The European Hydrogen Transition:

An exploration of hydrogen ecosystems in the EU

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Preface

This thesis is written to finalise the Master programme Environment and Society and its specialisation in European Spatial and Environmental Planning. The research is about the development of hydrogen ecosystems in several regions of the EU. I chose this topic because I am always interested in innovations that can help society become more sustainable. Therefore, I see this new development as exciting and wanted to learn more about it.

Before the research starts, I would like to thank several people that helped me during this rollercoaster of completing the master. First, I would like to thank my supervisors, Dr Anyango-van Zwieten and Mr Koene, for their wisdom, support and guidance during this research. Secondly, I would also like to thank my other colleagues from Oost NL for providing me with a supportive and friendly environment to conduct the study. Thirdly, I would like to thank all my respondents for taking the time to help me with my research and to provide me with the correct information. Lastly, I would like to my friends for taking the time to read the study and to provide me with the necessary feedback that only improved the research (especially the English).

Summary

The energy transition is one of the main challenges in Europe in becoming climate neutral by the year 2050. Green hydrogen is addressed in the EU as one of the key ingredients to making this transition a success. This is because hydrogen can potentially make the transport, industry and building sectors more sustainable. Moreover, hydrogen can serve as energy storage to diminish the effect of renewables' intermittency problem. Therefore, a new momentum for hydrogen arose in the EU. However, hydrogen had multiple interest peaks, but it never took off. This is because various barriers, like high production costs or lack of infrastructure, hinder hydrogen development. Therefore, the hydrogen value chain must be created simultaneously to overcome the barriers. The development of hydrogen is expected first to take off locally. However, in the literature, a gap is found in exploring this early stage of hydrogen development on a regional level. Therefore, this research uses a multiple case study approach by exploring the regions of North Jutland, Brittany and Lower Saxony. The research has the following main question: *How are different EU hydrogen ecosystems developing from a niche towards the realisation of hydrogen value chains?*

The study used the entrepreneurial ecosystem theory from Isenberg (2011) to explore the hydrogen ecosystems of the different regions. This research uses a combination of the theory multilevel perspective of Geels (2011) and the diffusion of innovation theory of Rogers (1995) to analyse the development trajectory of innovation in society.

The results show that the Lower Saxony and North Jutland cases are developing faster than the Brittany case. This relates to multiple causes, such as the high availability of wind in North Jutland and the presence of large industries in Lower Saxony. On the other hand, in Brittany, there is a lack of renewable energy and large industries. Nevertheless, the Brittany case shows interesting hydrogen development using a more bottom-up approach. Overall, the hydrogen development toward a regional hydrogen value chain is influenced by different barriers presented in this research. These barriers make hydrogen development, therefore, a complex one. To overcome this, the interaction and collaboration between the actors in the ecosystem are vital.

Contents

1. Introduction

1.1 A new alternative in the energy transition

In 2016, nations worldwide signed the Paris Agreement to tackle climate change's effects. The agreement's goal is to keep the temperature rise below 2 degrees Celsius by 2050. Consequently, the global greenhouse gasses should be reduced by 85%, which requires a worldwide energy transition from fossil fuels to renewable energy (Brandon & Kurban, 2017). This transition has, however, the disadvantage of intermittency. This entails fluctuations in the renewable energy production pattern because of its dependency on the weather (Brandon & Kurban, 2017). For example, there are days when there is not enough sun or wind to produce the right amount of energy (troughs), and there are days when there is an abundance in the production of solar and wind power (peaks) (Semeraro, 2021; Verzijlbergh, De Vries, Dijkema, & Herder, 2017). These fluctuations can cause a mismatch between the supply and demand of renewable energies. During peaks, this mismatch can become too high for the energy grid to handle, making it sometimes necessary to curtail renewable energy production (Li, Shi, Cao, Wang, Kuang, Tan, & Wei, 2015).

Due to the peaks and troughs, a new challenge arises to provide a stable energy supply where more flexibility is needed (Semeraro, 2021; Verzijlbergh et al., 2017). The term flexibility describes how an energy system can manage or balance the variability in energy production and consumption (Verzijlbergh et al., 2017). In the case of renewable energy, storage plays a significant role in increasing its flexibility. For example, when there is a peak in energy production, this can be stored and used later when there is a trough. In such an energy system, hydrogen can serve as a storage medium as it can be produced from renewable electricity and converted into electricity and heat (Odgen, 2018). This offers an opportunity to use the otherwise curtailed energy to produce hydrogen and improve the grid's flexibility (Odgen, 2018).

Besides using hydrogen for energy storage, hydrogen can also serve as a sustainable alternative for industrial and transport applications. It can, for example, serve as an alternative in the chemical industry or as green fuel for heavy-duty transport (Ogden, 2018; Oliveira, Beswick, & Yan, 2021). This is because hydrogen does not emit CO2 when used, which is suitable for the climate and public well-being (Brandon & Kurban, 2017). This is important since there are around half a million premature deaths yearly due to air pollution in the EU (Tagliapietra, Zachmann, Edenhofer, Glachant, Linares, & Loeschel, 2019). On the other hand, greenhouse gasses can be emitted during the hydrogen production process (Hermensmann & Müller, 2022). This is because hydrogen can be produced from different primary sources. For example, a type of hydrogen already used in the chemical industries, representing almost the entire global hydrogen production, uses fossil fuels as a primary source for its production (grey hydrogen) (IEA, 2019). However, this research focuses mainly on hydrogen that uses a renewable energy source as a primary source for its production (green hydrogen). In 2020, green hydrogen was estimated to be less than 0,1% of the global hydrogen production (Ajanovic & Haas, 2020). This difference comes because of the high production costs of green hydrogen compared to grey hydrogen, which also symbolises one of the main barriers to its implementation (Ajanovic & Haas, 2020).

Despite the current low percentage of green hydrogen production, the EU perceives it as a critical element in supporting the decarbonisation policy of the European Green Deal (European Commission, 2020). This policy was published in 2019 and offers a pathway for how the EU can become climate neutral by 2050 (European Commission, 2019). Following the Green Deal, the EU presented their hydrogen strategy by 2020 to strengthen Europe's hydrogen ambition (European Commission, 2020). The policy focuses primarily on the previously mentioned usage of hydrogen as storage to balance the grid and on implementing hydrogen in industry and transport. These sectors are currently accountable for 20% (industry) and 25% (transport) of the EU's emissions and are, therefore, priorities for Europe's decarbonisation pathway (European Commission, 2020; Hafner & Raimondi, 2020). The focus is, however, not only on the uses of hydrogen but also on creating the entire hydrogen value chain (production, distribution, storage and end-use) to build a dynamic European hydrogen ecosystem (European Commission, 2020). Without this approach, there is the danger of the so-called chicken and egg problem that symbolises the problematics of earlier attempts at hydrogen implementation (Brandon & Kurban, 2017). This entails the issue of, for example, the lack of hydrogen cars because there are no hydrogen refuelling stations versus the lack of refuelling stations because of the lack of hydrogen cars (Van den Heuvel, 2020). Therefore, this problem indicates the importance of simultaneously creating the whole value chain, where supply and demand are synchronised. the distribution and end use of green hydrogen is also in an early stage of development and not yet widely adopted (European Commission, 2020).

Due to the supposed future increase in renewable energy and hydrogen production, the EU is becoming less dependent on fossil fuels from other countries in the future. The importance of this independence grew even more within the EU since the Russian invasion of Ukraine in 2022 exposed the EU's dependency on Russian gas (Hosseini, 2022). The EU, therefore, created the REPowerEU plan to accelerate the energy transition to become less dependent on Russian gas (Lonergan, Gabrielli, & Sansavini, 2022). In this plan, the role of hydrogen became even more essential. For example, the target of 10 million tons of hydrogen production in 2030 is doubled with another 10 million from hydrogen import. This shows the ambition of the EU regarding hydrogen but also implies the considerable challenges to realise these targets as the whole value chain is currently missing (European Commission, 2022). The expectation is that hydrogen ecosystems first emerge on a local level and then, later on, expand into larger (regional) ecosystems (European Commission, 2020; Lambert, 2020). The so-called Hydrogen Valleys are expected to be the first movers in this (Gas For Climate, 2020). These are areas where an integrated hydrogen ecosystem should be developed that ideally should cover the whole hydrogen value chain (FCH, n.d.). In the EU hydrogen strategy, it is expected that the valleys will develop in the period from the year 2025 to 2030 (European Commission, 2020).

The previous shows the vital role hydrogen can have in the EU's decarbonisation pathway to become climate neutral in the year 2050 and create more energy interdependency. However, hydrogen had multiple interest peaks in the past but never took off (IEA, 2019). Green hydrogen is therefore not yet widely implemented and can still be regarded as something new that shows, next to its potential, challenges in its production, distribution and end-use. Despite this, the EU sees it as a critical element and supports its development, which created a new momentum for hydrogen in the EU (Lambert, 2020). However, the current literature shows gaps in hydrogen development within a regional context, whereas the expectation is that hydrogen will first take off locally. Therefore, this research uses a multiple-case study approach to address this regional perspective. This way, the research enriches the literature with new and practical knowledge about hydrogen's current and future development during this momentum in different European regions.

The European areas that this research explores are North Jutland in Denmark, Brittany in France and Lower Saxony in Germany. The choice for these areas is because all showed ambitions with implementing hydrogen into their territory. Additionally, the regions also participate in the Hydrogen Valley Partnership. The selection will be further substantiated in section 5.3.2. The research chose to explore the development of hydrogen till 2030 because this year can be regarded as a milestone in multiple policy documents, such as the European Hydrogen Strategy or the Green Deal.

1.2 Research aim

Hydrogen shows the potential to support the energy transition and multiple sectors in their decarbonisation pathway. However, its implementation is challenging as hydrogen is not yet widely used or produced because of barriers preventing earlier attempts to take off. The research aims to explore the development of hydrogen ecosystems towards 2030 and to analyse the obstacles and trajectory of hydrogen as a niche towards realising entire value chains in multiple regions of the EU. Regarding the barriers, it is essential to emphasise that those are expected to influence hydrogen development in North Jutland, Brittany and Lower Saxony. Therefore, the barriers are an integral part of the development hydrogen ecosystem.

For hydrogen to transition from a niche to becoming widely adopted in society, it needs to have an ecosystem that supports its development to overcome the barriers. Therefore, this research uses Isenberg's entrepreneurial ecosystem (2011) to explore these hydrogen ecosystems. This is because this theory offers the exploration of several factors that are necessary to create a conducive environment for hydrogen. However, this theory provides the research not with the know-how about how hydrogen can develop from its current stage towards a potential future stage. Therefore, the approach from Geels (2011) and Roger's (1995, in Matinaro & Liu., 2015) is used to describe the trajectory of sustainable innovation as niches, such as hydrogen, in society.

1.3 Main research question and sub-questions

The previous sections lead to the following main and sub-questions:

Main question: How are different EU hydrogen ecosystems developing from a niche towards the realisation of hydrogen value chains?

Sub-question 1: How are the different ecosystem domains of North Jutland, Brittany and Lower Saxony developing towards 2030?

Sub-question 2: How do the different hydrogen ecosystems develop in comparison to each other in realising a regional hydrogen value chain?

1.4 Scientific relevance

A gap was found in European regions' academic literature about hydrogen development. Because hydrogen will first emerge locally and regionally, enriching the academic hydrogen literature with this regional perspective is relevant. Furthermore, the currently existing academic literature, in general, is mainly concerned with calculations and focused on a specific hydrogen subject. For example, the estimations of the costs of hydrogen vehicles in the research of Ajanovic and Haas (2020) or the costs of hydrogen distribution via trucks by Lahnaoui, Wulf, Heinrichs, and Dalmazzone (2019). This regional perspective will enrich the existing academic literature by focusing not only on a specific hydrogen application, such as trucks but also on the broader context and the entire hydrogen value chain from production to end-use.

Another reason this research is scientifically relevant relates to the lack of research about hydrogen using an ecosystem approach. Ochoa Robles, Giraud Billoud, Azzaro-Pantel, & Aguilar-Lasserre, (2019) study about hydrogen airport ecosystems came close. Still, they used a quantitative approach and missed the broader context of other factors, such as culture or human capital. Because of the complexity and importance of understanding the broader context of hydrogen, this research regards it as relevant and helpful to apply the entrepreneurial ecosystem of Isenberg (2011). This choice can be a first step to extending the use of the entrepreneurial ecosystem to hydrogen, which is strengthened by applying a multiple-case study approach that has the advantage that it is suitable for improving theory building (Bryman, 2012). The analysis can therefore offer future research improved criteria for collecting data.

Concerning the entrepreneurial ecosystem theory, a critique from Stam and Van de Ven (2019) is that the approach only provides a list of factors without a clear explanation of their interdependencies. This research improves that by using the stages of the hydrogen value chain; production, distribution, storage, and end-use. Applying this method can therefore lead to a better understanding of the interdependencies. For example, the influence of the ecosystem domain policy on the production side of hydrogen can affect the end use of hydrogen. Using the value chain can increase the theory's scientific relevance.

Finally, a lack of hydrogen research is found concerning the scientific knowledge based on the previous master's thesis of Radboud University. For example, this research is the second research focusing on hydrogen that a Radboud University student is conducting. The other study about hydrogen filling stations is from Van den Heuvel (2020). Mainly because of the potential hydrogen has in future environmental and spatial planning, this research contributes to the knowledge creation for Radboud University. The study is therefore beneficial for future researchers and helpful for introducing the topic in some courses at Radboud University.

1.5 Societal relevance

As explained in the introduction subsection, hydrogen can contribute to multiple topics relevant to society, such as climate change, energy security and air pollution. Therefore, hydrogen is essential for the EU to become climate neutral by 2050 (European Commission, 2020). However, hydrogen has had multiple historical interest peaks but never took off (IEA, 2019). This indicates the complexity of creating a hydrogen ecosystem. Consequently, it is essential to look at this early stage of hydrogen and to explore the bottlenecks and how the development is going in different regions. Therefore, the research is helpful for actors, such as policymakers or businesses, searching for more sustainable strategies in the explored areas and actors outside of those regions. For example, the Port of Amsterdam is currently studying the feasibility of realising Europe's most prominent green hydrogen cluster (Port of Amsterdam, 2020). Therefore, this research is helpful for them to learn how the development is going in other areas and what kind of barriers are identified.

Concerning energy security, this research can be considered relevant because of the Russian invasion of Ukraine in 2022, where the vulnerability of the EU energy supply is exposed (Hosseini, 2022). This caused an increase in the price of electricity and gasoline, influencing the welfare of civil society (Lonergan et al., 2022; Ozili, 2022). Additionally, many businesses depend on Russian gas, and they need to find new strategies to secure their energy supply. Otherwise, the prices of their products will go up, which will influence the welfare of the whole society (Ozili, 2022). Therefore, hydrogen can be essential in decreasing the dependency on Russian gas.

Regarding the danger of air pollution within the EU, hydrogen can contribute to better air quality because hydrogen does not emit CO_2 when used (Brandon & Kurban, 2017; Tagliapietra et al., 2019). Therefore, realising a green hydrogen ecosystem in areas with polluting industries or transport can improve the air quality of the surrounding areas. Consequently, researching the development of hydrogen ecosystems can contribute to societal well-being.

Finally, this research was conducted during an internship at the organisation Oost NL. Therefore, the results are used directly within the organisation. With this direct knowledge utilisation, this research has a direct societal impact.

2. Introduction to hydrogen's future role

Before moving on towards the theoretical framework, this research regards it essential to understand the context of hydrogen's future role in the EU. Therefore, this chapter starts by zooming out to focus on previous global energy transitions and interest peaks of hydrogen. Afterwards, the critique of the literature on this energy transition is discussed. After that, previous EU energy policies are discussed to build up toward the European hydrogen strategy and the REPowerEU, which are essential for hydrogen development in the EU. Finally, the hydrogen value chain and its barriers are discussed because they are central to the research's theory and results.

2.1 The energy transition and hydrogen

Energy transitions are not something new when looking at the history of humanity. Solomon and Krishna (2011) explain that humans have been customary to changing their primary energy sources throughout history. However, these changes were primarily related to the local level, with, for instance, a scarcity of wood supply, and not to the global level (Solomon & Krishna., 2011). The first significant energy transition was from wood to fossil fuels, which lasted from the early 1700s to the end of the 19th century (Solomon & Krishna., 2011). Nowadays, humanity needs to undergo another significant energy transition from fossil fuels to renewable energy because of climate change (Nicita, Maggio, Andaloro, & Squadrito, 2020). However, the difference from previous transitions is that society does not have the same time to achieve this (Fouquet, 2010). This short time is illustrated in the first global agreement on climate change, the Paris Agreement of 2015, which aims to stay below a global temperature rise of 2°C by 2050 (Brandon & Kurban, 2017). However, when looking at the history of energy transitions, it seems almost impossible to achieve this in such a short period (Fouquet, 2010; Solomon & Krishna, 2011). However, the Intergovernmental Panel on Climate Change (IPCC) provided the world with different pathways for humanity to achieve the goal of the Paris Agreement and realise this energy transition (Rogelj, Shindell, Jiang, Fifita, Forster, Ginzburg, Handa, Kheshgi, Kobayashi, Kriegler, Mundaca, Séférian, &, Vilariño, 2018). The role of governments in this global transition seems to be a crucial element for niches and innovations to be protected in developing new and greener pathways (Fouquet, 2010).

The idea of using hydrogen for establishing new pathways is not a new concept. Already in the 1970s, the potential of hydrogen for transport was acknowledged because of the oil crises, air pollution and acid rain (IEA, 2019). However, when the oil price was lowered again and sufficient measures were taken against air pollution and acid rain, the interest in hydrogen decreased (IEA, 2019). In the 1990s and 2000s, hydrogen interest increased again cause of concerns about climate change and fear of running out of oil (IEA, 2019). The attraction, however, decreased again due to weak climate policies, a declining fear of running out of oil and the rise of battery electric vehicles (IEA, 2019). Since the Paris Agreement in 2015, the interest in hydrogen has increased again. In the agreement, leaders worldwide agreed to join the goal of staying below a global temperature rise of 2°C (Brandon & Kurban, 2017).

The difference between the previous interest peaks and this new momentum is that now it is the first time the world is working together to decarbonise society (Brandon & Kurban, 2017). In this transition, the air quality improvement and the increase in renewable energy support the hydrogen momentum (Odgen, 2018). This is because hydrogen does not emit CO2 when used, and an increase in renewable energy leads to more fluctuations on the energy grid due to intermittency in renewable energy production (Odgen, 2018). Therefore, more flexibility is needed to balance the grid, which hydrogen can offer because it can serve as storage for the produced renewable energy (Odgen, 2018). Hydrogen can thus be made when there is a peak production of renewable energy and later on be converted back to electricity when there is a lack of renewable energy production (Odgen, 2018). Furthermore, this momentum is strengthened by the rapid technological advancement of fuel cell systems (these systems generate electricity or heat) (Odgen, 2018). Finally, the momentum was strengthened by the Russian invasion of Ukraine in 2022, which showed the dependency of the EU on Russian gas (Hosseini, 2022). Therefore, the EU predicts a vital role for hydrogen to decrease the current reliance and increase their energy security as hydrogen can be stored for an extended period (Hosseini, 2022).

2.2 Sustainability of the energy transition

The energy transition towards renewables should increase the sustainability of society. However, renewable energy sources are not always sustainable and can hurt the environment (Harjanne & Korhonen, 2019). Their sustainability can therefore be discussed (Harjanne & Korhonen, 2019). An example of this relates to the discussion around biomass. Despite being a renewable energy source, biomass can harm the environment (Harjanne & Korhonen, 2019). For example, biomass production requires large amounts of plant-based materials that can damage surrounding ecosystems by depleting local resources (Harjanne & Korhonen, 2019). Furthermore, CO2 is emitted during the production of energy from biomass (Harjanne & Korhonen, 2019). Its sustainability can therefore be questioned.

Another discussion relates to solar and wind energy. Even though these sources do not emit CO2 when producing electricity, the overall sustainability can be discussed (Harjanne & Korhonen, 2019). The discussion primarily concerns the raw materials and critical elements needed for constructing wind turbines and solar panels, such as tellurium (Harjanne & Korhonen, 2019). The extraction of those materials often involves a heavily polluting industry, which primarily runs on fossil fuels (Dunlap, 2021). Furthermore, the extraction methods have a devastating impact on their surrounding environment (Dunlap, 2021). Dunlap (2021) mentions the example from a BBC report of Maughan in 2015. Here, Mongolia's Baotou mining and process area are called hell on earth because of the polluting cluttered industries and artificial lakes of black toxic sludge (Dunlap, 2021).

Besides the polluting processes of extracting suitable materials, Rhodes (2019) explains that there are not enough resources of several metals required to install the renewable energy system needed to fulfil the global energy demand by 2050. This indicates the vast need to find replacements for these rare materials. Another issue concerning these materials is the difficulty of recycling and waste management of materials inside solar panels and wind turbines (Dunlap, 2021; Rhodes, 2019). This results in that in some countries, like the USA, the landfill price for a wind turbine blade is lower than recycling (Dunlap, 2021). With solar panels, this is often also the case (Rhodes, 2019).

The previous section showed current discussions and difficulties in realising a global energy transition. Despite the critique of renewable energy, an increase in the share of renewables still seems crucial in the fight against climate change (Nicita et al., 2020). However, these discussions are valuable to realise in the case of hydrogen because if hydrogen wants to be green, it needs to use a renewable energy source for its production (Hermensmann & Müller, 2022).

2.3 The European hydrogen strategy

The EU has been a pioneer and leader in global environmental policy since the early 1990s (Knill & Liefferink, 2021). Looking at earlier energy and climate policies, the EU initiated several policies: The Green Package in 2009, The Climate and Energy framework in 2014 and the Clean Energy for all Europeans package in 2019 (Hafner & Raimondi, 2020). All these policies aimed to reduce greenhouse gas emissions and increase the share of renewable energy and energy efficiency (Hafner & Raimondi, 2020). However, the previously mentioned policies were estimated to only reduce greenhouse gas emissions by 60% by 2050 (Hafner & Raimondi, 2020). Therefore, the Green Deal was created in 2019 to achieve the targets of the global Paris Agreements of 2015 (European Commission, 2019). The EU climate law from the Green Deal, a legal objective, forms the institutionalised basis for its member states and regions to reduce 55% greenhouse gas by 2030 and become climate neutral by 2050

(Fleming & Mauger, 2021; Schlacke, Wentzien, Thierjung, & Köster, 2022). Hydrogen shows the potential to support these targets to realise this transformation (Hafner & Raimondi, 2020). The EU acknowledged this potential, illustrated in the creation of the EU hydrogen strategy in 2020 and the REPowerEU in 2022. Due to the importance of these strategies for Europe's hydrogen development, a summary is given.

EU Hydrogen Strategy	
Phase 1 (2020 -2024)	• 6 GW of installed electrolysis capacity • 1 million tons of green hydrogen production
Phase 2 (2025 – 2030)	• 40 GW of installed electrolysis capacity • 10 million tons of green hydrogen production • Development of Hydrogen Valleys
Phase 3 (2030 – 2050)	▪ Large-scale deployment

Table 1. Overview of the EU hydrogen roadmap, based on the EU hydrogen strategy (European Commission, 2020)

The first phase of the roadmap is from 2020 to 2024. This phase aims to have an electrolysis capacity of 6 GW and produce around 1 million tons of green hydrogen (European Commission, 2020). The projected first off-takers in this phase should be the industries already using hydrogen and some heavy-duty vehicles (European Commission, 2020). A network of hydrogen refuelling stations that run on locally produced hydrogen should be realised to support heavy-duty vehicles (European Commission, 2020). This objective expresses, therefore, the local and regional role in starting the hydrogen economy.

In the second phase, from 2025 – 2030, the goal is to have an installed electrolysis capacity of 40 GW and to produce around 10 million tons of green hydrogen (European Commission, 2020). In this part, the uses should be expanded to, for instance, the steel industry, trains and maybe some maritime applications (European Commission, 2020). Another development related to this research's case selection is that of the Hydrogen Valleys (European Commission, 2020). These are areas (clusters, cities, regions, Etc.) where an integral hydrogen ecosystem should be created and the whole value chain is ideally installed (FCH, n.d.). Another highlight of this phase is the start of the European Hydrogen Backbone, which will form the foundation for European hydrogen development (European Commission, 2020). The hydrogen backbone relates to the plan of different European transmission operators to establish a network of pipelines for hydrogen transportation (European Commission, 2020). One of the goals of this backbone is to connect multiple valleys because it is expected that these regions will be the first movers with a regional hydrogen infrastructure (Gas For Climate, 2020).

In the third phase, from 2030 to 2050, hydrogen should be deployed at a large scale, and the uses should be extended to aviation, shipping and commercial buildings (European Commission, 2020).

Besides the previous strategy, the EU also published the REPowerEU strategy in 2022 due to the current situation in Ukraine (Lonergan et al., 2022). The policy should increase the pace of the European energy transition by becoming less dependent on Russian gas (European Commission, 2022). Therefore, hydrogen's role is getting more critical, which is illustrated by doubling the objective of 10 million tons of hydrogen production by 2030 with an extra 10 million tons from hydrogen import (European Commission, 2022). Another objective is the increase of €200 million for the development of Hydrogen Valleys (European Commission, 2022). An essential role in these plans is the infrastructure to distribute 20 million tons of hydrogen. Therefore, acceleration is needed as cross-border hydrogen infrastructure is still in its infancy (European Commission, 2022). The total costs for the vital infrastructure are estimated to be between €28 and €38 billion and €6 and €11 billion for the storage

(European Commission, 2022).

