TU Delft

The role of gas infrastructure for integrating offshore wind in the North Sea region

Floor van Dam

The role of gas infrastructure for integrating offshore wind in the North Sea region

Analysing different energy visions in the North Sea region

by

F. van Dam

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Preface

Throughout my Bachelor applied physics and Master's in Sustainable Energy Technology, I have always been interested in technology and the economic, political and geographical context they are placed into. Therefore, I have thoroughly enjoyed exploring the complexity and multidimensionality of our energy system during this research; figuratively peeling through several of its layers, be it an onion.

I would not have been able to deliver this thesis without the help of my supervisors. I am very grateful for Pier Stapersma as my daily supervisor at Clingendael International Energy Programme (CIEP). Together with my other colleagues at CIEP (Coby, Kyle, Jasper, Jabbe, David and Wendy), I have enjoyed our discussions ranging from my thesis topic, current themes in the energy world and even more general political and economic issues. The setting of these discussions in Park Clingendael made this even more enjoyable, though sometimes restricted due to the COVID 19 pandemic.

Furthermore, I would like to thank Toyah Rodhouse for her critical insights, especially regarding the theoretical elements of this study and her feedback on my writing. Together with my first supervisor, Aad Correljé, they have also helped me keep a critical and holistic mindset throughout the project. I would also like to thank both Kas Hemmes and Linda Kamp for being part of my thesis committee and for taking the time to read my thesis and giving valuable feedback.

Furthermore, I would like to thank all experts that were able to take the time to discuss my research in interviews, which has led to some interesting insights.

Last, I would like to thank my family and friends. They provided some necessary breaks, which helped me to stay motivated during the past months. In particular, I would like to thank my housemates. They were great company for working on a thesis during a pandemic. In addition, I would also like to thank my housemate Elsje Burgers for her valuable feedback on my report.

F. van Dam
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Executive summary

This research explores the different envisioned roles of gas infrastructure for integrating offshore wind into the energy system of the North Sea Region (NSR). In this research, the NSR is defined as consisting of the Netherlands, Germany, Belgium, Norway, Denmark and the United Kingdom. The NSR is characterised by the increasing use of their considerable offshore wind potential, its current decommissioning developments of coal and nuclear energy, and its history in supplying, transporting and consuming natural gas.

Within the NSR, there are different visions on how to integrate and leverage the full potential of offshore wind. This research focuses on how these coexisting visions can be made more compatible; by being able to exist or occur together without problems or conflict. Of particular interest to us due to its large economic benefit is the repurposing of gas infrastructure. We aim to answer the following question:

Focused on gas infrastructure as a solution for integrating offshore wind, how can the coexisting energy visions in the North Sea region be made more compatible?

This research is conducted using a theoretical framework called pattern modelling, provided by New Institutional Economics. In short, this pattern modelling framework takes a qualitative, abductive and holistic approach because analysis of the interrelated energy system is deemed essential for understanding the individual components.

The contribution of this research is that the pattern modelling approach is combined with the method of inductively coding different energy visions. We define an energy vision as a “collectively held and performed vision of desirable and realistic futures for energy sources, technologies and systems in a specific geographically bounded area” [Rodhouse, 2018]. From these energy visions, important themes and their relationships in the energy system of the NSR are derived. In our research, published energy vision reports and strategies of several actors in the NSR are analysed, and several actors are interviewed. In this research, we take into account as actors the government, electricity and gas Transmission System Operators (TSOs) and large industrial associations for each NSR country.

Electricity and gas infrastructure are interrelated by electrolysers producing hydrogen gas using electricity and gas-fuelled power plants producing electricity. Focusing on the integration of offshore wind in the energy system and the envisioned role of gas infrastructure, this research initially identified several important themes in different energy visions, such as the locations envisioned for placing electrolysers. In short, these themes entail both technologies, infrastructure choices, socio-economic drivers, policies and regulations.

Subsequently, this research concluded that some themes are envisioned differently by various actors. These differences lead to multiple types of (in)compatibility of the different envisioned future energy systems in the NSR. In order to answer our main research question, the current state of compatibility in the NSR is characterised. This is done by subdividing the different identified themes into four different groups with varying (in)compatibility levels termed ‘Group A. Celebrated themes’, ‘Group B. Themes where actors envision the same approach’, ‘Group C. Themes with competition between different types of approaches’ and ‘Group D. Themes where there is no co-existence possible’.

A. Celebrated themes

The first group contains themes on which actors have identical visions, which are collaborated upon (celebrated) in collaborative groups and associations. This is the most compatible group, because when actors collaborate, their visions are able to be executed together without problems or conflict. Several themes are celebrated by actors in the NSR. Most importantly, the recognised potential for offshore wind within the NSR is a celebrated theme.

B. Themes where actors envision the same approach

The second group contains themes on which actors also have identical visions but which are not collaborated upon explicitly. In this case, there is a possibility of competition between actors, as they all aspire to gain a first-mover advantage. This group is relatively compatible because previous research shows that compared to a more collaborative approach, more regional competitive action can also allow more rapid experimentation and tailoring of policies and thus developments in general. However, the group is not as compatible as more collaborative actions at an (inter)national level also provide better coordination which leads to an increase in efficiency of a system.

A theme considered part of this group is the role actors see for becoming a production, consumption and transit hub of hydrogen. Both competition and need for collaboration are identified, because together the NSR actors aspire to become hydrogen production (DK/NO/NL/UK), transport (NL/BE) and large consumption hubs (NL/DE).

C. Themes with competition between different types of approaches

The third group contains themes that are also relatively compatible because actors have different co-existing visions and are in competition on the approach. Previous research concluded that a competitive approach allows for technological and regulatory experimentation, does not constrain ambitious front runners, is more robust to regulatory design errors, and is more adapted to the different preferences of actors. However, previous research showed there is a risk that actors do not consider the externalities they inflict on the whole system by optimising their own sub-system, leading to incompatibility. The following paragraphs highlight three themes defined in this research that are considered to be part of this group.

The first theme is the consideration of ratios of gas and electricity consumption. Different consideration of this ratio leads to different visions actors have on the infrastructure deemed necessary. Although, different consumption patterns in industry, mobility, and heating are identified between national regions, this research does not consider it problematic for infrastructure alignment due to most consumption differences occurring within a national scale.

The second theme is the role of electrolysers envisioned for integrating offshore wind energy into the energy system. The existence of differing visions on this theme leads to actors seeing a different role for electrolysers in both capacity operation of electrolysers (ramping up and down or running at full capacity) and electrolyser location (nearby offshore wind production or hydrogen consumption). This co-existence of different ideas can be regarded as beneficial because in this research we expect this competition of different approaches to eventually lead to a good combination of different uses for electrolysers. Although, one must be mindful of the competing claims of offshore wind that could arise, as it would be impossible for both electrolysers and direct electricity consumption to 'claim' the same offshore wind capacity.

The third theme is the role of flexible (gas-based) net-zero power plants. In times of a shortage of wind energy, most actors see a role for flexible power plants. However, there are different visions on the exact process (Carbon Capture and Storage(CCS) post or pre-combustion) of producing such flexible electricity. In the case of CCS post-combustion, natural gas would be transported to a power plant, and CO2 would be transported from a power plant to a CO2 storage location. In the case of CCS pre-combustion, blue hydrogen would be produced from natural gas and would be transported to hydrogen-fuelled power plants. Blue hydrogen could then be produced nearby a natural gas supply and CO2 storages. Due to these differences in visions, a parallel pipeline network for hydrogen, natural gas and CO2 is likely to develop. This development of competing pipeline networks is not considered to be the most efficient system. However, it is also not considered to be completely incompatible because the co-existence of different gas infrastructures is possible.

D. Themes where there is no co-existence possible

The fourth group contains themes on which actors also have different visions, but where co-existence of ideas is not possible; if energy visions were to be executed, there would be a conflict of interests between actors. By definition, this is an incompatible group.

An identified theme considered part of this group is the form gaseous fuels are envisioned to be transported in. Problematic is that both modes of transport of pure hydrogen and blended hydrogen with natural gas are discussed in different energy visions. Also of interest is the role seen for the reuse of gas infrastructure currently used for natural gas. Mostly Dutch actors currently see the economic benefit of reusing gas infrastructure. This could lead to possible misalignments on the timing of hydrogen pipeline transport. As any part of gas infrastructure can only transport a single gas, conflicting visions on the timing of infrastructure repurposing could be problematic.

This research concludes that there are differing visions of themes in the NSR, that for a large part are based on fixed underlying societal and geographical themes. It is therefore impossible for actors to collaboratively pursue one uniform compatible energy integration vision, with the exact same details envisioned by every actor in the NSR. Therefore, this research recommends collaborative futuring, defined as maintaining one's vision whilst considering other existing visions within the relating geographical and dimensional (gas, electricity, hydrogen, offshore wind, etc.) scope. Considering the four previously mentioned groups, when one is 'collaborative futuring', one accepts that not every theme can develop into a group 'A. Celebrated themes'. In order to gain insight into how different themes can be collaborated upon, this research has designed a 'collaboration framework' to structure the (in)compatibility levels of different themes.

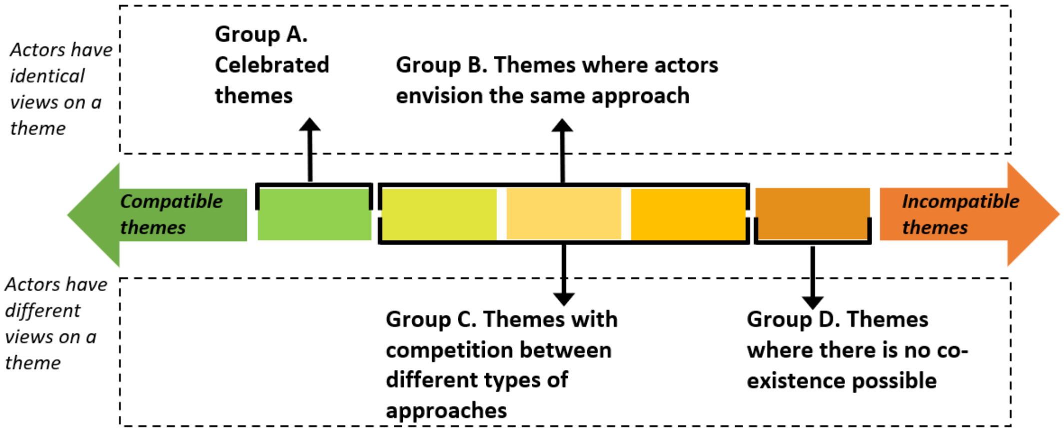


Figure 1: A schematic overview of the 'Collaboration framework'. In the middle of this figure, a scale is shown ranging from compatible to incompatible themes. The farther to the right the themes are placed, the more incompatible the themes are. This makes group A themes the most compatible themes, group B and C themes equally 'relatively' compatible, and group D themes the most incompatible themes. Furthermore, groups that are placed above the scale depict themes on which actors have identical visions. In contrast, groups that are placed below the scale depict themes on which actors have different visions. This framework was specifically designed by the researcher.

This research has four recommendations to make the coexisting energy visions in the North Sea region more compatible, using the 'collaboration framework' as the leading framework.

Firstly, this research recommends that actors better consider other actors' perspectives neighbouring them, both geographically and dimensionally, in their individual energy visions. Specifically, this consideration could be increased by actors using the same planning time frames and same terms. Consideration of other actors' perspectives is especially important for themes that differ significantly per actor due to the energy systems' geographical and historical elements entailed in group 'C. Themes with competition between different types of approaches'. Additionally, it is important for actors to consider how other neighbouring actors envision themes in group 'B. Themes where actors envision the same approach'. This is important because possibly there is currently a lack of collaboration due to actors not being aware of their shared visions.

Secondly, actors should consider the option to widen mandates of (gas) TSOs for both transporting hydrogen and for installing electrolysers in specific locations to decrease societal costs of transporting energy. This mandate would essentially make hydrogen transport a public affair, which would increase the consideration of societal infrastructure costs. This discussion could also function as a starting point for discussing whether it is (currently) necessary for electricity and gas TSOs to merge specific activities.

Thirdly, this research recommends actors to better maintain a whole system approach in (already existing) discussion groups, primarily focusing on themes in group ‘D. No co-existence’. Additionally, it would also be beneficial to include some specific discussion topics from groups ‘B. Themes where actors envision the same approach’ and ‘C. Themes with competition between different types of approaches’, because these themes could otherwise develop into group ‘D. Themes where there is no co-existence possible’ as energy visions become more specific as the envisioned moment comes closer. In addition to the current discussions that are mostly held between different geographical actors, it is important that discussions are also held between different dimensional (gas, electricity, hydrogen, offshore wind, etc.) actors.

Fourthly, this research recognises a necessity for an overarching NSR vision for themes in group ‘A. Celebrated themes’, and for themes subdivided into groups B, C and D that are deemed beneficial to mention to create a more stable investment environment. Considering the current developments in the NSR, this could result in an overarching vision recognising the importance to decarbonise the full energy system with offshore wind (and not only the electricity system) and recognising that gas infrastructure should be considered by all actors when integrating offshore wind.

List of abbreviations

- **ATR:** Autothermal reforming, a method to produce hydrogen from methane.
- **BE:** Belgium
- **Blue hydrogen:** this is defined as hydrogen produced by the reforming of methane into hydrogen and CO2, storing or reusing the captured CO2
- **Brownfield:** based on existing infrastructure
- **CAPEX:** Capital expenditures
- **CCC:** Committee for Climate Change in the UK
- **CCS:** Carbon Capture and Storage
- **CC(U)S:** Carbon Capture (Utilisation) and Storage
- **CHP:** Combined Heat Power
- **CO2:** Carbon dioxide
- **DE:** Germany
- **DK:** Denmark
- **DSR:** Demand Side Response
- **DSO:** Distribution System Operator
- **ENTSO-E:** European Network of Transmission System Operators for Electricity
- **ENTSO-G:** European Network of Transmission System Operators for Gas
- **EU:** European Union
- **(FC)EV:** (Fuel cell) electric vehicle
- **GHG:** Greenhouse gasses
- **Greenfield:** based on new infrastructure
- **Green hydrogen:** this is defined as hydrogen produced with an electrolyser supplied with electricity from renewable energy sources.
- **Grey hydrogen:** this is defined as hydrogen produced from fossil fuels, be it natural gas or from an electricity grid where electricity is produced from fossil fuels.
- **H-gas:** High-calorific gas
- **IEA:** International Energy Agency
- **L-gas:** Low-calorific gas. This type of gas is characteristic for the gas reserves in the North of the Netherlands (Groningen).
- **LNG:** Liquid Natural Gas
- **NGN:** Northern Gas Network (gas TSO in the UK)
- **NL:** The Netherlands
- **NO:** Norway
- **NSR:** North Sea Region
- **OPEX:** Operating expenditures
- **PtG:** Power to gas
- **PtX:** Power to X
- **R&D:** Research and development
- **RES:** Renewable Energy Sources
- **SMR:** Steam methane reforming
- **SQ:** Sub-question
- **TRL:** Technology readiness level
- **TSO:** Transmission System Operator
- **TYNDP:** Ten Year National Development Plan
- **UK:** United Kingdom

Contents

1

Introduction

This chapter explains the reasoning behind the focus of this research. This study focuses on the envisioned roles of gas infrastructure in the North Sea Region when integrating offshore wind. This chapter starts with an explanation of the challenges that arise when integrating offshore wind. To overcome these challenges, the concept of 'sector coupling' is presented. In section 1.1, the necessity of interplay between gas and electricity infrastructure is presented as a specific element of 'sector coupling'. Subsequently, section 1.2 presents the problem statement of this specific research, followed by an explanation of the importance of energy visions (in section 1.3) to solve the problem stated. Lastly, section 1.4 presents the research objective and section 1.5 the sub-questions of this research.

As all countries agree in the Paris Agreement, climate change is one of the defining crises of our time. A critical element of tackling this challenge is decarbonising the energy sector. One of the drivers of this change is the use of renewable energy sources such as offshore wind. With its strong winds and relatively low water depths, the North Sea Region (NSR) is estimated to have an offshore wind potential of 200 GW, which is significant compared to the total EU target of 300+ GW offshore wind capacity by 2050 [Nordic TSOs, 2020]. The NSR is a focal point for offshore renewable energy within Europe. In different researches, the NSR is defined differently. In this research, the NSR is defined as consisting of the Netherlands, Germany, Belgium, Norway, Denmark and the United Kingdom (see figure 1.1).

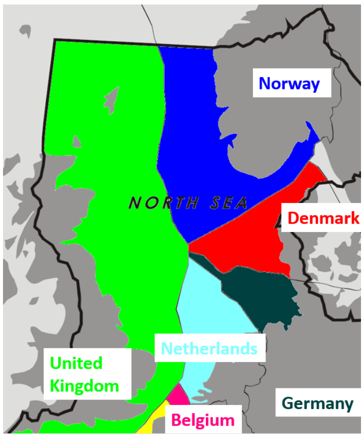


Figure 1.1: Exclusive economic zones for the North Sea [Inwind, 2008].

Offshore wind is expected to play a large role in the decarbonising of the energy system in the NSR [ENTSO-E, 2019a]. One of the downsides of offshore wind energy is its volatile nature; with wind speeds being liable to change rapidly and unpredictably [Zupančič et al., 2017]. With the share of wind energy in total energy provision increasing, there will be an increase in system integration challenges in the NSR. In this research, the term ‘system integration’ focuses on the integration of renewable energy sources into the existing energy system, using gas and electricity infrastructure. System integration challenges entail both ‘balancing challenges’ and ‘network challenges’, explained in the next paragraphs [Zupančič et al., 2017].

The balancing challenge of offshore wind energy is twofold. Firstly, the existing energy system must be able to integrate large peaks of offshore wind energy, as the system will otherwise have to deal with an enormous amount of unserved and curtailed energy. Secondly, the existing energy system must be able to meet electricity demand in times of a lack of offshore wind energy, managing the necessity for a large reserve capacity for fast-acting peak generation [ENTSO-E, 2019a]. Installing an abundance of spare generation capacity is said to be economically inefficient because large investments would have to be made solely to handle rare occasions [ENTSO-E, 2019a][Frontier Economics, RWTH Aachen University, 2019].

Aside from balancing challenges, the volatile nature of offshore wind also brings challenges for infrastructure necessities. Specifically, to ensure sufficient grid capacity during high generation peaks, one would have to install spare electricity capacity in bulk. Installing capacity on such scale would likely exceed both resources and available (publicly acceptable) sites, making the approach technically infeasible [Frontier Economics, RWTH Aachen University, 2019].

A recently proposed solution to integrate volatile wind electricity into the energy system is ‘sector coupling’. Sector coupling, also known as an *integrated energy system transition* [CIEP, 2018], is defined as creating synergies between different sectors and infrastructures to optimise stability, flexibility and affordability of the overall energy system [Maruf and Islam, 2019]. For example, using the battery of an electric vehicle during the day to store solar energy for use in the evening.

This research specifically focuses on the coupling of the electricity and gas infrastructure. This topic is of interest because, in contrast to most renewable energy sources initially providing an electricity supply, not all current molecule-based (gaseous) energy consumption can shift to become electric (cost-efficiently). Quantitatively, research shows that in 2050, 40-60% of energy consumption is expected to remain molecule-based. This is still a large part of total energy consumption, compared to the current 80% of energy consumption being molecule-based [Gasunie,TenneT, 2019b][Energinet, 2019f].

1.1. Power-to-X: the interplay between gas and electricity infrastructure

Specifically focused on coupling electricity and gas, sector coupling involves the conversion of renewable electricity into chemically bounded (molecule-based) energy (and vice versa). Figure 1.2 illustrates this interplay between gas and electricity infrastructure. The main technological route from electricity to gas is an electrolyser, and the route from gas to electricity is a power plant. Both of these technological routes could help stabilise electricity grids at moments of excess production and could help supply the remaining consumption demands at moments of lacking production [Energinet, 2019f][Gasunie,TenneT, 2019b]. This principle is called Power-to-X (PtX), which entails electricity conversion, energy storage, and reconversion pathways that use electric power [Energinet, 2019f].

Hydrogen is expected to become one of the most abundant PtX energy carriers. Hydrogen is produced with electrolysers with (renewable) electricity. It can be used as a source of energy and can also be processed further into green gas or chemically based high-value products such as ammonia.

Hydrogen has increasingly become a current topic, as also the European Commission has published a hydrogen and energy system integration strategy in June 2020 [European Commission, 2020]. The gas is of strategical importance for the NSR countries, which is visible in the recent emergence of strategy/vision documents on hydrogen and system integration in the North Sea. Furthermore, there are currently 80 hydrogen (demonstration) projects in progress in Northwest Europe [Team Consult Gas, Power Experience, 2020].

1.2. Problem statement

This study considers the role of sector coupling between electricity and gas infrastructure when integrating offshore wind into the energy system of the NSR. Considering this topic, key players currently lack insights into what other key players are envisioning for the region. This is thought to lead to a decrease

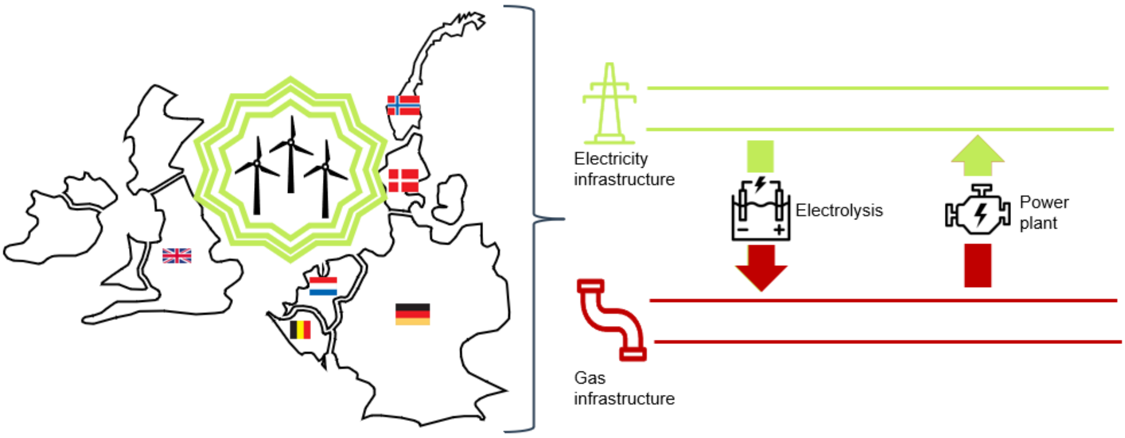


Figure 1.2: A schematic overview of sector coupling of electricity and gas infrastructure with as a starting point the offshore wind electricity production in the NSR. This illustration was made by the researcher.

in compatibility of the different energy systems, currently present in the NSR; considering geographical differences between varying national and regional energy systems and dimensional differences between the electricity and gas-based energy (infrastructure) systems in the NSR.

This section demonstrates that compatibility of these ideas is currently underdeveloped and why this is problematic. First, the term compatibility is defined. Subsequently, studies are presented that have already identified current incompatibilities in the visions on energy sub-systems in the NSR. In the last paragraph of this section, three different problems are elaborated on, which could arise if the envisioned roles of gas infrastructure are incompatible with each other in the NSR.

Within the NSR, there are different energy sub-systems present; different geographical (national and regional) energy systems and different dimensional energy systems. An example of such systems are the electricity and gas-based energy (infrastructure) systems. Different energy sub-systems in the NSR are incompatible with each other when (preventable) challenges arise, making the different sub-systems incapable of coexisting. In this research, compatible sub-systems are defined as a group of energy sub-systems that are able to exist or occur together without problems or conflict. It should be emphasised that if sub-systems are compatible with each other, not every sub-system necessarily uses the exact same technologies and the same processes.

