1016/j.eist.2020.08.003

Lundvall, B.-Å. (2007). National Innovation Systems-Analytical Concept and Development Tool. *Industry and Innovation*, *14*(1), 95–119. https://doi.org/10.1080/13662710601130863

Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy*, *31*, 247–264.

Manley, K. (2002). The Systems Approach to Innovation Studies. *Australasian Journal of Information Systems*, *9*(2). Retrieved from https://journal.acs.org.au/index.php/ajis/article/view/196/170

Markard, J., Hekkert, M., & Jacobsson, S. (2015). The technological innovation systems framework: Response to six criticisms. *Environmental Innovation and Societal Transitions*, *16*, 76–86. https://doi.org/10.1016/j.eist.2015.07.006

Mattes, J., Huber, A., & Koehrsen, J. (2014). *Energy transitions in small-scale regions-What we can learn from a regional innovation systems perspective*. https://doi.org/10.1016/j.enpol.2014.12.011

Mowery, D., & Rosenberg, N. (1979). The influence of market demand upon innovation: a critical review of some recent empirical studies. *Research Policy*, *8*(2), 102–153.

Negro, S. O., & Hekkert, M. P. (2008). Technology Analysis & Strategic Management Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany. *Technology Analysis & Strategic Management*, *20*(4), 465–482. https://doi.org/10.1080/09537320802141437

Nelson, R. (1993). *National Innovation Systems: A Comparative Analysis*.

Nicita, A., Maggio, G., Andaloro, A. P. F., & Squadrito, G. (2020). *Green hydrogen as feedstock: Financial analysis of a photovoltaic-powered electrolysis plant*. https://doi.org/10.1016/j.ijhydene.2020.02.062

Notton, G., Nivet, M.-L., Voyant, C., Paoli, C., Darras, C., Motte, F., & Fouilloy, A. (2018). *Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting*. https://doi.org/10.1016/j.rser.2018.02.007

Port of Rotterdam. (2020). *Waterstofvisie Port of Rotterdam*. Retrieved from https://www.portofrotterdam.com/sites/default/files/2021-06/waterstofvisie-havenbedrijf-rotterdam-mei-2020.pdf

Port of Rotterdam. (2022). Half Year Report 2022. Retrieved from https://www.portofrotterdam.com/sites/default/files/2022-07/Half-Yearly-Report-2022.pdf

Programma Verduurzaming Industrie. (n.d.). Industrieclusters. Programma Verduurzaming Industrie. Retrieved from https://www.verduurzamingindustrie.nl/industrieclustersre/industrieclusters/default.aspx

PwC. (2021). HyWay 27: hydrogen transmission using the existing natural gas grid? Final report for the Ministry of Economic Affairs and Climate Policy. Retrieved from https://www.hyway27.nl/en/latest-news/hyway-27-realisation-of-a-national-hydrogen-network