This section showed the EU's ambition in climate policies and the current momentum for the future implementation of hydrogen. Despite these ambitions, some barriers across the hydrogen value chain still need to be overcome. The following section will therefore explain the hydrogen value chain and its obstacles.

2.4 The hydrogen value chain and its barriers

The hydrogen value chain is essential for this research because green hydrogen is not yet widely deployed or adopted (European Commission, 2020). Therefore, the whole value chain from production to end user needs to be developed (Anajovic & Haas, 2020; Ogden, 2018). For instance, it does not make sense to only install a production facility without having end users. Therefore, the European Commission (2020) states that the whole value chain (production, distribution, storage, and end uses) needs to be addressed and developed simultaneously. However, the literature showed several barriers that hinder the installation of a hydrogen value chain, like the work of Ogden (2018) or Anajovic and Haas (2020). Therefore, understanding the hydrogen value chain and its barriers is essential to this research's approach. Due to its importance, the hydrogen value chain is later used in the conceptual model to improve the entrepreneurial ecosystem theory of Isenberg (2011).

2.4.1. Production

As explained in the introduction section, hydrogen can be produced from renewable energies that are otherwise being curtailed from the energy grid (Verzijlbergh et al., 2017). However, hydrogen can be made from different primary energy sources (Anajovic & Haas, 2020). The most common types of hydrogen are expressed by the colours: grey, blue and green (Van Renssen, 2020; Straatsma, 2021).

The term 'grey' hydrogen is used when hydrogen is produced by natural gas through steam methanol-reforming (Hermensmann & Müller, 2022). This is the most common and cheapest method of producing hydrogen, which is being applied globally in different chemical industries, such as refineries (Anajovic & Haas, 2020). A consequence of this method is that it emits CO2, which is not sustainable (Hermensmann & Müller, 2022). The term 'blue' hydrogen is used when the carbon is captured and stored after hydrogen production by steam methanol-reforming (Hermensmann & Müller, 2022). Blue hydrogen is more sustainable than grey but is still not 100% sustainable (Van den Heuvel, 2020). Hydrogen can be seen as 'green' when it is produced using a renewable energy source, such as solar, wind or biomass (Hermensmann & Müller, 2022). The difference is that blue and grey hydrogen uses fossil fuels as their primary energy source (Straatsma, 2021).

Several techniques can produce green hydrogen, such as gas purification with biomass or electrolysis (Wan, M., Wang, G., Sun, Zhang, & Xu, 2019). This research focuses on electrolysis, the only current mature technology that can convert renewable energy into hydrogen (Anajovic & Haas, 2021). In this technology, renewable energy is used to convert water into hydrogen and oxygen (Straatsma, 2021). For more information about this and other forms of producing hydrogen, this research would recommend the work of Wang et al. (2019), *'Review of renewable energy-based hydrogen production processes for sustainable energy innovation'*.

In 2020, the current production of hydrogen through electrolysis was estimated to be less than 0,1% of the world's total hydrogen production (Ajanovic & Haas, 2020). One reason for this is the high production costs of green hydrogen compared to the other methods (Oliveira et al., 2021). Green hydrogen prices are almost twice that of blue and grey hydrogen (Oliveira et al., 2021). The literature showed several causes for this: Firstly, due to the significant investment costs of the production facility for electrolysis (Ajanovic & Haas, 2020; IRENA, 2020). Secondly, energy gets lost in the production process, which is reflected in its energy efficiency (El-Eman & Özcan, 2019). For example, the Alkaline electrolyser, which is currently the most advanced and used, has an efficiency of between 62% and 82% (El-Eman & Özcan, 2019). In the overall process, the efficiency can even be between 20% and 30%

(Anajovic & Haas, 2020). Lastly, the most cost-cutting in the production of green hydrogen is the high price of renewable energy (Yu, Wang, & Vredenburg, 2021; Zandén Kjellen, 2021). This can sometimes be up to 80% of the total costs (Zandén Kjellen, 2021).

Furthermore, when only depending on renewable energies, there are also times when there is low availability of on-site electricity. Therefore, most hydrogen production facilities need a grid connection, which can also exist out of non-renewable sources, to have enough full-load hours to be more cost-effective (Anajovic and Haas, 2020; Hermensmann & Müller, 2022).

In general, a future decrease in production costs is expected due to increased renewable energies, technological advancements and large-scale green hydrogen production (Greene, Ogden, & Lin, 2020).

2.4.2 Distribution and Storage

One of the main advantages of being an energy carrier is that hydrogen is the only sustainable option for long-term energy storage (Oliveira et al., 2021). In this way, hydrogen offers a solution to the current and future grid congestion due to the intermittency of renewable energy sources (Ogden, 2018). Regarding this supply's distribution, two options were found in the literature. The first option is a network of pipelines (Greene et al., 2020: Ogden, 2018). Realising this would require a considerable investment, as the REPowerEU illustrated, and is more suitable when large quantities of hydrogen are needed (Greene et al., 2020; Ogden, 2018). The second option is by truck (Greene et al., 2020: Ogden, 2018). This option is seen as more suitable when fewer quantities of hydrogen are needed in a region (Greene et al., 2020: Ogden, 2018). However, to be sustainable, it must be transported with a truck that does not emit CO2, such as a hydrogen truck.

There is also a difference in what kind of substance hydrogen is distributed (Ogden, 2018). Hydrogen can, for instance, be distributed as gas or liquid (Ogden, 2018). The consideration between the options is that gas is cheaper and more efficient, but that liquid has a higher energy density (Ogden, 2018). Therefore, the gas option is expected to be more suitable for short distances and the liquid option for long distances (Ogden, 2018). Generally, the better and more efficient the distributing system is, the lower the price of hydrogen will be (Cunanan, Tran, Lee, Kwok, Leung, & Fowle, 2021).

2.4.3 End Uses

This section explains the possible end uses of hydrogen. The introduction mentioned the potential of green hydrogen in the transport and industry sectors. Another potential multiple research address is the use of hydrogen in the building sector (Brandon & Kurban, 2017; Ogden, 2018; Oliveira et al., 2021). These three sectors will therefore be explained in this section.

2.4.3.1 Industry

As explained earlier, grey hydrogen is used in several industries (Anajovic & Haas, 2020). Hydrogen is used here as a chemical feedstock in, for instance, oil refineries, ammonia synthesis and methanol production (Oliveira et al., 2021). 17% of the energy-related industry emissions worldwide come from this grey hydrogen production for chemical synthesis and other industry processes (Oliveira et al., 2021). Besides the previous industries, different industries can also use green hydrogen to replace their current polluting practice (Liu, Zuo, Wang, Xue, Ren, & Yang, 2021; Oliveira et al., 2021). For example, green hydrogen can be used in the steel industry to replace the everyday use of fossil fuels (Liu et al., 2021; Oliveira et al., 2021). Therefore, Green hydrogen can play a vital role in decarbonising industries, which emit a lot of CO2 (Liu et al., 2021; Oliveira et al., 2021). Another argument for green hydrogen use in this sector is that direct electrification from solar or wind energy is impossible in many chemical synthetic processes (Oliveira et al., 2021). Therefore, switching from grey to green hydrogen is the only option for reducing emissions (Oliveira et al., 2021). However, as explained in the production section, green hydrogen is estimated to be twice the price compared to blue and grey. This influences green hydrogen use in those industries (Oliveira et al., 2021).

2.4.3.2 Building sector

The CO2 emissions from the buildings and heating sector are estimated to be 12% of global emissions of CO2 (Oliveira et al., 2021). In this sector, hydrogen can be used in buildings and residential areas, for example, for heat or cooking (Oliveira et al., 2021). Moreover, using hydrogen in existing or new pipelines offers an alternative to the electrification of heat with, for example, heat pumps or solar heating (Brandon & Kurban, 2017). The advantage of using hydrogen is that this can be a stable source. In contrast, these electrification alternatives depend on the intermittency of renewable energies, which can require a behavioural change in society (Brandon & Kurban, 2017). This application is, nevertheless, still in the early phase of developing the right and safe technology for it (Straatsma, 2021).

2.4.3.3 Transport

Another potential for hydrogen is projected to be in the transport sector. In the EU, the transport sector is accountable for a quarter of the total emissions (Tagliapietra et al., 2019). It is the only sector where emissions increase, describing the enormous challenge of becoming climate neutral (Tagliapietra et al., 2019). Hydrogen or hydrogen-based fuels can be used for mobility on land, trains, boats and aviation, which will be discussed in the following sections (Straatsma, 2021).

In 2020, hydrogen road transport accounted for 0.01% of the vehicles being used globally (IEA, 2019). The low percentage can be traced back to the total ownership costs (TCO). This method calculates the business case of, for example, hydrogen truck usage (Jones, Genovese, & Tob-Ogu, 2020). The two most cost-cutting factors in TCO regarding hydrogen road transport are the current high investment costs and the high price of green hydrogen, which can not compete with a conventional diesel truck (Ajanovic & Haas, 2020). For example, the price of a fuel cell truck (hydrogen) is 2.6 to 3.4 times higher (Westport Fuel Cell Systems, 2021). However, the future investment costs of hydrogen vehicles are expected to drop due to technical improvements and a lower price for green hydrogen (Brandon & Kurban, 2017). Another development that influences the uptake of hydrogen vehicles is the competition with battery electric vehicles (Straatsma, 2021). In general, hydrogen vehicles have a more extended range and a faster refuelling time, which makes them potentially more suitable for long distances (Anajovic & Haas, 2020). Therefore, hydrogen is expected to have the most potential for heavy-duty vehicles that need to cover these long distances (Oliveira et al., 2021). On the other hand, battery electric vehicles will probably be the best alternative for short distances (Oliveira et al., 2021). Trains, ships and aviation running on hydrogen are still in an early stage of development (Brandon & Kurban, 2017; Straatsma, 2021). Despite this, hydrogen can be used as a basis for low-carbon or other synthetic fuels to decrease emissions. The production costs of these synthetic fuels are seen as the main barrier (Straatsma, 2021).

The chicken egg problem is a general term used in the literature to describe the difficulty of implementing hydrogen in the transport sector (Brandon & Kurban, 2017; Van den Heuvel, 2020). This problem illustrates the mutual interdependency between refuelling stations and hydrogen cars; Van den Heuvel (2020) explains this as follows: *''These circumstances create a lock-in situation, vehicles are not bought because of a lack of filling stations and filling stations are not built because of a lack of vehicles or customers'' (p.4).* Here, the complex relationship in the hydrogen development between the production, distribution and use becomes clear. A long-term policy framework that supports hydrogen development and removes the barriers is regarded as necessary to overcome these barriers (Brandon & Kurban, 2017; Ogden, 2018).

2.4.4 Overview Barriers

From the previous sections, table 2 was created to give a clear overview of the discussed value chain and its barriers.

Supply chain	Barrier
Production	➢ The high costs production facility ➢ The high price of renewable energy ➢ Having enough full-load hours
Distribution and Storage	➢ The high costs of creating infrastructure
End Use	➢ The high investment costs ➢ The high price of green hydrogen ➢ Chicken egg problem

Table 2. Overview of hydrogen barriers

3. Theoretical framework

This chapter will explain the theoretical foundation used to analyse the different cases. This section will begin by providing a better understanding of the trajectory of adopting innovations, such as green hydrogen. This is done using the theories of Geels (2011) and Rogers (1995, Matinaro & Lui, 2015). Subsequently, the ecosystem theory of Isenberg (2011) will be explored to elucidate elements conducive to developing a hydrogen ecosystem.

3.1 Development trajectory of sustainable innovations

3.1.1 Multilevel perspective

The multilevel perspective of Geels (2011) is used to understand the development of sustainable innovations in society. The model is shown below in figure 1. In Geels' (2011) model, shown in figure 1, the following three main concepts are used: 1. Landscape 2. Regime 3. Niche innovations. The model's primary focus is on how niches can become part of the regime (Geels, 2011). This model describes niches as protected spaces where radical innovations can develop (Geels, 2019). In these niches, internal momentum is built up through internal drivers, such as price/performance improvements or support by powerful actors (Geels, 2019). A regime can be described as the mainstream system where society lives (Geels, 2019). This stable system is hard to change because of multiple lock-in mechanisms (Geels, 2019). Examples of this are; sunk investments or existing regulations that favour the current regime (Geels, 2019). Finally, the landscape can be described as the external context of slowly changing developments or shocks, such as wars (Geels, 2019).

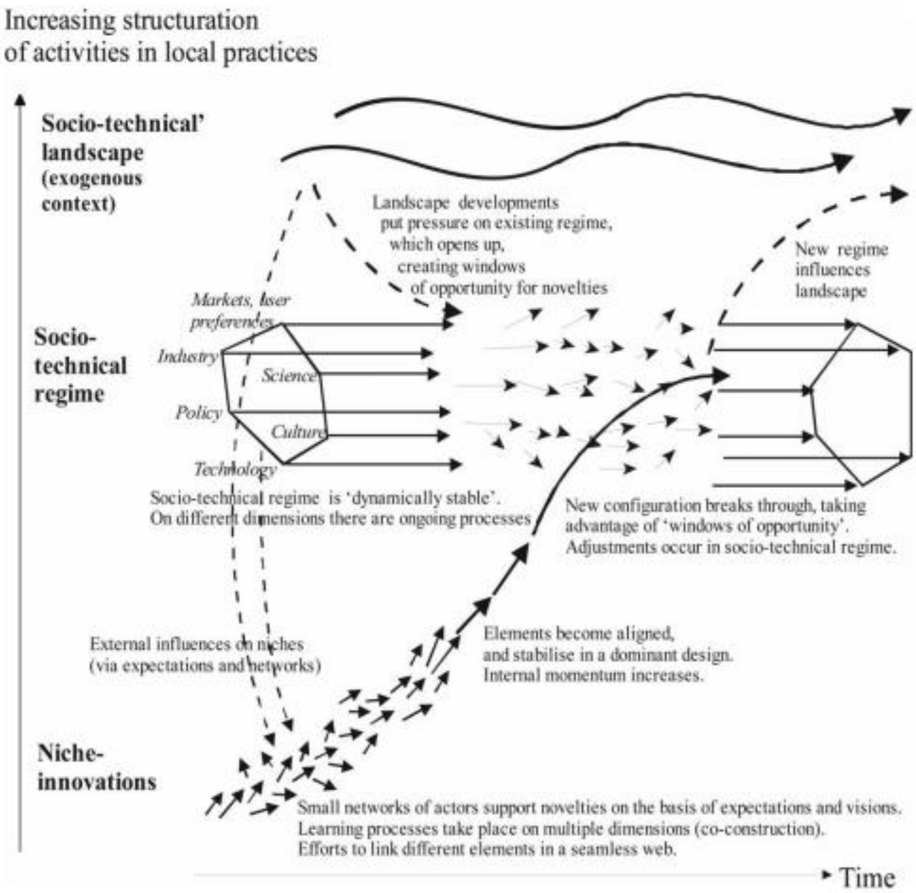


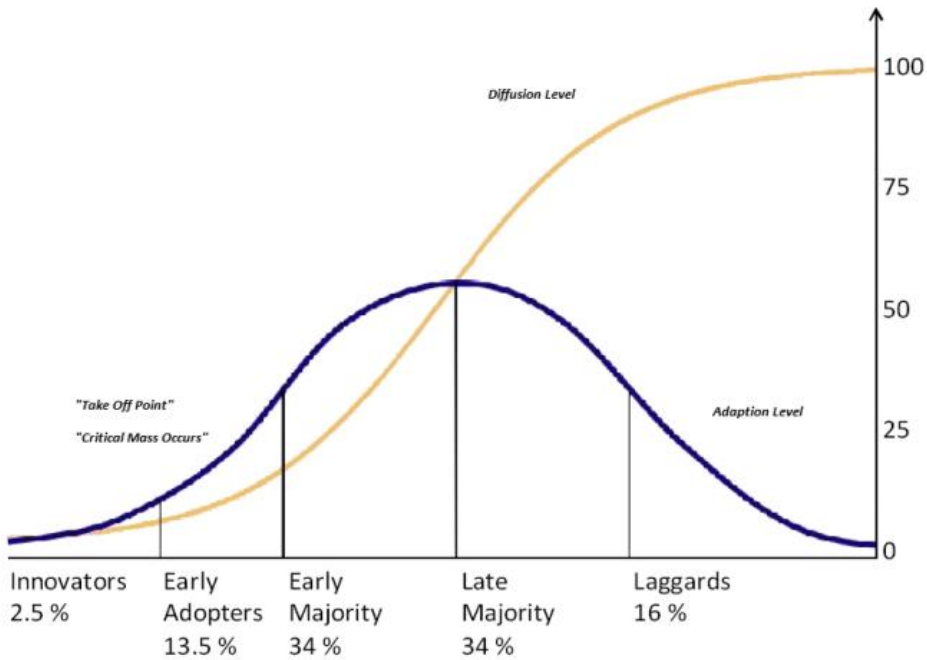
Figure 1. Multilevel perspective (Adapted from Geels, 2011)

For a transition to happen, the landscape cracks open the regime to create a window of opportunity (Geels, 2011). In this momentum, niches can use their internal momentum and become a part of the new regime, thereby changing the mainstream system with their innovation (Geels, 2011). For example, a cheap hydrogen car that can compete with a fossil fuel car can change the existing regime of fossil-fuelled vehicles, as more people would buy a hydrogen car.

The literature review already explained that there is a new momentum for hydrogen due to climate change and the current situation in Ukraine. Therefore, the research uses Geels' (2011) multilevel perspective as a theoretical foundation, focusing on the hydrogen trajectory as a niche toward the regime during this momentum. The next part will discuss innovation adoption in more detail to examine this trajectory.

3.1.2 Diffusion of innovation

Innovations can be described as something perceived as new by an individual (Sahin, 2006). In his research, Sahin (2006) states, '' *An innovation may have been invented a long time ago, but if individuals perceive it as new, then it may still be an innovation for them'' (p.14).* Therefore, green hydrogen can be perceived as something new, as it only counts for less than 0,1% of the world's total hydrogen production (Ajanovic & Haas, 2020). Another aspect of innovations is that they are constantly introduced in different places. Still, not all are capable of taking advantage of their momentum and becoming part of the new regime (Geels, 2011). This research will use the theory of Rogers (1995, in Matinaro & Lui, 2015) to describe this. Figure 2 is therefore used to illustrate and explain the trajectory of the adoption of innovations.



Group	Explanation
Innovators	Venturesome actors that like to take a risk (Orr, 2003)
Early Adopters	Actors that make a well-informed decision based on the data from the results of the innovators (Orr, 2003)
Early Majority	Actors that are prudent and want to avoid risk. They are open to innovations that can improve their practice if the innovations are proven (Kaminski, 2011)
Later Majority	Actors that are cautious and respond to peer pressure. The innovation needs to be bulletproof (Kaminski, 2011)
Laggards	Actors that are more traditional or isolated and suspicious of innovation (Orr, 2003).

Figure 2. Rogers' diffusion of innovation curve with an explanation of the five groups (Modified by Matinaro & Liu, 2015, from Rogers, 1995, p.262)

In figure 2, there are five groups illustrated and explained: 1. Innovators 2. Early adopters 3. Early majority 4. Late majority 5. Laggards. An essential element in this model is the critical mass needed for an innovation to take off and become widely adopted (Matinaro & Liu, 2015). In the case of high-tech innovation gaps, Moore (1991) argues that chasms occur between the different groups. Chasms can be defined as gaps between the various groups that illustrate the challenges of innovation to become more widely adopted (Moore, 1991). For example, suppose an innovation wants to go from innovators to early adopters. In that case, there will be specific barriers, like technical uncertainties, that the invention needs to overcome before it can go to the next stage of early adopters. Otherwise, the chasm ensures that the innovation is not adopted and stays in the same category (Moore, 1991). Matinaro and Lui (2015) argue that the most significant chasm is before the point of take-off when the critical mass is needed for the innovation to survive and become commercial. Concerning hydrogen, the current barriers can also be regarded as a chasm that hinders several hydrogen innovations from taking off.

While figure 2 provides a better understanding of the adoption and diffusion of innovation, there are some critical remarks. Firstly, the chart does not include the influence social systems and norms can have (Rogers, 1995, in Matinaro & Lui, 2015; Van den Heuvel, 2020). Secondly, the graph does not include the influence of the usefulness of an innovation (Rogers, 1995, in Matinaro & Lui, 2015; Van den Heuvel, 2020). For example, the adoption of hydrogen will increase when individuals perceive it as an advantage compared to other alternatives. The previously mentioned reasons show the importance of context-related elements influencing adoption. An entrepreneurial ecosystem theory is used to provide the research with this context, which will be explained in the next section.

3.2 Entrepreneurial Ecosystem

For hydrogen to develop from a niche toward the regime, the most significant chasm before the take-off must be overcome to increase the adoption and diffusion of hydrogen. Therefore, this research considers it essential to develop an innovative and supportive environment in which hydrogen can flourish. Theories about entrepreneurial ecosystems were identified to support this. This is because entrepreneurial ecosystems can focus on one sector, for example, hydrogen, and are all about developing a supportive or conducive environment for that sector (Mason & Brown, 2014).

3.2.1 Nature of ecosystems

Before moving on to the entrepreneurial ecosystem, this section will briefly describe the nature of an ecosystem to get a better understanding of its complex system. In the publication of Stam and Van de Ven (2019), they use the three core elements from the research of Hawley (1950) about organisational community ecology to describe this. These elements are *co-evolution*, *mutualistic interdependence* and *complex nested systems*. An ecosystem is defined here as a complex system with multiple actors that all play a role in sustaining the ecosystem (Stam & Van de Ven, 2019). Every actor has his practice but is also mutually interdependent on other actors. For example, entrepreneurs develop mutualistic financial interdependencies with investors or mutual knowledge interdependencies with research institutions (Stam & Van de Ven, 2019). Because of these mutualistic interdependencies, an ecosystem is a complex system that focuses on the co-evolution of actors that can rise or fall together (Stam & Van de Ven, 2019). The role of other actors, like universities or governments, is therefore perceived as vital (Brown & Mason, 2017). These core elements also reflect the difficulties in realising a hydrogen value chain, for example, the previous interdependency between hydrogen transport and refuelling station (Van den Heuvel, 2020). Because one cannot develop without the other, they need to co-evaluate to reach the take-off point. Therefore, an ecosystem theory supports the research by exploring this complex system where co-evolution and mutualistic interdependencies play an essential role in establishing a hydrogen value chain.

3.2.2 Entrepreneurial ecosystem

Due to a broad range of studies, such as those by Isenberg (2011), Maroufkhani, Wagner, & Wan Ismail (2017) and Stam (2015), there is not a single definition of an entrepreneurial ecosystem. Despite this, the research chooses to use the description of the study of Isenberg (2011) based on the following arguments. Firstly, Isenberg (2011) is one of the most influential works about entrepreneurial ecosystems in geographical research (Malecki, 2018). Secondly, the theory provides the study with a comprehensive set of domains and subdomains for exploring the cases. The definition defined by Isenberg (2011) is as follows:

> *This entrepreneurship ecosystem consists of a dozen or so elements [...] that, although they are idiosyncratic because they interact in very complex ways, are always present if entrepreneurship is self-sustaining. So although the combinations are always unique, in order for there to be self-sustaining entrepreneurship, you need conducive policy, markets, capital, human skills, culture, and supports (p. 6).*

This conducive environment Isenberg (2011) is talking about is also something that, according to Maroufkhani et al. (2018), is needed for entrepreneurship to innovate and flourish. The idea of this environment can be traced back to former economic geography clustering theories where the focus was on social, cultural and institutional elements, such as the work by Saxenian (1996) about science and technology parks (Maroufkhani et al., 2018). The entrepreneurial ecosystem complements these previous studies by creating an ecosystem that enables new concepts and business models (Maroufkhani et al., 2018). The publication of Isenberg (2011) explains the following domains, shown in table 3 and described below.

Domains	Subdomains
Policy	➢ Government ➢ Leadership
Finance	➢ Financial capitals
Culture	➢ Success Stories ➢ Societal norms
Supports	➢ Infrastructure ➢ Support professions ➢ Non-government institutions
Human capital	➢ Labour ➢ Educational institutions
Markets	➢ Early customers ➢ Networks

Table 3. Ecosystem domains and subdomains based on the entrepreneurial ecosystem from Isenberg (2011).

The first domain refers to the policy domain divided into the subdomains of government and leadership. The subdomain government explains the governance to remove the barriers influencing entrepreneurship and the creation of stimulation institutions, such as research institutions (Isenberg, 2010; Maroufkhani et al., 2018). The subdomain leadership refers to strong public support and embracement of entrepreneurship (Isenberg, 2010; Maroufkhani et al., 2018).

The second domain relates to the finance domain, in which the subdomain of financial capital refers to the available finance for entrepreneurs (Isenberg, 2010; Maroufkhani et al., 2018).