In this research, different visions of actors of different sub-systems are analysed. This is done to determine if these visions on these sub-systems are compatible with each other. We take into account as actors the government, electricity and gas Transmission System Operators (TSOs) and large industrial associations for each NSR country.

The incompatibility of envisioned renewable energy integration solutions (in the NSR) is recognised in previous research; both between actors within a country and between actors from different countries. Both are seen as equally important, and they are interconnected because internal incompatibilities can lead to internal congestions, which are often pushed to the borders [European Commission, 2018][TNO, 2020].

Previous research, mostly focused on the differences between countries, concluded that the current energy systems in Europe are all divergent. The reason given for this is that the “path dependency and the need to consider local concerns, resources, and political agendas” are likely to cause different regions to require different energy system integration solutions [Cambini et al., 2020](*Page 3*)[Gea-Bermúdez et al., 2020][Kristiansen et al., 2018][GL, 2020][CIEP, 2018]. In other words, previous research shows that the future of electricity in Europe is more likely to be characterised by multiple and differentiated national energy system integration solutions. This is caused by countries “moving at different speeds and maintaining a national lens as they develop strategies and policies in line with their own industrial priorities and resource bases” [Bolton et al., 2019](*Page 4*)[Dignum, 2018].

The following paragraph focuses on the role of gas infrastructure. Research shows that different countries have different potential for decommissioning gas infrastructure [Onyango et al., 2020]. This transnational incoherence and progress mismatch is problematic for the sustainable management of the NSR. It can lead to three problems [NorthSEE, 2020b][Dignum, 2018][Wieczorek et al., 2015]. Firstly, it can lead to delay. Secondly, it can lead to a decline in technical efficiency of the energy system. Thirdly, it can lead to a decline of economic efficiency in the energy system. These three problems are elaborated upon below.

Firstly, due to initially conflicting future visions on environmental licenses and necessary spatial planning, cross-border infrastructure projects are often delayed [Questionnaire][NorthSEE, 2020a]. This delay leads to increasing (organisational) costs and leads to (governmental) goals necessary to combat climate change not being achieved in time.

Secondly, a lack of technical alignment within the NSR could be problematic. Without national cooperation a regional approach could result in ”new lock-ins where incompatible systems [are] developed in a fragmented manner” [Bolton et al., 2019](*Page 10*), which could lead to larger challenges in maintaining security of supply [Wieczorek et al., 2015]. A lock-in is a certain form of economic path dependence where the market selects a certain technological standard. Even though market participants are better off with an alternative technology, the market then gets stuck or ‘locked-in’ with such a standard due to network effects [Unruh, 2000].

Thirdly, reuse of gas infrastructure is said to be cost-saving due to the savings in decommissioning costs [EZK,CIEP, 2020]. The International Energy Agency (IEA) gives an insight into what economic value is at stake, by stating that there are potential synergies between offshore wind and oil & gas sectors reaching a value of $275- 360 billion in Europe over the next two decades [IEA, 2019]. Another study roughly estimates that together Belgium, the Czech Republic, Denmark, France, Germany, the Netherlands, Sweden and Switzerland can save EUR 487 billion to 802 billion Euros between today and 2050 through the continued use and repurposing of gas networks. This is based on a comparison of system costs between a modelled “Electricity and Gas Infrastructure” scenario and an “All-Electric plus Gas Storage” scenario, where gas networks are no longer used [Frontier Economics, RWTH Aachen University, 2019].

In summary, previous research shows there are currently incompatible visions on offshore wind integration and the role of gas infrastructure in the NSR, which affects both the technical and economic efficiency of the energy system. Therefore, previous research states there is a ”need for bespoke approaches that takes into consideration these peculiarities and provides a context-specific framework”, co-evolving with the energy system [Cambini et al., 2020](*Page 3*).

This research aims to define the current mismatches, points of discussion and uncertainties when analysing and comparing different energy integration visions in the NSR. Subsequently, this research aims to determine how co-existing energy visions can be made more compatible. The analysis focuses on the role of gas infrastructure for the integration of offshore wind, considering the current misalignment between actors in the NSR and the enormous technical inefficiencies and financial losses this misalignment can lead to. Therefore, the main question of this research is: **Focused on gas infrastructure as a solution for integrating offshore wind, how can the co-existing energy visions in the North Sea region be made more compatible?**

1.3. Energy visions as a heuristic instrument in this research

In order to gain insight into the aforementioned misalignment problem, energy visions are used to clarify the different visions of actors within the NSR. They are a means to gain insights into the ‘tuning’ problems and friction points between the different actors in the NSR. In this research, an energy future is defined as a ”collectively held and performed vision of desirable and realistic futures for energy sources, technologies and systems in a specific geographically bounded area” [Rodhouse, 2018]. The concept of energy visions is used to maintain a more holistic approach to the energy system as opposed to a primary focus on specific energy technologies. This holistic approach is important as aside from the local (micro) or market (meso) level, the societal (macro) level of an energy system is also of interest [Rodhouse, 2018].

The long term aspect of energy visions is important when analysing infrastructure developments, as this research does. This long-term approach of energy visions aligns with the long term capital-intensive investments of energy integration infrastructure projects [Gea-Bermúdez et al., 2020]. Suppose one wants to have well-coordinated and cross-border integrated systems in the NSR. In that case, one has to start aligning different energy visions now as the developments for a net-zero energy system have already begun and will continue to do so in the coming years [ENTSO-E, 2019b].

1.4. Research objective

There is a lack of understanding of the possible roles for gas infrastructure when integrating offshore wind in the NSR. There is a research gap that becomes evident, as there are no recent research papers widely available concerning north sea gas and offshore wind integration. Specifically, when one searches in search engines such as Scopus or Web of Science for the key terms ”north sea”+”gas”+ ”offshore wind”+”integration”, no recent research papers are to be found. The need for increased insight into the different energy visions in different countries is also mentioned explicitly by Bert Roukens (Energy Envoy at the Ministry of Economic Affairs and Climate Policy) in an annual meeting with CIEP, mentioning their stake in adjusting the Dutch national energy vision accordingly.

In addition to the previously mentioned research gap, there is also a lack of academic insights because little research has previously been done on the activity of combining or collaborating on energy visions. This research gap is further elaborated on in chapter 2.

The aim of this research is to fill these current research gaps; increasing the insight into the current incompatibilities in energy visions. This would prevent the emergence of a delayed and both economically and technically inefficient energy system.

Therefore, the novelty of this research lies both in its social and scientific relevance. Firstly, this research has social relevance because of actors within the NSR currently lacking insight into the different existing energy visions regarding the role of gas infrastructure when integrating offshore wind. Secondly, this research has scientific relevance as no fitting theoretical elements have currently been designed to efficiently compare and collaborate on different co-existing energy visions (in the NSR).

This is a qualitative assessment. The value of this research does not lie in generalisation and abstraction; instead, we aim to provide a more contextualised, in-depth understanding of how differences in visions for integration emerge and create potential (future) compatibility issues. By comparing different actors’ visions within the NSR, a unique insight into the possibilities of regional system integration and into potential barriers in this particular region is gained.

Different energy visions are compared and analysed by combining both a pattern modelling method and inductive coding method. Both methods are further elaborated upon in chapter 3.

1.5. Research questions and sub-questions

Main question: Focused on gas infrastructure as a solution for integrating offshore wind, how can the co-existing energy visions in the North Sea region be made more compatible?

1. **Sub-question 1:** Focused on the interplay between electricity and gas infrastructure, what energy visions for system integration currently co-exist in the North Sea region?
2. **Sub-question 2:** To what extent, and based on what underlying reasoning, are these energy visions compatible or incompatible with each other?
3. **Sub-question 3:** How could these energy visions be made more compatible to improve international system integration in the North Sea region?

This report is structured as follows. First, in chapter 2 a short literature review is given on ‘energy visions’, as this concept is the epistemic tool that is used to identify the future development of the energy system and map important themes and relationships. Chapter 3 describes the research design of this study. Chapter 4 answers sub-question 1. This chapter identifies the important themes and relationships for the actors researched in each country of the NSR. Subsequently, chapter 5 answers sub-question 2, ‘zooming out’, and analysing, comparing and discussing the themes and relationships from a NSR (system or holistic) perspective. This chapter describes the current (in)compatibilities present in the NSR, and its consequences. Chapter 6 elaborates on sub-question 3, giving an overarching recommendation for improvement of the compatibility of these themes in the NSR. Respectively, a conclusion and subsequent discussion on the methodology used are given in chapter 7 and 8.

2

Conceptual framework: Energy futures

In this research, energy futures are the epistemic tool used to identify the future development of the energy system. In this chapter, the concept of energy futures is presented. Our research does not differentiate between the concept of energy futures (which has been used mostly in academic circles) and energy visions (which is more commonly used by energy practitioners). To be able to compare different energy futures amongst countries and actors in this research, it is important to understand what constitutes an energy future theoretically. The characteristics of energy futures, including their multi-dimensionality and their versatility, are discussed in section 1. In section 2, the impact and performativity of energy futures are characterised. Subsequently, section 3 describes the various themes presented in different energy futures. Lastly, section 4 explains the theory behind the collaborative futuring 'activity', which occurs when energy futures are compared and combined.

As mentioned in the introduction, energy futures are defined as "collectively held and performed visions of desirable and realistic futures for energy sources, technologies and systems in a specific geographically bounded area" [Rodhouse, 2018](*Page 3*). These futures identify and evaluate possible future events. Currently, policies on grid integration are built upon a particular perception of, and preference for, the future. These policies propose actions and measures to enact the future. In doing so, they help involved actors to minimise the risk of being surprised and unprepared [Bengston et al., 2012] [Poli, 2017].

2.1. Energy futures: a form of socio-technical imaginaries?

There are different theoretical streams that describe energy visions. These theories tend to overlap, although putting a focus on different aspects. This section discusses three theoretical streams, guiding visions, technological expectations and socio-technical imaginaries. This research defines the concept of energy futures by drawing from all three theories. To gain an understanding of energy futures, it is therefore important to understand these three theoretical streams. These are discussed in the next paragraphs.

Firstly, there are **guiding visions** originating from the geographical and planning literature, which help actors imagine, relate and guide them in technology development. Guiding visions, or leitbilder, are developed and desired by professionals and scientist to guide and justify future (government) activities [Dittrich, 1962][Späth and Rohracher, 2010]. Dierkes presents the function of guiding visions to be twofold. First, it helps actors imagine and relate, sketching a clear view of one's role in and personal benefits of the technology. Secondly, guiding visions guide actors in technology development stimulating certain behaviours or activities [Dierkes et al., 1996].

Secondly, there are **technological expectations** originating from technology innovation studies, which explicitly target one technology. Identical to guiding visions, technological expectations are desired prospects of a certain socio-technical future [Borup et al., 2006]. They are shared promises and visions that surround technology development and innovations [Rodhouse, 2018]. One could see it as an arena, where initially developers of a technology present their expectations. Subsequently, selectors of the technology affect the technological expectations. Selectors are the ones who need to solve a problem, and therefore assess how different technologies could form a solution to their problem. Together, developers and selectors create a dynamic process in which technological expectations are negotiated and developed. In addition, public actors and other stakeholders are gradually also invited into the arena to develop the technological expectation further [Bakker et al., 2011].

More recently, a third stream of theoretical work has used the concept of **socio-technical imaginaries**. This is defined as a publicly performed, collectively held, institutionally stabilised and vision of a desirable future [Rodhouse, 2018][Jasanoff and Kim, 2009].

They build on the insight that within society there is a shared narrative, where societies evolve by negotiating what future image they would prefer for themselves. Specifically, societies negotiate whose future becomes dominant in society, who influences negotiations and what impacts a specific strong focus. The outcome of these negotiations depends on the different combined lenses, frames, values, experiences and expertise present in society. These visions are not merely technological but also cultural, ethical, political and economic.

Socio-technological imaginaries are created by those with certain political agendas, who act to fulfil these conceptual images. In addition, they discourage behaviours and other imaginaries that might threaten the performance of their desired future. This action narrows down the number of pathways and goals that are both acceptable and realistic [Sovacool and Hess, 2017]. In summary, socio-technological imaginaries can be seen as both the product of and productive of, (political) legitimation efforts [Sovacool and Hess, 2017].

In this research, the concept of energy futures draws from all three theories (that also borrow heavily from each other).

Energy futures are embraced as being guiding visions which contain a range of technological expectations. However, the chosen definition of energy futures aligns more closely with that of the socio-technical imaginary. This is the case as this research focuses explicitly on the NSR and their socio-technical energy systems, rather than separate projected technologies.

Energy futures are continuously evolving, and both constructed and negotiated in interactions between industry actors and key stakeholders [Delina and Janetos, 2018]. In other words, the ‘energy transition’ is a continuous and ever-changing development, without a clear beginning and end. This characteristic also makes socio-technical imaginaries a fitting theory to draw from.

2.2. The impact and performativity of energy futures

To answer sub-question 1 (*Focused on the interplay between electricity and gas infrastructure, what energy visions for system integration currently co-exist in the North Sea region?*), different energy futures in the NSR are analysed and compared. Therefore, for this study, it is important to understand the multi-dimensionality of energy futures. Only by understanding the different uses and usefulness of energy futures can the researcher understand and compare the implicit characteristics of energy futures. In the upcoming paragraphs, the different uses of futures, respective usefulness of futures and their success are described.

A future can be used in different ways by different actors. For example, Braunreiter mentions that some use future scenarios primarily as a data source and others use them as “a reference for holistic descriptions of plausible energy futures” [Braunreiter and Blumer, 2018](*Page 123*). Different phases of energy futures can be defined where the future has different uses and impacts.

The first phase of energy futures is the process phase, where thinking patterns become defined and coordinated towards a vision. Subsequently, the vision becomes a public document. In this phase the vision’s range increases, different people accept the vision, and they align their thinking and investment accordingly. In the last phase, current developments are shaped, making use of the presented milestones and bottlenecks in a vision’s output. These current developments are shaped by the spread of the thought patterns and means of the vision.

Considering these different phases, one should keep in mind that the process is never-ending. A vision should not be perceived as an end goal but as an intermediary product that creates a shared horizon for structural transformation [Dignum et al., 2018].

Energy futures are useful as they provide justification and guidance for action and change [Quist, 2007]. This shaping property of a future is called the performativity and is extremely important in the context of energy infrastructures due to the long project development times [Dignum, 2018] [Grunwald, 2011]. A vision can potentially be performative on four dimensions: on different issues (meanings), on cognition (knowings), on material commitments (doings), and on government arrangements (organisings) [Longhurst and Chilvers, 2019].

Visions are always reflective of specific goals and interests or. They are “instrumentalized in order to achieve specific goals and support political or economic interests”[Grunwald, 2011](*Page 824*). These visions and scenarios eventually legitimise agendas and strategies, leading to feasible plans and (beneficial) allocation of resources within the overall development paradigm [Moriarty et al., 2005][Obrecht and Denac, 2016]. Figure 2.1 illustrates this, showing in a loop that a future is a specific part of each present and not separate from the present [Grunwald, 2011]. (Political) decisions today are therefore dependent on the assumptions for the future, with energy futures allowing to either open up or narrow down a particular public policy domain [Grunwald, 2011].

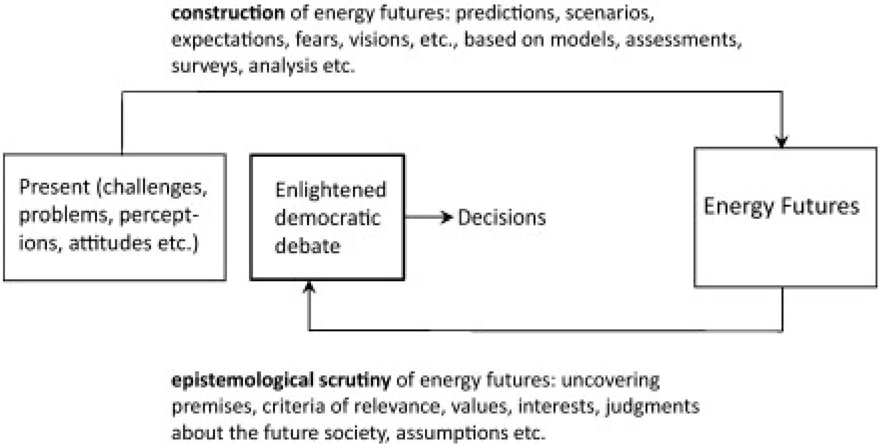


Figure 2.1: “The abstract orientation-providing loop via future analysis, reflection and back-casting” [Grunwald, 2011](*Page 823*).

In the two previous paragraphs, the uses and usefulness of energy futures are discussed. Both these characteristics lead to a particular success of energy futures. Generally speaking, an energy future is deemed successful if it “helps energy planners; influences the perception of the public or the energy policy community; captures the current understating of underlying physical and economic principles; or highlights key emerging social or economic trends” [Kwon and Østergaard, 2012](*276*).

The specific success of an energy future cannot easily be defined because it is subjective [Alipour et al., 2017][Obrecht and Denac, 2016][van Asselt et al., 2000] [Obrecht and Denac, 2016][van Asselt et al., 2000]. This subjectivity of success can be explained by the fact that peoples’ relationship with energy is seen to be normative, held by energy actors and shared in networks. The relationship is associated with strong assumptions on what public actors can and should do in decision-making on energy policy, planning, project and technology development.

Even the visions that seem descriptive have a certain normativity “in the form of imagined social, political and economic orders which extend beyond the exposition of future energy systems” [Longhurst and Chilvers, 2019](*974*). When analysing different energy futures, it is therefore important to be aware that energy futures can reflect a particular set of values or interests promoted as ‘objective’ information [O’Mahony, 2014].

2.3. Components of energy futures

To answer sub-question 1 (*Focused on the interplay between electricity and gas infrastructure, what energy visions for system integration currently co-exist in the North Sea region?*), different themes of energy visions are compared to each other. In order to formulate these themes of interest, it is important to have a general understanding of the common “underlying political drivers and the complex institutional and social context” different energy futures consider [Nilsson et al., 2011](*1127*).

Theoretically, futures contain multiple assumptions, suppositions, presumptions and premises about (dis)continuance of present trends and activities [Grunwald, 2011] [Kühnbach et al., 2020]. The futuring output, i.e. what is written down on paper, is only the top of the iceberg. Many underlying assumptions form the larger part of the iceberg underwater, which are not directly visible and often taken for granted [Cao et al., 2016]. In that sense, one could say that futures are institutionalised and build upon formal and informal rules and knowledge.

In the box below, this research presents a categorisation of future drivers which is introduced by Charles, and combine this with other literature [Charles et al., 2011].

In this research a holistic, or integrated, approach is taken. The goal of the following overview is merely to get an insight into the variety of existing themes from previous research. To emphasise, this classification will not be used as a 'check-list' when characterising energy visions. However, it will be used to get an insight into the different institutional components of energy futures. This approach explores themes within existing categories and is open to new drivers, themes and relationships, which is further explained in chapter 3.

- **Economic drivers:** this includes drivers of expectations in GDP (GDP growth rates), global development (convergence, divergence or confrontation), economic growth, growth in consumption per capita, population growth and energy and CO2 price. [Weimer-Jehle et al., 2016] [van Asselt et al., 2000].
- **Resource endowments of actors characterising dependency of fossil fuels and potential for RES deployment:** including drivers of expectations in energy, oil and natural gas price, how resources change due to climate change, national technical expertise, resource and infrastructure location, regional geophysical attributes and industry capacity [Obrecht and Denac, 2016].
- **Technological capacity:** in terms of both ratio of R&D spending to GDP and existing infrastructure systems, which are regarded as indication of capacity to develop and implement new technologies. Specifically, this includes factors such as energy conversion technology developments (technological innovations, breakthroughs and maturity); infrastructure (electricity grid, gas network, degree of digitalisation); demand (demand in sectors, flexibility options); large scale vs small scale technologies, distributed generation vs. supplemental; centrally driven expansion of infrastructure; energy efficiencies; infrastructure extension (slow, fast); growth of renewable energies; domestic energy savings and industrial energy savings [Weimer-Jehle et al., 2016] [van Asselt et al., 2000] [Obrecht and Denac, 2016].
- **Policy conditions regarding energy security, climate change and sustainable growth [Charles et al., 2011]:** the balance between the energy-trilemma of choosing between security, social impact and environmental sensitivity; socioeconomic aspects (participation, acceptance, consumer behaviour); energy system organisation (roles and responsibilities of actors, the size of market areas, control hierarchy, types of energy-related products); centrally vs. decentrally (prosumer driven) organised structures; planning legislation (incoherent, promoting speed, promoting participation); perceived importance of climate change (strong, moderate); acceptation of import dependency; necessity for security of supply; regional tensions; energy policy priorities; political priority (energy turnaround, security of supply, economic) and consumerist vs. community value [Kühnbach et al., 2020] [Weimer-Jehle et al., 2016] [Obrecht and Denac, 2016].
- **The different approaches in risk and responsibility** of a certain (technological) development and the (possibly pro-development) alliance between the state and technological expertise [Jasanoff and Kim, 2013] [Jasanoff and Kim, 2009]. Research by Cambini concluded that "under a regulatory scheme that allows the pass-through of capital costs, utilities tend to invest in more capital intensive solutions rather than less costly but risky innovative technologies" [Cambini et al., 2020](*Page 5*).

2.4. The act of collectively futuring

To answer the main question, and specifically sub-question 3 (*How could these energy visions be made more compatible to improve international system integration in the NSR?*), one must have an understanding of the act of futuring. This research aspires to make recommendations on how energy futures could be made more compatible with each other. Therefore, it is important to gain insight into how different energy futures could potentially interact with each other and emerge together. Accordingly, this section describes the act of futuring and collectively futuring. Next, three different degrees of collective futuring are explained.

The process of futuring is not always preconceived and planned. Sometimes futuring is an informal and automatic process in policy-making. Therefore, one could gain more control on futures by actively and consciously being aware of their individual futuring process.

Additionally, one could also gain more control on futures by actively being aware of the futuring processes around them; collectively futuring together. Hajer defines the process of collectively futuring as “practices bringing together actors around one or more imagined futures and through which actors come to share particular orientations for action” [Hajer and Pelzer, 2018](*Page 222*).

Turnheim defines alignment and bridging as two basic procedures of collectively combining and integrating futures in a “continuous iterative cycle” [Turnheim et al., 2015](*246*). As this research aspires to formulate recommendations on how energy futures could be made more compatible, it is important to understand these two procedures and their importance.

Firstly, alignment is defined as identifying the joint elements around which an integrated decision can be defined “in terms of applied concepts, problem-frames and empirical domains” [Turnheim et al., 2015](*246*). One can create a better understanding of diverse energy futures when the co-production between energy futures is acknowledged. These insights into co-production can reveal the respective partialities, exclusions and sociopolitical dimensions of different actors [Longhurst and Chilvers, 2019]. According to Longhurst, this offers a “more humble, reflexive, and responsible foundation for practices of future-making and sociotechnical transformation” [Longhurst and Chilvers, 2019](*989*).

Secondly, bridging is defined as building “active operational links between approaches around data and explanation in a common stream of analysis” [Turnheim et al., 2015](*Page 246*). When combining energy futures, different moving speeds, starting points of actors and “understanding of the dynamics between grand visions and pragmatic integration processes” can be defined [Bolton et al., 2019](*Page 67*). It is important to define certain biases and missed uncertainties in individual futures. This is the case because a diversity of energy futures could be at cross-purpose and lead to disorientation instead of helping more rational decision making [Braunreiter and Blumer, 2018] [Obrecht and Denac, 2016].