Rohe, S. (2020). *The regional facet of a global innovation system: Exploring the spatiality of resource formation in the value chain for onshore wind energy*. https://doi.org/10.1016/j.eist.2020.02.002
Rohe, S., & Chlebna, C. (2021). A spatial perspective on the legitimacy of a technological innovation system: Regional differences in onshore wind energy. *Energy Policy*, *151*. https://doi.org/10.1016/j.enpol.2021.112193
Rohe, S., & Mattes, J. (2022). What about the regional level? Regional configurations of Technological Innovation Systems. *Geoforum*, *129*, 60–73. https://doi.org/10.1016/J.GEOFORUM.2022.01.007
Rijksoverheid. (2022). Routekaart wind op zee 2030. Retrieved from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/documenten/publicaties/2022/06/10/routekaart-windenergie-op-zee
RVO. (2021). Analyse koplopersprogramma's Klimaatakkoord Industrie. Retrieved from https://open.overheid.nl/repository/ronl-01cd1113-de27-4389-9676-b59efc632e15/1/pdf/rapport-analyse-koplopersprogrammas-klimaatakkoord-industrie.pdf
Tigabu, A. D., Berkhout, F., & van Beukering, P. (2015). The diffusion of a renewable energy technology and innovation system functioning: Comparing bio-digestion in Kenya and Rwanda. *Technological Forecasting and Social Change*, *90*(PA), 331–345. https://doi.org/10.1016/J.TECHFORE.2013.09.019
TNO. (2018). Ondergrondse Opslag in Nederland. Retrieved from http://resolver.tudelft.nl/uuid:61adfcad-8bfa-45db-b606-1a6cdea2a195
Topsector Energie. (2022). *Overview of Hydrogen Projects in the Netherlands*. https://topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/Overview%20Hydrogen%20projects%20in%20the%20Netherlands%20-%20version%2015%20juni%202022.pdf
van der Loos, A., Normann, H. E., Hanson, J., & Hekkert, M. P. (2021). The co-evolution of innovation systems and context: Offshore wind in Norway and the Netherlands. In *Renewable and Sustainable Energy Reviews* (Vol. 138). Elsevier Ltd. https://doi.org/10.1016/j.rser.2020.110513
van Wijk, A. (2017). The Green Hydrogen Economy in the Northern Netherlands. Retrieved from https://profadvanwijk.com/wp-content/uploads/2017/04/NIB-BP-NL-DEF-webversie.pdf
van Wijk, A., & Hellinga, C. (2018). Hydrogen-the key to the energy transition. Retrieved from https://profadvanwijk.com/wp-content/uploads/2018/05/Technical-Report-Hydrogen-the-key-to-the-energy-transition.pdf
Wieczorek, A. J., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Science and Public Policy*, *39*, 74–87. https://doi.org/10.1093/scipol/scr008
Wieczorek, A. J., Hekkert, M. P., Coenen, L., & Harmsen, R. (2015). Broadening the national focus in technological innovation system analysis: The case of offshore wind. */ Environmental Innovation and Societal Transitions*, *14*, 128–148. https://doi.org/10.1016/j.eist.2014.09.001

Appendix A: Interview Guide

The interview guide was adapted to each interviewees' background. In an interview with government officials, for example, additional questions on regulation and policymaking were added. The interview guide below presents the questions that formed the basis for every interview.

National structures

- How did you see green hydrogen developing in the Netherlands over the past few years? Do you see increased/decreased attention? Initiatives?
- In case of increased activity, which parties are important for this increase? (for example: governments, private parties, knowledige institutes, network organisations?)
- Which major barriers have you seen that were overcome in the past years?
- Which major barriers are still relevant? Which are new?
- Which parties are responsible for the development and diffusion of knowledge?
- Do you feel think that there is sufficient support from policymakers for development of green hydrogen? (think of financial, regulation support)
- Do you think that growth of demand is sufficient for further development of green hydrogen activities?
- When a new (renewable) technology is scaled up, this can lead to resistance with societal actors. Example: development of onshore wind farms is confronted by Not In My Backyard stance by local actors. Do you see this happening for green hydrogen too, and do you think that this could be a threat to development?

Regional level:

- Can you describe how you see green hydrogen activities develop in [region]? (for example in production/transport/storage/use)
- How does this differ between the Northern Netherlands and Rotterdam Moerdijk?
- What causes these differences?
- What is the impact of these different development paths in the regions on the development of green hydrogen on the national level?
- What is the role of the regional and local governments in the development of green hydrogen activities in [region]?
- Do you feel like there is competition or cooperation between the regions?
- Does this have a stimulating or restraining effect on green hydrogen activity development in [region]?
- What is the influence of the geographical characteristics of [region] (for example proximity to other regions, possibly across the border)

Final remarks and request for additional interviewee suggestions.