The third domain relates to the culture domain. This domain exists in two subdomains, success stories and societal norms. Success stories are stories that inspire others and that serve as role models (Isenberg, 2010; Maroufkhani et al., 2018). Societal norms are about the acceptance in society of risk and failure that characterises entrepreneurship and innovation (Isenberg, 2010; Maroufkhani et al., 2018). Generally, a culture must accept entrepreneurship (Isenberg, 2010; Maroufkhani et al., 2018).

The fourth domain relates to the support domain, where the subdomains are infrastructure, support professions and non-government institutions. The infrastructure refers to the necessary infrastructure for entrepreneurs to perform (Isenberg, 2010; Maroufkhani et al., 2018). The support professions, such as technical experts, support the entrepreneurs on a contingency basis (Isenberg, 2010; Maroufkhani et al., 2018). Lastly, the non-government institutions relate to non-profits that help entrepreneurs network and promote entrepreneurship (Isenberg, 2010; Maroufkhani et al., 2018).

The fifth domain entails the human capital domain. This relates to the two subdomains of labour and educational institutions. Labour is explained here as having entrepreneurs with the right experience, knowledge and skills (Isenberg, 2010; Maroufkhani et al., 2018). Educational institutions refer to available entrepreneurship programs (Isenberg, 2010; Maroufkhani et al., 2018).

Lastly, the sixth domain entails the market domain. This domain has two subdomains, early customers and networks. Early customers relate to potential customers, and a network refers to linking entrepreneurs in a country or region (Isenberg, 2010; Maroufkhani et al., 2018).

3.2.3 Critique

Although entrepreneurial ecosystems have become popular, there are also critiques. Firstly, it is not clear what the best geographical scale for the analysis is (Stam, 2015). However, the regional scale seems appropriate as it is mentioned in multiple publications about entrepreneurial ecosystems, such as Spigel (2017) and Mack and Mayer (2015). Secondly, there is a lack of apparent cause-and-effect reasoning between the factors (Stam, 2015). The approach of Isenberg (2011) provides the research with relevant domains but not with a clear sense of cause and effect between the fields (Stam, 2015). This study tries to improve this clear reasoning by focusing on the entire hydrogen value chain to acknowledge this critique. An example of this could be that this can show the cause and effect of the lack of physical infrastructure (support domain) on the early customers (market domain). Lastly, Stam (2015) explains that the concept is tautologic, which is not always the case. This indicates that successful entrepreneurship occurs when there is an excellent entrepreneurial ecosystem and that an excellent entrepreneurial ecosystem results in successful entrepreneurship (Stam, 2015). Therefore, this research is aware of this critique and considers that where there are thriving hydrogen ecosystems in the explored regions, this does not automatically mean that there is also successful hydrogen activity and the other way around.

Besides the previous critiques, a discussion point may arise about the absence of an innovation element, whereas earlier, its importance was discussed for overcoming barriers. Entrepreneurial ecosystems play, however, a vital role in the early stages of innovation toward commercialisation (Dedehayir, Mäkinen, & Roland Ortt, 2018). This is because the ultimate outcome of entrepreneurial ecosystems is innovations that create new value in society (Stam, 2015). This element is, therefore, not present within the domains but is regarded as vital as it entails the outcome of the ecosystem. Moreover, innovation is essential to the case selection process, substantiated in 5.3.2.1.

4. Conceptual model

4.1 Conceptual model

This study combines three theories, Geels (2011), Isenberg (2011) and Rogers (1995, in Matinaro and Liu, 2015), in the conceptual model shown in figure 4. The previous chapter explained the theories that are the theoretical foundation of this research. The first theory from Geels (2011) is used to focus on the transition of hydrogen from a niche innovation toward the regime level during this hydrogen momentum, which is explained in the literature review. Therefore, the choice is made to take that influence as a given. The diffusion of innovation theory of Rogers (1995, in Matinaro and Liu, 2015) is used to complement the approach of Geels (2011) by zooming in on the trajectory of innovations in society. The theory of Rogers (1995, in Matinaro and Liu, 2015) shows that in the development of hydrogen, barriers must be overcome before hydrogen can reach its take-off point and become widely adopted in the regime. However, a conducive environment must be created where hydrogen can flourish to overcome these barriers. The entrepreneurial ecosystem theory from Isenberg (2011) provides the research with relevant factors to explore this.

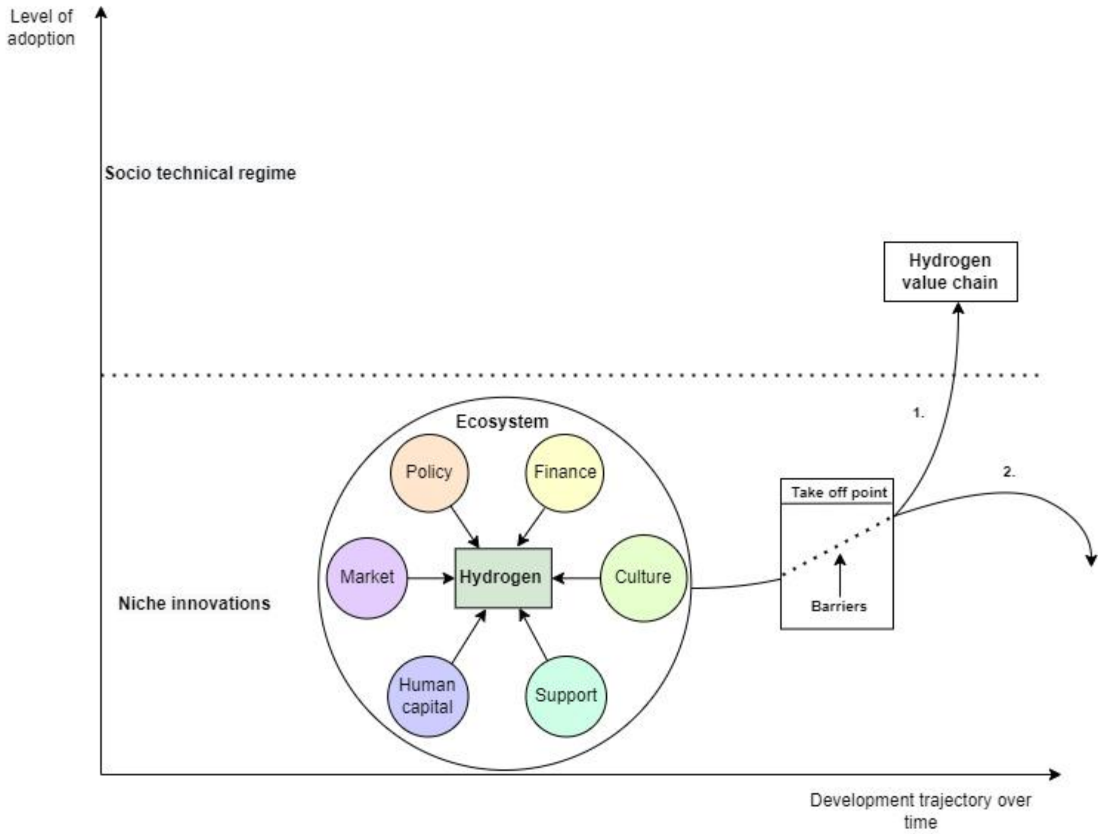


Figure 3. The conceptual model based on a combination of Geels (2011); Isenberg (2011); Rogers (1995, in Matinaro and Liu, 2015);

In the conceptual model, the ecosystem circle shows the current position of hydrogen as a niche innovation, indicating that it is not yet widely used or adopted. The ecosystem of Isenberg's (2011) six domains that influence hydrogen development and need to be present to create a self-sustaining hydrogen ecosystem are illustrated here. It is essential to mention here that, just as in the original model of Isenberg (2011), these domains are idiosyncratic, meaning they can all influence each other (Isenberg, 2011). The choice is made to illustrate them just as in the original model of Isenberg (2011). Otherwise, the model would be too cloudy with arrows, making it less clear.

Due to developments in the hydrogen ecosystem, the ecosystem can develop over time towards its take-off point. However, just as in the theory of Rogers (1995, in Matinaro and Liu, 2015), the barriers can hinder the take-off of hydrogen as it did in previous momentums. Arrows 1 and 2 illustrate the different pathways of this trajectory. Arrow 1 shows that the hydrogen ecosystem has created a conducive environment where the barriers are minimised. Hydrogen reaches its take-off point and can develop from a niche towards the regime. Arrow 2 illustrates that the ecosystem has not yet developed a conducive environment to overcome the barriers. Therefore, it must improve to overcome the obstacles and reach the take-off point. Thus, the trajectory of arrow 2 is followed, and hydrogen stays a niche innovation.

The following fictive example is used to clarify the model: The subdomain of leadership in the policy domain shows support for hydrogen development. The hydrogen ecosystem can, however, not take off because of the barriers. For example, the high production costs, the absence of infrastructure and no potential end users of hydrogen. The barriers causing that arrow 2 is followed, and hydrogen stays a niche. As a response, the policy domain can interact with the finance and support domains by making hydrogen production more attractive. This could be by funding or investing in the realisation of a hydrogen value chain. As a result, the market domain shows potential early customers for the end use of hydrogen. The last barriers are minimised through these interactions, and hydrogen can take off. Consequently, the trajectory of arrow 1 is followed towards the realisation of the hydrogen value chain.

The outcome of this hydrogen ecosystem would be the realisation of the entire hydrogen value chain. This is because hydrogen needs the whole value chain from production to end users to become more widely adopted (European Commission, 2020). Especially in its early stage, where there is also no other extensive ecosystem to connect to and where the created value will otherwise be limited. For example, producing lots of green hydrogen but not having end users using it.

4.2 Operationalization for the exploration

Section 3.2.2 explained the domains and subdomains of the entrepreneurial ecosystem of Isenberg (2011). In this section, the operationalisation is based on these descriptions from Isenberg (2010) and Maroufkhani et al. (2018). However, some explanations were regarded as too general or not yet clear enough. Therefore, this section will provide, when necessary, some more clarification. In the end, table 4 provides an overview of the overall operationalisation.

Firstly, the policy domain explores the subdomains of government and leadership (Isenberg, 2010; Maroufkhani et al., 2018). In the case of the subdomain government, this research will explore the national hydrogen policies. The national policy will be examined because creating such a strategy is necessary to remove the barriers to hydrogen development, according to the literature (Brandon and Kurban, 2017; Ogden, 2018). Moreover, examining national policies will give each case the proper context before going into detail about the regions. For the subdomain leadership, the choice is made to explore the regional hydrogen ambitions and policies to analyse the public support and embracement of hydrogen. The role of ambition in leadership is seen as significant as this causes more effective leadership, which can improve a region's development (Zuo, Harms, Landay & Wood, 2022).

Secondly, the finance domain will explore the available finance by looking at private finance and public funding for hydrogen. Isenberg (2010) and Maroufkhani et al. (2018) relate public funding to the government domain. However, this research uses it in finance to better understand the balance between private and public finance.

Thirdly, the cultural domain is divided into the subdomain's success stories and societal norms (Isenberg, 2010; Maroufkhani et al., 2018). In these subdomains, hydrogen success stories and the general acceptance of hydrogen will be explored.

Fourthly, the support domain exists of the subdomains infrastructure, support professions and non-government institutions (Isenberg 2010; Maroufkhani et al., 2018). In the infrastructure subdomain, the availability of the necessary infrastructure needed for hydrogen will be explored. In the subdomain of support professions, occupations that can support hydrogen development will be looked at. In the non-government institutions, the non-profits that help the hydrogen businesses with networking and promoting hydrogen are explored.

Fifthly, the human capital domain exists of subdomains labour and educational institutions (Isenberg 2010; Maroufkhani et al., 2018). The subdomain labour will explore the availability of a workforce with the proper knowledge to work in the hydrogen industry. This show similarities with the support professions subdomain in the support domain. To clarify this more, the choice is made to explore only the availability of the workforce here and the type of expertise in the subdomain support professions.

Lastly, the market domain exists of the subdomain's early customers and networks (Isenberg 2010; Maroufkhani et al., 2018). In the subdomain of early customers, there will be an exploration of potential first off-takers for hydrogen. In the subdomain networks, the role of networks that link hydrogen businesses in a country or region is explored. This subdomain shows similarities with the subdomain of non-government institutions in the support domain. Therefore, the choice is made to discuss this element in the market or support domain, based on the data analysis to determine where it fits best.

Domains	Sub-Domains	Exploration of
Policy	➢ Government	➢ National hydrogen strategy
	➢ Leadership	➢ Regional ambitions and hydrogen policy
Finance	➢ Private Finance	➢ Role of private investments in hydrogen
	➢ Public funding	➢ Role of public funding for hydrogen
Culture	➢ Success Stories	➢ Success stories about hydrogen that can inspire others
	➢ Societal norms	➢ The acceptance of hydrogen innovations in society.
Supports	➢ Infrastructure	➢ The presence of the necessary infrastructure for hydrogen
	➢ Support professions	➢ Professions can support the hydrogen development
	➢ Non-government institutions	➢ Non-profits that help hydrogen businesses network and promote hydrogen
Human capital	➢ Labour	➢ People with the proper knowledge and skills.
	➢ Educational institutions	➢ Educational programs about hydrogen
Markets	➢ Early customers	➢ Potential first-off takers of hydrogen.
	➢ Networks	➢ Networks that link hydrogen businesses to each other

Table 4. Operationalisation of the ecosystem domains and subdomains of the entrepreneurial ecosystem from Isenberg (2011), based on the descriptions from Isenberg (2010) and Maroufkhani et al.,(2018).

5. Methodology

This chapter explains the methods that the research used. These methods will clarify the steps taken to collect the data to provide a clear answer to the research question. The chapter starts with the research philosophy and will discuss the theoretical approach, research methods and the quality of the research design.

5.1 Research Philosophy

The research philosophy consists of the researcher's fundamental beliefs, which are constituted from ontology and epistemology concepts. The idea of ontology refers to the question of how we perceive reality. The concept of epistemology refers to the question of how knowledge is created (Moon and Blackman, 2014). These are essential aspects of the research process because they influence the research methodology, strategy, data collection, and analysis procedure (Saunders, Thornhill, & Lewis, 2019). In ontology and epistemology, two concepts can be distinguished; objectivism and subjectivism (Saunders et al., 2019). This research conducted multiple interviews with different actors within the hydrogen ecosystem to explore the construction of reality. Therefore, the reality is not perceived as if there is only one reality but as something composed of different realities of the respondents. In ontological terms, this refers more to subjectivism, which indicates multiple realities (Saunders et al., 2019; Guba & Lincoln, 1994). These different realities suggest that the research is difficult to generalise or measure because each respondent has a different reality. In epistemology, this also relates to subjectivism instead of objectivism (Moon & Blackman, 2014). Instead of generalising, subjectivists are interested in the opinions and narratives of different actors (Saunders et al., 2015). The context plays a vital role in subjectivism to better understand the multiple realities (Saunders et al., 2015).

Constructivism is used here as research philosophy, as this relates to the previously mentioned subjective nature of the research. In constructivism, the reality consists of multiple individuals, where knowledge is created through the interaction between the researcher and the respondents (Guba & Lincoln, 1994). The inquiry aim of constructivism is to have a better understanding and reconstruction of the situation (Guba & Lincoln, 1994). Concerning the explorative character of this research, constructivism is regarded as a sufficient basis for the methodology.

5.2 Theoretical Approach

This section is about the theoretical approach of the research, where the focus is on the terms inductive, deductive, and abductive (Saunders et al., 2015). In the study of Saunders et al. (2015), they make the following distinction between the terms:

<u>Inductive</u>: "Generalizing from the specific to the general." (p.153)

<u>Deductive</u>: "Generalizing from the general to the specific." (P.153)

<u>Abductive</u>: "Generalizing from the interactions between the specific and the general." (P.153)

This research uses both a deductive and an inductive approach. The deductive approach is indicated by using the domains and subdomains of the entrepreneurial ecosystem of Isenberg (2011) as a starting point for collecting the data. On the other hand, this research also uses an inductive approach by creating more knowledge about using an entrepreneurial ecosystem for hydrogen, which relates more to the logic of an inductive approach (Saunders et al., 2015).

5.3 Research methods

5.3.1 Methodological choice & research strategy

This research used qualitative methods to gather data and information. Qualitative methods study the participant's meanings and interactions to enrich the theoretical contribution of the research (Saunders et al., 2015). Thus, multiple qualitative techniques, such as interviews and desk research, were used to extract the correct data.

The research strategy links the philosophy and the data collection methods (Saunders et al., 2015). The approach that this research used is the multiple case study. A case study looks at the context and interactions within the case, wherefrom the researcher tries to make sense of the complex reality (Saunders et al., 2015; Yin, 2003). Therefore, understanding the context of a case study is seen as fundamental (Saunders et al., 2015). In collecting and analysing the data to provide a sufficient answer to the research questions, the case study supports the research in exploring and understanding the different cases.

5.3.2 Data collection

This section explains the data collection for this qualitative research in chronological order. It is essential to mention that this research was conducted during an internship at the regional development agency Oost NL, which represents the provinces of Gelderland and Overijssel in the Netherlands. As a development agency, the focus is on small and medium enterprises in the region. Oost NL has been involved in several projects where hydrogen could play a role and supports multiple hydrogen businesses. An example of this is their involvement in realising smart energy hubs in the region, where hydrogen, for example, offers a solution to utilise the excess of renewable energy, as the idea is in business park Hessepoort in the province of Overijssel (Oost NL, 2021). Another example is their investment in the local company HyGear (Oost NL, 2019). Despite their current activity, the organisation wanted to learn from hydrogen developments in other European regions and compare them with their regional hydrogen development. Due to the time constraints and page limit, it was impossible to include that in this research. However, in section 8.3, recommendations for Oost NL are given regarding this.

Throughout the data collection, the research excluded literature regarded as too 'old' concerning hydrogen. The criteria for this is literature that is published before 2015. The study made this choice because, in 2015, the Paris Agreements were established (Brandon & Kurban, 2017). The agreement strengthened the political interest in renewables and, thereby, in flexible storage solutions, which hydrogen is an example of (Brandon & Kurban, 2017). Another reason for this concerns the fast developments and transformations within the energy sector. For example, the recent RepowerEU policy showed that the targets for green hydrogen production in the year 2030 are doubled because of the current Russian invasion of Ukraine (European Commission, 2022). Another example can be found in the electrolysis facility's costs, which decreased by 50% in the last five years (Sadik-Zaka, 2021). The research, therefore, regards it as essential to use recent literature to have the latest information and updates.

5.3.2.1 Case selection

Case selection is a vital part of the data collection because it determines from which regions the research collected its data. However, there is no answer to selecting the correct number of cases (Creswell, 2013). Schoonwater's (2019) thesis from Radboud University mentions that having more than three cases is not feasible because of time constraints. This research acknowledges these constraints and selected three regions to gain profound insight into developing hydrogen ecosystems within the EU.

In the case selection, several steps were followed to have a well-substantiated selection of cases. The first step was to select regions part of the European Hydrogen Valley Partnership. This partnership wants to support the development of the technological readiness and commercial availability of hydrogen applications (S3 Platform, 2021). Therefore, the partnership consists of interregional collaboration and thematic working groups (S3 Platform, 2021). Additionally, the valleys are regarded as the first movers in realising regional hydrogen networks (Gas For Climate, 2020). In the valleys, the goal is to have an integrated hydrogen ecosystem within a geographical area, which could be a city, region, or industrial space (FCH, n.d.). The focus is to apply the whole value chain approach in the region (FCH, n.d.). Furthermore, the participants are expected to be active stakeholders in the hydrogen development of the EU (S3 Platform, 2021). The partnership characteristics are, therefore, good criteria for selecting the participating regions as a starting point.

However, the hydrogen valley partnership nowadays consists of 60 regions. Desk research, two exploring interviews with experts working in the field of hydrogen were conducted, and experts within the internship organisation were consulted to decrease the number of regions. The desk research was performed to verify the hydrogen ambition of the regions. Therefore, the study searched for policy documents and hydrogen activity within the areas, such as (planned) projects. The research used Google, Google Scholar, and the Hydrogen Valley Platform to search for these. Two choices were made to narrow the search results on Google and Google scholar. The first choice was to only search with the word green hydrogen. The second choice was to use the different stages of the hydrogen value chain, such as green hydrogen production or the distribution of green hydrogen. This way, literature and projects across the value chain were found. Besides retrieving more knowledge about hydrogen development in the EU, the two explored interviews were used to ask the respondents about interesting areas for this research. In addition, experts within the organisation were consulted about potential countries, regions, and projects. They provided the study with some guidance. However, they are in an exploring stage themselves where they want to use this research to retrieve more knowledge about other European regions. From the desk research, interviews, and consulted experts, a selection of areas was made, as shown in Table 5.

Regions	Country
Aragon	Spain
Brittany	France
Normandy	France
Nordrhein-Westfalen	Germany
Lower Saxony	Germany
Hamburg	Germany
North Jutland	Denmark
Gävleborg	Sweden
Møre og Romsdal	Norway

Table 5. Selection of regions

In the next step, the choice was made to choose regions from different countries. Because in the case study, the context is important (Saunders et al., 2015; Yin, 2003). However, when the cases are within the same country, this research regards the possibility of partially having the same context. For example, when looking at the finance or regulations, which are primarily nationally arranged. The study, therefore, regards it as better to use cases from different countries to enrich knowledge creation.

After that, the choice was made to select the regions Brittany, Lower Saxony, and North Jutland because of the results of the previously desk research and the responses or nonresponses of the areas listed in table 5. The desk research existed of the following information. In the case of North Jutland, their regional capital of Aalborg has been a pioneer in sustainable development since 1994 (European Commission, 2015). Moreover, Aalborg and the region are sometimes characterised as the Silicon Valley of green innovation (Green Hub Denmark, n.d.). The last reason was found in Denmark's national strategy, where hydrogen is an essential element for the region's development of a commercial beacon for Power-to-X (PtX) and Carbon Capture and Utilisation (CCU) (Danish Energy Agency, 2021). In the case of Brittany, the region already launched its roadmap for hydrogen in 2020. The region intends to become a leading region in hydrogen applications (Region Bretagne, 2020). In the case of Lower-Saxony, they already launched a hydrogen strategy together with the other northern regions back in 2019 (Wirtschaftsministerien, 2019). Furthermore, Lower Saxony is Germany's number one energy state, and they also want to become a central region for hydrogen in Germany (NWN, 2022e). Besides the previous desk research, the study also had to estimate if, within a region, enough data could be collected through interviews. In total, 20 emails divided over the areas in table 5 were sent to respondents based on Isenberg's entrepreneurial ecosystem (2011), for example, policymakers or hydrogen companies. The research regarded the three selected regions most suitable from the response and no response.

A final check was made by applying the Regional Innovation Scoreboard (RIS) of the European Commission (2021) to look at the innovative character of the regions. This choice was made because innovation is essential in green hydrogen development. The innovation index consists of the following categories: emerging innovator, moderate innovator, strong innovator and innovation leader. The regions Brittany and North Jutland are categorised as strong innovators. The region of Lower Saxony is split up into multiple districts where the index fluctuates between moderate innovators and innovation leaders. The previous shows that all the regions have an innovative character.

5.3.2.2 Interviews

The primary source of data collection was by conducting 25 semi-structured interviews. The internship organisation played a critical factor in collecting this data, as the email for potential respondents was sent using the organisation's email account, which increased the trustworthiness and value of the email. This probably led to a higher response than when a private email was used. In making a proper selection for the interviews, the choice was made to interview different types of actors present in Isenberg's entrepreneurial ecosystem (2011). Furthermore, the snowball method was applied by asking respondents if they knew other relevant actors to interview. This way, the research tried to better understand the different perspectives within an ecosystem until the saturation point. When the saturation point is reached, new interviews will give no further information (Saunders et al., 2015). However, no exact number of interviews need to be conducted to reach this point (Saunders et al., 2015). Despite that, this research strived to have a minimum of five interviews per case from different ecosystem domains.

Additionally, the study conducted two interviews with hydrogen experts from the EU level, as this research is written in an EU context. Therefore, it was regarded as essential to retrieve some information on it. Table 6 gives an overview of the full interviews per case. From table 6, looking at the quantities of the interviews, it seems that Lower Saxony is maybe less explored than the others. However, including the duration and collected data from the interviews, this difference between the cases was no limitation in the data analysis.

Case	Interview total	Organisation type	Domain
North Jutland	2	Incubator	Support
	2	Business	Market
	2	Business Developer	Support
	1	University	Human capital
	1	Network	Support
	1	Utility company	Support
Total	**9**		
Brittany	4	Businesses	Market
	2	Government	Policy
	1	University	Human capital
	1	Business Developer	Support
Total	**8**		
Lower Saxony	2	Network	Support
	1	Utility company	Support
	1	Research Centre	Human capital
	1	Research Institution	Policy
	1	Utility Company	Market
Total	**6**		
EU	2	Government	Policy
Total	**2**		

Table 6. Interview Overview

At the end of the research process, four respondents from North Jutland, four from Brittany, three from Lower Saxony, and two from the EU were mailed with follow-up questions. These questions had two purposes: Firstly, throughout the transcription and analysis process, unclarities arose about some arguments, where additional information was necessary to avoid misinterpreting statements. Secondly, the research used semi-structured interviews, meaning no strict interview guide was followed (Van Thiel, 2014). Each interview could therefore address new topics that were not present in the interview guide (O'Keeffe, Buytaert, Mijic, Brozović, & Sinha, 2016). This caused that in analysing the results, subjects occasionally arose that were not yet mentioned in the same case or the other cases but were still perceived as valuable for this research. Therefore, additional questions were also used to ask other respondents about these topics to verify them and to collect more data about them.