To shape and format energy futures, the settings and collective practices through which actors are involved play a fundamental role [Longhurst and Chilvers, 2019]. Collective futuring can be done to several increasing degrees ranging between ‘stakeholder inclusion’ and ‘participative futuring’. More recently, the process of ‘collaborative futuring’ is presented, fitting in between both processes. All three processes are discussed below.

2.4.1. Stakeholder inclusion (public participation)

Within different futuring methodologies, different stakeholders are asked to cooperate in building a future, defined as ‘user-modeller interaction’ [Braunreiter and Blumer, 2018]. Every future has essentially decided which actors are most important [Longhurst and Chilvers, 2019]. Such stakeholder dialogues could be organised by “defining combined analytical or governance problems to be tackled through integration; establishing shared concepts (boundary objects); and establishing operational bridging devices (data and metrics, pathways evaluation and their delivery)” [Turnheim et al., 2015](*Page 239*).

Stakeholders dialogue can have the function to be consensus building or can be more focused on debate. Consensus building seems to be the most dominant practise. However, a debate can also help critically assess arguments in favour and against [van de Kerkhof, 2006]. Such debate maps out the diversity of positions. This debate then enables more informed negotiations, resulting in important insights and increasing mutual understanding [Wiek and Iwaniec, 2014].

2.4.2. Participative futuring

Through participatory practices, energy futures are co-produced. This co-production in actor collectives is a step ‘up’ from stakeholder inclusion. In this case, public inputs do not prevent the formatting, conditioning and framing of processes done by the dominant imaginary actor of the future [Longhurst and Chilvers, 2019]. A group of diverse actors play an active role co-designing the futures, engaging surprise, disagreement, confusion and objections in an iterative process. This process leads to richer and more credible futures among stakeholders [van Asselt et al., 2000].

Settings set in a participatory design are answers to the questions ‘who participates with who’, ‘in/on what’, ‘to what extent’ and ‘with which procedure?’ [Wiek and Iwaniec, 2014]. Additionally, other more frequently ignored questions include: ‘how do my actual and planned actions relate to those of others’ and ‘what assumptions do I make about the role and behaviours of others and are these assumptions shared’ [Moriarty et al., 2005].

Previous sections concluded that visions tend to have several different functions. However, Spath concludes that *participative* visions almost always tend to reproduce and stabilise the status quo, as they are “closely bound to the slow metamorphosis of the normative and discursive landscape they are embedded in” [Späth and Rohracher, 2010](*Page 450*). Even creating new (technological) arenas for consideration does not guarantee “increased reflexivity of the politics of visioning” [Späth and Rohracher, 2010](*Page 451*).

2.4.3. Combining futures into collaborative futures

The term ‘collaborative futuring’ has not yet been used in previous academic literature. However, previous research does explain the necessity for collaborative futuring.

For example, Grunwald mentions that one can create an understanding of the large diversity of energy futures by both mapping and comparing different futures and researching their methodological approach [Grunwald, 2011]. Longhurst adds to this by mentioning that it is important to consider the “diversity of visions, particularly those that are more radical or peripheral” [Longhurst and Chilvers, 2019](*Page 974*). Using this information, one is seen to define the areas where contention exists rather than the areas that are closed down “around a specific narrow approach” [Longhurst and Chilvers, 2019](*Page 974*). Collaborative futuring is therefore defined as maintaining one’s own vision whilst considering other existing visions within the same envisioned scope.

Collaboration between visions is not always necessary. Advantages of only collaborating on a regional level and not on a high level are threefold; it simplifies the futuring process; centralisation could hinder experimentation and hold back ambitious front runners; and decentralisation is “more robust to design errors and accounts for heterogeneous national characteristics” [Dedecca et al., 2019](*Page 60*)[Hyysalo et al., 2014]. A “mix of top-down and bottom-up elements” is therefore recommended when collaboratively futuring [Dedecca et al., 2019](*60*), where flexible implementation is combined with rigid obligation [Gephart et al., 2015][Dedecca et al., 2019].

3

Research design

This chapter presents the methods used in this study. The first section (3.1) explains the approach taken when executing the 'pattern modelling' methodology used and also explains the reasoning for using this method. Secondly, section 3.2 presents the different steps of pattern modelling. Next, section 3.3 presents the scope used when pattern modelling.

Pattern modelling presents an overarching methodological orientation. Within this orientation, there is still room to choose certain research methods to collect and analyse the empirical data. Section 3.3 discusses these research methods and explains the specific research approach to answer each individual sub-question.

3.1. The pattern modelling approach

In order to understand the pattern modelling approach, one must first understand three important characteristics of institutionalism provided by the New Institutional Economics. Institutionalism is the theoretical tradition in which pattern modelling is applied. These three characteristics are the holistic, systemic and evolutionary focus and are discussed in the next paragraphs [Ramstad, 1986].

Firstly, the pattern modelling methodology systematically creates holistic knowledge [Ramstad, 1986]. Simply put, a holist is someone who studies by considering the whole.

In more detail, a holist recognises that providing understanding is the primary function of theory. The goal of the holist is to develop 'practitioners knowledge'. This is defined as "knowledge directed to the understanding and control of the specific case" [Ramstad, 1986](*Page 1075*). Holistic theories are linked together, as one focuses on the pattern of relations among the whole. Therefore, it is assumed that activities are only understood in their interrelations with other activities [Ramstad, 1986]. This includes "the belief that the parts are at once conditioning and conditioned by the whole" [Ramstad, 1986](*Page 80*). This holistic conception of reality can also be described as a set of values that express itself throughout the system or a particular socioeconomic structure that tends to condition everything else [Ramstad, 1986].

In comparison, when a formal method is used, the structure of theories is hierarchical; definitions and postulates are first established, and subsequently, the dynamics of a system are deduced. The appropriate framework in which to explain a subject matter is predetermined [Wilber and Harrison, 1978]. Based on the formal model, the position is that the "truth about reality lies in the logic of the theory" [Wilber and Harrison, 1978](*Page 63*).

Therefore, the goal of the formal model is to allow predictions and general knowledge, and the goal of the holistic approach is to provide an in-depth understanding of a specific case. Holists do not define any "covering laws" to provide an underlying conceptual structure [Ramstad, 1986](*1074*). As a result, an explanation based on a pattern model is thought by the formalist to merely be a description [Ramstad, 1986].

Another characteristic of institutionalism is the systemic focus. This focus believes that holistic parts make up a coherent whole and can only be understood in terms of the whole. It is therefore deemed necessary to study the whole living system, in contrast to taking one part out of context.

A systemic focus specifies the necessity of a whole system for understanding something, whereas a holistic focus specifies the necessity for relations between parts of the whole.

A third characteristic of institutionalism is the evolutionary focus. This focus considers changes in the pattern of relations to be the essence of social reality. The unfinished and always developing nature of human subject matters is thought to lead to incompleteness. This process of evolutionary change is driven by the interactions between the parts and the whole. In other words, a model of a particular system and time is thought to always include exceptions, ambiguities and inconsistencies.

These three focuses (holistic, systemic and evolutionary) seem very straightforward, although it is important to add a certain point of non-rationality. This is deemed necessary because of the important influences of “nonrational human behaviour” [Wilber and Harrison, 1978](*Page 72*).

In summary, pattern modelling creates an understanding of a system for which there are no fixed variables and causal relationships. Therefore, this is a descriptive, inductive and exploratory approach, in contrast to a deductive approach where certain hypotheses are tested. Most methodologies work with ‘check-lists’, searching for certain fixed themes within the empirical data (in this case, energy visions). With pattern modelling, a ‘check-list’ is created iteratively whilst going through the empirical data.

3.1.1. The importance of the pattern modelling approach for this research

To systematically carry out a comparative study of energy futures around the North Sea, the choice is made for the pattern modelling methodology. As this is a comparative study, this study is suitable to use the pattern modelling methodology as this is a comparative method [Ramstad, 1986]. There are two specific reasons for this research to use the pattern modelling approach.

Firstly, compared to using a formal method, energy futures are better analysed using a pattern modelling approach due to their multi-dimensionality. As previously described in chapter 2, energy futures are multi-dimensional. This is reasoned because different actors have different insights into what the main elements and underlying themes of a certain future are. Comparing these different multi-dimensional energy futures is presumed difficult to do quantitatively and normatively based on identical standards or theories. A more descriptive and qualitative approach is therefore preferred, as is the case with pattern modelling. This is also described by Wilber, who mentions that a pattern modelling approach is used when “an explanation involves many diverse factors, each of which is important” [Wilber and Harrison, 1978](*Page 85*). Additionally, Wilber also mentions that pattern modelling is also used “when the patterns or connections among these factors are important” [Wilber and Harrison, 1978](*Page 85*). These are both characteristics of the energy futures that are analysed.

Secondly, pattern modelling requires a largely abductive research attitude and approach, in which the researcher is not looking for predetermined themes. In contrast, the researcher is open to new themes and relationships of interest to the research topic. This characteristic is essential when analysing energy visions because the system is so complex that it would be impossible to analyse all existing themes in detail.

3.2. The steps of the pattern modelling methodology

Previously mentioned as one of the three characteristics of pattern models, the existence of a whole system comprises many interrelated parts or sub-systems. The steps of the pattern modelling process are distinguished in the following paragraphs.

Initially, the observer’s focus is on one part of the entire system, a sub-system. The aim is to let the context of this limited domain suggest meanings rather than testing previously derived hypotheses. Through close observation of only a part of the system, analytical *themes* emerge. These interrelated sub-systems are illustrated in figure 3.1, where themes are referred to as T1, T2 and T3. Subsequently, the focus is shifted to other parts of the whole in an attempt to determine whether the same themes can be isolated in other contexts. This technique thus relies on the comparison between different parts of the same system.

With every additional analysis of a sub-system, (emerging) themes are strengthened, or new unique themes are recognised. Increasingly, likely themes are tested through contextual validation, evaluating the plausibility of one's initial interpretations. If a theme or relationship is present in or across multiple sub-systems, this may indicate its relative importance for the whole system.

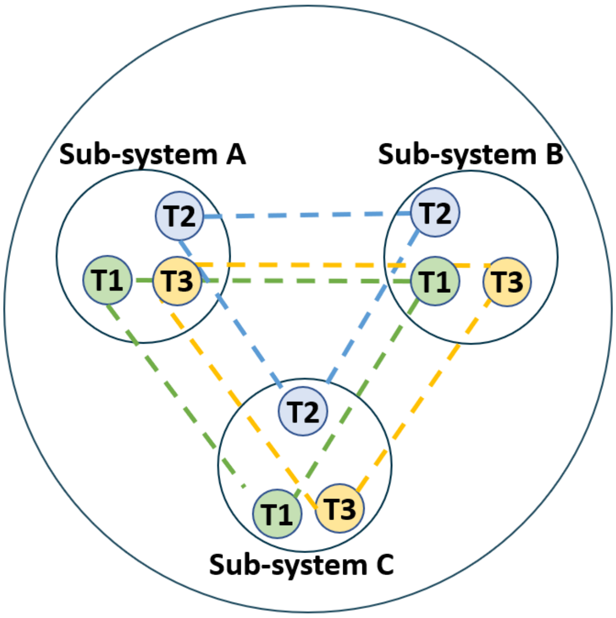


Figure 3.1: A schematic overview of a pattern model. The illustration is made by the researcher and based on [Ramstad, 1986].

Emphasising recurrent themes within or around the system, the researcher now tries to capture the linkages that establish a system's uniqueness. At some point, a theme becomes a 'tentative hypothesis' and the researcher then tests this hypothesis by consulting a wide variety of data sources. Subsequently, the descriptions of the sub-systems are then continually tested, as one tries to place new themes within the already existing pattern. Additionally, by comparing different data sources, similar themes are continuously validated. This process leads to a many-sided complex picture of the whole system.

After several themes are validated, they are linked into a network and interpreted to comprise a pattern model. This pattern model is tested by observing how well new data and themes can be incorporated into or explained within the pattern. As the final step of the holistic method, universal categories and general laws could emerge from the comparison of widely varying sub-systems. These 'general laws' are specific to this very system and do not explain the unity of the particular system. Instead, verification of a system lies in the whole because of the low level of reliability to any particular interpretation of a specific part. The reliability of a specific part is low because the interpretations of a specific part are only contextually validated.

The pattern model is open-ended. Increasing the coherence between the model and the real world is a constant process because the system itself is constantly changing, and new data could still be uncovered [Ramstad, 1986][Wilber and Harrison, 1978].

Once developed by the researcher, a pattern model cannot be verified by testing the accuracy of predictions. This is reasoned by Wilber, who considers that knowledge of the whole pattern and some of the parts does not necessarily enable the holist to predict any or all unknown parts [Wilber and Harrison, 1978]. When one uses a formal method, one is thought to understand something if one can predict it. In contrast, the holist believes that one understands something when one has an understanding of its place in the whole.

3.2.1. Applying the steps of pattern modelling in this research

Applying this framework to our research, a pattern model of a system emerges when themes (tentative hypothesis) are formulated that determine the role actors consider for gas infrastructure when integrating offshore wind.

In this specific research, the system is defined as the energy system in the NSR. This system can be defined geographically (a subsystem being a country) or dimensionally (a subsystem being a sector, e.g. electricity or gas infrastructure). The top illustrations of figure 3.2 depict both options, including a scheme of the different interrelated themes (T1, T2 and T3). Combining this geographical and dimensional approach, in this research, a sub-system is defined as a group of actors. This is schematically illustrated in the bottom illustration of figure 3.2. To show the complexity of the system dealt with, different themes are illustrated. This illustration also shows the many different types of relations that can occur both in and between sub-systems.

Considering the four actors (government, electricity TSOs, gas TSOs and industrial associations) and six countries, there are essentially 24 (4x6) different sub-systems. However, in total 22 different sub-systems are considered, as the electricity and gas TSO sub-systems of Denmark and the UK are combined into one sub-system. This is done as one TSO in these countries is responsible for managing both the gas and electricity infrastructure. These 22 different sub-systems or actors are seen as a part of the whole system. Although, the whole system is not considered to merely consist of these 22 sub-systems.

To conclude, the system, sub-system, themes, pattern model and role of energy visions are defined as follows:

- **System:** the energy system in the North Sea region
- **Sub-system:** the analysed sub-systems are the energy visions of different actors in the NSR. Specifically, the actors are the government, industrial associations and electricity and gas or combined TSO per NSR country. These sub-systems can be analysed geographically (differences between countries) and dimensionally (differences between the three actors). Throughout this report, these sub-systems are defined as ‘actors’.
- **Themes:** themes are the elements in different sub-systems. In short, these themes entail both technologies, infrastructure choices, socio-economic drivers, policies and regulations. They include themes on system integration technologies for renewable energy sources and themes on the different underlying reasoning given for the choice of certain integration technologies.
  The themes derived in this research (to some extent) correspond with previously characterised themes from past research, which were presented in chapter 2.3. Although these predetermined themes are not used a starting point in this research, they are used to verify themes derived in this research. The specific methodology used to derive these themes is further discussed in chapter 3.2.
- **Pattern model:** a pattern model is compromised of several validated themes that are linked into a network.
- **Energy futures/ energy visions:** these are epistemic tools with which the researcher identifies planned future developments of the system. Using energy futures, one can map important themes and their relations.

3.3. Research scope

A likely risk of the pattern modelling approach is that the researcher takes a too large scope of the existing empirical data. Therefore, good scoping is key. The following scoping of empirical data for this study is defined:

- **Geographical scope:** The Netherlands, the UK, Denmark, Germany, Norway and Belgium (NSR countries). These six countries are chosen because experts from CIEP considered they all play an important role in the NSR. Excluding one country would not give a correct overview of the region, and that is ultimately the research goal.
- **Time scale flexibility management:** long-term flexibility management of the electricity grid (hourly/ daily/ weekly/ monthly/ annually) is focused on. More short-term management (within an hour) is not included. This choice is made as volatility of renewable energy sources is significant on an hourly basis, taking, for example, the difference between day and night for solar energy. These time scales are depicted in more detail in figure A.1 [Allard et al., 2020].
  Additionally, flexibility management is not focused on quantitatively (e.g. how much capacity is needed at which moment due to a shortage of offshore wind). Flexibility management is focused on qualitatively, as no specific computational models are analysed in this research.

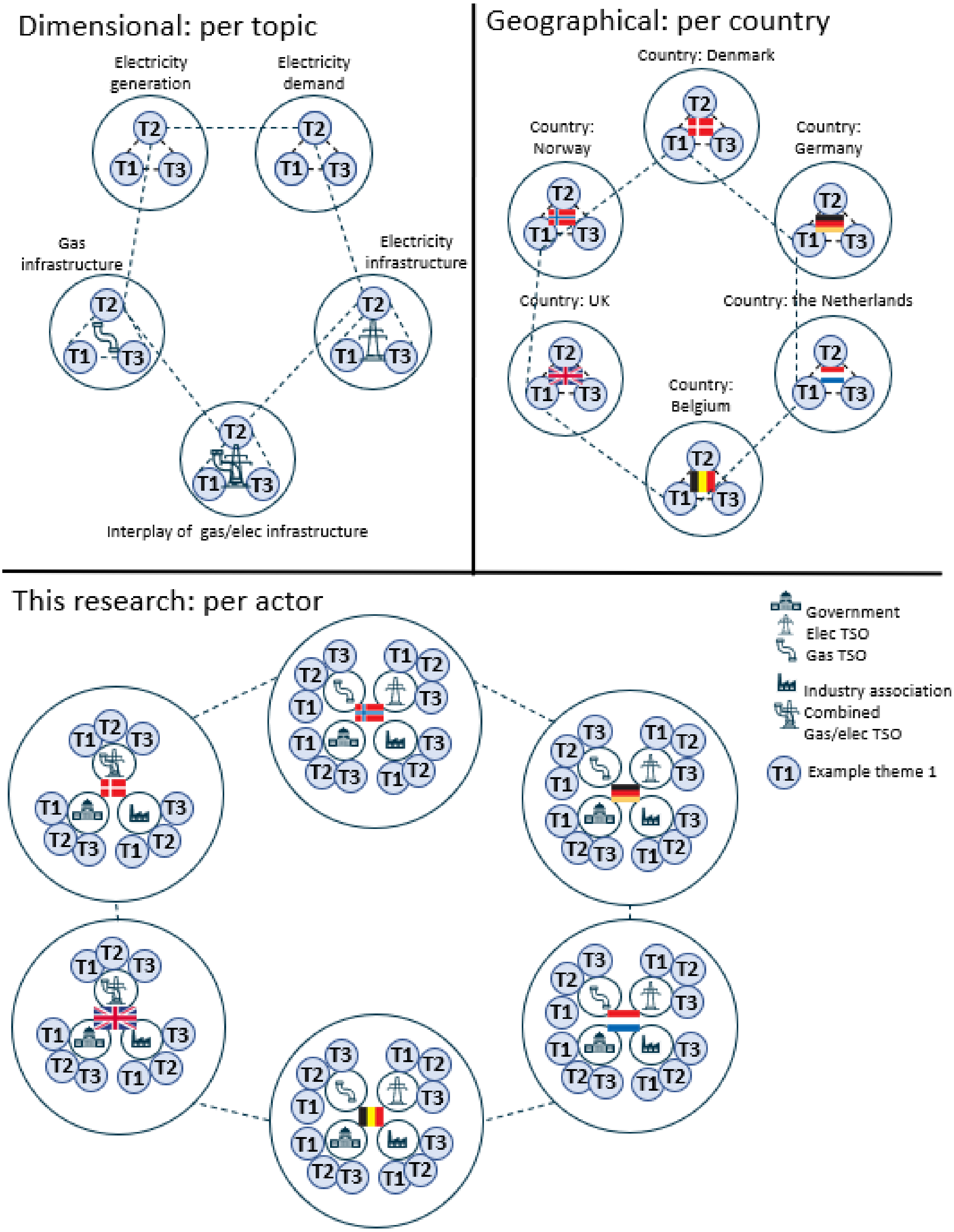


Figure 3.2: A schematic overview of a pattern model with a dimensional (figure on the top left) and geographical (figure on the top right) sub-system. The bottom figure illustrates the approach used in this research. This approach combines both dimensional and geographical approaches. To show the complexity of the system, as a figurative example, three different themes characteristic for the different actors are illustrated in blue circles labelled T1, T2 and T3. This also shows the complexity of relations between themes both within and between a sub-system. The illustrations were made by the researcher.

- **Actors researched within regions:** it is important to note that this project is not comparing nations in a nation focused approach. However, it is considering the national gas and electricity TSOs, governments as main actors and additionally (national) research institutes and large industry players. This study is not a comparative country analysis, aiming to gain a complete understanding of all ideas in a country and comparing these insights. Instead, the aim is to get an idea of the NSR as a whole by studying views of the most notable actors (such as TSOs and governments) within the limited time frame of this project. Due to this time frame, not all actors can be included, including some more regional TSOs and Distribution System Operators, wind farm developers, energy industry producers and consumers such as the oil and gas industry, fishing and shipping industry and other advisory or lobby organisations. All these types of organisations identified could also vary for the different regional, national and international (EU) levels [Satolli, 2015].
  Energy visions of TSOs and governments are analysed because these organisations tend to consider the visions of or are lobbied by their surrounding actors. Therefore, these visions are expected to include the main insights of the region. Some visions of research institutes and large industry players are also considered, adding to this general overview.
- **Time segments scope:** Visions published in the period from 2018 to mid-November 2020 are considered, giving the most recent data present.

3.4. The research approach to answering the research questions

It should be emphasised that a pattern model is not established based on a self-reasoned logic but from the information found in the empirical data. Within this research, energy futures are the epistemic tools that identify the future development of the system and map important themes and relationships.

Pattern modelling presents an overarching methodological orientation – however, within this orientation, there is still room to choose various research methods in the collection and analysis of data. In this section, the chosen methods are elaborated on and are presented per sub-question (see figure 3.3). As this figure illustrates, data collection in this research consists of both interviews and a content analysis of different energy visions, forming a certain triangulation of data. This section describes how both methods are used when answering the sub-questions.