Appendix B: Quotes

Section	Interviewee	Dutch quote	English translation
4.2.1.2.	B5	“Er hier van oorsprong heel veel gasinfrastructuur, natuurlijk omdat hier het aardgas gevonden is. Dus dat kunnen we gebruiken. De kennis aanwezig in het noorden, met kennisinstellingen maar de Gasunie zit hier ook.”	“Originally, there is a lot of natural gas infrastructure here because the natural gas was found here, of course. So we can use that. The knowledge is available in the North, with knowledge institutes but Gasunie is here as well.” (B5)
4.2.1.3.	B4	“Je kan op die manier ook investeren in opslag en dat noem ik even opslag als in een zoutcaverne om op die manier een grotere hoeveelheid voorraad te kunnen hebben, dus ook de balans functie van een systeem te kunnen vervullen.”	“You can invest in storage in this way, and I’m calling this storage as in a salt cavern to be able to store larger quantities, and thus also be able to fulfil the balancing function of a system.”
4.2.1.3.	K1	“Iedereen zegt heel makkelijk: we gaan waterstof opslaan in de ondergrond. Maar het aantal pilot projecten zijn op een hand te tellen. In zoutcavernes en gasvelden. Het is daar wel aangetoond dat het kan. Maar ook dat moet zich nog verder ontwikkelen. Dus die maturiteit is ook nog niet dusdanig hoog, en zeker nog niet in de gasvelden.”	“Everyone is quick to say: we will store hydrogen underground. But there are only a handful of pilot projects. In salt caverns and gas fields. It has been shown to be possible. But it has to develop further. So the maturity is not sufficient yet, and especially for the gasfields.”
4.2.1.4.	N1	“Maar omdat de regering heeft	“But because the government

		gezegd: wij gaan dat naar nul brengen betekent dat ook dat je dus ook moet kijken, wat is nou het effect daarvan, economisch? Voor de regio zal het betekenen dat het regionaal economisch product 8-10, en wellicht nog meer, procent zal dalen. Dat is dramatisch voor een regio, als je 12 procent minder inkomsten krijgt.”	has said: we will reduce that [natural gas production] to zero, that also means that you have to look at, what are the consequences, economically? For the region this means that the regional economic product will decline by 8-10, or maybe more, percent. That is dramatic for a region, if you receive 12 percent less income.”
4.2.1.4.	N1	“De Hydrogen Valley is eigenlijk een afgebakend gebied waarin je alle elementen van die waardeketen aanwezig hebt: productie van de waterstof, logistiek, opstartgebruik in industrie, mobiliteit, gebouwde omgeving. Dat hebben wij in Noord Nederland voor elkaar gekregen en daarom zijn we ook de eerste Hydrogen Valley van Europa geworden.”	“The hydrogen valley is basically a defined area where all elements of the value chain are present: hydrogen production, logistics, startup usage in industry, mobility, built environment. That is what we have achieved in the Northern Netherlands and that is why we have become the first hydrogen valley of Europe.”
4.2.2.1.	G3	“Ik heb het beeld dat blauw onvermijdelijk is in de transitiefase. Dat je het in de transitiefase nodig hebt, maar dat je wel moet oppassen voor lock-in. Dat je niet tot in lengte der dagen vast blijft houden aan blauw. Dus dan moet je aan de voorkant zeggen: we doen dit voor x aantal jaren en daarna stoppen we ermee en dan willen we helemaal overstappen op groen.”	“I get the idea that blue hydrogen is unavoidable in the transition phase. That you need it in the transition phase, but you have to be aware of lock-in. So you don’t hold on to blue hydrogen until the end of time. So then you will have to say in advance: we will do this for x amount of years and we will stop after that and switch to green entirely.”
4.2.2.2.	K2	“dan heb je in Rotterdam	“In Rotterdam, of course there

		natuurlijk, laten we de meest voor de hand liggende noemen: Shell en BP, twee hele grote raffinaderijen, Air Liquide en Air Products die nu grijze waterstof produceren, onder andere voor die raffinaderijen, maar ook allerlei chemische industrie and biomassa raffinage die het nodig hebben.”	is, let’s name the most obvious, Shell and BP, two very large refineries, Air Liquide and Air Products who both currently produce grey hydrogen for those refineries, among others, but also all kinds of chemical industry and biomass refineries that need it.”
4.2.2.3.	G2	“Dat was voor ons in ieder geval de aanleiding om ook een betere verbinding te gaan zoeken met de collega's van Noord-Nederland, Zeeland, Noord-Holland. We hebben daar pas een eerste gesprek over gehad om te kijken: hoe kunnen we, ook richting Europa, gezamenlijk die Noordzee goed op de kaart gaan krijgen?”	“That was a reason for us to search for an improved connection with our colleagues from the Northern Netherlands, Zeeland and North-Holland. We just had our first conversation on this topic to discuss: how can we, also towards Europe, get the North Sea in the picture as well as possible?”