5.3.2.3 Semi-structured interviews

As aforementioned, semi-structured interviews were used in this research. In these interviews, an interview guide should be created with different themes, but because it is semi-structured, there is no strict order in the question sequence (Van Thiel, 2014). An advantage of this freedom is that the interviewee and the respondent have more room to discuss other subjects related to the research (Van Thiel, 2014). Semi-structured interviews, therefore, support the explorative nature of this research by providing rich and detailed data sets with additional and valuable information that was previously unknown (O'Keeffe et al., 2016). Therefore, an interview guide was created for the semi-structured interviews to collect the data. The themes were based on the stages of the hydrogen value chain and the ecosystems domains of Isenberg (2011). The interview guide can be found in appendix 4.

5.3.2.4 Desk research

During the interview period, the earlier desk research was continued with a specific focus on North Jutland, Brittany, and Lower Saxony. This included analysing policy documents already found in the earlier desk research and those received or recommended by the respondents, like the hydrogen roadmap of Brittany from Business Developer 3 (pers.com. 02-05-2022). Google was used to search for these specific policy documents via governmental websites, such as the official webpage of the

Brittany Development Agency (BDI). Additionally, the results used websites to extract detailed information about specific topics or projects. For instance, in the Lower Saxony case, the Get H2 project is mentioned multiple times, but the exact stages of the implementation were not mentioned. The research only used websites related to the organisations or recommended by the respondents to ensure the reliability of sources. The websites were only used to strengthen an argument related to the interviews. Therefore, it was regarded as acceptable to use them.

5.3.3 Data Analysis

The interviews were first transcribed using the online program Otanscribe. This program enables researchers to transcribe interviews correctly. In the transcribing process, the choice was made to use a degree of intelligent verbatims because this increased the readability by leaving out words like "uhm" or "yeah" (McMullin, 2021). In this way, the transcript was more readable for the data analysis. Afterwards, the data is analysed based on the thematic analysis of Kiger and Vaprio (2020). This is because the thematic analysis can support the research in its search to understand the respondents' thoughts and to search for connections (Kiger & Vaprio, 2020). The transcripts were first read through carefully, and first impressions were written down per ecosystem domain and subdomain in Word to get familiar with the data. The transcriptions were then uploaded into the coding program Atlas.ti and were divided into the three different cases. In the next phase, the initial coding began. Afterwards, codes related to each other were merged to create themes and added to the ecosystem's domains. After that, the themes were added to a subdomain of the ecosystem. The information from these subdomains, in combination with the first impressions, served as the basis for the results. The codebooks can be found in appendices 6,7 and 8. The two European interviews were transcribed but not coded because it was only used as scoping to retrieve more knowledge about the European perspective. After the results were written down per case, several similarities and differences were identified that were used for the comparative analysis and identifying additional barriers.

The analysis of the different regions was complemented by extracting and analysing data from policy documents and websites of the desk research. The policy documents and websites were always scanned first and compared to the data from the analysis to check for consistency or potential gaps. The policy documents were examined and summarised to complement the information from the policy domain to provide a proper context for the results. The data from websites were only used to complete specific gaps from the data analysis of the interviews. The analysis is, therefore, less thorough than the analysis of interviews, but as it was only used to complement the data, this was regarded as sufficient.

5.4 Quality of the research design

The four tests for a case study from Yin (2003) will be discussed in this section to determine the quality of the research design.

5.4.1 Constructing Validity

The first test is about constructing validity that already starts in the data collection. This can sometimes be problematic in case study research because of the chance of developing insufficient criteria for research and subjective data collection (Yin, 2003). The data collection exists of multiple strategies that have been explained in detail to decrease this problem. Furthermore, the appropriateness of the fields is asked of respondents to validate the explored domains. This resulted in no new elements being proposed or left out. This test is also in-line with the tactic of Yin (2003) for constructing validity. Another tactic of Yin (2003) to construct validity was interviewing respondents from multiple ecosystem domains. Therefore, various sources with different perspectives were included, which increases the validity of the results, according to Yin (2003). Finally, because of using a multiple-case study, the research has the advantage that it is suitable for improving theory building (Bryman, 2012). The analysis can therefore offer future research improved criteria for collecting data.

5.4.2 Internal Validity

The second test relates to the internal validity of the research, which takes place in the data analysis. The internal validity relates mainly to the concept of causality (Bryman, 2012). According to Yin (2003), these casualties are not the goal of explorative case studies. Nevertheless, this research is still regarded to have some level of causality. For example, the hydrogen value chain is used to explain the influence of the different components of the value chain. Triangulation is a method of increasing internal validity (Van Thiel, 2014). Therefore, triangulation was used by analysing interviews, policy documents, websites, and sending follow-up questions via mail. Furthermore, the previous section about the data analysis explained how the methodology improves internal validity by combining policy documents and interviews.

5.4.3 External validity

The third test relates to the external validity of the research, which takes place in the research design phase (Yin, 2003). This concept relates to the generalizability of the results beyond the research context (Bryman, 2012). In the case of qualitative research, this can be hard to achieve compared to quantitative studies. For example, the results from the semi-structured interviews are less standardised than those from a questionnaire, resulting in less generalisable data (Van den Heuvel, 2020). Moreover, the findings of case studies are context-specific and, therefore, hard to generalise (Bryman, 2012). This is, however, not the focus of this research because the focus is on and between the cases themselves.

Another reason that decreases the generalizability relates to the research philosophy of constructivism. As explained in the research philosophy section, this relates more to subjectivism than objectivism. Therefore, the research will be harder to generalise as reality exists of multiple realities instead of one.

5.4.4 Reliability

The last test relates to the reliability of the research, which takes place in the data collection phase (Yin, 2003). This concept refers to the repeatability of the study (Bryman, 2012). For qualitative research, this is again harder to achieve compared to quantitative research (Bryman, 2012). For instance, the interviews are difficult to repeat because these were semi-structured, which gave the respondent room to discuss other related matters (Saunders et al., 2015). All the interviews had some fixed topics in the guide to increase the level of repeatability (appendix 4).

Another reason that reduces the reliability relates to the research philosophy of constructivism, which refers to subjectivism. This decreases the reliability of how the data is collected and analysed (Schoonwater, 2019). Therefore, the research is transparent about how the information is collected and analysed to increase repeatability to overcome this.

5.5 Ethics

The researcher regarded ethics as an essential part of the research process and its respondents. Firstly, It was asked if it was all right if the interview was recorded. Secondly, respondents were told that if their quotes were to be used, their permission would be required first. Thirdly, the researcher explained the research planning and asked the respondents if they wanted to have the final version of the research. Finally, to respect the respondents' privacy, it was decided not to refer directly to the respondents. Instead, the organisation type is used based on the actors of the entrepreneurial ecosystem, such as network organisation 1 or business development 3. This results in the following example: *Government 1 (pers.com, 19-04-2022) explained the excellent quality of this research.* Moreover, this reference strengthens the arguments by stating the type of actor the information comes from. For example, when talking about policy, the argument is more robust when it comes from an actor related to the government. Appendixes 1,2 and 3 show to which organisation the respondents are connected. Due to privacy, the names are not mentioned.

6. Results

6.1 Introduction results

It is essential to mention that the aim of the results is not to state that one region is 'better' than the other but to give an objective exploration and analysis of the data collected for this research. The structure of the chapter is based on the previous six ecosystem domains and subdomains discussed per case. From the exploration, each field will be given a colour (green, orange and red) to show the conduciveness of each domain to explain their development. **Green** means that a domain has only positive characteristics. **Red** means that a domain has only negative aspects. **Orange** indicates negative and positive characteristics. An overview of these colours will be given at each case's end. This table is only used to provide the research with a simplistic overview of each case's hydrogen ecosystem for a better general understanding of the case. After the explorations of the cases, the results will conclude with a comparative analysis, in which the value chain and barriers play a central role. The first section of the results supports the explorative part of the results. The second section, on the other hand, provides the results with a more in-depth analysis.

However, several adjustments or additions are made in multiple subdomains based on the data analysis. This will therefore be discussed first. Firstly, based on the operationalisation of section 4.2, a choice must be made concerning the role of networks. The decision was to explore networks in the subdomain of non-government institutions of the support domain instead of the subdomain of networks in the market domain. This is because the data showed that the emphasis of these networks is mostly on supporting hydrogen businesses, which offers more overlap with the non-government institutions subdomain. Another decision was made to replace the name of non-government institutions with networks, as the focus of data analysis and in the publication of Isenberg (2010) and Maroufkhani et al. (2018) also is on networks.

Secondly, the data analysis caused multiple adjustments in the culture domain. In the analysis, success stories of other innovations, failed stories, and potential future hydrogen success stories were identified and regarded as essential for understanding the role of hydrogen in a region. Therefore, these three types of stories were added to the subdomain of success stories. Another adjustment concerns extending the public acceptance from solely hydrogen to renewable energies. This decision was made because it was a repeated theme in the analysis influencing green hydrogen production.

The final adjustment is to change the name of early customers into the early market. This is because, in the analysis, this name seemed to fit better with the codes. After all, besides the early customers, more factors are essential for developing a hydrogen market.

6.2 North Jutland

6.2.1 Policy

6.2.1.1 Government

From the national policy, it became clear that Denmark has a strong ambition regarding its decarbonisation pathway. The federal government aims to reduce 70% of its greenhouse gas emissions by 2030, where green hydrogen is expected to play an important role (Danish Energy Agency, 2021). This is expressed in the Danish national Power-to-X (PtX) strategy, which was published and validated relatively late compared to other European countries (Incubator 1, pers.com., 17-03-2022; Network 1, pers.com., 20-04-2022). This is because the old government considered hydrogen only a niche. However, after the elections, the new government saw more potential in hydrogen and created a national PtX strategy (Business Developer 1, pers.com. 21-04-2022; Network 1, pers.com., 20-04-2022). The concept of PtX is explained as follows: ''*PtX is a blanket term for a number of technologies that are all based on using electricity to produce hydrogen.'' (Danish Energy Agency, 2021, p.7).* In the PtX strategy, the government pointed out four objectives (Danish Energy Agency, 2021):

1. *''Power-to-X must be able to contribute to the realisation of the objectives in the Danish Climate Act.''(p.4).*
2. *''The regulatory framework and infrastructure must be in place to allow Denmark's strengths to be utilised and for the Power-to-X industry to operate on market terms in the long run.'' (p.4).*
3. *''The integration between Power-to-X and the Danish energy system must be improved.'' (p.4).*
4. *''Denmark must be able to export Power-to-X products and technologies. '' (p.4).*

Therefore, the government's ambition aims to have an electrolysis capacity of 4-6 GW by the year 2030 (Danish Energy Agency, 2021). The renewable energy for this production will most likely come from off-shore wind parks (Danish Energy Agency, 2021; Network 1 pers.com. 20-04-2022).

Despite these ambitions, Demark's primary school of thought is to apply direct electrification where possible and only use hydrogen where direct electrification is impossible (Danish Energy Agency, 2021; Incubator 2, pers.com. 25-03-2022). For example, long-distance transport or particular industries, like the chemical industry (Incubator 2, pers.com. 25-03-2022; Network 1, pers.com. 20-04-2022). This relates to the lower efficiency of hydrogen in comparison with direct electrification, making its use in some applications not feasible (Danish Energy Agency, 2021; Incubator 2, pers.com. 25-03-2022). An essential objective concerning this subdomain is the development of the regulatory framework. This is still needed in several areas, like safety requirements or market regulation (Danish Energy Agency, 2021). To support hydrogen development, the government has already adjusted some rules. Network 1 (pers.com. 20-04-2022) explains the importance of this with two examples. The first example concerns the approval of connecting a windmill directly with an electrolyser, while in the old situation, the windmill had to be connected with the grid. This new situation results in decreased production costs because no tariffs need to be paid any more for using the grid (Network 1, pers.com. 20-04-2022). The second example relates to the salt caverns. Storing hydrogen in these caverns was first not allowed, but it became allowed due to the new national strategy (Network 1, pers.com. 20-04-2022). These examples, therefore, show the effect regulations can have on hydrogen development. Despite these changes, the rules are still one of the most significant barriers (Network 1, pers.com. 20-04-2022). The national policy even states that the private sector perceives this as more necessary than public funding because hydrogen cannot scale up otherwise (Danish Energy Agency, 2021). For these rules, the government also emphasises the importance of the EU to create a uniform framework across the EU, for example, to ensure the green value of PTX by certification (Danish Energy Agency, 2021).

Besides the focus on hydrogen in PtX, there is also a strong focus on converting hydrogen into green fuels, like methanol or ammonia. In this production, CO_2 is needed for the conversion (Danish Energy Agency, 2021; University 1, pers.com., 20-04-2022). Therefore, hydrogen development goes together with the development of carbon capture and utilisation techniques (CCU) to capture the needed CO_2 (Danish Energy Agency, 2021; Incubator 2, pers.com., 25-03-2022). In the national strategy, this process is perceived as climate neutral when the carbon comes from a biogenic source, such as biomass (Danish Energy Agency, 2021).

6.2.1.2 Leadership

Concerning North Jutland, the Danish government expects that PtX and CCU can become essential themes for the region. The focus on CCU is mainly because of a cement factory in Aalborg (Business Developer 1, pers.com. 21-04-2022). This factory is the largest CO_2 emitter in Denmark and is responsible for around 4% of the nation's emissions (Business Developer 1, pers.com. 21-04-2022). In their production process, it is not easy to replace fossil fuels. Instead, CCU can offer a solution in which the carbon can be used to produce methanol based on green hydrogen (University 1, pers.com. 20-04-2022).

North Jutland appears to have no regional policy regarding hydrogen. This is because of Denmark's size; policies are mostly arranged nationally (Business Developer 1, pers.com., 21-04-2022). Despite this absence, there is a strong political motive not to be excluded from the rest of Denmark. This urge relates to a national plan to make a bridge connecting Goteborg, Copenhagen and Hamburg, where Jutland will be left out. Therefore, a strong desire is present to avoid getting forgotten and being at the forefront with PtX and CCU. Business Developer 1 (pers.com. 21-04-2022) states the following about this: *''So, from a political issue there is a strong focus on how not to be forgotten, at least not on an international level and one of thing to avoid that is to have a strong industry and some results you can show''.*

In exploring the policy domain of North Jutland, the national PtX strategy offers first guidance and support in taking away the barriers and stimulating hydrogen development. A solid political motive is also present in the area to stay at the forefront of this development. However, the regulations are still a barrier that hinders development. Overall, the policy domain of North Jutland gets, therefore, the colour **orange.**

Domain	Subdomain	Characteristics
Policy	***Government***	➢ National policy for hydrogen as the basis for PtX ➢ Adjusted regulatory framework needed in some areas ➢ Uniform EU framework essential for PTX development
	Leadership	➢ The political urge not to be forgotten drives the ambition to develop PtX and CCU

Table 7a. Characteristics of policy domain

6.2.2 Finance

6.2.2.1 Private Finance

In North Jutland, there are currently ten hydrogen-related projects (Brintbranchen, 2022). Most of these projects were initiated by private companies before the national hydrogen strategy and started without public funding (Network 1, pers.com. 20-04-2022). Of the nine projects, there is also not one project initiated or 100% owned by the public sector (Business Developer 1, pers.com. 21-04-2022). However, public funding is still essential for these projects to overcome the high costs (Network 1, pers.com. 20-04-2022). The hydrogen sector is, therefore, driven by private actors that invest in projects and is complemented with public funding (Business Developer 1, pers.com. 21-04-2022).

6.2.2.2 Public Funding

The public funding of hydrogen depends on several types of funding from the EU and national level (Business 2, pers.com. 20-04-2022; Network 1, pers.com. 20-04-2022). An example is the 500 million Danish Krone allocation, around €67 million, for developing the eight commercial beacons (Danish Energy Agency, 2021). These are areas that, with the right incentives, can develop into essential regions within a specific theme and thereby create employment and income (Network 1, pers.com. 20-04-2022). The beacons are role models for others to follow; Business Developer 2 (pers.com. 20-04-2022) explains the following about this: ''*It is a showcase for upscaling thus a beacon for others to follow proving the technology and construction principles works and show a faster track from plan to implementation''.* The funding of these beacons will increase even more as the government will allocate another DKK 500 million from EU funds for this development (Danish Energy Agency, 2021). In the case of North Jutland, these themes are PtX and CCU (Danish Energy Agency, 2021). Another essential funding is the government's investment of DKK 1,25 billion, which is around €168 million, for a PtX tender. This funding aims to reduce the costs of hydrogen production to support the upscaling of hydrogen production and other PtX products (Danish Energy Agency, 2021). Generally, Denmark has a good funding program for green initiatives, like hydrogen (Business 2, pers.com. 20-04-2022).

In exploring the finance domain, an active private sector has already started investing in hydrogen projects before the national PtX strategy. However, they still depend on public funding, which is available. This section, therefore, also indicates the mutual interdependency of the private and public sectors in realising hydrogen projects. Based on this exploration, the finance domain receive the colour **green**, as there seems to be a good balance between private and public funding.

Domain	Subdomain	Characteristics
Finance	***Private finance***	➢ Private actors drive the hydrogen sector
	Public funding	➢ EU funding for the development of eight commercial beacons ➢ National funding for PTX tender to overcome high production costs

Table 7b. Characteristics finance domain

6.2.3 Culture

6.2.3.1 Success Stories

An example of a realised success story is the HyBalance project. The project entails a hydrogen production facility with a capacity of 1.2 MW (Business Developer 2, pers.com. 20-04-2022). The project proved that it could provide industries with grid balance and green hydrogen (Business Developer 2, pers.com. 20-04-2022). Even though the project ended in 2020, the production facility is still up and running (Business Developer 1, pers.com. 21-04-2022). Business Developer 2 (pers.com. 20-04-2022) even called the project an eye-opener for politicians, the public and industry in showing what hydrogen has to offer. This example shows the importance of success stories that inspire other regional hydrogen developments.

Another success story impacting the current green hydrogen development and ambition is the national 'windmill adventure'. This adventure started in the late 1970s and resulted in Denmark becoming an expert in wind energy development. This led to higher efficient wind turbines and economic revenue for the country (Network 1, pers.com. 20-04-2022; University 1, pers.com. 20-04-2022). The adventure received, therefore, much national support and transformed into a national pride (Network 1, pers.com. 20-04-2022). This success also resulted in the high availability of cheap green energy, of which a large part is present in Jutland (Network 1, pers.com. 20-04-2022). Due to this affordable energy, the price of producing green hydrogen also becomes less expensive. Therefore, producing green hydrogen is seen as a logical next step (Network 1, pers.com. 20-04-2022; Incubator

2, pers.com. 25-03-2022) states the following about this: *''In Denmark, in general, we want to be, just as with wind, on the forefront with the Power-to-x. ''*. This can be translated to a potential future success story: the currently largest regional project, the Green Hydrogen Hub (Brintbranchen, 2022). This project aims to become the world's first project where the production of green hydrogen will be stored in salt caverns (Business 1, pers.com. 12-04-2022; Green Hydrogen Hub, 2021). Furthermore, the project has planned to have an electrolysis capacity of 1 MW by 2030 (Green Hydrogen Hub, 2021).

6.2.3.2 Societal Norms

In general, there is little public rejection against hydrogen or PtX, which is also because hydrogen is currently not on people's minds (Network 1, pers.com. 20-04-2022). However, this could therefore change when it comes to people's minds when more hydrogen or PtX projects are realised. Another explanation that was not directly linked to public acceptance but seemed relevant is Denmark's strong belief in framing itself as an innovative and green country (Network 1, pers.com. 20-04-2022). This can be traced back to the windmill adventure, where the motivation is now to make PtX the next success story (Network 1, pers.com. 20-04-2022).

However, the public acceptance of renewable energy is a problem, despite the earlier success story of the wind, because there is still a strong Not In My Backyard (nimby) effect (Business Developer 1, pers.com. 21-04-2022). An example is that the Danish government had planned to have six near-shore small wind farms, where one of them was scheduled in North Jutland, and none have been realised yet, due to public rejection (Business Developer 1, pers.com. 21-04-2022). Moreover, the effect is increasing because the technology and turbines are getting bigger and taking up more space than before (Business Developer 1, pers.com., 21-04-2022).

In exploring the culture domain, the culture domains have some positive characteristics, like the presence of a success story and the drive to make PtX the subsequent success. However, the growing NIMBY effect is slowing the increase in renewable energy, which can also affect green hydrogen production. Hydrogen is also not yet on many people's minds, making it uncertain how people will accept it. Therefore, despite the overall positive culture for hydrogen, this domain receives the colour **orange** because of the growing NIMBY effect.

Domain	Subdomain	Characteristics
Culture	***Success stories***	➢ HyBalance is a realised success story and an eye-opener for others ➢ From windmill adventure towards PtX adventure ➢ Potential future success stories, like the Green Hydrogen Hub
	Societal norms	➢ General acceptance for PtX, but not yet on people's minds ➢ Framing Denmark as an innovative and green country ➢ Growing NIMBY effect for renewable energy

Table 7c. Characteristics culture domain

6.2.4 Support

6.2.4.1 Infrastructure

In North Jutland, there is not yet a regional hydrogen infrastructure. Nevertheless, the national strategy emphasised the importance of creating this future hydrogen infrastructure, which is considered necessary to scale up hydrogen ecosystems (Danish Energy Agency, 2021). University 1 (pers.com. 20-04-2022) also emphasises its importance: *''If we want to realise the power-to-x adventure, we need the hydrogen infrastructure and a larger capacity on electrolysis.''*. The infrastructure can support the scaling up of hydrogen towards its commercialisation, as the distribution costs are one of the high costs for green hydrogen (Incubator 2, pers.com. 25-03-2022). Transporting these large amounts by pipeline would be much cheaper and more feasible than with trucks (Incubator 2, pers.com. 25-03-2022). Without the possibility to scale up, hydrogen would also be less interesting for the private sector. This can harm the ecosystem, as the private actors are the drivers behind initiating hydrogen projects (Business Developer 1, pers.com. 21-04-2022). Business Developer 1 (pers.com. 21-04-2022) explains this: *''Because scaling up is the big buzzword in Denmark at the moment. Because if we cannot scale it up, it is not really interesting for the business, and if you do not have the private sector with us, we cannot do it.''.*

Besides the domestic relevance, having infrastructure is also essential for the ambition of Denmark to become a future exporter of hydrogen (Danish Energy Agency, 2021; Network 1, pers.com. 20-04-2022). Therefore, connecting to a common European hydrogen infrastructure, such as the European hydrogen backbone, is essential (Danish Energy Agency, 2021). This is because the more regions are involved, the more local companies within an area can benefit from this network (Incubator 2, pers.com. 25-03-2022). In the plans of the European hydrogen backbone, it is projected that in the first phase (till 2030), regional networks could emerge around the available storage facilities in North Jutland (Gas for Climate, 2020).

Zooming in on the ecosystem of North Jutland, the ClusterNortH2 project could be the basis of a future regional network (Business 1, pers.com. 12-04-2022). This project investigates the possibility of realising the first Danish hydrogen pipeline infrastructure by 2030 (Business 1, pers.com. 12-04-2022; Cluster NortH2, 2022). The intention is to connect several projects and areas to create the entire hydrogen value chain (Utility Company 1, pers.com. 02-05-2022).

One of these connection points is the earlier mentioned Green Hydrogen Hub Denmark (Business 1, pers.com. 12-04-2022). This project aims to have an electrolysis capacity of 1 GW and a storage capacity of 320 MW by 2030 (Green Hydrogen Hub Denmark, 2021). The project will be located in North Jutland due to the geographical location of the salt caverns, where the hydrogen can be stored naturally in large quantities and for an extended period (Business 1, pers.com. 12-04-2022). Due to this advantage of having storage ability, the total costs of hydrogen are decreased because it can be produced and stored when there is a surplus of cheap renewable energy (Business 1, pers.com. 12-04-2022).

Another connection point is where Green Hydrogen Hub also intends to have its hydrogen production. The plan is to build electrolysers around the on-shore wind and solar parks on the east side of North Jutland. In this area, there is a limited capacity for trucks, so transporting large amounts of hydrogen by truck is also not feasible (Utility Company 1, pers.com. 02-05-2022).

Industrial park GreenLab, located in Mid Jutland near the border of North Jutland, is another connection point (Utility Company 1, pers.com. 02-05-2022). The park has a special status in Denmark because it is one of the two regulation-free zones (Incubator 1, pers.com. 17-03-2022). Therefore, the park can test and experiment with innovations, such as green hydrogen, without considering the legislation (Incubator 1, pers.com. 17-03-2022). The site's goal is to create a symbiosis between various value streams, like heat or hydrogen, with the industries present in the park (Incubator 1, pers.com. 17-03-2022). There will be on-site production, which will probably be complemented by hydrogen production from other sources (Utility Company 1, pers.com. 02-05-2022).