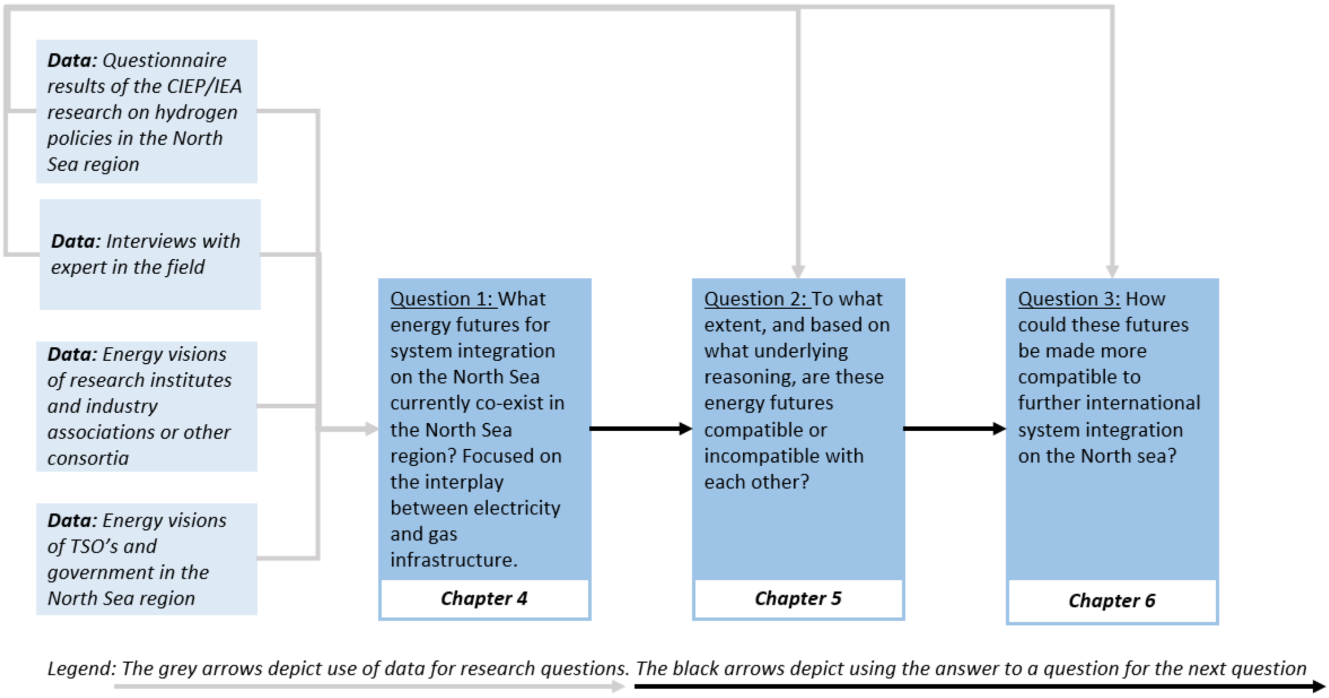


Figure 3.3: A schematic overview of research questions and research design. The illustration was made by the researcher.

3.4.1. Analysing different energy visions using content analysis

In this section, the content analysis of the energy visions is further described in four different phases. A schematic overview of the precise way data was structured in this research is illustrated in figure A.3 in the appendix.

Step 1: Identifying empirical data

As a starting point, relevant energy visions and strategies are searched for on both governmental and TSOs websites in all six countries. A report is deemed relevant for this study in three different cases. Firstly, a report was deemed relevant when it considered visions on integrating renewable energy sources (RES) (focused on electricity and gas infrastructure). Secondly, a report was deemed relevant when it considered hydrogen and other gaseous green-fuels that could be produced from RES. Thirdly, a report was deemed relevant when it considered the future use of gas infrastructure (for integrating RES). In other words, reports were deemed relevant if they matched the scoping mentioned in section 3.2.

Due to the specific locations of offshore wind for both the Netherlands and the UK, government visions on the situation in Groningen and Scotland are also considered.

Subsequently, visions of knowledge institutes and key industry players are also analysed. Here, a selection was made for various actors whose name was either often mentioned in the initially analysed visions, or whose name often arises when searching for the terms ‘hydrogen’ and ‘ ‘system integration offshore wind’ or whose name was mentioned in interviews.

Precise actors whose visions were analysed are found below. The exact documents are mentioned in the bibliography. The specific documents were selected throughout the research duration, so the most recent energy visions could be analysed.

Country: *government actors; TSOs; other (industry) associations*
Belgium: federal government, government of flanders; Elia, Fluxys ; VARIO
Denmark: national government; Energinet ; Ørsted, FutureGas Denmark
Germany: federal government, advisory DENA; TenneT, Gasunie, FNB Gas, NEP association; Frontier economics
The Netherlands: national government, Groningen government, advisory TKI Nieuw Gas; TenneT, Gasunie; TNO
Norway: national government, Nordic Energy Research; Statnett, Gassco; Equinor, Konnkraft
UK: national government, advisory CCC, Scottish government All-Party Parliamentary Group (APPG) Hydrogen; NationalGridESO, NationalGridGas, Northern Gas Networks, Ofgem; BP, Crown Estate Scotland
Non-national: EU, NorthSEE; ENTSO-E/ENTSO-G; Frontier economics, Imperial College London, Hydrogen Europe, Gas for Climate, Oxford Energy Forum

Most searches for documents are done in English or in Dutch (in the case of actors from Belgium and the Netherlands). Most analysed documents are therefore also written in English or Dutch. If a document was not available in both languages but was considered relevant, Google translate was used to translate the document and analyse it.

Step 2: Identifying themes by inductively coding empirical data

After acquiring the different documents to be analysed, sources were coded. For this step, the method of open coding is used. This is a process where concepts (codes) are attached to the observed data. It is important to emphasise that open coding is an inductive process, as the pattern modelling approach entails. This means that the researcher does not use a general list of themes from the start but labels themes once they are mentioned in documents. If the same theme is mentioned in another document, the researcher uses the same code [Bhattacherjee, 2012].

In general, every time an integration or flexibility method for renewables is mentioned, the given information (be it projects, standpoints etc.) is labelled and noted as a theme. The reasoning given for the envisioned choices is also noted as a theme [Bhattacherjee, 2012].

The inductively acquired coding scheme and descriptions are noted in appendix B. After the themes are characterised, this research characterises the codes in four different groups: “How much flexibility is needed?”, “Flexibility technologies for generation adequacy”, “Flexibility technologies for network adequacy” and “Reasons given for the system integration choices made, both electricity and gas infrastructure based”. Such a scheme prevents overlap (i.e. two different codes for almost the same phenomenon). It also prevents the reader from coding inconsistently (i.e. actually using the same code but worded slightly differently) [Bhattacherjee, 2012].

As an example of this process, if an ‘actor-X’ were to mention: “our future goal is to construct 2 GW of electrolyser capacity by 2025 (...) as we want to make a profit by exporting our abundant offshore wind potential”. Electrolyser technology is coded as a theme. Additionally, the included targets and other information on the project are also noted. Subsequently, the theme (of the actor wanting to use their abundance of offshore wind) is also labelled. Again, including the specific information given.

The information collected answers sub-question 1 (*Focused on the interplay between electricity and gas infrastructure, what energy visions for system integration currently co-exist in the North Sea region?*), giving a main sketch of the currently existing energy visions within the geographical sub-system of a country and what themes currently play a key role for every actor within this country. This acquired information is explained in chapter 4 of this study.

Step 3: Analysing and formulating overarching themes using axial coding
To answer sub-question 2 (*To what extent, and based on what underlying reasoning, are these energy visions compatible or incompatible with each other?*), themes are characterised by analysing the coded information previously used for the first sub-question. This entails a shift in abstraction level from a geographical sub-system, where different dimensional actors are considered, to the whole NSR region. Defining themes on a different abstraction level is an important step in the pattern modelling process.

The (overarching) themes are defined by using the pattern modelling approach, which has specifically been explained in section 3.1.2. According to this approach, themes are defined iteratively, building on the other themes initially characterised.

Considering the different phases of grounded theory, this corresponds to the methodology of axial coding. In the case of axial coding, “the categories and subcategories are assembled into causal relationships or hypotheses that can tentatively explain the phenomenon of interest” [Bhattacherjee, 2012](*Page 114*).

Additionally, in parallel, previously coded themes that are concluded to be interrelated are combined into one overarching theme. Eventually, several different overarching themes are defined that are of interest for determining (in)compatibilities in the NSR. Specific for this research, nine overarching themes are defined and described in chapter 5.

Considering the previous example, it could be the case that both Actor-X and Actor-Y have high electrolyser capacity targets. Additionally, both actors mention their offshore wind potential as a reason for having this ambitious target. Additionally, Actor-Z does not have a high electrolyser target and also does not have considerable offshore wind potential.

These themes, together with the underlying reasoning given, then lead to the overarching theme that actors with a large offshore wind potential see a large role for electrolysers. This theme then shows an overarching incompatibility as actors differently perceive the potential for offshore wind and therefore consider different electrolyser targets. After this theme is recognised, the theme is noted. Any subsequent information given in energy visions is also labelled as such, strengthening the initial theme recognised.

This research uses concept mapping to keep track of the existing themes in a structured manner. Concept mapping is a “graphical representation of concepts and relationships between concepts (e.g. using boxes and arrows)” [Bhattacherjee, 2012](*Page 115*). Typically, concepts are then laid out on sheets of paper or using graphical software programs, linked to each other using arrows and readjusted to best fit the observed data [Bhattacherjee, 2012]. Figure A.2 in appendix A shows an overview of the structure eventually laid out. In this research, the different themes found were scoped and combined into nine overarching themes. These themes are described in chapter 5.

Step 4: Reflecting on the pattern model that emerged from the defined themes
Lastly, sub-question 3 (*How could these energy visions be made more compatible to improve international system integration in the North Sea region?*) is answered. This question is answered by combining earlier insights on futuring theory mentioned in chapter 2 with the analysed themes and interview discussions from chapter 4 and 5. In the section below, the methodology used for interviews is elaborated on.

3.4.2. Interviews

Interviews were used to add to, evaluate, reflect on and verify the pattern model and its overarching themes in the NSR previously drafted. This is why they were executed relatively late in the pattern modelling process. Interviews were important in the process to verify the most current developments of different actors. Additionally, they were important to gain an understanding of the actors' standpoints on uncertain topics that are not elaborated on (in-depth) in public documents.

The interviews were used to answer sub-question 2 (*To what extent, and based on what underlying reasoning, are these energy visions compatible or incompatible with each other?*) and subsequently sub-question 3 (*How could these energy visions be made more compatible to improve international system integration in the North Sea region?*). Two types of interviews were executed.

Firstly, focusing on government actors, questionnaires were distributed to Ministries of Energy of Belgium, the Netherlands, Germany, the UK, Norway and Denmark by CIEP. These interview results were also used for an external CIEP project with the Ministry of Economic Affairs and Climate Policy of the Netherlands, in which the researcher was actively involved. The results used in this research are referred to as [Questionnaire *Country code*] or [Questionnaire] for general insights. The specific questions can be found in appendix C3.

Secondly, aside from these questionnaires, all 22 actors whose energy visions were analysed were approached for an interview. A total of 19 actors were interviewed specifically for this study, reasonably distributed over the six different countries and different types of actors (TSOs, objective energy experts and industrial actors). A list of interviewees and their functions can be found in appendix C2 and are labelled in this research with the code [PX] (where X is a number from 1 to 19) or [Anonymous] (if interviewees preferred a (specific) contribution to remain anonymous). Most interviews had a duration of an hour, with an exception for some interviews taking 30 minutes and others 1.5 hours.

All interview references and quotes mentioned in this report were verified after the interview took place via email with the interviewed experts. The participants were informed in advance about the objective of the study and the privacy regulations, and a 'test interview' was done with supervisor Pier Stapersma from CIEP to test the time planning and questions.

A 'semi-structured in-depth' interview approach is used as a research instrument. This is an approach where the researcher uses a set of questions and is flexible when examining issues that arise when discussing these questions. An in-depth interview is used as these questions go further into the subject to reach a substantiated conclusion [Drever, 1995].

Questions based on research sub-question 2 and 3 were discussed with all interviewed TSOs, experts and industrial players. The interview questions can be found in appendix C1. Due to the varying expertise of different actors, specific elements were discussed in more or less detail.

4

Energy visions in the North Sea Region

This chapter provides an overview of currently relevant themes, focused on the role of gas infrastructure in offshore wind integration in the North Sea Region (NSR). This overview answers sub-question 1 of this research (Focused on the interplay between electricity and gas infrastructure, what energy visions for system integration currently co-exist in the North Sea Region?). This chapter identifies the important and characteristic themes and relationships in the geographic sub-systems (countries). The themes presented in this fourth chapter are further analysed, compared and discussed in chapter 5, taking a holistic perspective of the whole North Sea Region.

The first section of this chapter gives a general overview of the future envisioned challenges actor envision when integrating offshore wind. This section also includes the actors' visions on national offshore wind potential and their plans for decommissioning both coal-fuelled power plants and nuclear power plants. After this first section, the actors' energy visions in the sub-system of the six analysed countries are described. Following the pattern modelling methodology, these six sections describe different themes in each sub-system. When the empirical data was collected, many more themes were identified. However, the themes discussed in this chapter have the most significant relevance for this research topic.

4.1. A general overview of energy visions in the North Sea Region

In this section, an overview is given of the shared characteristics of the energy systems present in the NSR. First, the shared ambitions of actors to develop a net-zero energy system are defined. Subsequently, the next paragraphs describe both the potential seen by actors for offshore wind and plans for decommissioning traditional energy sources. This section is then concluded with an overview of the size of the system adequacy challenges actors are expected to encounter. It is important to get an insight into this conclusion, as it forms a basis for the role subsequently seen for gas infrastructure.

4.1.1. Shared ambitions for a net-zero energy system

Almost every actor mentions they aspire a net-zero energy system by 2050. A net-zero energy system is defined as a system that (balanced out) emits zero greenhouse gasses into the atmosphere. This aspiration is reflected in the specific targets for CO2 reduction and installed renewable energy capacity. These targets are set by both national governments, the EU and internationally through the Paris agreement [DE BMWi, 2020b][EZK,CIEP, 2020][NationalGrid ESO, 2020b].

All countries have the same GHG reduction targets for 2050. However, different countries do have varying targets for reducing their emissions by 2030. The Netherlands aspires to reduce its emissions by 49% in 2030 compared to emissions in 1990. Norway, Belgium and Germany have set higher ambitions towards 50-55% domestic emission reductions by that time [BE federal government, 2020][Gassnova NO, 2020][EZK,CIEP, 2020][DENA, 2019]. Furthermore, the UK and Denmark seem most ambitious, aiming for around 70% GHG reduction in 2030 [UK ministry: Department for Business and MP, 2020][DK Klimaaftalen, 2020].

In line with these increasing carbon emission targets, the European Union's stricter quota system (EU ETS) and the increasing CO2 price are also often mentioned as drivers for industrial actors to reduce emissions [NO ministry, 2020a].

In summary, with the uniform net-zero target for 2050 in mind, all actors in the NSR remain almost equally ambitious. Although, it does remain unclear if all actors will also achieve their 2030 and 2050 targets, because the targets set by the governments are also merely the start of actual efficient and realistic policy leading to physical solutions [Energinet, 2019a][OFGEM, 2020][P5].

4.1.2. Offshore potential in the North Sea Region

In the coming decade, an addition of more than 300 GW of renewable power (wind, solar, hydro, biopower, and geothermal) to the energy system in Western Europe is expected (an increase of more than 60%) [Oxford Energy Forum, 2020]. Although all countries in this study neighbour the North Sea, their national areas of the sea and perception of the possibilities for offshore wind differ extremely [Anonymous].

Table 4.1 highlights some important energy statistics. The top 4 rows of table 4.1 show the different targets and potential seen for offshore wind by the NSR countries. The fifth row presents the share of electricity from renewable sources in total electricity generation in 2017. By analysing this row, one can get an impression of how close or far away a country is from supplying their electricity generation fully with only RES. For instance, it is important to highlight the high percentage of RES of Norway and Denmark. The sixth row shows the current dependency on energy imports of every country. Especially the Belgian and German dependency on energy imports is of interest for this research. Furthermore, it is also important to note the enormous amount of energy exports from Norway. Lastly, the seventh row shows the final energy consumption. This information gives a certain insight as to how large national offshore energy targets are, when compared to their different amounts of final energy consumption. The last two rows of this table are discussed in the next subsection.

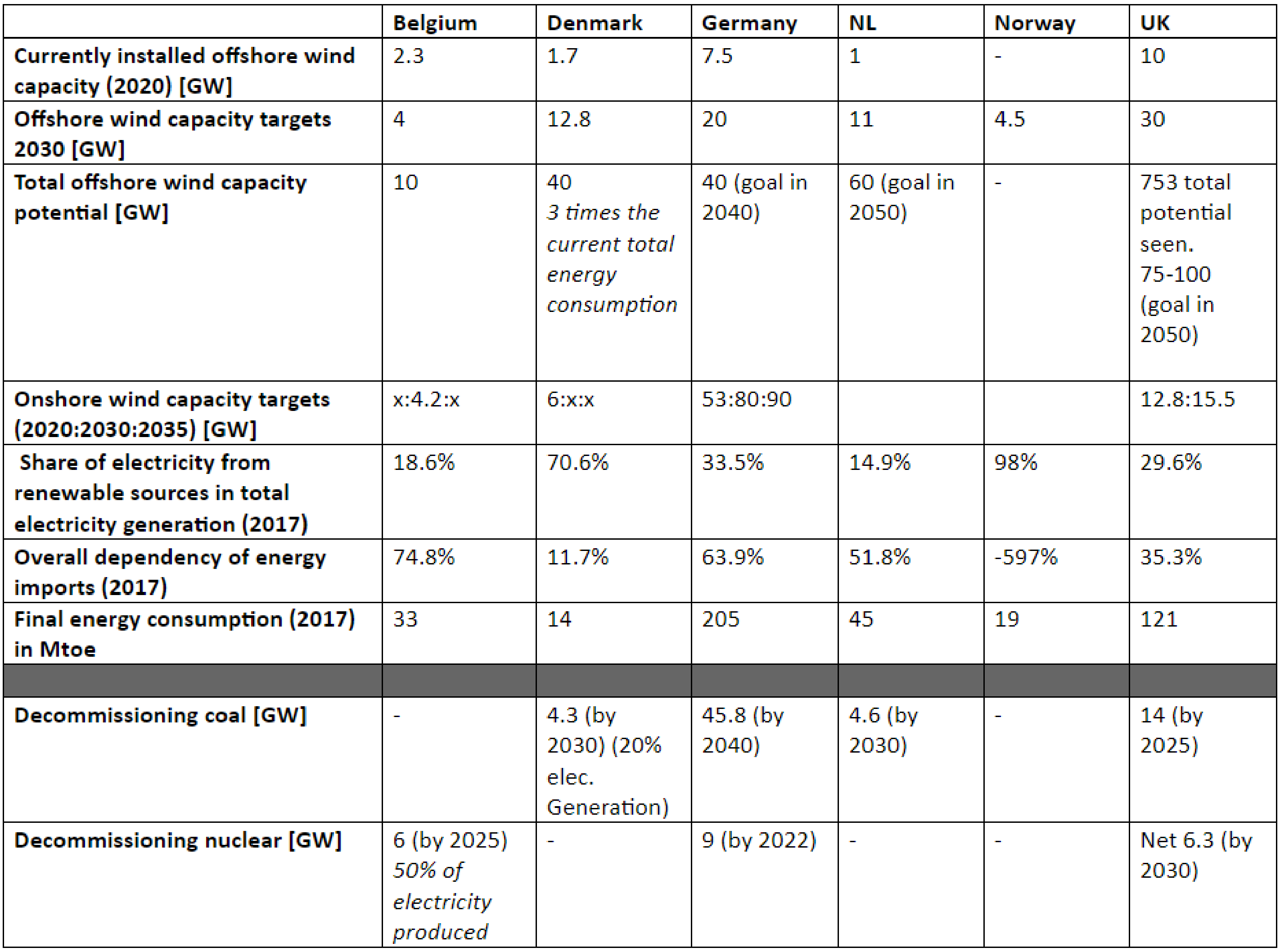
The data in this table illustrates that Belgium has the smallest offshore wind potential, and Denmark the highest when compared to its national energy consumption. Germany has a large offshore wind potential, although this is deemed to be lower relative to their on average high final energy consumption seen in row 7 of table 4.1. The same, to a smaller extent, is the case for the Netherlands. Norway sees potential in the far future for floating offshore wind due to the deepness of the Norwegian part of the North Sea. Lastly, the UK, especially the Scottish region, has a large offshore wind potential relative to its national energy consumption.

Different actors within the region expect the perceived increase in offshore wind to lead to a higher necessity seen for (electricity) grid reinforcements. This is further discussed in the next sections of this chapter.

4.1.3. Decommissioning of energy sources in the North Sea Region

Simultaneous with an increase in installed offshore wind capacity, conventional power capacity is expected to decline by 78 GW (a decrease of more than 19%). This development can be explained by the expected phase-out of fossil fuels. Specific in the NSR, this phase-out consists of the closure of gas, coal and nuclear-based power plants [Oxford Energy Forum, 2020]. This section focuses on both the decommissioning of coal and nuclear-based power plants. The planned decommissioning capacities are also illustrated in Table 4.1, in the eighth and ninth row below the grey bar. The decommissioning developments of gas-based power plants are described in more detail for each country in the next six sections of this chapter.

Several governments in the NSR have targets for decommissioning coal-based power plants. In the UK, all coal plants (approximately 14 GW) are assumed to close by 2025, in line with the government's commitment to phase-out unabated coal generation [NationalGrid ESO, 2020a]. The Netherlands expects a coal phase-out of 4.6 GW by 2030. Furthermore, Denmark expects a coal phase-out of 4.3 GW by 2030. The German government has the highest target for coal phase-out, aspiring to decommission 45.8 GW by 2040, with an intermediate goal of 17 GW by 2030 [DE BMWi, 2020b][Elia, 2019b]. In Germany, reductions in coal generation are recommended by the coal commission and are expected to be substituted by gas-based cogeneration facilities [50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][IEA,BMWi, 2020][FNB Gas, 2019]. Belgium and Norway have no (significant) coal consumption and therefore decommissioning goals.



	Belgium	**Denmark**	**Germany**	**NL**	**Norway**	**UK**
Currently installed offshore wind capacity (2020) [GW]	2.3	1.7	7.5	1	-	10
Offshore wind capacity targets 2030 [GW]	4	12.8	20	11	4.5	30
Total offshore wind capacity potential [GW]	10	40 *3 times the current total energy consumption*	40 (goal in 2040)	60 (goal in 2050)	-	753 total potential seen. 75-100 (goal in 2050)
Onshore wind capacity targets (2020:2030:2035) [GW]	x:4.2:x	6:x:x	53:80:90			12.8:15.5
Share of electricity from renewable sources in total electricity generation (2017)	18.6%	70.6%	33.5%	14.9%	98%	29.6%
Overall dependency of energy imports (2017)	74.8%	11.7%	63.9%	51.8%	-597%	35.3%
Final energy consumption (2017) in Mtoe	33	14	205	45	19	121
Decommissioning coal [GW]	-	4.3 (by 2030) (20% elec. Generation)	45.8 (by 2040)	4.6 (by 2030)	-	14 (by 2025)
Decommissioning nuclear [GW]	6 (by 2025) *50% of electricity produced*	-	9 (by 2022)	-	-	Net 6.3 (by 2030)

Figure 4.1: An overview of the current and envisioned offshore wind potential in comparison with the energy consumption of countries. Below the grey bar, the capacities for decommissioned energy sources are given. This table was created by the researcher based on information from [DE BMWi, 2020b][DE BMWi, 2020a] [Energinet, 2019d][NationalGrid ESO, 2019a][NationalGrid ESO, 2019b][Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019][NO ministry, 2020c][Statnett, 2019d][Energinet, 2019a][Elia, 2019b][Gasunie,TenneT, 2019a][Eurostat, 2019]. The 'overall energy import dependency' was calculated as a ratio. With a numerator (Net imports (Total imports – Total exports)) and a denominator (Gross available energy). Calculations are done for the total of all energies from the Eurostat dataset [Eurostat, 2019].

Several governments in the NSR also have targets for decommissioning nuclear power plants. Nuclear power plants have a steady and predictable generation, which currently plays an important role to maintain system stability. The currently installed German nuclear power plants (9 GW capacity) will be decommissioned by 2022 [DE BMWi, 2020b] [IEA,BMWi, 2020]. Furthermore, Norwegian actors perceive themselves to be dependent on the Nordic region. Therefore, they expect that the decommissioning of nuclear plants in Sweden and Finland will affect them and the rest of the Nordic region (which also includes Denmark) [Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019][Nordic Energy Research, 2020].

In Belgium, a nuclear phase-out is planned to be completed by the end of 2025, according to law. This phase-out is of great interest as nuclear generation currently represents 50% (40 TWh/6 GW [BE federal government, 2019b]) of electricity produced [Elia, 2019b]. However, the developments are still uncertain because this law has previously been postponed due to the foreseen security of supply issues [BE FOD Economie, 2019]. Therefore, a more gradual nuclear decommissioning might currently still be up for debate. Although postponing even further is becoming increasingly unlikely as, in the recent years, the necessary upgrades to the reactors have not been done, and their operating license would have to be renewed [Elia, 2019b].

In contrast, the UK does not plan to phase-out nuclear power plants. There are some expected closures (and installations) of nuclear plants in the future. Before 2023, 2.1 GW is planned to be decommissioned. Furthermore, by 2030, 3.2 GW is planned to be commissioned, with in parallel a decommissioning of 7.4 GW [NationalGrid ESO, 2020a]. Therefore, a net decommissioning of 6.3 GW is expected by 2030.

As these steady and predictable fossil fuel sources are replaced by more volatile renewable energy sources (RES), it increases demand in flexibility. Therefore, grid operators need to actively manage networks in times of increased volatility and flexibility, increased demand for electricity, and increasing numbers of (smaller and more decentralised) market participants. Additionally, this transition often also results in a change in the geographical location of energy generation. This change in location could then lead to difficulties in grid transmission.

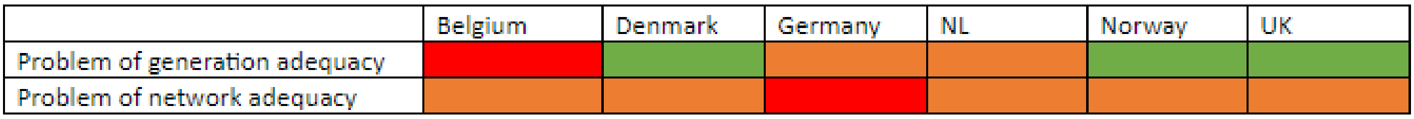
In conclusion of these paragraphs, new or strengthened electricity networks are necessary to accommodate the shift from old to new power sources [Oxford Energy Forum, 2020].

4.1.4. The future of energy and system adequacy in the North Sea Region

The main challenge of offshore wind integration in the NSR is to guarantee the security of supply and system adequacy in times of increasingly volatile energy production. System adequacy can be subdivided into three types: generation adequacy, network adequacy and market adequacy. Firstly, **generation adequacy** can be defined as “the presence of sufficient generating capacity (and imports) to meet demand on baseload and peak periods” [Zupančič et al., 2017](*page2*). These back-up generators or storage opportunities should be in place to maintain generation adequacy because of varying wind speeds and subsequent varying output of (offshore) wind turbines and demand of energy remaining the same. Secondly, **Network adequacy** is “the ability of sufficient network infrastructure to meet demand” [Zupančič et al., 2017](*page2*). To maintain **network adequacy**, flexible infrastructure needs to be in place to transport and balance a fluctuating energy supply. Thirdly, though out of scope in this project, market adequacy is “the ability of the market to facilitate the link between the producers and consumers of electricity” [Zupančič et al., 2017](*page2*) [Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019].

Existing research shows that almost all countries are having or are expecting problems with system adequacy [DNV GL Aurora Sáez Armentero, 2020]. The reasoning behind these conclusions is explained in more detail in the next six sections.

Focusing on network adequacy, actors in all NSR countries see this as a significant challenge. Furthermore, considering generation adequacy, Belgian actors are currently up for the most considerable challenge. German and Dutch actors expect to encounter slight challenges. The rest of the countries currently do not see such a large challenge for maintaining generation adequacy (see figure 4.2) [DNV GL Aurora Sáez Armentero, 2020]. This is further elaborated on in the next sections of this chapter.



	Belgium	Denmark	Germany	NL	Norway	UK
Problem of generation adequacy	🟥	🟩	🟧	🟧	🟩	🟩
Problem of network adequacy	🟧	🟧	🟥	🟧	🟧	🟧

Figure 4.2: An overview of the current challenges countries perceive for maintaining both generation and network adequacy. Red illustrates a large recognised problem, orange a slight (envisioned) problem and green no foreseen problems envisioned [DNV GL Aurora Sáez Armentero, 2020][IEA,BMWi, 2020][Gasunie,TenneT, 2020][DE BMWi, 2020b][Elia, 2017a][Elia, 2019b][Elia, 2019a][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][Nordic Energy Research, 2020].

In summary, the different actors in the different NSR countries all expect an increase in offshore wind in their part of the North Sea. Furthermore, they also envision an increase of other volatile RES and occasionally decommissioning some sort of conventional power capacity. These factors lead to all actors having a shared challenge of integrating offshore wind into the energy system. This challenge leads to the development that all actors within countries are looking for system integration solutions, all having a common denominator. Although, the necessity of integration of offshore wind does vary in time frame and size.

Focused on these differences, the Belgian energy system can be characterised by its plans for decommissioning a large capacity of nuclear power plants. The system also has a low energy self-sufficiency percentage. Denmark and the Netherlands are characterised by their relatively high (perceived) offshore wind potential. Germany is characterised by its large potential capacity for renewable energy sources and a large capacity of planned coal decommissioning. Norway is characterised by its low recognised potential for offshore wind. In this case, it seems that floating offshore wind potential is not yet identified on a large scale. Besides, Norway has an enormous self-sufficiency percentage due to its large hydro capacity. Last, the UK is characterised by its large offshore wind capacity currently and the countries' future wind potential. In the next subsections of this chapter, the themes present in the different energy visions of actors in the NSR are further elaborated upon.

Key term definitions specific for this research
System integration: Focuses on integration of renewable energy sources into the energy system using certain (gas/electricity) infrastructure. In this research offshore wind is mostly considered.
Sector coupling: Cross-sectoral network expansion, of electricity, heating and (green) gasses. For example, when offshore wind electricity is 'coupled' to the gas sector, as hydrogen is produced.
Interconnection: Physical interconnection of electricity and gas infrastructure cables to different countries. Where in the NSR, focus is mostly put on electricity grid interconnection.

In the following six sections of this chapter, the actors' energy visions in the sub-systems of the six analysed countries are described. A specific structure in the narratives can be recognised, which is identical for each section. The sections start with an introduction to the general role seen for natural gas and actors' current visions on integrating offshore wind into the energy system. Next, three different themes are characterised, specific for the visions on system integration of the actors in each country. Subsequently, the current and future roles perceived for gas infrastructure are defined in a subsection 'Role of gas infrastructure in energy visions'. A distinction is made between two roles; the role of gas infrastructure to fuel gaseous fuelled power plants and the role of gas infrastructure for Power-to-Gas developments (e.g. electrolysers). Lastly, an overview is given of the developments actors envision for hydrogen production, consumption and transportation in a subsection labelled 'Envisioned hydrogen applications'. This information was structured this way after initially following the pattern modelling methodology; analysing different energy visions in a holistic and inductive way.

4.2. Themes present in the energy visions of the actors in The Netherlands

In the Netherlands, natural gas currently covers 36% of Dutch energy demand [Frontier Economics, RWTH Aachen University, 2019]. Over the past few decades, the Netherlands has developed an extensive, connected and valuable onshore and offshore gas infrastructure. The use of this infrastructure is expected to decrease considerably because the Dutch government has made the political decision to phase out (low-calorific) gas production in Groningen. Quantitatively, natural gas extraction is set to decrease from about 22 billion cubic meters (bcm) in 2018 to 12 bcm in 2022 and zero bcm in 2030 [Questionnaire NL]. Due to the decrease in natural gas extraction, gas infrastructure is expected to be either decommissioned or reused in a more renewable energy system. This theme is discussed in more detail later in this section.

The aforementioned vast gas infrastructure is combined with extensive electricity infrastructure in the Netherlands. The TSOs Gasunie and TenneT are responsible for managing this gas and electricity infrastructure, respectively.

Infrastructure is also of importance considering the integration of offshore wind into the Dutch energy system. Dutch actors expect offshore wind energy to be a large part of the Dutch energy supply; currently recognising a potential for 70 GW offshore wind capacity [TNO, 2020]. Focused on offshore electricity infrastructure, the Dutch government has appointed TenneT to construct and operate electricity grids on the North Sea. TenneT's responsibility also includes the platforms needed to transport electrical energy from wind parks to high voltage stations on the mainland [Questionnaire NL]. At the moment, electricity grid reinforcements are still seen as the most reliable solution to integrate offshore wind electricity [TenneT, 2020b]. A guiding principle of TenneT is to develop such reinforcements for these areas at the lowest possible societal costs, with the least disruption to the environment [TenneT, 2020b].

The role of gas infrastructure when integrating offshore wind is not widely accepted. For example, a role for gas infrastructure is not mentioned in the national North Sea agreement, which was published in June 2020 (in which the government described the long-term developments of wind energy). However, the Dutch government has also commissioned a range of studies on the possibility to implement combined tenders for electrolysis and wind parks [NL EZK, 2020a]. Additionally, in collaboration with an international consortium (consisting of TenneT, Energinet, Gasunie and Port of Rotterdam) there are plans for the development of multiple large 'energy islands' in the North Sea [TenneT, 2020b][TKI Nieuw Gas, 2019]. An option for these energy islands would be to produce hydrogen offshore with offshore wind energy [TKI Nieuw Gas, 2019].

The following paragraphs focus further on this integration of offshore wind. There are several important themes according to Dutch energy actors. These themes are electrification and the combination of both grid reinforcements and interconnection. Another important theme is the Dutch public opinion on system integration.

Firstly, electrification is envisioned by some Dutch actors to be more reactive to the speed of RES growth than in other countries. The government sees opportunities for electrification but also mentions that it is evident that additional electricity demand and supply must develop in parallel to have a GHG reducing effect [NL EZK, 2020a].

This electrification leads to an increasing necessity for grid reinforcements. Here, TenneT prefers optimising networks above making additions to the grid [TenneT, 2019b]. Furthermore, they seem to perceive less urgency for grid reinforcements compared to other electricity TSOs in the NSR, possibly due to the current slower rise of RES. However, a larger sense of urgency is arising, exemplified as TenneT cannot always connect solar energy to the less dense electricity grid in the east of the country. This geographical challenge of the dislocation between energy demand and supply is becoming more apparent, especially considering the connection of offshore wind and energy demand in the mainland [TenneT, 2020b].

Almost analogue to grid reinforcements, the interconnection of electricity grids across Dutch borders is often mentioned in Dutch visions. Specifically, these visions focus on the interconnection of offshore wind with other neighbouring countries to increase the flexibility of the system [TenneT, 2020b].

Lastly, the theme of public acceptance is also widely present and mentioned in Dutch energy visions. Active lobbying groups have a relatively large influence on decisions for system integration technologies, sometimes also leading to fluctuations in policies. This role for lobbying groups could be seen as characteristic for the Netherlands. For instance, the national climate agreement is not actually a government document but an agreement concluded between hundreds of parties. Therefore, this is not necessarily reflective of the position of the Dutch government [Klimaatakkoord, 2020]. The fluctuations and dependence of public lobbying groups could sometimes lead to the creation of an unstable investment environment. Two particularly sensitive technologies in this respect are CCS and biomass.

Firstly, the public opinion on CCS is seen to demotivate and stifle government policy. Arguments against CCS include the fact that CCS locks in carbon-based technologies, that CCS is unsafe, and that CCS leads to health risks due to the emission of polluting gasses. However, the government is involved in CCS projects, such as Porthos (Rijnmond region) and Athos (Noordzeekanaal region), and is trying to create market incentives with a CO2 tax for large industrial players. Some actors even see the country as a hub for importing CO2 from Germany and Belgium and exporting it to Norway or the UK for storage [WPC, 2020][TNO, 2020][DNV GL, 2020][TNO, 2020].

Secondly, considering biomass, there has been a shift in the foreseen role of the energy source in the energy transition. Due to this shift, a different role is also foreseen for biomass in maintaining generation adequacy [Drift, 2020]. This shift is explained by the decreasing public acceptance in the sustainability of biomass, as it is unclear where the used biomass comes from exactly [NL EZK, 2020a]. For example, due to this uncertainty on the origin of biomass, the discussion arises if biomass transported by boat from Canada is necessarily a sustainable option.

4.2.1. Role of gas infrastructure in energy visions

The following paragraphs focus on the current developments of gas infrastructure in the Netherlands, and subsequently the role seen for gas infrastructure when considering both gas-to-power and power-to-gas technologies.

As mentioned in the introduction of this section, due to the reduced natural gas extraction in Groningen, parts of the Dutch gas infrastructure are expected to be out of use soon. Opportunities for reusing this existing gas infrastructure for transport and storage of green gasses were not considered thoroughly in critical policies and agreements until recently. Currently, because of the developments in Groningen, the opportunity for reuse of gas infrastructure is increasingly recognised.

This reuse of gas infrastructure also focuses on the reuse of offshore gas infrastructure, as Dutch actors also expect the extraction of natural gas offshore to decrease [Questionnaire NL]. For example, there is a pilot project in development (Project Neptune); placing an electrolyser on an old offshore gas production platform to test whether offshore hydrogen production is executable within current technological barriers [TNO, 2020].

The narratives around the reuse of gas infrastructure are very much future-based. For now and in the nearby future, gas infrastructure is still expected to remain important for natural gas distribution. This paragraph focuses on power generation with natural gas. According to the government, the role of natural gas in electricity generation is expected to decrease in the next thirty years. However, it could still be used in a CO2-free energy system in 2050 when combined with CCS [Klimaatakkoord, 2020]. Quantitatively, 15.6 GW of Dutch electricity is currently produced with gas-fuelled power plants, which is expected in the Dutch collaborative Climate Agreement to be 13.3 GW in 2030 [Klimaatakkoord, 2020]. In the long term, the use of clean hydrogen in gas plants is seen to offer the opportunity to sustainably realise flexible power capacity, as mentioned by the government in their hydrogen strategy. A good example is the Magnum project in the Eemshaven seaport, which is reviewing whether one of the gas turbines can be switched to hydrogen [NL EZK, 2020b][EZK,CIEP, 2020].

Both the Dutch government and TSOs envision ‘Power-to-Gas’ (PtG) to be an important aspect of the energy transition. This is exemplified in the collaborative study from TenneT and Gasunie, which mentions that “the overall transition route for Europe will be based on an interplay between the production of renewable electricity and the conversion of green electrons into green molecules, which are needed in bulk quantities outside the electricity system, e.g. for base chemical and plastics production” [Gasunie,TenneT, 2019a](*Page10*). To summarise, this statement mentions that if electricity grid capacity is present and demand can feasibly be electrified, electrification is key; otherwise, hydrogen and other green gasses could provide a solution. Dutch actors also recognise electrolysers to possibly contribute to resolving and preventing congestion problems in the electricity network. As these problems are resolved, more offshore wind could be integrated into the energy system. In conclusion, hydrogen is an energy carrier that a large number of actors have come to embrace as a promissory intermediary medium [TenneT, 2020b][NL EZK, 2020b].

Dutch actors present the country to have the potential to become a place for many demonstration projects [TKI Nieuw Gas, 2019] [TNO, 2020][P14]. In agreement with this vision, the Dutch government has recently launched a hydrogen strategy in which a systematic role of clean hydrogen is recognised [NL EZK, 2020b]. The Netherlands defines having a unique position for clean hydrogen with opportunities for companies and regions, an internationally oriented strategy and a current strong momentum with “adequate” funding and regulation [EZK,CIEP, 2020](*NL presentation slides*). This is expressed by a 70 million Euro subsidy in the DEI+, a new upscaling instrument, SDE++ subsidies for green and blue hydrogen production and a new temporary up-scaling instrument announced for hydrogen production [EZK,CIEP, 2020][NL EZK, 2020b]. Although these subsidies seem large amounts of money, these funds are not as large compared to other NSR countries (such as Germany) [DE BMWi, 2020b]. Some experts in the field even state that the highly ambitious Dutch visions on hydrogen are not in line with the number of funded hydrogen projects [P1][RLI, 2021].

Aside from the governments’ hydrogen strategy, Gasunie is also focused on hydrogen developments. In their strategy document, Gasunie plans to be “moving towards 2030 and 2050 with hydrogen” [WPC, 2020](*Gasunie Presentation slides*). Gasunie’s strategy is possibly related to the fact that a new strategy was deemed necessary after plans were published to decommission natural gas in Groningen

[WPC, 2020]. Shortly put, Gasunie transports gasses, if there are no gasses available to transport, they will otherwise be out of work.

The separate gas and electricity TSOs Gasunie and TenneT have published their *Infrastructure Outlook 2050*, which appoints a crucial role to hydrogen as a system fuel [Gasunie,TenneT, 2019b]. They are the only TSOs in the NSR to collaboratively publish an energy vision.

4.2.2. Envisioned hydrogen applications

The following paragraphs describe the roles Dutch actors see for hydrogen production, transportation and consumption in their energy system.

In the national hydrogen strategy, hydrogen production is envisioned to take place with the use of large electrolysers or production plants with CCS in the coastal regions. These large scale hydrogen production plants are also expected to be complemented by small-scale decentralised production sites [NL EZK, 2020b]. Blue hydrogen is considered a stepping stone for setting up a hydrogen market, because the roll-out and scale-up of electrolyser technology is uncertain and still in the development stage. The roll-out of blue hydrogen is considered to meet some of the Dutch industry needs and stimulate hydrogen infrastructure developments. Blue hydrogen is currently seen as more affordable than green hydrogen. Therefore, it is currently considered more feasible in the short term [NL EZK, 2020b][Questionnaire NL]. As also seen in other energy visions, CCS is not directly coupled to blue hydrogen (and sometimes, purposefully kept apart in an attempt to depoliticise the topic of blue hydrogen). The only link, for example, made in the Dutch hydrogen strategy is that the reference costs for grey and blue hydrogen largely depend on the price of natural gas and CO2 [NL EZK, 2020b].

Key term definitions specific for this research
Green hydrogen: hydrogen produced with an electrolyser supplied with electricity from renewable energy sources.
Blue hydrogen: hydrogen produced by the reforming of methane (natural gas) into hydrogen and CO2, storing or reusing the captured CO2.
Grey hydrogen: hydrogen produced from fossil fuels, be it by reforming natural gas or with an electrolyser supplied by electricity produced from fossil fuels.

The focus in political documents is put on green hydrogen, where the collaborative National Climate Agreement includes an ambition to scale up electrolysis to approximately 500 MW of installed capacity by 2025 and 3-4 GW of installed capacity by 2030. This electrolyser capacity target in 2030 is equal to approximately 28% of current national electricity consumption, of which currently about 15% is generated sustainably [Arends, 2020][van Santen, 2020]. The government is stimulating both capital expenditures (hereafter CAPEX) and operating expenditures (hereafter OPEX) with 35 million euros in subsidies and financial support annually [NL EZK, 2020a]. With its North Sea offshore wind potential, Dutch actors set the scope to produce much of its national energy needs (now more than 3,000PJ) sustainably, also seeing a role for green hydrogen.

However, the Dutch part of the North Sea is nowhere near large enough to generate the necessary 10,000 PJ of energy currently imported in the Netherlands to (partly) be exported as oil (products), natural gas and coal [NL EZK, 2020a]. Therefore, the government foresees reliance on a future international hydrogen market, where the Netherlands would be a net importer of hydrogen in the long term to satisfy the growing hydrogen demand [Questionnaire NL][NL EZK, 2020b][Gasunie,TenneT, 2020]. The developments in Groningen have initiated a shift in the mindset of Dutch actors from an exporter mindset towards an importer mindset [P4].

The Netherlands states its geographical location close to offshore wind potential, its industrial hubs, its ports and extensive gas infrastructure and (salt cavern) storage capacity as large benefits for not only hydrogen production but also for becoming a transit hub [NL EZK, 2020b][NL EZK, 2020a]. Although hydrogen demand is not expected to grow considerably until after 2030, the government currently sees an important role in developing hydrogen infrastructure. Considering the transport of the produced hydrogen elaborated upon in the previous paragraph, the Netherlands mentions aspirations to have a “European hydrogen backbone” [EZK,CIEP, 2020](*NL presentation slides*)[NL EZK, 2020a]. Previously, the Netherlands had the ambition to become the ‘natural gas roundabout’. This ambition has become outdated in light of recent decisions regarding Groningen natural gas production. However, the narrative of a roundabout has been revived around hydrogen; in the coming 30 years, the Netherlands wants to become the ‘energy-roundabout’ of North-Western Europe [DNV GL, 2020][DNV GL, 2020][NL EZK, 2020a][TNO, 2020]. An example of this transit function is the role seen for hydrogen transport towards industries in the south of Germany and other European countries [NL EZK, 2020a][P14].

Apart from transportation to and from the Netherlands, transportation of hydrogen within the Netherlands is still uncertain. The Dutch government states that the transportation method depends on the mode of transport that different companies deem useful [EZK,CIEP, 2020]. However, the TenneT and Gasunie are currently collaboratively researching what is necessary to realise a hydrogen network (HyWay-27 project) [Gasunie,TenneT, 2019a]. Currently, the existing hydrogen infrastructure is privately owned. Considering this collaborative research of TenneT and Gasunie, there is an ongoing discussion on whether future hydrogen infrastructure should be publicly or privately owned.

Aside from a transit hub, the Netherlands also focuses on becoming an industrial consumption hub, aspiring to become a leading example to demonstrate how industrial processes can be made more sustainable [NL EZK, 2020a]. In government strategies, green hydrogen is perceived as a key factor to decarbonise Dutch energy-intensive industries. To retain the existing industries, the Dutch government deems it crucial that companies can purchase zero-carbon energy carriers at internationally competitive prices in the country [NL EZK, 2020a]. Additionally, green hydrogen is also seen to possibly influence the decisions of (new European) companies on where to locate their industries [NL EZK, 2020b][NL EZK, 2020a].

Aside from hydrogen demand of industrial clusters and ports, hydrogen use is also envisioned for use in refuelling stations for heavy transport. Furthermore, hydrogen is considered to be used in lower quantities to heat buildings (in some cases) [Questionnaire NL].

In summary, in the Netherlands there are no large problems seen for generation adequacy currently, although there are challenges seen for network adequacy. The Netherlands is characterised by a drive towards hydrogen due to their offshore wind potential, (hydrogen) storage potential, presence of (petro) chemical and steel industries and the potential for re-using their gas infrastructure. Dutch actors in this research (TSOs, government and Port of Rotterdam) are the only ones to emphasise this reuse of gas infrastructure explicitly in the NSR. Furthermore, the actors seem to be balanced between being a production, transport and consumption hub and role model in the NSR, also looking outwards as they do not foresee becoming energy-independent.

4.3. Themes present in the energy visions of the actors in Belgium

Belgium does not have any active natural gas production. However, in Zeebrugge, the country has a major European natural gas transit hub to transport natural gas for their own use and for neighbouring countries [P1]. Furthermore, in the future natural gas is expected to become a larger part of the energy mix. Among others, as it is expected to replace nuclear generation, which currently supplies 50% of electricity consumption and is expected to be decommissioned in the following years [Elia, 2019b][Fluxys, 2019].

Belgium is expected to continue to rely on its extensive natural gas infrastructure, together with its electricity infrastructure in their energy system. Managing these infrastructures are their gas TSO (Fluxys) and electricity TSO (Elia). Managing renewable energy sources remains within the exclusive competence of the different regions in Belgium. The federal government is responsible for regulating the development of offshore wind farms because territorial waters are their responsibility [BE federal government, 2019a].