Besides GreenLab, the plan is to transport the produced hydrogen to the last connection point, the city of Aalborg. This is because, in Aalborg, a big off-take of hydrogen is expected shortly, for instance, for producing methanol (Utility Company 1, pers.com. 02-05-2022).

ClusterNortH2 is, therefore, an essential factor for the regional hydrogen ecosystem of North Jutland, as it will connect multiple projects and clusters. Without this project, the ecosystem can experience a setback. Utility Company 1 (pers.com. 02-05-2022) explains this: *''ClusterNortH2 is one of the flagship projects in Northern Jutland and closest to realisation. If not realised, the overall development of a hydrogen market in Northern Jutland may possibly experience a setback''.* Despite the importance of the network, there are not yet final investment decisions made for the ClusterNortH2 project. One of the reasons is that creating this infrastructure requires a massive investment (Business Developer 1, pers.com. 21-04-2022).

6.2.4.2 Support Professions

In North Jutland, there is a long history with PtX. For example, the Hydrogen Valley cluster has already been involved in PtX businesses for 15 years and is, therefore, one of the pioneers in this industry and Denmark (Incubator 2, pers.com. 25-03-2022). Due to this history, the region has one of the largest methanol fuel companies, focusing on high-temperature PEM systems for heavy-duty vehicles that run on methanol (University 1, pers.com. 20-04-2022). Besides this, the region also has one of the largest hydrogen fuel cell companies for stationary fuel cell systems and transport (University 1, pers.com. 20-04-2022). The basis of these developments is hydrogen, and because of its history, North Jutland has already acquired a head start and expertise in this (Incubator 2, pers.com. 25-03-2022; University 1, pers.com. 20-04-2022). Therefore, new hydrogen innovations, like the high-temperature PEM systems, have come up due to this expertise, supporting hydrogen development in the region.

6.2.4.3 Networks

In North Jutland, Hydrogen Valley is explicitly focused on supporting and linking businesses in the hydrogen sector. The organisation consists of two business legs. One is projected development, which helps businesses secure funding, set up projects and make connections (Incubator 2, pers.com. 25-03-2022). The other is a business park which hosts several companies related to the energy sector (Incubator 2, pers.com. 25-03-2022). Hydrogen Valley is, therefore, a central actor in the support domain of North Jutland for hydrogen development.

In exploring the support domain, the region shows potential in installing a regional infrastructure that connects the whole hydrogen value chain. Furthermore, the presence of salt caverns and the high availability of renewable are conducive to the ecosystem. Moreover, the region has already acquired expertise in hydrogen fuel cell systems and methanol, resulting in innovations supporting hydrogen development. Finally, with the Hydrogen Valley, an organisation is focused on supporting hydrogen businesses in the region. Overall, the support domain seems conducive to the region's hydrogen development. However, because there are not yet final investment decisions, the realisation of the ClusterNortH2 is still insecure. Due to this uncertainty, the support domain receives the colour **orange.**

Domain	Subdomain	Characteristics
Support	***Infrastructure***	➢ ClusterNorth2 project as a potential basis for creating a regional infrastructure ➢ Salt caverns are present for long-term storage. ➢ High presence and potential of renewable energy.
	Support Professions	➢ Long history in PtX and methanol ➢ Expertise in hydrogen fuel cell systems and methanol
	Networks	➢ Hydrogen Valley cluster that supports and hosts businesses related to the hydrogen and energy sector

Table 7d. Characteristics support domain

6.2.5 Human capital

6.2.5.1 Educational Institutions

The Aalborg university is an essential actor in the hydrogen ecosystem of North Jutland. This is because the university is the number 1 engineering university in Europe, where hydrogen is a focus area (University 1, pers.com. 20-04-2022). The combination of this university and the history of innovative businesses in hydrogen and methanol results in a creative environment. University 1 (pers.com. 20-04-2022) states this: *'' So, it is actually a good combination of the business demand and research capabilities, that mixture makes a very unique innovations in the northern part of Jutland.''.*

6.2.5.2 Labour

Another impact the university has on the ecosystem is that it provides the region with skilled engineers to work in this new field. For example, Business 2 (pers.com. 20-04-2022) mentioned that many of his colleagues went to Aalborg University. However, despite having this university, it is still not enough to employ the labour force needed in this new field (Business Developer 2, pers.com. 20-04-2022; University 1, pers.com. 20-04-2022).

In exploring the human capital domain, Aalborg University is a central actor in hydrogen research and education in the region. Nevertheless, the labour needed in the hydrogen industry is not present. Therefore, the human capital domain receives the colour **orange.**

Domain	Subdomain	Characteristics
Human Capital	***Educational Institutions***	➢ Number one European engineering university in Aalborg, with hydrogen as the focus area. ➢ The combination of Aalborg University with hydrogen-related business makes unique innovations
	Labour	➢ Need for labour force in the hydrogen industry.

Table 7e. Characteristics Human capital

6.2.6 Market

6.2.6.1 Early Market

Some characteristics were already mentioned in the previous domains that could influence the market domain. For example, the infrastructure to scale up hydrogen projects or the high wind availability lowers the price of renewable energy and green hydrogen production. Because of the excellent wind availability, Network 1 (pers.com. 20-04-2022) even states that the projects are moving towards the commercialisation phase in Denmark: *''So, in Denmark, we see that the phase of demonstration projects is moving towards the commercialisation. However, there is still funding needed.''.* The growth in hydrogen production projects illustrates this. For example, the HyBalance project currently has the biggest electrolyser with a capacity of 1.2 MW, but for 2030 the Green Hydrogen Hub Denmark should have a size of 1 GW (Business Developer 2, pers.com. 20-04-2022; Green Hydrogen Hub Denmark, 2021).

However, with this transition from demonstration projects towards commercialisation, the difficulty is finding local off-takers for hydrogen or the produced green fuels from the hydrogen (Business Developer 2, pers.com. 20-04-2022; Network 1, pers.com. 20-04-2022). This struggle is illustrated by a previous attempt to initiate the market of H2 cars in combination with the earlier mentioned HyBalance project. This project also distributed hydrogen to several refuelling stations, but their number decreased because the demand for H2 cars did not increase. This is related to the high price of hydrogen cars and green hydrogen (Business Developer 2, pers.com. 20-04-2022). North Jutland also used to have two refuelling stations, which are now closed (Business Developer 1, pers.com. 21-04-2022). There are also no concrete plans for realising new refuelling stations in the region (Business Developer 1, pers.com. 21-04-2022).

Despite this, the marine, aviation and transport sectors show potential early customers. Maersk ordered 12 ships that would run on methanol in the marine sector (Business 2, pers.com. 20-

04-2022). For the aviation sector, the government has expressed the ambition to have all domestic flights in 2030 running on green fuels (Network 1, pers.com. 20-04-2022).

In exploring the market domain, the region shows a massive increase in regional hydrogen projects' electrolysis capacity. Furthermore, there are potential first-off takers in the marine and aviation sector for its hydrogen or green fuels. However, finding local off-takers is one of their biggest challenges currently. Therefore, the market domain receives the colour **orange.**

Domain	Subdomain	Characteristics
Market	***Early Market***	➢ A massive increase in electrolysis capacity in the region's hydrogen projects ➢ A bad experience with hydrogen mobility and refuelling stations. ➢ Problem with finding local off-takers for Power-to-X ➢ Potential early customers in the marine and aviation sector.

Table 7f. characteristics Market

6.2.7 Summary of North Jutland

From the previous sections, table 7g is created. From this table, it can be concluded that not all the domains are conducive to the hydrogen ecosystem. However, looking towards 2030 and the orange colours for the policy, culture, support, human capital and market domain in table 13, the ecosystem show potential to become conducive. For example, when investments are made to realise the ClusterNorthH2. Moreover, the finance domain is green, which means the willingness of private and public sectors to invest in hydrogen development, which is essential when looking at the high costs associated with hydrogen. On the other side, current barriers like the regulations or the future demand for labour can also cause the hydrogen ecosystem not to take off. Therefore, there is still uncertainty in its hydrogen development trajectory.

Domain	Conduciveness
Policy	Orange
Finance	Green
Culture	Orange
Support	Orange
Human capital	Orange
Market	Orange

Table 7g. Conduciveness hydrogen ecosystem North Jutland, **Red= not a conducive element, Orange= Both conducive and non-conducive elements present, Green= Conducive element**

6.3 Brittany

6.3.1 Policy

6.3.1.1 Government

France aims to reduce its greenhouse gas emissions by 40% by 2030 (Ministère de la Transition écologique, n.d.). France was one of the first countries to publish a hydrogen strategy in 2018, which was succeeded by the latest policy in 2020 (Ministère de la Transition écologique, 2020). In this strategy, the following goals have been set (Ministère de la Transition écologique, 2020):

1. *''To install enough electrolysers to make a significant contribution to the decarbonisation of the economy'' (p.6)*
2. *''To develop clean mobility, in particular for heavy-duty vehicles'' (P.6)*
3. *''To build a French industrial sector that creates jobs and guarantees our technological prowess'' (p.6)*

To achieve the first objective, France wants to have an electrolysis capacity of 6.5 MW by 2030 (Ministère de la Transition écologique, 2020). This hydrogen production will use renewable and decarbonised energy, such as nuclear energy (Government 1, pers.com. 14-04-2022). The overall sustainability of their hydrogen production can therefore be discussed. As a result of the second objective, the emissions should be decreased by 6 Metric tons in 2030, which is equal to the annual CO2 emissions of Paris (Ministère de la Transition écologique, 2020). The focus on this sector can be traced back to the importance of the automotive industry to the France economy (Ministère de la Transition écologique, 2020). The strategy's last objective to support research and innovation in the field of hydrogen. The target is to create between 50,000 and 150,000 direct and indirect jobs in France (Ministère de la Transition écologique, 2020). However, in France, hydrogen regulations are still in an early phase because the development of hydrogen is also in an early stage, and it takes time to change rules (Business 3, pers.com. 07-04-2022; Government 1, pers.com. 14-04-2022). This causes it takes a long time to construct a hydrogen plant or to certify hydrogen vehicles (Government 1, pers.com. 14-04-2022). At the EU level, France wants to actively work on removing several barriers, such as regulations, to realise a sustainable and resilient European hydrogen value chain (Ministère de la Transition écologique, 2020).

6.3.1.2 Leadership

When focusing more on Brittanie's public support for hydrogen, they already published their hydrogen roadmap in 2020. In general, hydrogen development is planned to evolve with the region's ambition in smart grids and marine energy. A particular focus is here to support the marine and agricultural sectors in becoming more sustainable (Government 2, pers.com. 02-05-2022: Region Bretagne, 2020). This is because Brittany has a rich sea and agrarian culture, which is expressed by having one of the largest fishing fleets and agricultural sectors (cattle and vegetables) in France (Business 5, pers.com. 13-05-2022). The aim of the roadmap is as follows (Region Bretagne, 2020): *''The Brittany region wishes to position itself as a leading French region on the market of renewable hydrogen applications, both in terms of the expertise of its companies and in the distribution of technologies and their appropriation by citizens'' (p.8).* Government 2 (pers.com. 02-05-2022) explains that the roadmap has three phases to accomplish the region's hydrogen ambitions.

The first phase (till 2025) is the initial phase, where the focus is on starting the hydrogen development by creating eight local hydrogen loops. A loop is realised in small areas to demonstrate the value chain's production, usage and management (Government 2, pers.com., 02-05-2022). A crucial element in these loops is the integration of local actors to ensure the acceptability and involvement of public actors in the long term (Government 2, pers.com., 02-05-2022). The production of these local loops should be at least 200 kg of renewable hydrogen per day in each site, based on having an electrolysis capacity of 500 kW per site (Government 2, pers.com. 02-05-2022; Region Bretagne, 2020). Besides this, the goal is to realise an off-shore hydrogen production facility to support research and innovation activities (Government 2, pers.com. 02-05-2022).

The second phase (till 2030) is the consolidation phase, where the focus is on creating three hydrogen port ecosystems and a fleet of ten small ships (Government 3, pers.com. 02-05-2022; Region Bretagne, 2020). The renewable hydrogen production would be up to one ton each in the three port ecosystems (Government 2, pers.com. 02-05-2022; Region Bretagne, 2020). Additionally, Brittany aims to have a fleet of 2800 vehicles at this stage.

The last phase (after 2030) is the generalisation phase, where the focus is on expanding the regional hydrogen uses (Government 2, pers.com. 02-05-2022; Region Bretagne, 2020). With this roadmap, Brittany shows public ambition and support for the development of hydrogen.

In exploring the policy domain of Brittany, the national government has already published a second national strategy to stimulate hydrogen development and guide how it wants to overcome hydrogen barriers. Furthermore, the regional policy of Brittany shows the region's ambition for developing a regional hydrogen ecosystem by 2030. However, because the regulations are still early, this harms the speed of the hydrogen ecosystem trajectory towards its take-off point. Therefore, the policy domain receives the colour **orange**.

Domain	Subdomain	Characteristics
Policy	***Government***	➢ National strategy to support to initiate the hydrogen development. ➢ Regulations for hydrogen at an early stage
	Leadership	➢ Ambition to become a leading French region in the market of renewable hydrogen applications ➢ Creation of eight local loops, three port ecosystems and one off-shore hydrogen production facility by 2030 ➢ Focus on the marine and agriculture sector ➢ Hydrogen evolving with smart grids and marine energy

Table 8a. Characteristics Policy

6.3.2 Finance

6.3.2.1 Private Finance

In Brittany, large companies or industries that focus on hydrogen are absent. For private finance, the region depends on its entrepreneurship and other investors interested in doing a project (Business 5, pers.com. 13-05-2022). This resulted in 44 small demonstration or product development projects constructed, in service, or ongoing (BDI, 2022a). In Brittany, the private sector invests primarily in private refuelling stations, private fleets and production, which also depends on government funding. Outside these segments, the private sector is not very active and rarely intervenes without 50% public funding (Government 2, pers.com. 02-05-2022). The interplay between private finance and public funding is essential for regional hydrogen projects.

6.3.2.2 Public Funding

A national funding program started to support the realisation of regional hydrogen ecosystems. In these ecosystems, the whole value chain needs to be present to create more security so that the money is spent wisely (Government 1, pers.com. 14-04-2022). For example, when an electrolyser project wants funding, it needs to clarify where 25% to 50% of hydrogen will be consumed. Otherwise, nothing will be received (Government 1, pers.com. 14-04-2022). Concerning Brittany, the VHYGO project is currently the only project that received money from this call to develop a cross-regional hub. In Brittany, one subproject of VHYGO in Lorient received funding (Government 1, pers.com. 14-04-2022). The VHYGO project will be further explained in section 6.4.3.1.

In the case of Brittanie's roadmap, they have calculated that they need circa €245 million to accomplish their targets of the local loops, the ports and the fleet (Government 3, pers.com. 02-05-2022; Region Bretagne, 2020). These costs should be partially public and privately funded because the region cannot finance all of these targets by itself (Government 3, pers.com. 02-05-2022). To close the gap, national and EU funding are important sources (Business Developer 3, pers.com. 02-05-2022).

However, a mismatch is causing it to be difficult for Brittany to receive financing. The national and EU funding schemes mainly target heavy polluting industries or potential large projects (Business 5, pers.com. 13-05-2022; Government 3, pers.com. 02-05-2022). On the other hand, Brittany is characterised by their small and medium enterprises (SMEs) that often do not have the money to manage these big projects (Business 5, pers.com. 13-05-2022; Government 2, pers.com. 02-05-2022). Moreover, there is an absence of polluting industries and large companies. These two reasons cause a mismatch in the funding criteria, which makes it hard for Brittany or SMEs to receive funding (Business 5, pers.com. 13-05-2022; Government 3, pers.com. 02-05-2022). Therefore, choices must be made carefully on what sectors the region want to focus on (Government 2, pers.com. 02-05-2022). Despite this, Brittany still tries to create EU projects to finance its roadmap (Government 3, pers.com. 02-05-2022).

In exploring the finance domain, the region seems to have difficulty finding finance because of the absence of large companies and the mismatch in funding regimes. Despite this, there are 44 smaller demonstration and product development projects (BDI, 2022a). Therefore, the finance domain receives the colour **orange.**

Domain		Characteristics
Finance	***Private Funding***	➢ Relying on entrepreneurship and investors for private finance ➢ 44 small hydrogen demonstration or product development projects constructed, in service, or ongoing
	Public Funding	➢ Funding program for regional hydrogen ecosystems ➢ Mismatch in national and EU funding makes it hard to receive funding

Table 8b. Characteristics of the finance domain

6.3.3 Culture

6.3.3.1 Success Stories

In Brittany, there is not yet a big hydrogen project that could serve as a success story. Nevertheless, there are the earlier 44 mentioned smaller demonstration or product development projects that could be potential success stories. For example, a multiple-time project mentioned in the interviews is the Hylias project (Business 3, pers.com. 07-04-2022; University 2, pers.com. 06-04-2022). This is an ecosystem project that involves the realisation of a hydrogen passenger boat for transportation towards Brittanie's small islands and the installation of a hydrogen refuelling station in the port of Vannes (BDI, 2022b; Business 3, pers.com. 07-04-2022). Another example is the demonstration of a hydrogen ecosystem in the city of Lorient that involves the realisation of two refuelling stations, twelve buses, and two boats (Government 1, pers.com. 14-04-2022).

Another success story impacting the current hydrogen development and ambition is Brittanie's bright grid adventure. This adventure started in 2016 and led to more intelligent energy management systems in several parts of Brittany (BDI, 2021a). Therefore, hydrogen seems to be a logical next step as it increases the efficiency of the energy management system by providing more continuity, for example, through its storage ability (Government 2, pers.com. 02-05-2022).

6.3.3.2 Societal Norms

For the acceptance of hydrogen in Brittany, it is essential to understand the consequence of its geographical location as a peninsula in the west of France. The region is therefore considered more regionalist than centre-oriented (Government 3, pers.com. 02-05-2022). This feeling led to the social rejection of a national nuclear plant in the 1960s and later a gas power plant (Government 2, pers.com. 02-05-2022). This public rejection of large energy projects has not disappeared (Government 2, pers.com. 02-05-2022; University 2, pers.com. 06-04-2022). University 2 (pers.com. 06-04-2022), for instance, mentions that the wind park in Saint-Brieuc has been blocked for ten years. Another example is the five-year delay of a gas plant in Brittany (Business 6, pers.com. 17-05-2022). As a result of this public rejection, hydrogen is developed on a smart and local scale to create social understanding and acceptance (Business 6, pers.com. 17-05-2022). This also describes the importance of having these local demonstration projects that can influence the public's attitude towards hydrogen (Business 6, pers.com. 17-05-2022). On the other hand, Brittany is also characterised by having an innovative culture, which their SMEs express. Therefore, there is an ongoing regional interaction between these two types of people (Business 6, pers.com. 17-05-2022).

In the case of the hydrogen roadmap, there seems to be a relatively good acceptance as it was accepted unanimously by the public and the political side (Government 2, pers.com. 02-05-20). This could be because the roadmap promotes the more local bottom-up approach instead of large projects with less public engagement. However, there is also cautiousness in realising new success stories through possible risks for failed success stories. For example, a city switches from hydrogen buses to electric buses because these work better (Government 1, pers.com. 14-04-2022). Government 1 (pers.com. 14-04-2022) explains that they prefer something that works because there is not much experience with hydrogen, and a bad experience or failed story can break the momentum of hydrogen. Therefore, also cities and businesses need to be reassured that the technology works and that the risk of using new hydrogen technology is minimised (Government 1, pers.com. 14-04-2022). As a result of this cautiousness, this is slowing down the hydrogen development in the region by taking fewer risks in its usage (University 2, pers.com. 06-04-2022).

In exploring the culture domain, the region shows multiple projects that could be potential success stories. The region's previous smart grid success is now also causing hydrogen development is more interesting for the area. In the case of acceptance, there is a relatively good acceptance for the hydrogen roadmap perceived. On the other hand, there is a history of significant public rejection of large energy projects and cautiousness in realising hydrogen projects to avoid a possible story of failure. Therefore, the culture domain receives the colour **orange.**

Domain	Subdomain	Characteristics
Culture	***Success stories***	➢ Not yet a big hydrogen success story, but the potential for future success stories ➢ Hydrogen to complement the region's smart grid adventure.
	Societal norms	➢ Public rejection of large energy projects ➢ Cautiousness in developing hydrogen projects ➢ Demonstration project on a local scale essential to change the public attitude towards hydrogen. ➢ Relatively good acceptance of hydrogen roadmap

Table 8c. Characteristics culture domain

6.3.4 Support

6.3.4.1 Infrastructure

In Brittany, there is not yet a regional hydrogen infrastructure present. The region is currently investigating its feasibility due to the enormous investments (Government 1, pers.com. 14-04-2022). Therefore, Business 4 (pers.com. 19-04-2022) expects that for the next upcoming 10 or 20 years, hydrogen will be dispatched by trucks. This projection corresponds with the plans for the European Hydrogen Backbone, where there are no plans for Brittany (Gas For Climate, 2020). However, there are plans to connect with Nantes by the year 2035, located near the border of South Brittany (Gas for Climate, 2020).

The realisation of local hydrogen ecosystems is vital for making green hydrogen available locally, as no regional pipeline infrastructure could connect the production to the end use (Business 4, pers.com. 19-04-2022). An example is the VHYGO project, an interregional project between Brittany, Normandy and Pays de la Loire (Business 4, pers.com. 19-04-2022). The ambition is to realise an infrastructure of renewable hydrogen refuelling stations within a range of 100 km from each other by the year 2030. In 2030, green hydrogen should be sold for €8 per kg (Business 4, pers.com. 19-04-2022). According to Business 4 (pers.com. 19-04-2022), this price can be achieved because the local hydrogen production directly connects with the wind turbine. Furthermore, transport costs are reduced due to the close distance between production and consumption (Business 6, pers.com. 17-05-2022). In the project, the hydrogen will be dispatched by trucks as there is currently no other option. Government 1 (pers.com, 14-04-2022) mentions that distributing by truck is, on the other hand, not a future-proof solution for the region. This can be a solution in the initial phase, but when projects want to scale up, more trucks will be needed and even when it is a clean truck, the consumption will increase while the goal is to reduce consumption (Government 1, pers.com. 14-04-2022). Government 1 (pers.com. 14-04-2022) explains the following about this: *''You will have to buy hydrogen trucks and that is a problem because if you massificate the ecosystem you will have more and more trucks on the road and we do not want to have trucks to decarbonise the energy''.*

Concerning Brittanie's energy supply, the previous mentioned public rejection caused a lack of energy (Government 3, pers.com. 02-05-2022). Therefore, the region heavily depends on other areas for its energy supply (Government 1, pers.com. 14-04-2022). The aforementioned smart grid development is one solution to increase the region's energy security (BDI, 2021a; Government 3, pers.com. 02-05-2022). Another solution is the region's massification of renewable off-shore wind and marine energy development (Government 3, pers.com. 02-05-2022). In the case of wind energy, there are two wind parks in realisation, one of 450 MW and the other one of 65 MW and more are planned (Business 6, pers.com. 17-05-2022; Region Bretagne, 2020). However, the total time to construct an off-shore wind farm can take 10 to 12 years due to the lengthy approval procedure (Government 3, pers.com. 02-05-2022). This procedure hinders the increase of renewables. In the case of marine energy, there are currently two dedicated ports (Brest and Lorient) and three test sites for tidal and wind turbines (Bretagne Ocean Power, 2022; Government 3, pers.com. 02-05-2022).

The development of hydrogen, smart grids, and marine and off-shore wind energy are therefore taking place side by side to improve the energy security of Brittany. Here, hydrogen is a potential part of the solution as it can be produced (on and off-shore) from future marine and wind energy and used by the smart grid for balancing the energy grid and other end uses (Government 3, pers.com. 02-05-2022). The off-shore hydrogen production will probably only happen after 2030, as there are no funding calls from the state with the needed feed-in tariffs for these projects (Government 3, pers.com. 02-05-2022). This can also be related to the previously mentioned mismatch in funding regimes. Till 2030, the production of hydrogen is from on-shore wind and solar power, which in almost all cases is complemented by energy from the national grid, which is 75% of nuclear energy (Government 3, pers.com. 02-05-2022). The sustainability of the hydrogen ecosystem till 2030 can therefore be questioned.

Another source that has much potential to increase hydrogen production in Brittany is biomass (Business 5, pers.com. 13-05-2022). Due to the mentioned sizeable agricultural sector in Brittany, much biomass can be used to produce hydrogen (Business 5, pers.com. 13-05-2022). This is also confirmed by the hydrogen roadmap, where it is calculated that biomass can complement the hydrogen production by renewables to meet the region's internal demand (Government 3, pers.com. 02-05-2022). However, this technology is in an early stage of experimentation and needs to be developed first (Business 3, pers.com. 07-04-2022; Government 1, pers.com. 14-04-2022).

6.3.4.2 Support Professions

Brittany's entrepreneurial culture mainly exists out of SMEs (Government 2, pers.com. 02-05-2022). From these SMEs, it was analysed that Brittany has various small private actors with specific expertise in each part of the hydrogen value chain (Government 2, pers.com. 02-05-2022).

Specific expertise can be found in the earlier mentioned strong sea culture, expressed by having the regional name 'Sailing Valley' (BDI, 2021b; Government 3, pers.com. 02-05-2022). Brittany is an expert in the construction of smaller ships and has two clusters that support companies in making innovative eco-friendly performing ships (Government 3, pers.com. 02-05-2022; Invest in Bretagne, 2021). These two clusters are the Eurolarge innovation and the Pôle Mer Bretagne Atlantique. These clusters are also looking into how to construct clean hydrogen vessels (Invest in Bretagne, 2022). An example could be the building of a Crew Transfer Vessel, used to transport workers from land to an off-shore wind park, that uses hydrogen to decrease its emissions (Business 6, pers.com. 17-05-2022). In this way, the construction of off-shore wind parks is also getting more sustainable.

Another expertise can be found in the digital sector. The region started this development in 2000 to develop skills and expertise for digital and cyber specifications (Government 3, pers.com. 02-05-2022). This expertise was later linked to Brittanie's smart grid development, in which hydrogen can now be used to balance the grid and make the grid thereby even more intelligent (Government 3, pers.com. 02-05-2022).

6.3.4.3 Networks

In Brittany, the Bretagne Development Innovation agency (BDI) has a vital role in creating a regional voice by working with regional businesses and universities (Business 6, pers.com. 17-05-2022). As a result, the BDI can support local businesses by connecting them to national or European projects (Business Developer 3, pers.com. 02-05-2022). Furthermore, The BDI created an overview by mapping all the hydrogen-related stakeholders and projects. Through this mapping, the BDI wants to create a community where businesses and research centres can work together, strengthening the culture of collaboration and innovation within the ecosystem of Brittany (Business Developer 3, pers.com. 02-05-2022).

In exploring the support domain, the region shows difficulty realising a supportive infrastructure that will be necessary to scale up green hydrogen projects. This is because of the absence of plans to install hydrogen pipelines and the current lack of energy. However, the region's energy security is expected to improve due to increased marine and wind power and smart grid development. Nevertheless, hydrogen production needs to be completed with energy from the national grid, which exists 75% out of nuclear energy, until 2030. The domain also shows other conducive characteristics, as Brittany seems to have different expertise supporting the region's hydrogen development. Lastly, the BDI functions as a regional voice as it tries to link other hydrogen businesses to national and European hydrogen projects. Therefore, this domain receives the colour **orange.**

Domain	Subdomain	Characteristics
Support	***Infrastructure***	➢ In the near future, distribution is expected to be by truck ➢ VHYGO project for creating an infrastructure of refuelling station ➢ Current lack of energy security ➢ Hydrogen production till 2030 with onshore renewable energy and nuclear energy from the grid
	Support professions	➢ Specific expertise from small companies in each segment of the hydrogen value chain ➢ Expertise in building ships and the digital sector
	Networks	➢ BDI as a regional voice to connect businesses and link them with national or European projects

Table 8d. Characteristics Support domain

6.3.5 Human Capital

6.3.5.1 Educational Institutions

In Brittany, there are three universities in Brest, Rennes and Lorient (University 2, pers.com. 06-04-2022). University 2 (pers.com. 06-04-2022) explains that the university Bretagne Sud in Lorient is the one that is the most focused on hydrogen in the region. The university is also developing a particular degree in hydrogen that should start in September 2022 (University 2, pers.com. 06-04-2022). However, in general, the development of hydrogen education at the beginning (Business 3, pers.com. 07-04-2022). The roadmap also states that hydrogen and energy research lack visibility in the region (Region Bretagne, 2020*)*. Therefore, a particular objective in the strategy is dedicated to deploying hydrogen expertise centres to boost hydrogen development in the initial phase (Region Bretagne, 2020*)*.

6.3.5.2 Labour

In Brittany, It is currently difficult to find experienced people in the hydrogen sector (Business 5, pers.com. 13-05-2022). This problem is even more significant in Brittany because of its decentralised location as a peninsula (Business 5, pers.com. 13-05-2022). Therefore, University 2 (pers.com. 06-04-2022) explains that the new hydrogen engineering degree in Lorient will be based on a survey spread among different partners and companies to create this new labour force. This way, the needed engineering type can be identified and educated (University 2, pers.com. 06-04-2022).

In exploring the human capital domain, it seems that this element is not yet conducive to the hydrogen ecosystem because of the absence of a hydrogen laboratory and the difficulty of finding an experienced workforce. Moreover, hydrogen education in the region is also only at its beginning. Still, this is progressing, for example, with the development of the new hydrogen degree or the policy to support the deployment of hydrogen expertise centres. Therefore, the human capital domain receives the colour orange.

Domain	Subdomain	Characteristics
Human Capital	***Educational institutions***	➢ Absence of a hydrogen laboratory in the region ➢ Development of hydrogen expertise centres ➢ Education for hydrogen at its beginning
	Labour	➢ Difficulty in finding experienced labour in the hydrogen industry ➢ New hydrogen degree based on specific needs of regional businesses

Table 8e. Characteristics Human Capital

6.3.6 Market

6.3.6.1 Early Market

The roadmap states that the generalisation phase, where hydrogen should become widely used, is planned to happen after 2030 (Region Bretagne, 2020). Towards 2030 the region will try to initiate the market by realising these smaller local ecosystem projects, like Hylias or the Lorient project, that are spread across the region (Government 2, pers.com. 02-05-2022). This method can be described as a more bottom-up strategy in which the public is involved as much as possible to increase the public acceptance and adoption of hydrogen (Government 2, pers.com. 02-05-2022). One of the focus areas of using hydrogen is the ports because they are one of the primary energy consumers and show potential for different hydrogen applications, such as boats or trains (Government 3, pers.com. 02-05-2022; Region Bretagne, 2020). The ports are also vital for future off-shore hydrogen production by wind and marine energy (Government 2, pers.com. 02-05-2022). When focusing on developing a market for inland uses, the creation of the local loops is the starting point. Here, the demand is mainly initiated by investment in public fleets, like hydrogen buses, garbage trucks, and other public vehicles (Government 1, pers.com. 14-04-2022). The Lorient project of twelve buses, two boats and two refuelling stations is an example of that (Government 1, pers.com. 14-04-2022).

However, the market is also influenced by some characteristics of the previously explored domains. Firstly, the current lack of (renewable) energy, because of public rejection, causes less green hydrogen availability for end uses (Government 2, pers.com. 02-05-2022). Secondly, the absence of a pipeline infrastructure causes difficulty if projects want to scale up and use larger quantities of hydrogen (Business 4, pers.com. 19-04-2022). Finally, the absence of large industries or companies, like the steel industry, causes there to be no potential first large off-takers that could have been the basis for reaching the critical mass. Moreover, there is a funding mismatch due to this absence. Therefore, the region needs to be cautious about which sectors they want to fund (Government 2, pers.com. 02-05-2022).

In exploring the market domain, the region seems to use a more bottom-up approach to create a more local uptake of hydrogen uses, where the focus is primarily on ports and the public fleets for the local loops. However, when the market wants to scale up, characteristics from other domains, like the lack of energy, must be solved first. Therefore the market domain receives the colour **orange**.

Domain	Subdomain	Characteristics
Market	***Early market***	➢ Bottom-up approach for creating demand and public acceptance by realising smaller local projects ➢ Focus on hydrogen uptake in the ports and local loops ➢ Influenced by not having first large off-takers, lack of renewable energy, mismatch in funding and no pipelines infrastructure

Table 8f. Characteristics Market

6.3.7 Summary of Brittany

From the previous sections, table 8g is created. From this table, it can be concluded that none of the domains is entirely conducive to hydrogen development. However, the orange colour of all the fields shows potential for realising a future regional hydrogen value chain, despite much need to be developed first. For example, if the targets of the regional hydrogen roadmap are met, this can be the basis for a developed hydrogen ecosystem in the future. On the other side, development speed is harmed by barriers that are not easily overcome, like the lack of renewable energy and finance. Therefore, the upcoming years will decide if the region can overcome or minimise these barriers that will determine its hydrogen development trajectory.

Domain	Conduciveness
Policy	
Finance	
Culture	
Support	
Human Capital	
Market	

Table 8g. Conduciveness hydrogen ecosystem North Jutland, **Red= not a conducive element, Orange= Both conducive and non-conducive elements present, Green= Conducive element**

6.4 Lower Saxony

6.4.1 Policy

6.4.1.1 Government

Germany wants to decrease their emissions by 65% in 2030 (BMWK, 2020). In 2020, the national government published their national hydrogen strategy to support this ambition (BMWK, 2020). The policy consist of 13 goals and 38 measures that are focused on four themes (BMWK, 2020):

1. Hydrogen production
2. Fields of applications (transport, industry sector and heat)
3. Infrastructure and supply
4. European and international level

The strategy is divided into two phases; phase one (2020 – 2023) consists of a market ramp-up to lay the basis for a domestic market, and phase two (2024 – 2030) consists of strengthening that ramp-up nationally and also internationally (BMWK, 2020). The national government aims to install an electrolysis capacity of 5 GW by 2030 to establish a domestic market. This ambition is planned to be doubled by the newly elected government of 2021 (Research Institution 1, pers.com. 17-05-2022). However, due to the limited availability and potential of renewable energies, a future import of hydrogen is needed to meet Germany's expected internal hydrogen demand (BMWK, 2020: Utility Company 2, pers.com. 28-03-2022). In addition, an adjusted national or international regulatory framework is needed to make green hydrogen economically viable (BMWK, 2020). For example, hydrogen is incompatible with fossil fuels, which can be reduced by including costs for CO2 emissions (BMWK, 2020). Moreover, new regulations are fundamental concerning trust building in society, as these standards must ensure the safety and quality of hydrogen projects (BWMK, 2020). Therefore, the current framework does not allow the large out roll of hydrogen yet, as there is not yet a quality assurance infrastructure of safety requirements and technical assessments for hydrogen production, distribution and end use (BMWK, 2020). In developing this framework, the national policy emphasises the importance of creating a uniform European framework because it would not work if every country had different rules or standards regarding hydrogen (BMWK, 2020).

6.4.1.2 Leadership

Focusing more on the public support and ambition of Lower Saxony for hydrogen, the region created, together with the four other northern areas (Bremen, Hamburg, Mecklenburg-Western Pomerania, and Schleswig-Holstein), the Northern German Hydrogen Strategy in the year 2019 (Wirtschaftsministerien, 2019). The strategy's primary goal is to establish a green hydrogen economy by 2035 (Wirtschaftsministerien, 2019). Therefore, the northern regions aim to reach an electrolysis capacity of 5 GW in 2030, equalising the national strategy target (Wirtschaftsministerien, 2019). The strategy's first step is realising hydrogen hubs that should operate by 2025 (Wirtschaftsministerien 2019). These hubs should develop around territories with a critical mass for hydrogen consumption and where the whole value chain can be realised in proximity (Wirtschaftsministerien, 2019). In particular, the hubs should be visible to increase public understanding, focusing on the industry and mobility sectors because these offer the most potential for developing a hydrogen market (Wirtschaftsministerien, 2019). The idea is that these hubs later on grow and get interconnected to create a regional hydrogen ecosystem (Wirtschaftsministerien, 2019).

Parallel to the previous development of hydrogen hubs, there is a particular focus on developing expertise in the manufacturing of components across the entire hydrogen value chain (Network 3, pers.com. 03-05-2022; Wirtschaftsministerien, 2019). Therefore, SMEs are crucial for developing this expertise and hydrogen components that can be used in future hydrogen projects (Network 3, pers.com. 03-05-2022). As a result, the region wants to become more self-sufficient by having the knowledge and technology expertise to realise hydrogen projects. Network 3 (pers.com. 03-05-2022) explains this: *''Because if Lower-Saxony and SMEs can establish the knowledge there, then they will be an integral part of future hydrogen workplaces and also future hydrogen projects, so this is a huge part we see there''.*

In exploring the policy domain, Lower Saxony shows relatively positive characteristics conducive to hydrogen development. The national government established a national strategy that provides the region with guidance from the federal level. Moreover, Lower Saxony's collaborative policy shows the ambition of the area to become a prominent future hydrogen region in Germany. The aspiration of realising hydrogen hubs and expertise are, therefore, factors that are conducive to the region's hydrogen development. However, the current absence of proper regulations harms the large-scale roll-out of hydrogen. Overall, the policy domain, therefore, receives the colour **orange.**

Domain	Subdomain	Characteristics
Policy	➢ *Government*	➢ A national policy that supports the hydrogen development ➢ Need for a regulatory framework for hydrogen
	➢ *Leadership*	➢ Collaborative strategy with the northern regions. ➢ Initiating hydrogen development with the creation of hydrogen hubs. ➢ Developing expertise in manufacturing components of the entire hydrogen value chain.

Table 9a. Characteristics policy domain

6.4.2 Finance

6.4.2.1 Private Finance

Private investments are a decisive factor in the hydrogen ecosystem of Lower Saxony. This is because hydrogen production and consumption mainly depend on industries that want to use or produce it (Utility Company 3, pers.com. 13-04-2022). However, for these industries to invest in green hydrogen, like refineries or steel production, there must be a security of hydrogen supply that can be reassured over a long time, which is not yet (Utility Company 3, pers.com. 13-04-2022). This is because these industries and businesses need this security to plan for the future. Otherwise, there will be too much insecurity for them to transition toward green hydrogen (Utility Company 3, pers.com. 13-04-2022). Especially in the case of green hydrogen production, which is also not an attractive investment due to high costs (Wirtschaftsministerien, 2019). Therefore, it all starts with private companies that want to invest in hydrogen projects, which can later be backed with public funding (Utility Company 3, pers.com. 13-04-2022).

6.4.2.2 Public Finance

The funding of hydrogen projects comes from the national or EU level (Research Institution 1, pers.com. 17-05-2022). An example of this federal funding is the HyLand program that supports regions in creating integrated regional hydrogen concepts (BMWK, 2020; Network 2, pers.com. 11-04-2022). In this program, there is a division between the following three HyLands:

1. HyStarter, a region at the beginning stage of its hydrogen development, needs organisational support and therefore receives help from a consortium of hydrogen experts (HyLand 2022b).
2. HyExperts, a region that receives €400,000 funding for establishing their first practical hydrogen concepts (HyLand, 2021).
3. HyPerformer, a region that has already established multiple hydrogen concepts and wants to roll out specific hydrogen technologies and projects, is receiving €20 million in funding (HyLand, 2022a).

Concerning Lower Saxony, the region has three HyStarter projects, four HyExperts projects and one HyPerformer project (NDS, n.d.). The importance of this program is that without the Hyland program and its financial support, some regions would not have the resources to focus on hydrogen (Network 2, pers.com. 11-04-2022). In this way, the overall development of hydrogen is accelerated (Network 2, pers.com. 11-04-2022).

Another crucial funding program is the Important Project of Common European Interest (IPCEI), which will significantly impact infrastructure development (Utility Company 3, pers.com. 13-04-2022). In Lower Saxony, seven projects have applied for this funding (NDS, n.d.). Once the decisions about which projects are receiving this funding are made, it will become clear how the future network will evolve, as Utility Company 3 (pers.com. 13-04-2022) explains:

> *''But once the decision for the IPCEI funding is being made, so once you know where the money goes and which projects are being pushed by the government and the EU, I think this will all sort of solidifying which projects are done and which are not and which networks really stand for the future to build the hydrogen economy.''*

Even though there are different funding possibilities, Network 3 (pers.com. 03-05-2022) explains that there is still much insecurity on the business side due to lengthy approval procedures. For example, some large infrastructure projects that applied for the IPCEI funding hesitate to start because they are waiting for the final decisions (Network 2, pers.com. 11-04-2022). Furthermore, Network 3 (pers.com. 03-05-2022) explains that this lengthy procedure caused multiple project ideas to end.

In exploring the finance domain, the importance of the private sector became clear in initiating hydrogen projects that can be backed with the available public funding. The interaction between these two types of finance is therefore crucial. However, for the private sector to invest, there must be a security of hydrogen supply, which is not yet. Furthermore, the lengthy approval procedure causes hesitation to start and has already stopped some project ideas. Overall, the finance domain receives, therefore, the colour **orange.**

Domain	Subdomain	Characteristics
Finance	***Private Finance***	➢ Private actors are drivers behind hydrogen projects ➢ Security of hydrogen supply is needed for industries to invest in green hydrogen
	Public Funding	➢ National and EU funding is essential and available ➢ Lengthy approval procedures for funding barriers stopped project ideas

Table 9b. Characteristics finance domain

6.4.3 Culture

6.4.3.1 Success Stories

In Lower Saxony, there is currently not yet a big finished project that could pave the way for other projects (Network 2, pers.com. 11-04-2022). Nevertheless, multiple large projects are planned in different sectors (transport, industry, agriculture) that could serve as potential success stories in the upcoming years. An example of the transport sector is the Hyperformer project from the Hyland funding program, HyWays for Future (HyLand, 2022a). The project tries to overcome the chicken and egg problem by ramping up the supply and demand side to realise a hydrogen transport market in two years (Utility Company 2, pers.com. 28-03-2022). Therefore, the project already got the funding, the location and the initial demand to realise five hydrogen refuelling stations (Utility Company 2, pers.com. 28-03-2022). Another project is the SALCOS project in the steel industry, which aims to develop a plant that can use green hydrogen in its process and thereby reduces CO2 emissions by more than 95% (Network 2, pers.com. 11-04-2022). The first type of this plant should be in operation by 2026 (NWN, 2021c). In the agricultural sector, the H2Agrar project demonstrates the use of green hydrogen in tractors. When a success, this project can result in serial production (NWN, 2021a).

6.4.3.2 Societal Norms

In Lower Saxony, the so-called current 'hydrogen hype' is perceived as accurate. Utility Company 2 (pers.com. 28-03-2022) explains that the culture may be too hyped in governments and businesses: ''*I would say in relation to hydrogen that there is a big motivation here. The culture is pretty positive, so it is maybe too hyped. Because everyone is excited about it and wants to do something with it.''*. However, outside this hydrogen bubble, Network 2 (pers.com. 11-04-2022) noticed that it is not yet on people's minds.

In the realisation of renewable energies, Network 3 (pers.com. 03-05-2022) explains that there has been a massive realisation of renewable energy. However, this stopped due to law cases against wind parks, especially environmental organisations complaining about its effect on nature (Network 3, pers.com. 03-05-2022). The noise and the distance between a wind park and houses were other arguments that caused these law cases (Network 3, pers.com. 03-05-2022). Nowadays, there is more of a consensus about this energy transition, but the public acceptance of renewable can still be improved (Network 3, pers.com. 03-05-2022).

In exploring the culture domain, it seems that the region has multiple potential success stories in development but not yet one big realised project. The hydrogen hype is furthermore perceived as accurate, which is conducive to the development of hydrogen. However, it is uncertain how the public will accept hydrogen because it is not yet on many people's minds outside the hydrogen sector. Furthermore, the acceptance of renewable energy can still be improved. Overall, this domain receives, therefore, the colour **orange.**

Domain	Subdomain	Characteristics
Culture	***Success stories***	➢ Not yet a big success story realised ➢ Multiple potential success stories in the industry, transport and agriculture
	Societal norms	➢ Hydrogen hype is perceived as accurate in the region. ➢ Not yet on people's minds outside the hydrogen sector ➢ Public acceptance of renewable energy can be improved

Table 9c. Characteristics culture domain

6.4.4 Support

6.4.4.1 Infrastructure

In Lower Saxony, a regional infrastructure for hydrogen is not yet present. In the region, the focus is primarily on transporting through pipelines. This is because it is expected that there will be a massive demand for hydrogen because of the presence of multiple industries, like refineries or steel factories (Utility Company 3, pers.com. 13-04-2022). As the finance domain explained, these industries require a secure hydrogen supply. Depending on only decentralised local hydrogen production from local wind turbines would therefore be too risky for these industries (Utility Company 3, pers.com. 13-04-2022). Therefore, a more extensive network of connected centralised hydrogen production and storage facilities is necessary to supply these industries (Utility Company 3, pers.com. 13-04-2022).

Utility Company 3 (pers.com. 13-04-2022) explains this: *'' So, the refineries and the steel works really need a lot of green hydrogen, and this is not possible with decentralised production, which means that* *you need a centralised production with a connecting network''.*

Lower Saxony has two advantages for installing such a network. Firstly, in the region, there are two kinds of pipelines for gas, one for low-calorific gas (L-gas) and one for high-calorific gas (H-gas) (Utility Company 3, pers.com. 13-04-2022). The L-gas is only produced in the Netherlands and Germany, whereas the H-gas is produced in other countries, like Norway, Russia and the USA (Utility Company 3, pers.com. 13-04-2022). These two gas types cannot be combined and therefore need separate pipelines. The advantage is that the L-gas is phased out by 2024, which means that these pipelines will become available and are also suitable for hydrogen (Utility Company 3, pers.com. 13-04-2022). Secondly, there are salt caverns where large quantities of green hydrogen can be stored (Utility Company 2, pers.com. 28-03-2022).

Concerning the realisation of pipeline infrastructure, Lower Saxony has two main projects. The first one is the Hyperlink project, which wants to create the infrastructure of pipelines in the region before 2030 (Gasunie, 2021). To accomplish this, the planning of the project exists will include three different phases:

- The first phase, till 2025, connects the northwest part of Lower Saxony with Bremen and Hamburg (Gasunie, 2021).
- The second phase, till 2028, includes connecting with the Dutch network, which should be finalised in 2025 and extending the regional network to Hannover and Salzgitter (Gasunie, 2021).
- The third phase, till 2030, includes connecting with the Danish network (Gasunie, 2021).

The project will have a length of 610 km and a capacity to distribute 7.2 GW of hydrogen (Gasunie, 2021). This project is also closely connected to the Green Hydrogen Coastline, which aims to integrate 400 MW electrolysis capacity into the energy supply system by 2026 (EWE AG, 2021).

The other project is the Get H2 project, located in Lower Saxony and Northrhein Westfalen (Utility Company 3, pers.com. 13-04-2022). This project has the following phases:

- The first phase, till 2024, is to create a 130 km hydrogen network from Lingen (Lower Saxony) and Gelsenkirchen (Northrhein Westfalen). The green hydrogen will be produced from local wind energy, and there will be an electrolysis capacity of 100 MW (Get H2, n.d.).
- The second phase, till 2025, is to connect with the Dutch network in light of the European hydrogen backbone. The capacity will be increased to 200 MW (Get H2, n.d.).
- The third phase, till 2026, will include connecting to a salt cavern for hydrogen storage and increasing the production to 300 MW. In addition, Salzgitter will launch an electrolyser powered by wind on location (Get H2, n.d.).
- The fourth phase, till 2030, will connect Salzgitter to the network (Get H2, n.d.).

The project and its three sub-projects can ultimately avoid up to 16 million CO2 emissions by 2030 (Get H2, n.d.). Both infrastructure projects are linked to the European hydrogen backbone and are, therefore, part of the projects that applied for the IPCEI funding (Utility Company 3, pers.com. 13-04-2022; Network 3, pers.com. 03-05-2022). However, it is not yet determined which projects will receive funding (Utility Company 3, pers.com. 13-04-2022). These decisions will therefore be crucial for the previously mentioned projects.

Nevertheless, Lower Saxony will still need to import hydrogen despite the previously mentioned networks for two reasons. Firstly, there is not enough future renewable energy availability and potential to produce enough green electricity and green hydrogen (Research Institution 1, pers.com. 17-05-2022). However, it must be noted that Lower Saxony already has a high renewable energy supply (Wirtschaftsministerien, 2019). Utility Company 2 (pers.com. 28-03-2022) mentions that their energy grid in the northern part of Lower Saxony exists 90% of renewable energy. Secondly, the internal demand is so high that even if the green hydrogen production is doubled, this is still not enough, as Utility Company 3 (pers.com. 13-04-2022) explains: *''But even if we can multiply the production of green hydrogen, this will not be enough to provide enough to satisfy the demand of all the companies that need green hydrogen, so we need to import a lot hydrogen''*. Therefore, the region has two main projects related to the import of hydrogen. The first project is the Green Crane and consists of creating an international value chain, transporting hydrogen from Spain towards the port of Rotterdam, where it will be transported inland towards the BP refinery in Lingen (NWN, 2022a). The second project is making the Wilhelmshaven port ready to import green hydrogen and constructing an electrolyser. When the project is finished, this should lead to 300,000 tons of green hydrogen import and production, which equals around 10% to 20% of the national hydrogen demand in 2030 (NWN, 2022b).

Next to the pipeline infrastructure and import, there is a focus on creating a refuelling stations network in the region. In the Northern strategy, it is acknowledged that, if possible, the stations will be used for multiple transport types, such as trucks and trains (Wirtschaftsministerien, 2019). As earlier explained, the HyWays for Future projects already got the funding and locations to employ five refuelling stations (Utility Company 2, pers.com. 28-03-2022).

6.4.4.2 Support Professions

An expertise of the region can be found in the transport sector, whereas Lower Saxony is the home region of Volkswagen (Network 3, pers.com. 03-05-2022). Therefore, many SMEs have expertise in producing car components and are searching for new sustainable business models (Network 3, pers.com. 03-05-2022). When hydrogen's role in transport is more evident, this expertise can, for example, support the current lack of available hydrogen trucks on the market (Utility Company 2, pers.com. 28-03-2022).