Focusing on offshore wind, Belgian actors perceive themselves to have a relatively small exclusive economic zone in the North Sea. Belgian actors estimate the total potential of offshore wind capacity to be 10 GW [Elia, 2019b]. This is relatively small compared to other NSR countries. The government expects to fulfil this potential soon, with a current ambition to achieve 4 GW of installed offshore wind capacity in 2028. Elia mentions this ambition as the main driver for increasing flexibility needs in the energy system [Elia, 2019b].

At present, offshore wind parks are connected using a modular offshore grid. With this approach, a platform combines power from different wind farms and transports this power to the mainland using electric cables [Elia, 2019a][BE federal government, 2019b]. The necessary grid reinforcements to bring electricity onshore are currently in the permitting phase, and actors do not currently see a role for gas infrastructure when integrating their offshore wind [BE federal government, 2019b].

In the previous paragraph, a general insight is presented on the current developments in Belgium. Specifically, three different themes are characteristic for Belgian actors. Belgian energy visions on system integration are firstly characterised by electricity interconnection, secondly by grid reinforcements and thirdly by the role perceived for CCS.

Elia sees a necessity for an increase of 40% of flexibility compared to 2020. Forms of flexibility presented in this study are the flexible use of production units, DSR, electricity storage and international interconnections [BE federal government, 2019b].

Belgium has achieved an electricity interconnection rate of 24% in 2020, with an expected increase to about 33% in 2021 [BE federal government, 2019b]. An electricity interconnection rate is defined as the electricity import capacity over the installed electricity generation capacity. Further improving interconnection with neighbouring electricity grids is one of the most essential measures envisaged in Belgium. Elia mentions international interconnection as a solution to integrate renewable energy on a European scale and have access to the most competitive prices on the international market [Elia, 2019a].

The Belgian actors perceive their country as an “energy roundabout” (as stated by [Elia, 2017a](*page3*) with a great geographical location nearby large countries with both renewable energy sources and consumer centres, for example, via Dutch RES imports [BE federal government, 2019a][VARIO, 2020][Fluxys, 2019][P3][P4]. Especially the integration of renewable energy on a European scale is an interesting theme considered by Belgian actors. This international scope is related to the limited possibilities Belgian actors see for domestic renewable energy generation. Specifically, only part of future domestic demand is expected to be met with Belgian (offshore) renewable energy capacity [Elia, 2017a][Elia, 2020][Elia, 2019b][Elia, 2019a][BE federal government, 2019b][BE FOD Economie, 2019][P2][P3]. Additionally, nuclear energy is also expected to be decommissioned in the next years. Several Belgian actors see this decommissioning of nuclear sources as a factor for an increase in interconnection [Elia, 2017a][Elia, 2020][Elia, 2019b][Elia, 2019a][BE federal government, 2019b][BE FOD Economie, 2019][P2].

However, Elia is also aware that interconnections do not give a 100% guarantee on its energy security of supply, and they deem a reserve capacity necessary [Elia, 2019a]. Belgium has a disadvantage because it is dependent on energy imports and its main suppliers (France, Germany, the Netherlands) seem to have a domestic energy shortage just when demand in Belgium rises [Elia, 2019b]. The other way around, at a European level, Belgian flexible gas-fired power plants are also expected to have a prominent place with strong interconnections improving the market position of the more efficient Belgian installations [Elia, 2017a].

The aforementioned interconnections, together with other factors, lead to an increased necessity for grid reinforcements. Elia mentions this importance by stating that if timely investments are not made, the internal backbone network and interconnections are expected to be confronted with major overloads and grid congestions [Elia, 2018][Elia, 2019a]. Grid reinforcements are therefore deemed necessary by Elia to counter congestion in the electricity grid, especially considering that the development times of RES are recognised to be faster than the lead times of grid infrastructure [Elia, 2018][Elia, 2019a][Elia, 2020]. Due to the challenge perceived, Elia does not deem the so-called ‘status quo’ an option for the coming decade if one aspires a timely and efficient energy transition with maximum welfare for society [Elia, 2018]. The use of gas infrastructure might therefore be a welcome addition to the necessary electricity grid reinforcements.

Thirdly, CCS is also an important theme in the energy visions of Fluxys, Elia and the Belgian government. These actors deem CCS necessary to carry on with both electricity production from fossil fuels and part of the industrial processes present in Belgium [BE federal government, 2019a][Fluxys, 2019]. This role leads to a use envisioned for the Belgian gas infrastructure; creating a CO2 backbone with transport and (temporary) storage, and becoming a circular carbon economy [BE federal government, 2019a]. Belgian actors also have an internationally oriented vision of storing CO2 outside of Belgium in empty gas or oil fields, as Belgium can not store large amounts of CO2 themselves.

4.3.1. Role of gas infrastructure in energy visions

The following paragraphs focus on the current developments of Belgian gas infrastructure, and subsequently the role seen for gas infrastructure when considering both gas-to-power and power-to-gas technologies.

A current development is that the Belgian government is planning to switch its gas grid from low to high calorific gas between 2017 and 2029. This switch is planned to deal with falling Dutch imports, which entail 43% of Belgian consumed natural gas [BE federal government, 2019b][BE FOD Economie, 2019]. Fluxys foresees investment projects for a total amount of EUR 549 million for the period 2018-2027. The Belgian government mentions three different expected consequences for these investments. A first consequence is the continuation of their position as a natural gas hub in Central-Western Europe. A second consequence second is that additional and/or relocation of demand can be met. Lastly, a third consequence mentioned is that new developments in the market can be anticipated using these investments (e.g. alternative transport fuels, power-to- gas) [BE federal government, 2019b].

Belgian natural gas infrastructure is renovated and not decommissioned as all Belgian actors expect natural gas to keep playing a role towards 2050 (despite decreasing operating hours). This characterisation is specific for Belgian actors, mentioning natural gas' contribution to sustainability in the short term as coal installations are replaced [Elia, 2017a]. Other reasoning for the necessity of natural gas is its role in providing flexibility and making up for any shortages due to decommissioning of nuclear power generation [Elia, 2017a][Elia, 2019b][BE federal government, 2019b] [Fluxys, 2019][Elia, 2017b]. Both Elia and Fluxys mention that for the coming decades, natural gas is well placed to "play an important role in building a carbon-neutral economy" [Fluxys, 2019](*page33*).

Belgian energy visions also consider the route Power-to-Gas (PtG) (or what other NSR actors mention as sector coupling). Unlike the case for other NSR actors, the Belgian actors' business case for hydrogen is not mainly built on congestion of offshore wind [EZK,CIEP, 2020].

Fluxys' strategy is to make maximum use of the existing (gas) infrastructure and the complementarity of the electricity and gas infrastructure. They also call for technology neutrality in general, where one only focuses on the affordability, sustainability and reliability when choosing a specific technology. In other words, Fluxys wants each form of energy supply to be used most efficiently. Another driver for PtG, given by Fluxys, is the significant difference between the current electricity peak capacity (14 GW) and peak of the gas system (57 GW). Considering this fact, Fluxys deems the necessity for PtX self-explanatory as they mention that a "fully electrified system is not deemed realistic" [Fluxys, 2019](*page12*).

In the analysed documents of Elia, the term sector coupling is not mentioned once. Therefore, the 'relationship' between PtX and Fluxys is considered stronger than the 'relationship' between Elia and PtX [Elia, 2019b]. The Belgian government also mentions PtX; considering PtX as an option to use green electricity that would otherwise be lost, as a solution to the need for electricity storage and to keep the energy system in balance [BE federal government, 2019b].

Considering PtG plans and funding, the Energypact by the federal government mentions the aim to promote pilot projects for PtX projects insofar as they are economically and ecologically justifiable [Belgium Interfederal Energiepact, 2018][BE federal government, 2019b]. Due to the recent absence of a Belgian government, a *specific* strategy on sector coupling and hydrogen is yet to be published. In more detail, a Flemish strategy was published in November 2020, and a federal Belgian hydrogen strategy is expected to be developed and published in 2021 [P1].

The Belgian government does define the risk that they "will miss opportunities and even hand over our trump cards" due to this delay [VARIO, 2020]. Although in the case of Belgium, a lack of strategy has not necessarily withheld actors from developing hydrogen projects (which are abundant in the region and already funded) [EZK,CIEP, 2020][P1]. Within the country, the Belgian policy is seen as a "patchwork quilt" where initiatives work side by side and sometimes against each other [VARIO, 2020](*page5*).

4.3.2. Envisioned hydrogen applications

The next three paragraphs discuss the envisioned roles of hydrogen production, transport and consumption.

As previously mentioned, a role is envisioned for PtX technologies by Belgian actors. However, the actors' energy visions do not necessarily mention a large role in hydrogen production. A reason given for this approach is the countries' lacks of sufficient renewable energy resources and subsequent need for renewable energy imports [P3][Frontier Economics, RWTH Aachen University, 2019]. Subsequently, a study on only 1 GW of electrolyser plants is announced for the coming years [P1][P3]. There is a focus on hydrogen imports, as the market price of hydrogen production (including transport costs) is expected to be cheaper outside of Belgium (although this remains uncertain). As an example, government actors are even considering green hydrogen production in South America [P1][P2][Frontier Economics, RWTH Aachen University, 2019].

In contrast to hydrogen production, Belgian actors do foresee a role for becoming a hydrogen transit hub in interconnection with their neighbouring countries. Focusing on this role, they expect to make use of their harbours, their current natural gas hub in Zeebrugge (transforming the existing natural gas pipelines to hydrogen), and to build upon the already existing hydrogen grid owned by Air Liquide [P2][P4][P1][BE federal government, 2019a][Fluxys, 2019]. Although the country does not have any salt caverns, and therefore options for hydrogen storage, the possibility of using the existing natural gas storage capacity in Loenhout is studied [P4][P1].

It is not yet certain how these gasses will be transported, be it as pure hydrogen, as biomethane (where carbon is added to hydrogen to form methane) or blended into the natural gas grid. All actors do mention the possibility of blending hydrogen into the gas grid [Elia, 2017a][BE federal government, 2019b][Fluxys, 2019][BE federal government, 2019a]. Explicitly, the federal governments' 'Energypact' mentions the ambition to develop the gas networks for transporting hydrogen or other renewable gasses (e.g. biogas, synthetic gas) if this is eventually deemed necessary [Belgium Interfederal Energiepact, 2018].

The large Belgian chemical and steel industry is a driver for hydrogen consumption in Belgium [P1]. Specifically, the Belgian energy-intensive industrial hub (nearby the port of Antwerp) is a key driver to become a hydrogen consumption hub [VARIO, 2020][P4]. This hub includes harbours and a petrochemical cluster, which is part of the Antwerp-Rotterdam-Rhine-Ruhr area cluster (ARRRA) which accounts for 40% of petrochemical production in Europe [NL EZK, 2020a][BE federal government, 2019a] [EZK,CIEP, 2020][P4].

Considering these visions on a hydrogen consumption hub, the Flemish government has expressed the ambition to become the *European leader in hydrogen technology* (mostly) focused on hydrogen applications. Belgian actors proudly present their track record of "unique" Flemish demonstration projects mainly focused on (heavy) transport and possibly (blue) hydrogen production due to its active harbour [VARIO, 2020][BE federal government, 2019a][FCHJU, 2020]. Flanders has a relatively large number of important technology players in the field of hydrogen and both consumers and producers of renewable electricity [BE federal government, 2019a]. The actors expect to build a European value chain in the field of hydrogen, securing a significant share of European projects and funds [VARIO, 2020][BE federal government, 2019a][FCHJU, 2020]. This expectation is interesting due to the small role Belgian actors see for hydrogen production from offshore wind energy.

The Belgian government considers hydrogen to have a strategic nature. This is reasoned because the future Belgian economic developments are said to (partly) depend on the emergence of a Belgian and European industrial supply [BE FOD Economie, 2019].

In summary, due to Belgian nuclear-decommissioning developments and RES integration, both generation and network adequacy challenges are perceived. These current challenges drive Belgian actors to currently available solutions. These solutions mostly include natural gas based flexible thermal generation and electricity grid reinforcements. Due to their low potential of off-shore wind and dependency of other countries for RES, Belgian actors have an international scope of the energy system, mostly following (gas infrastructure and hydrogen) developments of its neighbouring countries. Therefore, actors see a large role for interconnection. Belgian actors currently see themselves as a transit hub for electricity and natural gas and aspire to become one for hydrogen and/ or CO2 in the future.

4.4. Themes present in the energy visions of the actors in Denmark

As Denmark does not have a large gas supply, there is not much gas infrastructure in the country compared to other NSR countries [P9]. Responsible for this gas infrastructure is the Danish TSO Energinet, also responsible for electricity infrastructure [Energinet, 2019a].

One of the Danish electricity infrastructure's roles is to integrate offshore wind in the energy system. Due to the large potential seen for offshore wind, gas infrastructure is seen as a welcome addition to integrate offshore wind. Energinet assessed that the envisioned massive build-out of offshore wind might require up to 5-8 GW of electrolysis in Denmark around 2035. In contrast, without electrolysers, only a relatively small amount of the additional 10 GW of offshore wind is expected to be brought ashore and used effectively in Denmark [Energinet, 2020][P9].

Such electrolysers are envisioned to be located offshore. Energinet envisions a hub solution to support a large scale offshore wind build-out; distributing energy via electricity and hydrogen connections to the NSR [Energinet, 2019b]. This is exemplified in the innovative plans of Danish actors to build the world's first two energy islands/platforms. Both islands or hubs distribute the energy via electricity and/or hydrogen or green fuel connections to the North Sea region. The first island is planned to have an expected capacity of 2 GW, with room for at least 10 GW offshore wind expansion. The second island is planned to have an expected capacity of 2 GW. [Energinet, 2019b][DK Finansministeriet, 2020][EZK,CIEP, 2020][P9]. This expansion of in total 4 GW is deemed massive as it corresponds to more than all of Danish households' annual electricity consumption [DK Finansministeriet, 2020].

Considering the energy visions for system integration, the roles seen for biomass, grid reinforcements and interconnection are characteristic for Danish actors.

Biomass has played and currently plays an essential role in the Danish energy system. Danish actors deem biomass use advantageous because it decreases their energy dependence from other countries [Energinet, 2019d][Energinet, 2019e]. In 2019, (imported) biogas accounted for 12% of Danish gas consumption from the gas grid, while a further 7% was directly used for Combined Heat Power (CHP) [Energinet, 2019a]. Therefore, Energinet's planning of the gas transmission system also focuses on biogas production and developments [Energinet, 2019e]. The Danish biogas industry even sees a technical potential for fully covering the Danish gas consumption in 2035 [Energinet, 2019e]. Although considering cost efficiency and discussions on the renewable character of biomass, the government has paused the current subsidy scheme. This pause could decrease investors' interest in biogas [Energinet, 2019e]. Therefore, a gradually reduced consumption of biomass is expected by the Danish council. Among other things, this is seen as a result of increased electrification of society, along with increased deployment of wind turbines, solar cells and heat pumps [Danish Council on Climate Change, 2020].

Energinet mentions an urgent necessity for electricity grid reinforcements. Recent developments demonstrate this urgency; Energinet currently deems demanded connection to the grid too unrealistic to execute on a short-term basis. Energinet states that this urgency is driven by both an increase in the electrification of energy consumption and an increase in placement of new unsubsidised RES plants. Specifically, unsubsidised RES plants increase the challenge of coordinating grid reinforcements, because they are unexpectedly placed [Energinet, 2019b]. Energinet presents a dilemma when planning for electricity grids; either being aggressive with grid reinforcements with a chance for over-investments or being conservative with grid reinforcements and risking bottlenecks in the grid [Energinet, 2019c][Energinet, 2019d].

The theme of an increase in grid reinforcements, mentioned above, can be coupled to the theme of grid interconnections. Historically, efficient system integration with neighbouring countries has been key to integrating Danish wind power generation [Energinet, 2019f]. This international scope can be explained by understanding what currently happens in times of abundance of wind in Denmark. During such times of abundance, Danish offshore wind energy is currently exported using the interconnected energy system. Due to the expected further increase in offshore wind, the export of green energy to neighbouring countries is expected to be an increasingly important theme in the future [DK Finansministeriet, 2020]. Energinet is working to strengthen the Danish position as an energy hub between Nordic countries and Europe. Energinet calls this connection between Denmark and Europe the “silk road for green power” or the export of green power via the “electricity highways” [Energinet, 2019d](*Page30*). Energinet does not only perceive interconnections as an economic opportunity but also as one of the ways to maintain the security of supply in times of low wind speeds [Energinet, 2019d]. For example, (Norwegian) pumped hydro is seen as an important energy import to guarantee generation adequacy [Statnett & Fingrid & Energinet & SvenskaKraftnat, 2020].

4.4.1. Role of gas infrastructure in energy visions

In the following paragraphs, the current and future roles Danish actors see for sector coupling are explained. Subsequently, the specific developments and plans for sector coupling are elaborated on further.

Energinet is one of the only actors in the NSR that mentions their experience with sector coupling throughout history. They define three different phases of sector coupling.

Firstly, in the previous years, Energinet has focused on district heating and decentral Combined Heat Power (CHP) plants. In CHP’s, surplus heat from electricity production is utilised, and gas generators produce electricity and heating alternately.

The second phase of sector coupling is currently perceived to be implemented. This phase entails both the direct electrification of the energy system and an increase in biogas production from (mostly) residual products in the agricultural sector.

The third phase of sector coupling is Power-to-X (PtX) (presented as a form of indirect electrification), which is said to currently only be implemented on a small scale [Energinet, 2019a]. Danish actors present several drivers for PtX; their good offshore and onshore wind potential, good bio-resources for e-fuel production, a well-established gas system, salt caverns for storing gasses and an efficient district heating system where surplus heat can be utilised in district heating systems [Energinet, 2019a][Energinet, 2020].

PtX ambitions are abundant among Danish actors, with actors stating that in the past, they have paved the way for wind power and will now also do so with PtX [DK Klimaaftalen, 2020][Energinet, 2019d][Energinet, 2019a]. Actors also mention that the first stage of PtX is making a serious move in the countries around them. Some actors feel they are a bit late when it comes to publishing a strategy on such topics, as they mention that a Danish CCUS and PtX strategy is planned to be launched in 2021 [Energinet, 2019a][P9].

However, the fact that there is no specific government strategy on PtX certainly does not mean there are no developments on this front. For example, an energy expert reasoned that civil servants are currently too busy with their specific Danish PtX plans, and therefore have not yet published a general PtX strategy [anonymous]. These specific Danish PtX plans are included in the Danish Climate Agreement for Energy and Industry from 2020. In this agreement, large Danish funds for PtX are presented, which include a 1.1 billion Euro investment in large-scale hydrogen production, a tender of a minimum of 100 million Euro to support the establishment of large-scale Power-to-X plants and plans for two energy islands [DK Finansministeriet, 2020]. Additionally, a new consortium of some of the largest Danish companies (Ørsted, Maersk, SAS, DFDS and DSV Panalpina) has presented plans to build possibly the world’s largest hydrogen plant. This plant will be built in 3 phases, from 10 MW in phase one to 1.3 GW in phase 3 [FuelCellsWorks, 2020].

4.4.2. Envisioned hydrogen applications

The following paragraphs discuss the envisioned roles of hydrogen production, transport and consumption, respectively.

Considering hydrogen production, the Danish government wants to ensure their favourable position as a green hydrogen production hub. For example, currently Danish actors mention plans to export green hydrogen to Germany [Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019][P9][EZK,CIEP, 2020][Ørsted, 2020][Energinet, 2019a][Energinet, 2019f][P7]. Additionally, Danish actors also aspire to have a greater international effect on decarbonising the energy system. They aspire to do so by sharing their attained knowledge and experience from integrating renewable energy into the electricity system with other less knowledgeable actors [DK Klimaaftalen, 2020][Energinet, 2019d][Energinet, 2019a][Danish Council on Climate Change, 2020][Danish Council on Climate Change, 2020][Energinet, 2019a][P9].

Lastly, focused on hydrogen production, blue hydrogen production is not mentioned in any Danish energy strategies and visions, which is specific for Danish actors in the NSR.

Considering hydrogen transport, actors are still uncertain on how a hydrogen grid should be designed. Decisions on hydrogen transport are said to be determined in the context of three developments; firstly, considering domestic demand for hydrogen and methane, secondly, the ongoing developments in the EU and thirdly, the ongoing development in neighbouring countries which are supplied with methane from Denmark (often coming from Norway) [Energinet, 2020]. In the far future, actors envision a hydrogen backbone connecting offshore wind hubs to large industrial centres in the Netherlands and Germany [P7]. The hydrogen infrastructure necessary for a hydrogen backbone is expected to be newly developed, mostly because of the small potential perceived for reuse of Danish gas infrastructure [Frontier Economics, RWTH Aachen University, 2019][P9].

Danish actors expect hydrogen production to be far larger than domestic demand, particularly in the next 10 years considering the currently low Danish hydrogen demand [EZK,CIEP, 2020][Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019][P9]. Hydrogen is envisioned to mostly be used domestically in the Danish industry and heating sectors.

Furthermore, focused on both domestic consumption and export of hydrogen, Danish actors focus on certain high-value products. Such high-value products include e-fuels, methanol and ammonia. In particular, the fuels are expected to be applied in the transport sector for heavy transport and air transport as well for certain industrial processes [Questionnaire DK]. With the use of carbon from biomass and CO2 point sources, such high-value fuels are expected to be most profitable towards 2035 [FuelCellsWorks, 2020]. The removal of CO2 directly from the air using direct air capture is also recognised as potentially competitive compared to the production of green fuels [Energinet, 2020][Energinet, 2020][Danish Council on Climate Change, 2020]. On the other hand, Energinet does mention the uncertainty of the price of carbon that would be necessary to produce high-value fuels. In the case of a high carbon value, direct use of hydrogen may be more competitive compared to carbon fuels [Energinet, 2020] [Energinet, 2019a].

The storage function of hydrogen is also often mentioned by Energinet. Energinet states that storing energy as fuels such as hydrogen, methane gas or liquid fuel is more than “100 times cheaper than storing energy as electricity in a battery” [Energinet, 2020](*Page15*). The storage function is therefore seen to maximise the export value of Danish offshore wind because it allows offshore wind energy to be allocated and utilised with price flexibility [Energinet, 2019a][Questionnaire DK][Ørsted, 2020][Energinet, 2019f].

In summary, the Danish actors foresee no challenge for maintaining their own system adequacy, partly due to their large offshore wind capacity and also because the Danish energy system is electrically interconnected to the Norwegian pumped power capacity. Denmark can be characterised by its urge to become a role model into the energy transition, where it wants to export its relatively large offshore potential. Furthermore, their combined gas and electricity TSO puts a large focus on sector coupling of both electricity and gas infrastructure. Specifically, electrolysers are seen as a necessity to expand their offshore wind potential, with a potential focus on offshore energy islands.

4.5. Themes present in the energy visions of the actors in Germany

Natural gas plays an important role in Germany in both power supply (13% of the German power supply), industry (35%) and residential heating (46%) [DE BMWi, 2020a]. Approximately 93% of German natural gas consumption is currently imported. This dependence on imports is expected to increase further, because domestic natural gas production is likely to decrease due to depletion of fields [IEA,BMWi, 2020].

Due to this large role for natural gas, the gas transmission network can deliver more than four times as much power compared to the electricity transmission network [FNB Gas, 2018]. Responsible for both infrastructures are 4 electricity TSOs supervised by the Bundesnetzagentur, and 15 gas TSOs (with 700 regional distribution network operators for gas) who are united in FNB Gas association [DE BMWi, 2020a]. This research considers the energy visions of the gas TSO association (FNB Gas), electricity TSO in its collaborative Netzentwicklungsplan Strom, Gasunie and of TenneT. TenneT and Gasunie are responsible TSOs in both the Netherlands and part of Germany [Gasunie,TenneT, 2020].