Another expertise can be found in the industrial sector. In this sector, some industries, like refineries, already have the experience and knowledge to work with hydrogen (Wirtschaftsministerien, 2019).

6.4.4.3 Networks

In Lower Saxony, multiple sectors are present, such as the marine, agricultural and industry sectors. This diversity sometimes makes it difficult to achieve a consensus but also offers the regions a lot of possibilities (Network 2, pers.com. 11-04-2022). A network can create more synergy and can be a place where companies can learn from each other (Network 2, pers.com. 11-04-2022). In Lower Saxony, there are 14 local hydrogen networks and one regional network, Niedersächsisches Wasserstoff-Netzwerk (NWN)**,** which is described as the network of networks (Network 2, pers.com. 11-04-2022). The importance of the NWN is that it organises events where companies searching for more sustainable business models can exchange knowledge and find role models that inspire them, as Network 3 (pers.com. 03-05-2022) explains:

> *''We organise events and professional circuits and this is really crucial in this process because there are a lot of companies that want to join the hydrogen field or are not really sure if their business model is suitable. So, they need this networking and this exchange with other companies also to have role models to see how it works and how successful projects are.''*

By facilitating interaction between the businesses, the government and the research institutions, the networks attempt to combine the strengths of different players in the ecosystem.

In exploring the support domain, Lower Saxony is active in planning a regional infrastructure to create a security of hydrogen supply for its potential large off-takers. Here, the region has the advantage of having available pipelines by 2024 and the presence of salt caverns for storage. However, the infrastructure projects are not yet sure of their funding. Despite these projects, there will also be a need to import hydrogen due to the high demand for hydrogen and the lack of future renewable energy for hydrogen production. Therefore, they are already involved in two projects related to this import. Concerning the support profession, the region's technical expertise in the transport sector and their know-how in working with hydrogen in industries support hydrogen development. Moreover, Lower Saxony has extended networks conducive to the region's hydrogen development. Overall, the support domains receive, therefore, the colour orange.

Domain	Subdomain	Characteristics
Support	***Infrastructure***	➢ Not enough renewable energy for hydrogen production is present ➢ Two hydrogen import projects to complement the internal production ➢ Two hydrogen pipelines project will be the basis of a regional and European network ➢ Available pipelines for hydrogen ➢ Salt caverns are present for long-term storage ➢ Construction of refuelling stations planned
	Support professions	➢ Expertise in the transport sector ➢ Experience in how to work with hydrogen in the industry
	Networks	➢ One regional and 14 local networks present to support hydrogen businesses in finding role models

Table 9d. Characteristics support domain

6.4.5 Human Capital

6.4.5.1 Educational institutions

In Lower Saxony, the Energy Research Centre is a joint centre of five regional universities from Braunschweig, Göttingen, Clausthal, Hannover and Oldenburg (Research Centre 1, pers.com. 16-05-2022). Concerning hydrogen, Research Centre 1 (pers.com. 16-05-2022) explains that in 2018, a group of motivated professors set up a hydrogen research competence network within the EFZN. Furthermore, the research centre received €6,5 million from the ministry of Lower Saxony to realise five innovation labs (NWN, 2022d). These resulted into the following projects: H2-Wegweiser Niedersachsen, InnoEly, WaVe, THEWA and H2-ReNoWe (EFZN, n.d.). These projects all include an area where they can research different hydrogen technologies in practice, such as a combination of hydrogen storage and conversion processes in H2-WegWeiser Niedersachsen (NWN, 2022d).

An essential aspect of hydrogen research within the Energy Research Centre is focusing on the quadruple helix approach, which includes the civil society aspect of hydrogen research (Research Centre 1, pers.com. 16-05-2022). This can, therefore, contribute to a better understanding of the public perspective on hydrogen, which is essential because they are necessary for making this transition (Research Centre 1, pers.com. 16-05-2022). The centre currently has 80 professors of the social sciences working on hydrogen (Research Centre 1, pers.com. 16-05-2022).

6.4.5.2 Labour

In Lower Saxony, the transition towards hydrogen also means that the currently missing labour force must be trained to work in this field (Network 2, pers.com. 11-04-2022). Therefore, the region is working on several initiatives to improve the labour force in different hydrogen fields (Network 2, pers.com. 11-04-2022). One of these projects is H2 skills, which aims to investigate the specific needs among the region's hydrogen businesses to develop specific training and certificate courses for this (Network 2, pers.com. 11-04-2022; NWN, 2022c). Another project is the Employee qualification for H2 vehicles in the logistics sector (NWN, 2021b). This project aims to prepare vehicle users for this transition towards hydrogen as this switch brings up new requirements, such as vehicle maintenance (NWN, 2021b).

In exploring the human capital domain of Lower Saxony, there seems to be a relatively conducive environment for hydrogen research. The development of the five hydrogen innovation labs from the Energy Research Centre illustrates this. Concerning the labour force, some programs are being developed to prepare and train the future labour force that is currently not present. Because this is still a work in progress, the human capital domain receives the colour **orange.**

Domain	Subdomain	Characteristics
Human capital	***Educational institutions***	➢ Energy Research Centre is a joint research centre for five regional universities. ➢ The establishment of a Hydrogen competence network ➢ The realisation of five innovation labs for hydrogen
	Labour	➢ The future labour force must be trained ➢ The H2skills and Employee qualification for H2 vehicles in the logistics sector prepare the future labour force

Table 9e. Characteristics human capital domain

6.4.6 Market

6.4.6.1 Early Market

Lower Saxony has the advantage of having industries serving as potential first off-takers. The chemical industry, for instance, already uses grey hydrogen and therefore only needs to switch from grey to green (Network 2, pers.com. 11-04-2022). Another example is the steel industry, where green hydrogen can reduce emissions by more than 95%, as mentioned in the SALCOS project (Network 2, pers.com. 11-04-2022; NWN, 2021c). These two industries need large amounts of hydrogen and can boost the market by providing a solid basis for hydrogen off-take. However, this transition towards green hydrogen also asks for huge investment as green hydrogen production is financially not yet an attractive option for these industries (BMWK, 2020). Moreover, these industries need a secure hydrogen supply to transition towards green hydrogen (Utility Company 3, pers.com. 13-04-2022). Therefore, the realisation of infrastructure and hydrogen import is also decisive for the early market of green hydrogen in these industries (Utility Company 3, pers.com. 13-04-2022).

Another sector where the region wants to establish a market is the transport sector. As explained, the HyWays for Future project intends to initiate the hydrogen market for transport within two years (Utility Company 2, pers.com. 28-03-2022). The project has, therefore, created a demand side by cooperating with local bus and waste truck companies (Utility Company 2, pers.com. 28-03-2022). Another example is the Green Hydrogen Coastline project, which can lay the foundation for 12.000 hydrogen vehicles by 2026 (EWE AG, 2021). The focus of this project is also on heavy-duty vehicles (Utility Company 2, pers.com. 28-03-2022).

In exploring the market domain, Lower Saxony showed a significant potential for green hydrogen uptake in their industries, as some sectors only need to switch from grey to green hydrogen. However, much need to happen before this is realised. Other potential end users can be found in the transport sector. Therefore, the market domain receives the colour orange.

Domain	Sud Domain	Characteristics
Market	***Early market***	➢ Large industries present to be the first off-takers. However, this depends on the security of the hydrogen supply ➢ Potential market off-take in hydrogen transport

Table 9f. Characteristics market domain

6.3.7 Summary of Lower Saxony

From the previous sections, table 9g is created. From this table, it can be concluded that the policy, finance, culture, support, human capital and market domain are not yet totally conducive to hydrogen development. However, towards 2030, the region shows potential to overcome its barriers and realise a regional hydrogen value. Especially if the infrastructure projects, like the Get H2, are installed, this will enable the hydrogen ecosystem to scale up and develop further towards the hydrogen value chain. On the other hand, the case also showed some uncertainties that hamper hydrogen development in Lower Saxony, like the regulatory framework or the lengthy approval procedure for funding. Therefore, its hydrogen development trajectory is not yet determined despite the ecosystem's potential.

Domain	Conduciveness
Policy	(orange)
Finance	(orange)
Culture	(orange)
Support	(orange)
Human Capital	(orange)
Market	(orange)

Table 9g. Conduciveness of hydrogen ecosystem Lower Saxony, **Red= not a conducive element, orange= Both conducive and non-conducive elements present, Green = Conducive element**

6.5 Comparative ecosystem analysis

From the previous exploration, table 10 is created to give a total overview of the cases. It became clear that there is not yet an entirely conducive environment for hydrogen in all the regions, and still much needs to be developed. On the other hand, the explorations also do not show signs of domains that are fully non-conducive. Therefore, the regions show potential but also uncertainty about the ecosystem's further development towards a regional hydrogen value chain.

In this chapter, a comparative analysis discusses this development of the hydrogen ecosystem towards the hydrogen value chain, as explained in the conceptual model. Therefore, the chapter starts by comparing the initial phase to analyse the niche level where all ecosystems are currently present. From this, the development of the hydrogen value chain will be compared by using the barriers from the literature review. After that, the additional obstacles from the exploration are discussed.

Domain	North Jutland	Brittany	Lower Saxony
Policy			
Finance			
Culture			
Support			
Human Capital			
Market			

Table 10. Conduciveness of hydrogen ecosystem Lower Saxony, **Red= not a conducive element, orange= Both conducive and non-conducive elements present, Green = Conducive element**

6.5.1 Initial phase

Before analysing the hydrogen value chain, this section will compare the initial phase of how the regions plan to initiate hydrogen development. This is important for understanding the trajectory of hydrogen towards the hydrogen value chain.

When looking at the different policy domains of the regions, they all start with some form of a hub where the whole value chain is present. In Lower Saxony, the policy is to start with hydrogen hubs; in Brittany, the plan is to start with local loops; and in North Jutland, the commercial beacon could be an example. However, the project sizes differ between the cases despite the same starting point. The exploration shows that in North Jutland and Lower Saxony, there are, for example, projects planned for respectively 1 MW (Green Hydrogen Hub) and 400 MW (Green Hydrogen Coastline) (EWE AG, 2021; Green Hydrogen Hub Denmark, 2021). On the other hand, in Brittany, the focus is on creating smaller projects of, for instance, 0,5 MW (local loop) (Region Bretagne, 2020). Despite these differences, Business 5 (pers.com. 13-05-2022) explains that this is not necessarily a disadvantage for initiating hydrogen development in Brittany. The reasoning behind this relates to the complexity of realising these larger projects compared to smaller ones. These big projects require high investments, lots of administration and convincing people and public entities (Business 5, pers.com. 13-05-2022). Therefore, producing and using on a smaller local scale also has advantages because these projects are less complex.

6.5.2 Trajectory towards a hydrogen value chain

In the previous section, a comparison is made between the different hydrogen ecosystems at their beginning stage. However, for them to take off, the literature review already exposed several barriers shown in table 11. This section will therefore use these barriers to compare the trajectory of the cases toward the regional value chain. After this, the additional obstacles found in the results are discussed.

Supply chain	Barrier
Production	➢ The high costs production facility ➢ The high price of renewable energy ➢ Having enough full-load hours
Distribution and Storage	➢ The high costs of creating infrastructure
End Use	➢ The high investment costs ➢ The high price of green hydrogen ➢ Chicken egg problem

Table 11. Overview of the barriers and solutions

6.5.2.1 Production

In the data, no specific numbers are found about the price of renewable energy, full-load hours or the high investment costs. However, there are numerous developments related to these barriers identified.

For the production of green hydrogen, renewable energy is needed. An increase in this would also decrease the price of renewable energy because it will be more available (Incubator 2, pers.com. 25-03-2022). In the case of North Jutland, there is high availability and potential wind energy, which is only planned to increase (Network 1, pers.com. 20-04-2022). In the case of Brittany, there is a lack of renewable energy (Government 2, pers.com. 02-05-2022). However, projects are going on to increase this supply, like the two offshore wind parks (Business 6, pers.com. 17-05-2022). Lower Saxony has a high renewable energy supply (Wirtschaftsministerien, 2019). For instance, Utility Company 2 (pers.com. 28-03-2022) explains that their grid in the northern part of Lower Saxony exists out of 90% renewable energy. However, due to their massive internal hydrogen demand, there will be a lack of renewable energy in the future for the region's hydrogen production. Therefore, the import of hydrogen will be needed (Utility Company 3, pers.com. 13-04-2022). In the North Jutland and Lower Saxony case, their high renewable energy supply and their projected large production can cause a potential decrease in the price of green hydrogen. This is because the production facilities will have more full-load hours, making them more cost-efficient (Anajovic and Haas, 2020; Hermensmann & Müller, 2022). On the other hand, in Brittany, the investment costs of the facility will be less because these are smaller (Business 6, pers.com. 17-05-2022). However, the price of renewables will probably be higher due to their lack of renewables. To compensate for this and to have enough full-load hours, the production will be connected to the national grid (Government 2, pers.com. 02-05-2022). However, it is unclear what this will do for the price of hydrogen and how green the hydrogen will be.

Nevertheless, in all the cases, private investments in hydrogen production need to be complemented with funding cause of the high costs. This is most recognisable in the case of North Jutland. This case shows that even though the projects are moving towards the commercialisation phase, the projects still depend on funding (Network 1, pers.com. 20-04-2022). Therefore, this illustrates that the total production costs are still a barrier for all cases in realising hydrogen production.

6.5.2.2 Distribution and storage

The high investment costs for a pipeline infrastructure are a barrier that is noticeable in all cases. Due to this, the Brittany case shows their choice for transporting the hydrogen per truck near the consumption on a smaller scale to reduce transportation costs (Government 2, pers.com. 02-05-2022). In Lower Saxony and North Jutland, there are plans for creating a pipeline infrastructure to scale up their hydrogen production and end use. However, due to the high costs, the Lower Saxony case describes that some infrastructure projects hesitate to start because they are waiting for the IPCEI funding (Network 2, pers.com. 11-04-2022). Moreover, this funding will decide which networks will hold in the future (Utility Company 3, pers.com. 13-04-2022). In North Jutland, the ClusterNortH2 is also cautious in installing the infrastructure. This is because they want to ensure the system works, as it asks for a significant investment (Business Developer 1, pers.com. 21-04-2022). Therefore, the high costs of distribution seem to be influencing all cases. However, the Lower Saxony and North Jutland cases show the potential to overcome this barrier when infrastructure projects are financed.

6.5.2.3 End users

For the end uses, the cases describe different possibilities. In North Jutland, the local off-take for their large projected production of hydrogen or green fuels is an issue, but there are potential signs for off-take in the marine and aviation sectors (Network 1, pers.com. 20-04-2022). In Lower Saxony, the exploration describes that the region focuses on multiple sectors; industry, transport and agriculture (Network 2, pers.com. 11-04-2022). In Brittany, the focus is on transport, marine, and agricultural uses (Network 2, pers.com. 11-04-2022). In these cases, the potential end uses are mainly projects that demonstrate innovative end uses, which can reduce future investment costs. For instance, the tractor in the H2Agrar project in Lower Saxony (NWN, 2021a), the boat in the Hylias project in Brittany (Government 2, pers.com. 02-05-2022), or the testing of methanol vehicles in the port of Aalborg in North Jutland (Business 2, pers.com. 20-04-2022).

Furthermore, In Brittany and Lower Saxony, there are attempts to overcome the chicken-egg problem. In Brittany, the local ecosystems exist of projects where production and consumption are planned simultaneously (Government 2, pers.com. 02-05-2022). For example, the Lorient project consists of 12 buses, two refuelling stations and two boats (Government 1, pers.com. 14-04-2022). In Lower Saxony, the HyWays for Future project is an example, with the realisation of five refuelling stations and where the demand side is also secured with city buses and waste management trucks (Utility Company 2, pers.com. 28-03-2022). However, because these projects for end uses are all in a demonstrating phase, there is uncertainty about their actual development. For example, the transport market in Lower Saxony and Brittany seems to be driven mainly by the public sector in transforming public vehicles, like buses or garbage trucks, and not the private sector. This was also the case in the attempt to initiate the hydrogen mobility market in North Jutland, where the H2 vehicles were mainly from the municipalities (Business Developer 2, pers.com. 20-04-2022). However, one of the main reasons it did not take off was the high investment costs (Business Developer 2, pers.com. 20-04-2022). Therefore, this example shows the uncertainty in creating a market for new uses due to their high investment costs.

In the case of the high price of green hydrogen, the production section showed this has the potential to decrease mainly in the cases of North Jutland and Lower Saxony. However, this process will take time before the price of green hydrogen can be compatible with fossil fuels (Business 2, pers.com. 20-04-2022).

6.5.2.4 Additional barrier: Regulations

In the development of the hydrogen ecosystems, table 10 illustrates that not all the policy domains are conducive yet. This is because the regulations are one of the most significant barriers to hydrogen development. For creating such a framework, the policy domains refer to the importance of the EU level to create a uniform framework that can support an EU-wide hydrogen ecosystem. The EU is working on this, but this is not going fast, as Utility Company 2 (pers.com. 28-03-2022) from Lower Saxony explains: ''*That is actually a problem, the policies. It would be really helpful if policies would be there faster and we would have more information about upcoming regulations. From the EU side, there are a lot of things we are waiting on as well as on the national side.''.* Although it is a work in progress, these decisions on the EU level will be vital for hydrogen development, as Europe 1 (pers.com. 14-03-2022) and Europe 2 (pers.com. 29-03-2022) explain.

A significant outcome of these decisions is the current revision of the Renewable Energy Directive (RED II) (Europe 1, pers.com. 14-03-2022). The grandfathering clause is an example in this revision that shows the impact. At the moment, electrolysers need to use a renewable energy source that is not older than 36 months after the electrolyser was installed (Hydrogen Europe, 2022; Kurmayer, 2022). Additionally, When an electrolysis wants to add a renewable energy source to its production, it can only be a renewable energy source built on-site within 24 months after the construction of the electrolyser (Hydrogen Europe, 2022; Kurmayer, 2022). This means that when renewable energy comes not from one of these so-called additional sources, hydrogen production cannot be regarded as green (Utility Company 3, pers.com. 13-04-2022). Consequently, some renewable energy sources are excluded from producing green hydrogen. Therefore, this additionality principle decreases the potential sources for hydrogen production. On the other hand, the proposed grandfathering clause makes it possible that this previous additionality principle will not be applied until January 2027 (Hydrogen Europe, 2022). Therefore, this can impact the cases of Lower Saxony and North Jutland, which already have high availability of renewable energy sources.

Another essential European regulation that is mentioned in multiple interviews, Utility Company 3 (pers.com. 13-04-2022), Business 2 (pers.com. 20-04-2022), and Business 1 (pers.com. 12-04-2022), is the CO2 tax. or example, increasing the tax on fossil fuels would make green hydrogen a more attractive alternative.

6.5.2.2 Additional barrier: Funding

Concerning the funding, the finance domains of the exploration explain that not all regions have the same access to EU funding. For example, the Brittany case explains that it is difficult for them to apply for funding due to the absence of large companies and heavy industries (Government 3, pers.com. 02-05-2022, Business 5, pers.com. 13-05-2022). However, funding is crucial in developing a hydrogen ecosystem concerning the high costs related to hydrogen. Therefore, its fairness can be questioned when the finance tends to go more to the larger companies and industries. On the other hand, Utility Company 3 (pers.com. 13-04-2022) in the Lower Saxony case, states that these heavy industries will determine if the climate goals can be achieved. This is because these large industries are the main CO2 contributors. So, this is also something to consider when discussing the fairness of funding.

However, applying for these funds also brings business insecurity (Network 3, pers.com. 03-05-2022). For example, the Lower Saxony case shows that big projects hesitate to start due to the lengthy approval procedure of the IPCEI (Network 2, pers.com. 11-04-2022). The ClusterNortH2 project in North Jutland also wanted to apply for this funding but found it too tedious, so they decided to start without this finance (Utility Company 1, pers.com. 02-05-2022). However, Utility Company 1 (pers.com. 02-05-2022) mentions that the project would probably have been further with the IPCEI funding. Therefore, this illustrates how this approval procedure hinders hydrogen development.

6.5.2.3 Additional barrier: Culture

Another barrier in the regions is the impact of the public rejection or nimby on the realisation of renewable energies. The challenge regarding this barrier is most remarkable in North Jutland, where despite the windmill adventure's success, there is the nimby effect (Business Developer 1, pers.com. 21-04-2022). In the case of Brittany, the public rejection also caused their current lack of renewable energy (Business 6, pers.com. 17-05-2022; Government 3, pers.com. 02-05-2022).

The exploration of the public acceptance of hydrogen shows that this is not yet determined, as hydrogen is not yet on people's minds outside the hydrogen sector (Network 1, pers.com. 20-04-2022; Network 2, pers.com. 11-04-2022). This explains the importance of how acceptance for hydrogen will develop when more is realised in the upcoming years.

6.5.2.4 Additional barrier: Labour force

The labour force may not have been discussed in detail in the explorations, but it is essential to mention it. This is because a hydrogen ecosystem cannot sustain itself without its labour force that knows how to operate in the system. Europe 1 (pers.com. 14-03-2022) also mentions the importance of labour when a hydrogen ecosystem wants to scale up because it needs the right skills and labour force. In the cases, this is perceived as challenging, as in all regions, there is a need for a (future) labour force in the hydrogen sector, according to Business Developer 2 (pers.com. 20-04-2022) from North Jutland, Business 5 (pers.com. 13-05-2022) from Brittany, and Network 2 (pers.com. 11-04-2022) from Lower Saxony. This shows the importance of the education and training currently going on or being prepared in the regions to decrease this barrier.

6.5.4 Overall assessment

An overall assessment of the development of regional hydrogen value chains shows the influences of barriers on the trajectory of the hydrogen ecosystem. For Brittany, these barriers cause, for instance, the absence of multiple MW production projects, whereas these are present in North Jutland and Lower Saxony. Nevertheless, in the hydrogen ecosystem, both types of projects are needed, the big projects to ramp up the market and the smaller projects to create local up-take and public understanding of hydrogen (Business 5, pers.com. 13-05-2022). Business 5 (pers.com, 13-05-2022) explains this: *''Both are not contradictory, we need both, we need the infrastructure with the big projects, but we also need the acceptance, the everyday use at the lowest scale possibly of the individual or the family or the small business.''.* However, the barriers show the complexity and challenges of hydrogen development. Therefore, interaction and collaboration between public and private actors are needed to overcome all these challenges, as they are mutually interdependent. The public needs the private sector to succeed in its climate goals, and the private sector needs the public sector to overcome the high costs and for its adoption and acceptance in society. Moreover, this collaboration is not only required on a regional level but also on a national and EU level. Therefore, hydrogen development is not only a regional project but also a national and European project.

7. Conclusion

This chapter will answer the following main question: *How are different EU hydrogen ecosystems developing from a niche towards the realisation of hydrogen value chains?* In doing so, this chapter answers the first sub-questions.

7.1 Sub question 1

How are the different ecosystem domains of North Jutland, Brittany and Lower Saxony developing towards 2030?

In North Jutland, the policy domain described the region's focus on PtX and CCU, where hydrogen is the basis for producing green fuels like methanol. Although specific regulations have already changed in favour of hydrogen production and storage, this is still regarded as one of the main barriers to hydrogen development. The region showed in the finance domain to have an active private sector that had already invested in hydrogen projects without public support. On the other hand, the national strategy provides the private sector with multiple funding options for hydrogen development. The previous active private industry is illustrated in the cultural domain with an already realised success story. Another success story of the windmill adventure caused a drive to make PtX the next adventure and also caused a decrease in hydrogen production costs due to the high availability of cheap wind energy. However, a nimby effect in North Jutland hinders the increase in renewables. Concerning the support domain, this shows the importance of the infrastructure project ClusterNorth2. The pipelines in this project can connect all the parts of the hydrogen value chain and can, therefore, be a basis for a regional hydrogen ecosystem. Additionally, the salt caverns' presence is essential for the infrastructure development in the region for storing hydrogen. Moreover, the long history with PtX and methanol has given North Jutland a head start in the technical expertise related to hydrogen. The human capital domain explained how the expertise of Aalborg University increased this. However, this is not enough to educate the needed labour force. Lastly, the market domain explains that despite the increase in project sizes for green hydrogen production, it has difficulty creating local offtake. However, there are signs for early customers in the marine and aviation sectors.

In the case of Brittany, the policy domain explains the region's ambition of being a leading French region for hydrogen applications (Region Bretagne, 2020). Therefore, Brittany has created a hydrogen roadmap connected to the region's smart grid and marine energy development. However, the hydrogen regulations are in an early phase, hindering the speed of hydrogen projects. In accomplishing the regional roadmap, the finance domain shows the region's need for public and private investments. However, a mismatch in funding criteria because of the absence of large companies and industries makes it hard for the region to receive funding. Concerning the cultural domain, this explains the public rejection of large energy projects, which caused the current lack of energy and renewables for hydrogen production. Therefore, the support domain shows that until 2030 hydrogen production will be complemented by power from the national grid. In trying to create more social understanding and acceptance of hydrogen, a bottom-up approach was identified by initiating demonstration projects that could serve as a success story for its surroundings. There are currently no plans for the region's infrastructure to install a hydrogen pipeline infrastructure, which causes the hydrogen will be dispatched by truck. The hydrogen development will therefore focus on establishing local ecosystems where the production is near consumption. Concerning the human capital domain, this needs to be improved as this domain is still in an early phase of development in educating a hydrogen labour force. Finally, the market domain of Brittany is probably to develop around the ports, and eight local loops, primarily focussing on boats and public fleets. The region's entrepreneurial culture and specific expertise in construction ships are, here in, factors that can support the initiation of the market.

In the case of Lower Saxony, the policy domain elaborate the region's ambition to establish a green hydrogen economy by 2035. Lower Saxony wants to initiate the ecosystem by realising different local hubs where the whole value chain can be installed. A particular focus of the region was on supporting the development of SMEs along the value chain to secure future expertise. However, the absence of a regulatory framework hinders the large rollout of hydrogen. In the finance domain, creating a solid hydrogen supply is vital for the private sector to invest and transition towards green hydrogen. Therefore, the decision about the IPCEI funding will decide which current infrastructure projects will stand in the future to create security of hydrogen supply. Furthermore, the government has a comprehensive national funding program, supporting eight Lower Saxony areas in hydrogen development. The culture domain explains that there are no significant success stories yet. Although, in the next couple of years, multiple projects will be realised in the industry, transport and agricultural sector that could serve as a success story. The support domain explains that pipeline infrastructure is needed because there will be a massive demand for green hydrogen. This is because particular heavy industries can use green hydrogen to replace their current polluting processes. Therefore, the infrastructure is a crucial factor in connecting production, distribution, storage and end users by installing an infrastructure that can transport this large amount of hydrogen. The region also shows activity in establishing a network of refuelling stations in the transport sector. Despite the current high availability of renewable energy, Lower Saxony does not have enough renewable energy to produce the needed green hydrogen. Therefore, the import of green hydrogen from other countries will be required. Furthermore, the support domain described the region's extensive knowledge in working with hydrogen, which can be traced back to the presence of industries that use grey hydrogen. This knowledge, combined with the region's expertise in the transport sector, can support the development of the hydrogen ecosystem. The human capital domain explains the Energy Research Centre's active role in hydrogen research and the construction of five hydrogen innovation labs. However, the human capital also described the need to educate the future labour force that is needed in the region. Finally, the market domain elaborates on the region's advantage of having large industries that could serve as first off-takers, thereby creating mass uses of green hydrogen. Moreover, the transport sector also shows potential to initiate a hydrogen transport market.

7.2 Sub question 2

How do the different hydrogen ecosystems develop in comparison to each other in realising a regional hydrogen value chain?

Different pathways to fulfilling the hydrogen ambitions were described in comparing the cases. The Brittany case is, for instance, developing at a different pace compared to Lower Saxony and North Jutland, looking at the project sizes. On the other hand, the regions also show similarities in trying to initiate their hydrogen ecosystem. The creation of hubs in Lower Saxony, the beacons in North Jutland and local loops in Brittany illustrate this. However, multiple barriers hinder the trajectory towards the realisation of a hydrogen value chain.

In hydrogen production, the high costs are a barrier due to the high price of renewables and investment costs. Therefore, all the cases show a planned growth in the renewable energy supply. However, public rejection was seen as a disruptive factor for the development of renewables in the regions. Despite this, Lower Saxony and North Jutland show a high availability of renewable energy compared to Brittany's lack of renewable energy. In North Jutland and Lower Saxony, this increased availability of renewables can, in combination with their large hydrogen production projects, decrease the production costs for green hydrogen in the future. However, at the moment, funding is still essential in all cases to make hydrogen production attractive for the private sector.

In comparing the realisation of distribution and storage infrastructure, the high investment costs are a barrier that hinders its implementation. Therefore, in Brittany, the choice is made to produce on a smaller scale where the production is near the consumption to decrease transportation costs. On the other hand, several pipeline infrastructure projects exist in Lower Saxony and North Jutland. However, in both cases, the high investment costs and the needed finance create cautiousness for its implementation.

In comparing the end uses, the regions show multiple possibilities in the industry, transport, marine and agricultural sector. However, in North Jutland, a difficulty in realising local offtake for their projected hydrogen or green fuels production was explored. In Lower Saxony and Brittany, the regions want to try to overcome the chicken-egg problem by creating production and consumption simultaneously. However, the end-use projects that are explored are mainly demonstration projects. Therefore, there is uncertainty in what way these end-uses will develop. A failed attempt in North Jutland to initiate mobility sectors illustrates this uncertainty.

Moreover, the comparison analysed a barrier that hinders the overall development of hydrogen. This is the absence of regulations from the national and EU level, which is a significant obstacle to the current hydrogen development. Especially, the decisions at the EU level will shape future hydrogen development. Therefore, in the national policies of the cases, it is emphasised to create a uniform European regulatory framework to create no differences between the countries.

7.4 Main question

How are different EU hydrogen ecosystems developing from a niche towards the realisation of hydrogen value chains?

This research shows that the development of regional hydrogen ecosystems within the EU is taking place based on different implementation strategies and is influenced by several characteristics within the domains of the ecosystem. Progress is made, but the results show that not all the domains are currently beneficial to the hydrogen ecosystem. This is because in the development trajectory from the niche level towards the realisation of a hydrogen value chain is harmed by multiple barriers. Therefore, hydrogen development is still an enormous challenge. On the other side, the research also shows the potential when specific obstacles are overcome. The most crucial factor in this seems to be installing an infrastructure. This is because this enables the scaling up of hydrogen development in the region, such as Lower Saxony and North Jutland. In Brittany, implementing their local ecosystems provides an alternative to realising local hydrogen value chains. However, the region also shows the need for a pipeline infrastructure when it wants to scale up.

Nevertheless, the results also show other characteristics affecting the hydrogen ecosystem's development. This underlines the complexity and mutual interdependency between the ecosystem domain and its actors. Therefore, the interaction of actors in and outside the regional ecosystem is essential. Otherwise, the trajectory of hydrogen ecosystems from a niche toward the regional hydrogen value chain will be impossible. The determining factor is, therefore, collaboration.

8. Discussion

8.1 Results of this research

The first discussion point about the results is the colour coding used in the exploration. However, it is mentioned that this provides only a simplistic overview to illustrate the ecosystem development. Its use can be discussed. This is because all hydrogen ecosystems seem more or less the same when looking at the summary (table 10). After all, every domain is almost orange. However, within the orange colour coding, there can be differences between the impact of the characteristics within that domain. For example, when comparing the support domain of North Jutland and Brittany, both colours are orange. In the case of Brittany, it is the lack of renewable energy in combination with the public rejection of large energy projects. In the case of North Jutland, it is the NIMBY effect for renewable energy. When comparing, the challenge of Brittany can be seen as more complex than the NIMBY effect in North Jutland, which only delays the already high availability of renewables. Therefore, the colour scheme can provide the research with a clear and simplistic overview of each case and its development. However, comparing the regions with this table can give a distorted view of reality.

The second discussion point about the results concerns the fact that hydrogen is maybe too hyped. This is because there is still uncertainty about how hydrogen will genuinely develop. For example, Utility Company 3 (pers.com. 13-04-2022 mentions that it is not yet decided in Lower Saxony if the industries mentioned in the results will also use green hydrogen. The projects in the upcoming years can, for instance, also turn into failed stories instead of success stories, like the attempt of the North Jutland case to implement a hydrogen mobility market. Government 1 (pers.com, 19-04-2022) from Brittany also mentioned that there was first funding for smaller hydrogen vehicles, but this stopped because the battery car seemed to be a better alternative. This also illustrates that the solution does not necessarily have to be hydrogen but can also be a different innovation. Therefore, there is a danger that this hydrogen hype triggers reversal priorities because hydrogen is only part of the solution (Van Renssen, 2020). Energy efficiency, renewables, and direct electrification are, for instance, even essential to realising the goal of becoming climate neutral (Van Renssen, 2020). Another related point to this discussion is the grandfathering clause mentioned in this research. When this clause is activated, this means on the side that more sources can be used for hydrogen production, which is suitable for hydrogen. On the other hand, this can also mean that regions have fewer stimulants to increase their renewable energy supply.

The last discussion point relates to the complexity of hydrogen development. In this research, the complexity was already described in implementing hydrogen on a regional level, as everybody needs to be on the same page. However, the more zooming out, the more complex it gets. For example, Lower Saxony needs hydrogen import for their internal demand. Therefore, their connections with other countries are essential. However, when the development there stagnates, this would also affect the possibility for Lower Saxony to import hydrogen. Furthermore, Van Renssen (2020) describes that the biggest challenge in European hydrogen production is the lack of potential renewable energy. Therefore import routes to potential hydrogen producers outside the EU must also be created. Otherwise, the hydrogen economy cannot be sustained in the EU (Van Renssen, 2020). Hydrogen is, therefore, not only a regional project but also an international one that requires much collaboration.

8.2 Reflection of the research

8.2.1 Reflection on theory

In this research, the entrepreneurial ecosystem of Isenberg (2011) formed the basis for exploring the hydrogen ecosystems. The theory provided the study with a broad set of domains helpful in exploring the development of hydrogen ecosystems. On the other hand, this also limited the research to discussing every domain and subdomain in detail, related to the research its time span. During the investigation, it became clear that every subdomain could be a research of its own. Therefore, some domains are maybe missing information that was not required in the data due to this broader view. For example, not every funding program for hydrogen and its effect is explored in the finance domain because this would consume too much time. The same counts for the educational institutions where not every institution in the region could be interviewed to explore possible hydrogen programs or courses. Therefore, the results could have a different outcome if the focus had been on one domain. Nevertheless, the results still provide a comprehensive first insight into the hydrogen ecosystems of the areas, which is in line with the explorative character of the research.

However, because this theory was initially used for entrepreneurship, this caused adjustments of particular domains and subdomains in the conceptualisation phase and the data analysis. For example, the shift of the public funding from the policy towards the finance domain in the conceptualisation. Or the adjustment from the data analysis to add stories of failure and public acceptance of renewables to the subdomain societal norms in the culture domain. Therefore, the original values of the fields changed, which could have led to different results than the theory intended.

On the other hand, the usage of the entrepreneurial ecosystem of Isenberg (2011) led to the creation of an ecosystem that is more capable of showing the complexity and context of hydrogen. This type of ecosystem was not found in the literature. Therefore, this research contributes to theory building. Additionally, the study wants to suggest adding a new geography domain to the ecosystem. This is because green hydrogen is produced from renewable energy, which heavily depends on a region’s geographical location. Moreover, the geographical advantage of being located near salt caverns is an advantage for storing large quantities of hydrogen. However, this could also mean that when an area does not pose these advantages, other domains in the ecosystem need to compensate for that, for instance, the hydrogen import in Lower Saxony.

8.2.2 Reflection on methods

The first limitation of the research methods can be identified in the interview guide. This is because the interview guide was in some interviews too long. Therefore, not every domain could sometimes be adequately discussed. Just like the theory, this caused some information was sometimes too general. However, this limitation was minimised by sending following-up questions and using the websites for detailed information.

A second limitation can be identified in the case selection process. The selection of Lower Saxony as a region was maybe too ambitious because of the enormous size of the region. Consequently, it was more difficult to explore this Lower Saxony than Brittany and North Jutland. Moreover, the size also means differences between the areas within Lower Saxony. For example, the north is at sea, and the south is far more inland. The results of this case can, therefore, sometimes not be representable for the whole region.

A third limitation can be found in the coding process. This is because first impressions for the results were already written down per domain after the transcribing phase. However, this is not the original method according to the coding process of Kiger and Varpio (2020). Therefore, the coding process began may be more subjective than otherwise. On the other hand, this also improved the coding process because of the familiarity with the data.

The last limitation is that the interview respondents are not equal between Lower Saxony, Brittany and North Jutland. For instance, North Jutland and Lower Saxony have no government respondents, and Brittany has two government respondents. Despite this, the interviewed respondents were able to provide the research with the necessary data and information. Therefore, the saturation point for all the cases was still reached.

8.3 Recommendations for Oost NL

This research was written during an internship at the regional development agency of the provinces of Gelderland and Overijssel, Oost NL. The internship aimed to explore how hydrogen development is going on in other European regions. In this way, the internship organisation wanted to learn from other regions and too see if possible connections can be made for an EU project. Before making recommendations for this, getting a first impression of the situation in the regions of Gelderland and Overijssel is essential. Therefore, the following will serve as a first impression of the areas and hydrogens' role (Some information is based on data from experts within the organisation):

In the provinces, there are problems with grid congestion due to the increase in renewable energy. Therefore, the regions want to develop decentralised energy systems, so-called smart energy hubs (Oost NL, n.d.). In these hubs, multiple solutions are looked at to decrease this grid connection, of which hydrogen is one. Besides these smart energy hubs, the regions also develop H2 hubs. Examples are the H2 Hub Twente and business park IPKW, where businesses and education institutions work on hydrogen developments (Oost NL, n.d.). Moreover, there are already multiple businesses in the region that focus on the development of hydrogen technologies. From this first impression, the research would recommend exploring the following connections with the cases:

- First of all, the Brittany case shows some interesting similarities. Firstly, the region wants to initiate their hydrogen development by creating local decentralised ecosystems where hydrogen consumption is near the production. This implementation shows similarities with the decentralised smart energy hubs from the regions Gelderland and Overijssel. Furthermore, Brittany wants to use their smart energy grid expertise and hydrogen to make its grid more flexible. Therefore, this can be an interesting connection for Oost NL, as these smart grids, in combination with hydrogen, can offer a potential solution for the region's grid congestion.
- Secondly, the Lower Saxony case also shows similarities with Oost NL as they also experience grid constraints in the northern part of the area due to its high energy availability in the grid. Moreover, the region is developing multiple hydrogen hubs, where the first should be operating by 2025. Therefore, a valuable connection can be made for Oost NL to learn from the hydrogen developments in these hubs in combination with regions' grid constraints. This can be helpful information as it can be compared to their development of handling grid constraints with hydrogen in the smart energy hubs. Moreover, the plans of the European Hydrogen Backbone show that in this first stage (till 2030), the network will cross Gelderland, Overijssel and Lower Saxony (Gas for Climate, 2020). Therefore, a possible interesting connection could also be made here.
- Thirdly, the North Jutland case shows an interesting connection with their symbioses net, where hydrogen is not the only solution looked at. Therefore, this can be interesting when looking at the smart energy hubs, where the answer is not on hydrogen production but can also be production heat, for instance. Moreover, their focus on carbon capture, combined with hydrogen production to make green fuels, could be an exciting connection point in making industries in Gelderland and Overijssel more sustainable.

Besides these possible connection points, the research also has the following recommendations for policymakers:

- First, the focus should not be solely on hydrogen because this is just part of the solution. Therefore, this research would recommend focusing on other solutions supporting the energy transition in the regions besides hydrogen.
- Secondly, the research would recommend already investing in an early stage in creating more social understanding of hydrogen. This can not only increase the hydrogen uptake but also can decrease potential future public rejection.
- Thirdly, the research showed the importance of the regulations at the EU level. Therefore, this research would recommend keeping updated with these regulations and synchronising their policy with them.
- Lastly, the research would recommend already investing in educating a future labour force, as this seems to be a challenge in all cases.

8.4 Future Research

In this section, some recommendations are made for future research related to hydrogen:

- The first recommendation concerns how the upcoming EU regulations, such as the RED II directive, influence hydrogen development. This regulation is crucial because it determines how old the renewable energy source can be if the hydrogen production wants to be green. In some regions, this can considerably impact hydrogen production.

- The second recommendation relates to researching the difference between the public acceptance of hydrogen and renewable energy and what causes this. Is it, for example, because hydrogen is not yet widely deployed? And if so, how can a future public rejection be avoided when comparing it to the acceptance of renewable energy?

- The third recommendation concerns exploring the fairness of the hydrogen transition. The Green Deal states that the energy transition should be fair (European Commission, 2020). However, the Brittany case shows they have more difficulty receiving funding than regions with more prominent industries or companies. Additionally, the plans for the EU hydrogen backbone are primarily focused on West-Europe and neglect East-Europe (Gas for Climate, 2020). Therefore, it would be interesting to research how fair the hydrogen transition genuinely is.

- The last recommendations relate to researching the influence of the Russian invasion of Ukraine in 2022 on the momentum of hydrogen. On the one hand, this development seems to strengthen the internal momentum illustrated in the REPowerEU strategy. On the other hand, the interview Network 3 (pers.com. 03-05-2022) explains that it is not clear yet what effect this will have.

9. References

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Appendix

Appendix 1: Respondents North Jutland

Reference	Organization	Domain
Incubator 1	GreenLab	Support
Incubator 2	Anonymous	Support
Business 1	Corre Energy	Market
Network 1	Hydrogen Denmark	Market
Business 2	Anonymous	Market
University 1	Aalborg University	Human Capital
Business Developer 1	Green Hub Denmark	Support
Business Developer 2	Energy Cluster Denmark	Support
Utility Company 1	Evida	Support

Appendix 2: Respondents Brittany

Reference	Organization	Domain
University 2	University Bretagne Sud	Human capital
Business 3	Anonymous	Market
Government 1	ADEME	Government
Business 4	LHYFE	Market
Business Developer 3	Bretagne Développement Innovation	Support
Government 3	Brittany Region	Policy
Business 5	H2Gremm	Market
Business 6	Entech	Market

Appendix 3: Respondents Lower Saxony

Reference	Organization	Domain
Utility Company 2	EWE GASSPEICHER GmbH	Support
Network 2	Hydrogen Network Lower Saxony	Support
Utility Company 3	GET H2	Support
Network 3	Entrepreneur Associations Lower Saxony	Market
Research centre 1	Energy Research Centre of Lower Saxony	Human capital
Research institution 1	Fraunhofer-Institut für Windenergiesysteme	Human capital

Appendix 4: EU respondents

Reference	Organization	Domain
Europe 1	Hydrogen Valley Northern Netherlands	Policy
Europe 2	Hydrogen Europe	Policy

Appendix 4: Interview Guide

Introduction:

- Thank you for your time in answering some of my questions. Is it also all right if I record the interview?
- Could you tell me something more about the background of the organisation?
- What is the role of the organisation in the hydrogen ecosystem?
- What is the current status of hydrogen in the region?

Production:

- Which source is used to produce hydrogen? And why?
- Is the production more local and close to the end-users? Or more centralised?
- What are the pros and cons of this?
- What type of Elektrolyser is used? And why?
- What is the total amount of green hydrogen produced at the moment? And in 2030?

Distribution:

- How is the distribution going to be arranged in the region?
- How is the distribution (more availability) affecting the local adaption of hydrogen in the regions?
- Is there in the future enough supply of green hydrogen for the demand?

Applications:

- What type of hydrogen applications are there in the region?
- To what extent are there already commercial uses of hydrogen in the region?
- Are there still future applications that the region wants to invest in?

Ecosystem:

- What are essential actors in the hydrogen ecosystem for the region?
- What are important factors for the creation of a hydrogen ecosystem?
- To what extent are the initiatives of hydrogen capable of scaling up? In other words, capable of unlocking the carbon lock-in.
- What is the influence of the current situation in Ukraine on hydrogen development?
- In the end section, I will explain the ecosystem elements and discuss your perspective.

Domains	Sub-Domains
Policy	➢ Leadership ➢ Government
Finance	➢ Private finance ➢ Public funding
Culture	➢ Success Stories ➢ Societal norms
Supports	➢ Infrastructure ➢ Support professions ➢ Non-government institutions
Human capital	➢ Labor ➢ Educational institutions
Markets	➢ Early customers ➢ Networks

Appendix 6. Codebook North Jutland

Code	Description	Domain	Subdomain
Cement factory and CCU PtX	Political support to decarbonize the cement factory with CCU and PtX	Policy	Leadership
Commercializations signs	Growth of hydrogen production projects	Market	Early market
Drive to be innovative	Explanations of innovative character of North Jutland	Cutlure	Societal norms
District heating	Success story of district heating	Culture	Success story
Early market	Multiple examples of increases in hydrogen end use	Market	Early market
EU backbone	Connection regional network to European network	Support	Infrastructure
Explanation of Jutland	General information about North-Jutland	Policy	Government
Failed story	Failed attempt for hydrogen mobility	Culture	Success
Funding	Different types and importance of funding	Finance	Funding
Future infrastructure	Potential infrastructure projects North2 and Green Hydrogen Hub	Support	Infrastructure
Hybalance	Realized hydrogen production plant	Culture	Success story
Hydrogen valley	Organization with long history in hydrogen and supporting businesses	Support	Support professions
Influence ukraine	Consequences of the situation in Ukraine on hydrogen development	Policy	Government
Labor force	Situation of labor force in the region	Human capital	Labor force
Long history with hydrogen	Multiple examples of the history and expertise in fuel cell technologies	Support	Support professions
Methanol production	Explanation of methanol production	Policy	Government
National policy	Information about the national policy related to hydrogen	Policy	Government
Network	The role of networks in the region	Support	Networks
Nimby	The influence of the nimby effect in the regions concering renewable energy	Culture	Societal norms
Policy	Information about the regional policy related to hydrogen	Policy	Public leadership
Problem of end users	Diffculty in finding end users for the (planned) production of hydrogen and green fuels	Market	Early market
PTX projects North Jutland	Around 4 PtX projets planned in North Jutland	Market	Early market
Public support	Public support for energy transition	Culture	Societal norms
Regulations	Examples of changed regulations and importance of it	Policy	Government
Renewable energy	Availability of wind energy	Support	Infrastructure
Stronger PTX in Denmark	PtX development stronger in Denmark then other EU countries	Policy	Government
Symbioses	Explanation of the symbioses netwerk of GreenLab	Support	Infrastructure
Technical expertise	Biggest fuel cell company in the world present in the region	Support	Support professions
University of Aalborg	Imporant actor in the ecosystem of North Jutland for the development of hydrogen innovations and labor force	Human capital	Educational institutions
Windmill adventure	Previous succes story that influences that is of inlfuence on the hydrogen development	Culture	Success story

Appendix 7. Codebook Brittany

Code	Description	Domain	Subdomain
Acceptance hydrogen	Cautiousness acceptance for hydrogen and innovations	Culture	Societal norms
Available ports	Several ports in Brittany that show future importance for hydrogen and renewable energy	Support	Infrastructure
Bottom up approach	Working as much as possible with local smaller projects	Culture	Societal norms
Businesscase	Advantages of small scale production	Market	Early market
Creating champions	No large players, but potential	Policy	Leadership
Culture	Brittanies culture in marine and argiculture	Culture	Societal norms
Current status of hydrogen	Lack of current hydrogen projects	Culture	Succes stories
Difficulty for finance	Due to the absence of large industries and companies	Finance	Private finance
Early market	Potential first sign of market creation	Market	Early market
EU interaction	Importance of EU projects	Finance	Public Funding
Expertise	Expertise of marine and smart grid	Support	Support professions
Funding	Funding possibilities and conditions	Funding	Public funding
Future production	Future production of hydrogen by national grid	Support	Infrastructure
Human capital	Current state of labor force and hydrogen education	Human capital	Labour
Hydrogen production	Regional policy for hydrogen production	Policy	Leadership
Infrastructure	About the current and future infrastructure	Support	Infrastructure
Lack of energy	Lack of energy due to history with public rejection	Culture	Societal norms
Network	Role of BDI as regional network	Support	Network
Policy	Regional policy for hydrogen	Policy	Leadership
Public rejection renewables	Pubic rejection for large wind projects	Culture	Societal norms
Renewable energy increase	Expected increase due to wind and marine energy	Support	Infrastructure
Solve energy problem	Energy problem before hydrogen development	Policy	Governmemt
Succes story	About Hylias and ecosystem Lorient	Culture	Succes stories
University	Hydrogen course at university	Human capital	Educational institutions

Appendix 8: Codebook Lower Saxony

Code	Comment	Domain	Subdomain
Businesscase hydrogen	Difference between the costs smaller and larger projects	Market	Early market
Creating early market	Factors that are important for the market creation	Market	Early market
Cross border collaboration	Connections with other regions and countries	Policy	Public leadership
End uses	First off-takers for hydrogen in the region	Market	Early market
Finance	The role of private investments and approval procedure	Finance	Private finance
Funding	Funding programs	Finance	Public funding
Future labour force	The need for educating the new labor force	Human capital	Labour force
Hydrogen acceptance	Hydrogen hype perceived as real in the region	Culture	Societal norms
Import	The need for hydrogen import	Support	Infrastructure
Infrastructure	Infrastructure projects and importance of it	Support	Infrastructure
Network	The important role of networks in the region	Support	Network
Policy	EU, National and regional policy	Policy	Government
Projects within the region	Information about multiple projects in the region that can serve as success stories	Culture	Success stories
Public acceptance renewables	Increase of renewable energy stopped due public acceptance	Culture	Societal norms
Public leadership	Regional hydrogen ambitions	Policy	Public leadership
Public understanding	The importance of project to create social understanding	Culture	Societal norms
Renewable energy	High renewable availibility but not enough for interal hydrogen demand	Support	Infrastructure
Storage	Role of salt caverns	Support	Infrastructure
Volkswagen region	Importance for transport sector	Support	support professions
University	Hydrogen activities in universities	Human capital	Educational institutions