Together with the government, these electricity TSOs mention the current plans to connect offshore wind with a direct electrical connection to minimise electricity losses [TenneT, 2020a][DE BMWi, 2020a]. In Germany, offshore wind energy is one of the main pillars in energy transition and climate plans. However, offshore wind capacity is rolling out slowly compared to onshore wind capacity. Currently 7.5 GW offshore wind capacity is installed, and about 53 GW onshore wind capacity is installed. On average, onshore wind supplies a total of 21% of annual electricity demand. The German government has set ambitious goals for an increase in offshore wind capacity in their ‘offshore agreement’. This entails 20 GW by 2030 and 40 GW by 2040 installed offshore wind capacity [Energinet, 2019d][TenneT, 2020a][DE BMWi, 2020a].

The necessary offshore grids are planned centrally by the government since 2013. Expanding their geographical scope, recently, the Danish and German TSO have collaborated on a ‘combined grid solution’. With such an approach, the power available on the interconnector can be traded between the two countries[DE BMWi, 2020a]. In contrast, German actors mention no specific role for offshore gas infrastructure for offshore wind integration when analysing the visions of the different German actors [DE BMWi, 2020a][IEA,BMWi, 2020].

In German actors’ energy visions, three main reoccurring themes are characterised. The first theme is the challenge German TSOs face to transport electricity from the northern to the southern part of the country. The second theme entails the envisioned electricity grid reinforcements, and the third theme describes the role German actors envision for CCS.

In 2020, 36% of the German electricity supply was renewable [Eurostat, 2019]. However, throughout the year, this percentage fluctuates because there are moments of renewable electricity production surpluses where RES are curtailed, and other moments of renewable electricity shortages where flexible conventional power stations ensure reliability [DE BMWi, 2020a][DE BMWi, 2020a]. Most of these RES are located in the north of the country, and most power demand (in industrial clusters) is located in the south and west. This difference in locations results in a connection challenge to bridge the RES production and consumption hubs [TenneT, 2020a][TenneT, 2019a][DE BMWi, 2020a][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019]. Such an imbalance has resulted in the curtailment of RES in the north to avoid network congestion and “re-dispatch” measures in the south, costing consumers hundreds of millions of euros annually [IEA,BMWi, 2020]. In addition, German actors expect this imbalance to worsen as the last of the country’s commercial nuclear power plants in the south and northwest are expected to close, and more offshore wind is expected to be installed in the north [IEA,BMWi, 2020]. To partly solve such generation adequacy challenges, German actors have just completed a project with Norway. This project makes it possible to store a part of German wind energy in Norwegian reservoirs in times of abundance of electricity. Additionally, the Norwegian reservoirs are also able to supply the German energy system with electricity in times of shortage of electricity [DE BMWi, 2020a].

This increase in RES and electrification leads to a necessity for electricity grid reinforcements. In 2018 a wake-up call can be observed as the German government realised that the expansion of (national) transmission networks was far behind the expansion of renewable energies. This wake-up call has lead to the Grid Expansion Acceleration Act, entering into force in 2019 [DE BMWi, 2020a][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019]. German actors now perceive heavyweight grid reinforcements to be a trend within Germany; with a need for modernising and expanding the electricity network by approximately 2030 recognised by both TSO and government [DE BMWi, 2020a][Gasunie,TenneT, 2020][TenneT, 2020a][P13][Gasunie,TenneT, 2020].

A third theme that is characteristic of German actors is the role envisioned for CCS technologies. Currently, CCS is not widely accepted. This lack of acceptance can be explained by the lack of political acceptance. Additionally, it can also be explained by the opinion of some German actors that renewables are a better option to decarbonise the energy system, opposed to creating a lock-in with CCS technologies [DE BMWi, 2020a]. Although German actors are not explicit proponents of CCS, they do monitor the developments abroad. By some actors, CCS is considered a solution for unavoidable emissions [DE BMWi, 2020a]. Compared to other NSR countries, the role of CCS is most uncertain in Germany.

4.5.1. Role of gas infrastructure in energy visions

The following paragraphs focus on the current developments of the gas infrastructure in Germany. First, a focus is put on the role envisioned for gas-to-power technologies. Next, a focus is put on power-to-gas technologies. Lastly, the specific developments and plans for hydrogen are elaborated on further.

Gas currently accounts for about 13% of the German power supply [DE BMWi, 2020a]. Germany's gas-fired power stations play an important role in the electricity supply in terms of delivering system stability. This is particularly the case in periods of low feed-in of energy from renewable energy sources, or in the case of grid congestions which particularly occur in the south of Germany [DE BMWi, 2020a].

German government and gas TSO both conclude that natural gas will not be phased out any time soon because of its flexible character. Further electrification of the energy system is expected to result in higher peak loads. According to German TSOs, this justifies the construction of new gas plants (which would deliver a total of 95 GW in 2050) [Gasunie,TenneT, 2020]. This long term vision for natural gas use is also illustrated by the planned investment of 2 billion Euros for the conversion and expansion of the gas infrastructure. German actors deem this investment necessary because of the conversion of part of the gas infrastructure to high-calorific natural gas. This conversion is necessary as the German energy system is currently partly dependent on gas imports from the Netherlands [DE BMWi, 2020a][IEA,BMWi, 2020][P5][FNB Gas, 2019].

However, considering this long term vision for the use of natural gas, there is still uncertainty of the size of the role of natural gas. This uncertainty is deemed dependent on the CO2 price and volatility of electricity price. Eventually, natural gas is expected to be replaced by CO2-neutral gases (hydrogen and methane) according to both TSOs and the German federal government [50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][Gasunie,TenneT, 2020]. Building upon these insights, the government mentions that hydrogen production could form a higher level of security of supply because fewer energy imports would be necessary [DE BMWi, 2020a].

Considering PtG, to understand future designs of the integrated energy system for Germany and the Netherlands, the (German and Dutch) TSOs TenneT and Gasunie have conducted a study termed the 'Infrastructure Outlook 2050' [Gasunie,TenneT, 2020]. In summary, this study had two important conclusions. Firstly, the study concluded that an energy system based on domestic RES would have to rely on coupled electricity and gas grids. Secondly, the study concluded that adequately located PtG units and gas storages have the potential to reduce the need for additional electricity lines [Gasunie,TenneT, 2020][TenneT, 2020b]. Due to the (current) geographical supply and demand mismatch, German actors perceive gas infrastructure as a welcome option for their energy system [FNB Gas, 2019].

Focusing on hydrogen, Germany recently launched its hydrogen strategy. The hydrogen developments mentioned in this strategy are planned in different phases. By 2023, the goal is to start a market ramp-up of hydrogen production, transport and consumption. Subsequently, by 2030 the German government specifies the goal of having strengthened this market ramp-up (inter)nationally. In their strategy, ambitious goals for electrolyser capacity are also published. In short, the German government intends to build 5 GW electrolyser capacity by 2030 and 10 GW by 2040. This is a substantive target when compared to the currently installed German electricity generation of 211 GW [VARIO, 2020][APPG, 2020][DE BMWi, 2020b].

Additionally, the strategy is also paired with a high amount of funding available to execute the German strategy. To be precise, the hydrogen strategy specifies that 7 billion euros are planned to be invested for the market roll-out of hydrogen and 25 million euros annually for R&D of hydrogen technology [VARIO, 2020][APPG, 2020][DE BMWi, 2020b]. Due to the size of these funds, relative to other NSR countries, this strategy could be labelled as very ambitious.

Aside from these large investments, in their recently launched hydrogen strategy, the German government does not mention integrating volatile RES as an important driver for hydrogen. The only (slightly relevant) information mentioned in the strategy is that supply and demand imbalances are recommended to be considered together [DE BMWi, 2020b].

4.5.2. Envisioned hydrogen applications

In the following paragraphs, the roles German actors envision for hydrogen production, import and export, transport and consumption are discussed.

The German government's strategy envisions green hydrogen to be produced when there is an excess of renewable electricity compared to electricity demand. Electrolysers are not envisioned to run on non-renewable electricity. As renewable electricity production is set to increase, this leads to the insight that electrolysers will become more advantageous towards 2050 [Gasunie,TenneT, 2020]. Furthermore, German actors do not specifically perceive offshore wind energy as a driver for hydrogen production, but also mention onshore wind and other renewables such as solar energy [DE BMWi, 2020b][VARIO, 2020][P5].

Several ongoing projects are producing green hydrogen. Considering these projects, electricity and gas TSOs are collaborating on large-scale PtG/PtX technologies [Energinet, 2019f].

Furthermore, the government states in their hydrogen strategy that it will not close the door for blue hydrogen if the technology is deemed necessary. German actors currently perceive blue hydrogen to be relevant temporarily in the coming ten years to stimulate an emerging global and European hydrogen market. German actors are driven to blue hydrogen consumption because they want to make use of their already existing gas infrastructure and because they need to decarbonise their current grey hydrogen demand [DE BMWi, 2020b][DNV GL, 2020][NL EZK, 2020a].

Although in contrast to these promising visions on blue hydrogen production, the term CCS is only mentioned once in the whole national hydrogen strategy [DE BMWi, 2020b]. This lack of mentioning of the term CCS is of interest because CCS technologies are used when producing blue hydrogen. A reason for not linking blue hydrogen to CCS technology could be the lack of public and political acceptance for CCS technologies, as previously mentioned.

Aside from its own production, the German government deems it "unlikely that the large quantities of hydrogen that will be needed for the [German] energy transition can be produced in Germany alone" [DE BMWi, 2020b](*Page3*). Therefore, the German hydrogen vision emphasises fostering and intensifying international cooperation and partnerships on hydrogen. In total, 2 billion euros are allocated for import partnerships, also outside of the NSR and Europe [DE BMWi, 2020b]. This role seen for imports is presented as a significant industrial and geopolitical factor. The Federal Government believes that both a global and European hydrogen market will emerge in the coming ten years. Furthermore, they also believe that carbon-free hydrogen will be traded on this market [EZK,CIEP, 2020][DE BMWi, 2020b].

Considering hydrogen transport, in May 2020, the gas TSOs estimated what the first steps of a hydrogen transport network could be in 2030. This envisioned hydrogen transport network, H2-Startnetz 2030, is mostly (for over 90%) based on converted former natural gas pipelines [KAPSARC, 2020][FNB Gas, 2020]. The envisioned hydrogen grid makes use of the parallel pipelines now all used for natural gas [P5]. The grid is primarily intended to start with hydrogen generation in north Germany and combine this with key areas of demand in the south [FNB Gas, 2020].

Focusing on hydrogen consumption; gaseous and liquid energy carriers are seen as an important feedstock for current and future decarbonised industries [EZK,CIEP, 2020][FNB Gas, 2019]. The existing grey hydrogen feedstock for industrial use is an important driver for German actors' envisioned hydrogen developments. Hydrogen is already an important base material in the industrial sector, with an annual consumption of grey hydrogen of around 55 TWh [DE BMWi, 2020b][EZK,CIEP, 2020][CCC, 2020][P5]. Hence in the German hydrogen strategy, hydrogen is set to play an important long-term role in safeguarding the industrial sectors' attractiveness [DE BMWi, 2020b].

Aside from industrial use, hydrogen is expected to be used to decarbonise sectors that cannot be electrified to meet climate targets, such as part of the transport sector [NL EZK, 2020b][Questionnaire

DE][EZK,CIEP, 2020][FNB Gas, 2019]. A study on hydrogen demand in the industrial and traffic sectors showed that compared to 2030, the demand for hydrogen was expected to double by 2050, concentrated in the Ruhr and Rhine region [FNB Gas, 2019].

Possibly later in the future, a role is considered for hydrogen in the heating of the built environment. Coupling the heat sector to the electricity sector, as the role of renewable electricity for heating increases.

Additionally, the German government also envisions by-hydrogen products such as ammonia, methane and other synthetic fuels to become a large part of the decarbonised gases market. One of the reasons for this vision is the expectation that many applications cannot use hydrogen in its initial form [EZK,CIEP, 2020][DE BMWi, 2020b][Gasunie,TenneT, 2020].

In summary, both generation and network adequacy challenges are currently present in the German energy system, and perceived to become more extensive in the future. The country is characterised by a large geographical difference in energy production based on offshore and onshore wind (up in the north) and large industrial clusters (down in the south). This large demand of energy seems to be a driver for Germany envisioning to become both a hydrogen importer and a hydrogen producer. Furthermore, there is still an ongoing internal discussion on the role of gas infrastructure for hydrogen transport. Lastly, considering the political discussion on CCS, there is also still uncertainty about the future role of blue hydrogen production.

4.6. Themes present in the energy visions of the actors in Norway

The energy system of Norway is characterized by its large natural gas supply [NO ministry, 2020b]. Currently, Norway delivers about 25% of the total natural gas consumed in continental Europe and the UK. Additionally, two-thirds of the Norwegian gas resources have not yet been extracted [Gassco, 2019a][NO ministry, 2020a]. The gas TSO, Gassco, therefore also has the strategy to maintain a high level of gas exports after 2030 (in a decarbonising society), investing in expanding and maintaining their current gas infrastructure [Gassco, 2019a] [Statnett & Fingrid & Energinet & SvenskaKraftnat, 2020][P17].

In parallel with this high supply of natural gas, Norway has a highly electrified energy system with an extensive electricity grid. The Norwegian electricity TSO Statnett and government advisory board also mention this, stating that they are proud to be one of the “most electrified societies” [Statnett, 2019c](*Page 4*). The actors are expecting to increase further electrification in new data centres, industry processes, and the transport sector [Statnett, 2019c][Statnett, 2019b][Nordic Energy Research, 2020][NO ministry, 2020c].

Norwegian actors take a more reactive stance when it comes to their offshore wind potential. This reactive stance is explained by the fact that most of the Norwegian North Sea is so deep that floating offshore wind is the only applicable large-scale option in Norwegian seas. Compared to ‘normal’ offshore wind installations, floating offshore wind is still in its development phase.

Currently, Norwegian businesses and industry are setting growth targets for floating wind farms. These actors expect floating wind farms to have a large potential for export to international markets, especially considering the synergy between offshore wind and the petroleum and maritime industry. As a starting point for floating offshore wind, the Norwegian government has assigned two areas for the development of 4.5 GW of floating wind power. Norwegian actors expect that it will take time for the costs of floating offshore wind technology to fall to a competitive level. Therefore, actors perceive this capacity of 4.5 GW as a starting point for larger floating wind developments [Statnett, 2019d][NO ministry, 2020c]. This mindset of actors perceiving 4.5 GW wind capacity as a starting point shows the total floating offshore wind potential is large relative to other NSR countries. This is especially the case when compared to the 10 GW total offshore wind potential considered for Belgian waters.

Due to the offshore wind’s small current role, specific strategies for integrating offshore wind (for export) are not mentioned in Norwegian energy visions. Norwegian actors also perceive no role for gas infrastructure when integrating renewables. Statnett even mentions that “there is currently little evidence that it would be socially economically profitable to develop the power grid in a fundamentally different way” [Statnett, 2019d](*Page 3*).

In summary of the previous paragraphs, the Norwegian energy system has a large natural gas supply and a growing potential perceived by Norwegian actors for floating offshore wind. The following paragraphs focus more specifically on important themes that are characteristic of the Norwegian energy system. Respectively, the next paragraphs discuss Norwegian actors' energy visions on the abundance of hydropower, grid interconnection and CCS.

The Norwegian energy system is characterised by its large share of renewables in electricity production (98%) [NO ministry, 2020b]. A total of 94% of electricity production is supplied by pumped hydropower. Due to the flexible nature of pumped hydropower, about three-quarters of Norwegian electricity production capacity is adjustable [Nordic Energy Research, 2020].

The geographical potential for pumped hydro in Norway is higher than the capacity currently installed. Previous research showed that pumped hydro could supply half of Europe's necessary energy storage capacity in potential. However, the Norwegian government does not plan on expanding its pumped hydropower supply. The government concludes that, in order for them to increase capacity, greater price volatility than today would be necessary for expansion to be profitable [NO ministry, 2020a][Nordic Energy Research, 2020].

Due to its hydropower, the Nordic region system can export energy in wet years and import energy in dry years. This variability over the years is said to couple well with a 'continental-system' which has large weekly variations [Nordic Energy Research, 2020][NO ministry, 2020b][NO ministry, 2020c].

In order to balance these annual and more seasonal fluctuations, Norwegian electricity infrastructure is well connected to neighbouring countries. For example, the system is connected well to Germany; who Statnett also mentions as their ideal energy-partner [Statnett, 2019d]. Many other neighbouring countries also want to make use of the flexibility that Norwegian hydropower can supply. This interest is deemed beneficial by the Nordic TSOs; making use of increased price differences across borders due to the more volatile continental power prices [Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019]. Far into the future, the electricity TSOs expect commercial incomes from these trades to pay development costs and help reduce grid tariffs for electricity customers [Statnett, 2019a][Statnett, 2019d]. Nonetheless, this income is not expected to increase rapidly because in the near future, there are no specific plans for further development of interconnectors to the continent and the UK. The only exception to this statement are both the currently developed Nord Link and North Sea Link [Statnett, 2019d].

The third theme, characteristic of Norwegian actors' energy visions, is the role Norwegian actors envision for CCS. A large role is considered for CCS technologies because of the considerable potential for CO2 storage on the Norwegian continental shelf. This role is perceived to be so large that Norwegian actors expect that aside from themselves, actors within other countries will also increasingly use their CO2 storage potential [NO ministry, 2020a][Gassco, 2019a]. Norwegian actors also aspire to lead CCS technology development internationally. These CCS (technological) developments are still needed because the deployment of large-scale CCS solutions is currently progressing slowly. Norwegian actors explain this slow deployment of CCS solutions by pointing out the current lack of suitable large-scale point sources of CO2 [NO ministry, 2020b][Gassco, 2019b][NO ministry, 2020a][NO ministry, 2020c][NO ministry, 2020b].

4.6.1. Role of gas infrastructure in energy visions

In the following paragraph, the roles Norwegian actors perceive for sector coupling are explained. Subsequently, the specific developments and plans for sector coupling and specifically hydrogen developments are elaborated on further.

This section does not discuss the theme of gas infrastructure supporting gaseous fuelled power plants. This theme is not discussed because it is not a relevant theme in the Norwegian energy visions. The theme is irrelevant because although a lot of natural gas is produced in the Norwegian energy system, almost no natural gas is consumed. As an example, the Norwegian energy system currently only has a small capacity of 0.2 GW fossil-fuelled thermal power plants (e.g. based on natural gas and coal) [Gassco, 2019a][Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019].

As previously mentioned in the introduction, Norwegian actors mostly expect gas infrastructure to remain in use for natural gas exports [Gassco, 2019a] [Statnett & Fingrid & Energinet & SvenskaKraftnat, 2020][P17]. This focus on exporting natural gas could be considered a reason for Norwegian actors not mentioning the term sector coupling in their energy visions. Especially Gassco does not mention any expected developments for sector coupling.

Hydrogen is mostly considered to be an economic opportunity and not a solution for (in the case of Norway almost nonexistent) integration and flexibility issues [NO ministry, 2020a]. The Norwegian hydrogen strategy merely describes that "synergies across applications, in addition to efficient value chains, can be an important contributor to better profitability in hydrogen projects" [NO ministry, 2020a](*Page 26*).

Additionally, Statnett mentions that the hydrogen production processes require energy and therefore result in energy losses. Due to these energy losses, hydrogen production with electrolysers is perceived to be more expensive than using electricity directly [Statnett, 2019c].

Although the term hydrogen is not mentioned once in Gassco's annual report in 2019, the Norwegian government and Statnett (to a certain extent) do focus on hydrogen in their recently published hydrogen strategy [Gassco, 2019a][NO ministry, 2020a]. In this strategy, the Norwegian government aspires to take advantage of the opportunities in the green shift. Additionally, the strategy also mentions Norwegian actors should prioritise efforts in those areas where they have unique advantages, as an exporter of their abundance of energy [NO ministry, 2020a].

An increased focus on hydrogen in Norway is in line with their goal of having internationally competitive businesses which develop "the technology and solutions addressing tomorrow's challenges" [NO ministry, 2020a](*Page 5*). Therefore, the Research Council of Norway has supported research and development related to hydrogen, fuel cells, and water electrolysis by about NOK 550 million (55 million Euros) from 2009 to 2019 [NO ministry, 2020a]. The most important policy instruments are the broad energy research programme ENERGIX (for green hydrogen production) and the CCS programme CLIMIT (for blue hydrogen production). In light of COVID-19 investments, the Norwegian government additionally granted an additional NOK 120 million (approximately 12 million Euros) to the Research Council of Norway's ENERGIX programme [Questionnaire NO].

4.6.2. Envisioned hydrogen applications

The following paragraphs discuss the roles Norwegian actors envision of blue hydrogen production, green hydrogen production, hydrogen transport and hydrogen consumption.

Norwegian actors consider blue hydrogen production as an opportunity for energy export. The Norwegian government perceives blue hydrogen production as a way to adapt the large Norwegian gas supply into a long-term energy source, by combining it with their CCS potential [NO ministry, 2020a][NO ministry, 2020b][Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019][NO ministry, 2020c]. The Norwegian potential for blue hydrogen production is enormous. The Norwegian hydrogen strategy demonstrates this by mentioning that the current Norwegian natural gas exports correspond to an amount of energy 3 to 4 times of Europe's total hydrogen consumption today [NO ministry, 2020a].

The Norwegian government aspires to make Norwegian blue hydrogen competitive with green hydrogen in the European energy market. In their hydrogen strategy, it is already estimated that large-scale production of blue hydrogen will have lower costs than green hydrogen production [NO ministry, 2020a][Questionnaire NO].

Hydrogen exports from Norway to Europe are expected to need a significant scale to justify investments in new infrastructure (pipelines). Therefore, the establishment of blue hydrogen production near customers in combination with the transport of CO2 back to Norway is now being considered first. Norwegian actors currently deem this a cheaper option [NO ministry, 2020a]. Norwegian actors could be considered to be a more reactive market player, expecting to wait for the demand for a hydrogen market to emerge. The Norwegian government mentions this reactive attitude in their hydrogen strategy, mentioning that "ultimately, it is up to the market actors to assess whether it will become commercially attractive to export blue hydrogen from Norway in the future" [NO ministry, 2020a](*Page 48*).

Nonetheless, Norwegian actors are already experimenting with a variety of new blue hydrogen production technologies. For example, actors are experimenting with carbon capture, transport and storage processes in the Norwegian full-scale Longskip project. This project could facilitate blue hydrogen production from natural gas with carbon capture and storage, resulting in hydrogen with "very low emissions" [Questionnaire NO].

The Norwegian government sees many uncertainties for green hydrogen production. As previously mentioned, most Norwegian actors consider blue hydrogen the cheaper and more feasible production route for hydrogen [NO ministry, 2020a].

Nonetheless, in the Norwegian hydrogen strategy, the opportunity is also envisioned to create a market for renewable hydrogen produced by electrolysis and powered by (floating) wind. This proposal is driven by the possible profit one can attain by producing high-value products based on green hydrogen, such as jet fuel. Such a production route is envisioned to possibly create continued high investor interest in offshore wind farms [NO ministry, 2020a].

Converting hydrogen into ammonia is also presented as an option in the Norwegian hydrogen strategy. Ammonia is considered to be both a hydrogen carrier and used directly as a fuel. The gas is perceived as a possibly cheaper zero-emission alternative option to hydrogen. The total price of ammonia is expected to be lower because the transport costs of ammonia are considered lower than hydrogen. These transport costs are lower as ammonia has a higher energy density, it is a gas at normal temperature and atmospheric pressure, and it is easier to be stored [NO ministry, 2020a].

This paragraph focuses on the development Norwegian actors envision for hydrogen transport. In contrast to other NSR countries, the reuse of gas infrastructure is not a prominent theme envisioned by Norwegian actors. This lack of interest can be explained by the long-term use considered for gas infrastructure for transporting natural gas [Gassco, 2019b]. Therefore, Norwegian actors consider it more “rational” to establish the production and blending of hydrogen in the gas network close to the users in Europe [NO ministry, 2020a](*Page 49*). Only in the future, a role is envisioned for hydrogen transport with ships or in existing gas pipelines, given that there is available capacity [NO ministry, 2020a][Questionnaire NO]. Nonetheless, the Norwegian government does consider a hydrogen value chain to possibly make use of existing gas infrastructure because it is said to reduce the need for new investments in infrastructure [NO ministry, 2020b]. In the 2021-budget, an investment of NOK 100 million (10 million Euros) has been proposed for developing and establishing hydrogen infrastructure and for identifying hydrogen clusters, nodes and value chains. The Norwegian government expects these investments to bring them closer to a commercial market for hydrogen [Questionnaire NO].

This paragraph focuses on the applications Norwegian actors envision for hydrogen. The value of hydrogen is deemed lower in the Norwegian power system than in Europe. As an explanation for this decrease in value, Norwegian actors mention that hydrogen is not able to compete with the low prices and flexibility of hydropower. Widespread use of hydrogen in many applications is deemed entirely dependent on cost reductions from future technology development occurring outside Norway [NO ministry, 2020a].

For some specific applications that lack network access, the Norwegian government perceives some hydrogen solutions to be competitive today [NO ministry, 2020a]. Such applications include industrial processes and heavy mobility (e.g. trucks, ships). Especially marine transport is of Norwegian interest, due to the large (expected) use of hydrogen in this sector [NO ministry, 2020a][Questionnaire NO]. Refuelling ships offshore with hydrogen produced from offshore wind energy could be a significant first niche application for hydrogen in Norway.

In summary, Norwegian actors do not foresee considerable challenges to maintain system adequacy [DNV GL Aurora Sáez Armentero, 2020]. They are driven to become a role model exporting their abundance of energy. Therefore, in their visions, Norwegian actors maintain an international scope. There is almost no visible overlap between the gas and electricity TSO, as both TSOs focus on their responsibilities and tasks. The Norwegian energy consumption is to a large extent (approx 50%) electrified with pumped hydro. The presence of pumped hydro in the Norwegian energy system has lead to a robust electricity grid. Norwegian gas infrastructure is therefore mostly used for exporting the large Norwegian natural gas supply. Together with their large potential for CO2 storage, Norwegian actors perceive options for producing blue hydrogen. Farther into the future, green hydrogen production opportunities are also mentioned. Some Norwegian actors consider this a way to exploit the large Norwegian potential for floating offshore wind.

4.7. Themes present in the energy visions of the actors in the United Kingdom

Official government forecasts suggest that natural gas will remain an essential and critical part of the UK energy mix for the foreseeable future, during the transition to net-zero energy system [World Oil, 2020]. The UK is increasingly reliant on imported natural gas from continental Europe and international trade in natural gas. UK actors expect production from the UK Continental Shelf to decline because existing fields are nearly depleted but not replaced [NationalGrid ESO, 2019b][OFGEM, 2019]. In combination with this high dependence and low domestic supply of natural gas, the UK energy system is also based on various electricity sources.

To manage both these energy sources, UK actors foresee a large role for their current gas and electricity infrastructure. Currently, these gas networks transport three times the energy that electricity networks transport [APPG, 2020]. Ofgem manages this infrastructure as the independent energy regulator, ensuring that network companies (e.g. TSOs/DSO's) deliver a safe and reliable service [H-Alba]. There are several TSOs responsible for this infrastructure, with the NationalGrid being responsible for both gas and electricity for most parts of the UK [NationalGrid ESO, 2020a][NationalGrid ESO, 2019b]. Additionally, the Northern Gas Network (NGN) is also of interest for this research as they are one of the key actors expected to integrate the large offshore potential in Scotland.

Scotland has a large offshore wind potential of 735 GW, relative to other regions in the NSR. This potential of 735 GW is said to be equal to 25% of European wind potential. Due to this large potential in Scotland, Scottish actors envision offshore wind energy exports into England and Wales most of the time. Offshore wind targets set in the national Sector Deal include the ambition for 30 GW installed offshore wind capacity by 2030 and 50 GW in 2050 (although other actors advise 75 GW) [NationalGrid ESO, 2019b]. In NationalGrid's and the UK governments' energy visions, this relatively large potential for offshore wind is not highlighted explicitly as such. This potential is only highlighted explicitly in the energy visions of Scottish actors [NationalGrid ESO, 2019a].

UK TSOs envision offshore wind capacity to be integrated using electricity infrastructure. Additionally, these actors mention the use of (cost-efficient) multi-purpose hybrid-interconnectors, that combine offshore wind generation and market to market electricity interconnection with other countries [NationalGrid ESO, 2020b][OFGEM, 2020][NationalGrid ESO, 2020a]. In the UK Offshore wind Sector Deal, other hybrid projects are also presented as possible future cost-effective solutions; not only connecting offshore wind with electricity interconnection but also with large scale energy storages and hydrogen production [UK Department: Department For Business, 2020]. The industrial actors of the Oil and Gas consortia envision a more promising flexible role for electrolysers; stating that “electrolysis could be required to convert a significant portion (25%-40%) of windpower electricity to green hydrogen to mitigate renewables intermittency” [UK Oil & Gas authority et al., 2020](*Page 15*).

The following paragraphs focus more specifically on the themes that are characteristic of UK energy visions on integrating offshore wind. Three important themes are characterised: electricity storage options, electric grid reinforcements and the role perceived for CCS technology.

Grid reinforcements, and especially ‘classical’ electricity-based solutions, are typically mentioned by UK government and TSO actors as technologies that are expected to help integrate offshore wind into the energy system. These ‘classical’ electricity solutions include the use of electricity interconnections (with other countries to integrate variable renewable energy supply), batteries (to store a surplus of renewable energy and use this energy in times of a shortage) and demand side response (to shift energy use away from peak electricity demand) [NationalGrid ESO, 2020a][CCC, 2020]. This focus on ‘classical’ electricity-based solutions is exemplified when considering the Electricity Ten Year National Development Plan (TYNDP). This electricity TYNDP only considers new storage (battery, EV, heat pumps) and interconnector developments as a solution for the increasing challenge to integrate RES into the grid. Additionally, the term hydrogen is not mentioned once in this electricity TYNDP [NationalGrid ESO, 2019a].

The UK TSOs energy visions are also characterised by their strategy for a relatively large expansion in electricity grid capacity. Such a large expansion is considered a low regrets option by UK TSOs, because of the price insensitivity recognised of over-sizing the grid [CCC, 2020][NationalGrid

ESO, 2019a]. This urge of actors wanting to achieve the most cost-effective solution is often used as reasoning in all UK based energy visions.

Expanding the scope of these electricity grid reinforcements, the NationalGrid also expects electricity interconnectors to play a long-term role in the UK energy system. Nonetheless, interconnectors are also perceived as a burden sometimes. They are perceived as a burden when electricity exports via interconnectors increase simultaneously with wind generation in the north, resulting in high power flows across the whole network to the south [NationalGrid ESO, 2019a][NationalGrid ESO, 2020b]. These enormous energy flows from the north to the south of the country can be explained by the high potential of offshore wind in the north. Grid reinforcements are increasingly needed in the north, because the electricity network is currently limited and because there is a large growth of RES capacity possible [NationalGrid ESO, 2019a]. To solve this challenge, UK actors increasingly mention a role for electric grid reinforcements but not a role for gas infrastructure.

The role UK actors envision for CCS technologies is also characteristic. UK actors envision CCS technology to play a large role in the decarbonisation process of the power sector. A role for CCS is considered due to the technologies' cost-efficiency and opportunities perceived in the UK for storing CO2 in their UK Continental Shelf [CCC, 2019] [UK Oil & Gas authority et al., 2020][Savenkova, 2020] [NationalGrid ESO, 2020a][P17]. CO2 storage potential is not considered a binding constraint. Previous research estimated that the total storage capacity could support 50 GW of gas CCS plant running all year, for 500 years. Additionally, oil and gas infrastructure are also envisioned to be reused for CCS developments [CCC, 2020][CCC, 2019][UK Oil & Gas authority et al., 2020][Savenkova, 2020]. This reuse of gas infrastructure for CO2 is characteristic for UK actors, as (for example) Dutch actors mostly envision a role for the reuse of gas infrastructure when considering hydrogen developments.

4.7.1. Role of gas infrastructure in energy visions

The following paragraphs focus on the role UK actors see for gas infrastructure when considering gas-to-power (power plants), and subsequently power-to-gas (electrolyser) technologies. Additionally, the specific visions on power-to-gas of Scottish actors are also considered.

The NationalGrid expects thermal energy generation to play a large role as a peaking power plant; providing electricity at times of high demand or low renewable output [NationalGrid ESO, 2019b][Power Responsive UK, 2019][NationalGrid ESO, 2019c][NationalGrid ESO, 2020a]. The UK government energy advisory board (the CCC) assumes that in a future decarbonised energy system, 23% of power generation will come from gas-fired plants fitted with CCS. The CCC mainly assumes this because of their perceived limitations of biomass that can be grown or imported in large quantities [CCC, 2019].

This large future role seen for natural gas is considered an incentive to re-use and end expand existing gas infrastructure [NationalGrid ESO, 2019b]. Due to the ageing gas grid and conversion from low to high calorific gas, the UK Gas Network Development Plan 2018–2028 includes expansion measures costing around EUR 2 billion [CCC, 2020][NationalGrid ESO, 2019c]. These investments are expected to be already made at the time of a potential conversion to hydrogen. Nonetheless, the investments are presented as an additional benefit in the course of a hydrogen conversion because plastic pipes can also be used to transport hydrogen [CCC, 2020][H-Alba].

Focusing on Power-to-Gas (PtG), a lot has changed in NationalGrid's energy vision in 2020. Previously, PtG sector coupling was not explicitly mentioned by the TSO in their Future Energy Scenarios report (FES) 2019. However, in the FES 2020, one of the four key messages concerns hydrogen. One of the interviewees claimed that the new Net-Zero government target mostly drove this change; "leaving no room for emitters in the energy sector going forward" [P19][NationalGrid ESO, 2020a].

Considering sector coupling, UK actors consider opportunities in the energy system in the heat and gas sectors for sector coupling with the electricity sector. Both heat and gas sectors are of interest because the energy consumption of both sectors is abundant in the UK energy system and is expected to be decarbonised in the nearby future. Furthermore, both sectors also have quite a flexible demand which balances out well with an electricity system with less flexibility. Future research is therefore considered necessary, focused on the "significant potential for the power sector to access the flexibility embedded in other energy sectors, particularly the heat and gas sectors" [Shakoor and Poyry, 2017](*Page 10*)[CCC, 2020].

UK actors briefly mention hydrogen developments in most energy visions. However, no specific UK government hydrogen strategy has yet been published. A release of such a strategy is expected in early 2021. According to UK actors, this development is driven by the recent “accelerated timeline” and pressure to showcase something in the year they organise COP (an annual UN Climate Change Conference) [EZK,CIEP, 2020](*Presentation UK energy ministry*).

In a presentation of the planned hydrogen development, UK government actors perceive hydrogen as a key enabler of the shift towards net-zero emissions in 2050. Firstly, they consider hydrogen to be coupled with their offshore wind potential and the recent fall in offshore wind price. Secondly, UK government actors consider hydrogen developments could make use of the existing technical strengths and expertise. Thirdly, the actors consider CCS options in the UK to be a large driver for hydrogen development. Due to these three hydrogen enablers, the actors mention a “serious amount of money is being invested” in hydrogen [EZK,CIEP, 2020](*Presentation UK energy ministry*).

Aside from the general energy visions on hydrogen in the UK, Scotland has a slightly different vision. This energy vision is characterised by the country’s “enormous offshore wind resources, strong offshore experience and proximity to growing markets for clean hydrogen” [EZK,CIEP, 2020](*Presentation Scotland energy ministry*). The Scottish government recognises the potential to become a large exporter and has published a hydrogen action plan and policy statement in December 2020. Unfortunately, this document is out of scope for this research.

Current projects, as of 2020, include the hydrogen hub in the northeast of Scotland, the ACORN hydrogen project, H100 project, Aberdeen vision project and the Shetland energy hub. Additionally, the Scottish National Gas proposes building a blue hydrogen production facility in Scotland to produce hydrogen ashore with CCS. Recommissioning of gas infrastructure is therefore also a theme in Scottish energy visions. In more detail, the Scottish government mentions building their hydrogen vision on the (gas) infrastructure already in place [EZK,CIEP, 2020](*Presentation Scotland energy ministry*).

A significant insight to conclude with is that hydrogen visions in the whole of the UK are not presented as a solution for integrating variable RES. Scottish actors are the only one to envision such a role for electrolysers; mentioning that electrolysers could be directly connected to offshore wind sources, putting fewer constraints on the existing electricity grid [EZK,CIEP, 2020](*Presentation Scotland energy ministry*).

4.7.2. Envisioned hydrogen applications

The following three paragraphs discuss the envisioned roles of blue hydrogen production, green hydrogen production, transport and consumption.

Considering hydrogen production, UK actors and specifically TSOs, do not have ‘grand’ vision aspirations of becoming a specific hub or role model [NationalGrid ESO, 2019a]. However, specifically Scottish actors do share high ambitions for both green hydrogen and blue hydrogen production.

UK actors collaborate closely with Norwegian actors on blue hydrogen production developments [H-Alba][EZK,CIEP, 2020]. This cooperation can be explained due to the Norwegian energy system having an abundance of natural gas and the UK energy system having a great demand for decarbonised gases. Additionally, both countries also have a large potential for CO2 storage.

The vision for initially blue and subsequently green hydrogen production is characteristic for UK actors. Although the specifics do vary across different energy visions [EZK,CIEP, 2020]. The UK government considers blue hydrogen a prioritised low-regret option to kick-off hydrogen developments. This prioritisation is exemplified in the current ambition to include low-carbon hydrogen production in at least one CCS cluster by 2030 [CCC, 2020]. Furthermore, in the UK H21-project, the potential is presented to replace all UK natural gas with hydrogen, including deep decarbonisation of power generation, transport and residential, commercial and industrial heat by 2050 [APPG, 2020].

On the other hand, the UK government concludes that producing hydrogen in bulk with electrolysers would be much more expensive than producing blue hydrogen or importing hydrogen [CCC, 2020]. Although UK actors do envision that “in time and with electrolyser cost reductions and changes to regulations, large scale cost-effective green hydrogen sources will become more viable” [Crown Estate Scotland, 2018]Page 46][CCC, 2020]. In contrast, Scottish government actors have extremely ambitious expectations for green hydrogen production. These ambitious expectations are mostly driven by the perceived Scottish offshore wind potential [CCC, 2018].

Some Scottish actors even consider that their large offshore wind potential could make the UK a hydrogen exporter [EZK,CIEP, 2020]. However, focused on becoming a hydrogen importer or exporter, UK government actors do not present a specific preference for one of these options. Considering this role, UK actors mostly focus on the most cost-effective path and conclude that, when including costs of hydrogen conversion and transport, similar costs are expected to produce hydrogen directly in the UK or to import hydrogen [CCC, 2020].

Considering hydrogen transport, in the UK government's 2017 Clean Growth Plan, the conversion of natural gas networks to 100% hydrogen is considered as one of the large-scale credible options for decarbonisation [GL, 2020]. Additionally, several UK gas distribution networks and other TSOs are working on projects to inject 100% hydrogen or hydrogen and natural gas blends into the network by 2030. These projects consider both new gas grids and repurposed gas grids [APPG, 2020][GL, 2020][NationalGrid ESO, 2019c].

In some cases, there may be opportunities to repurpose parts of the natural gas transmission system for the transportation of CO2 or hydrogen. Although UK actors perceive these options to be restrained by both the feasibility of conversion of gas infrastructure and the continued use of the transmission system for natural gas [CCC, 2018][P19].

Considering the different uses of hydrogen, the most potential seen for hydrogen by both Scotland and Great Britain are the applications where electrification is deemed challenging and where significant infrastructure changes are not required [CCC, 2018]. Considering these requirements, the expected lead route for hydrogen are applications in industry and heavy transport.

Considering industry, the UK Government aims to establish at least one low-carbon industrial cluster by 2030 and the world's first net-zero cluster by 2040 [CCC, 2018].

Other applications envisioned by UK actors include using hydrogen for industrial processes and heating, for dispatchable power and for heating in the built environment. Gas network operators especially see an opportunity for using hydrogen to heat buildings because they find that other alternatives for decarbonising heat are limited. Furthermore, 90% of their UK customers are already connected to the gas network, and there is substantial inter-season variation in demand for heat which makes it 'inefficient' to be supplied by electric sources [OFGEM, 2019][GL, 2020].

The Scottish government differs from this narrative by categorising power generation and personal transport at a lower probability only applicable when hydrogen achieves a large scale and low cost as currently there are other more competitive low carbon alternatives [EZK,CIEP, 2020].

In summary, UK actors foresee challenges in maintaining network adequacy in the future. This entails the challenge of integrating the large offshore wind potential in the north of Scotland. Currently, UK actors envision this energy source to be integrated using electricity storage options and an increase in electricity grid reinforcements. Gas infrastructure is currently not envisioned to play a large role in integrating offshore wind. Although, natural gas is considered part of the UK's future energy system, because of the UK actors' experience with natural gas, the presence of natural gas infrastructure and (geographical) opportunities seen for CCS. For the necessary flexible thermal generation, (decarbonised) natural gas and blue hydrogen are expected to play a role.

Lastly, in their energy visions UK actors are often driven by cost-efficiency. Due to this driver, actors tend to maintain a whole system approach when it comes to the choice for integration technologies. Nonetheless, other themes in UK energy visions are also important, which include feasibility of delivery, public acceptability, import dependence and retaining options for long term decarbonisation [CCC, 2018].

4.8. Summary

This chapter identified the different themes present in the different actors' energy visions in the subsystem of a country. These themes are seen to be of a more technical, geographical, economical, political and/or social nature, in line with the themes found in academic literature presented in chapter 2. It can be concluded that there are several geographical differences found in relevant themes between actors in the NSR.

Aside from these differences, themes can also be categorised in their dynamism. For example, some countries have unchangeable geographical themes, which form a basis for the decisions made. This characteristic is of interest to consider when in chapter 5, different overarching themes are defined within the whole system of the NSR. In table 4.1 the different themes present in the different analysed sub-systems (countries) are summarised.

Table 4.1: Table summarising the characteristic themes of actors' energy visions in each of the six countries analysed.

Actors within country	**Themes characteristic for the country sub-system**
The Netherlands	- High (perceived) offshore wind potential - Due to a decrease in natural gas extraction: an opportunity to reuse unused gas infrastructure
Belgium	- Plans for decommissioning a relatively large capacity of nuclear power plants - A low energy self-sufficiency percentage, for both offshore wind and fossil fuels, and therefore high dependency on energy imports
Denmark	- A high (perceived) offshore wind potential, especially in comparison with domestic energy demand
Germany	- A large potential capacity for renewable energy sources in parallel with a relatively large domestic energy demand in comparison with other NSR countries - Plans for decommissioning a relatively large capacity of coal-based power plants
Norway	- A currently low offshore wind energy capacity, but high potential is seen for floating offshore wind - An enormous energy self-sufficiency percentage due to its large hydro capacity and large natural gas supply
UK	- Large offshore wind energy capacity currently installed and potential is seen for in the future

5

Themes in the North Sea Energy integration system

In this chapter, nine overarching themes are presented concerning the role of gas infrastructure when integrating offshore wind. Different actors appoint different levels of relevance and approaches to these nine themes, leading to possible incompatibilities. These themes are of interest to the (holistic) system of the NSR. The chapter's overarching themes build upon the themes introduced in the previous chapter, which were focused on different sub-systems (countries) within the region. Essentially the second sub-question is answered in this chapter: to what extent, and based on what underlying reasoning, are these energy futures compatible or incompatible with each other? This chapter gives an understanding of the current state of compatibility of different sub-systems in the NSR.

A combination and comparison of the nine characterised overarching themes result in a pattern model that explains the future (in)compatibilities of envisioned sub-systems in the NSR. Every section concludes with a paragraph that summarises the state of compatibility of that specific theme. This chapter concludes with a categorisation of the themes and their state of (in)compatibility.

After one understands how compatible different sub-systems are, one can then answer the third sub-question of this research. This third sub-question focuses on how co-existing energy visions in the North Sea region can be made more compatible, elaborated upon in chapter 6.

5.1. Theme 1: Visions on competitive claims on offshore wind

As was concluded in chapter 4, many actors see opportunities to produce green hydrogen produced from electrolysers fuelled by offshore wind [DE BMWi, 2020b][DE BMWi, 2020a] [Energinet, 2019d]. To produce green hydrogen (with electrolysers) on a large scale, more renewable electricity will be needed than is currently being produced in the NSR energy system. As a result, there is a need for either an increase in renewable energy production or imports to produce green hydrogen on a large scale [CCC, 2020]. The capacity size of 'large scale green hydrogen production', should not be underestimated. For instance, when adding up all electrolysers targets in the NSR, approximately 20 GW of electrolyser capacity is expected in 2040. This is considerable when compared to a total offshore wind target of approximately 80 GW by 2030 in the NSR (*the data this claim is based on can be found in Appendix table A.1* [VARIO, 2020][Energinet, 2020][KAPSARC, 2020][TenneT, 2020c][DE BMWi, 2020b][Ørsted, 2020][Klimaatakkoord, 2020][Oxford Institute For Energy Studies, 2020]).

5.1.1. Different visions on offshore wind potential

Comparing actors nationally, some actors see electrolysers as a driver to install more offshore wind at a faster rate because it can relieve the electricity grid (some Danish, Dutch and Scottish actors) [Energinet, 2020][P9][UK Oil & Gas authority et al., 2020][TKI Nieuw Gas, 2019].

In contrast, other actors consider electrolysers to 'claim' offshore wind energy which could otherwise be used directly for electric-based applications (some UK, Belgian and Dutch actors) [P3][CCC, 2018][TKI Nieuw Gas, 2019][van Santen, 2020]. These actors envision the whole of Europe to lack sufficient RES capacity relative to its total energy consumption. Building upon this claim, actors conclude that ‘scarce’ offshore wind should be consumed in the form of electricity and not as hydrogen because this is perceived to be more efficient [Gasunie,TenneT, 2020][P3]. A role for offshore wind to supply electrolysers is only seen after all current electricity consumption is supplied with RES, and after all energy consumption that can be electrified has been done so and is supplied with RES (by EU expected approximately 47% of energy use). This direct use of more regionally generated RES is perceived to be more efficient because so called ‘inevitable’ energy imports are not likely to be electric but gaseous; as transportation of gas is more efficient and easier over long distances compared to electricity [CCC, 2018].

Belgian actors are most explicit in their perception of this scarcity of RES in the whole of Europe and therefore the NSR, whilst Scottish and Danish actors explicitly perceive more of an abundance of RES. Other actors are not as explicit on the scarcity or abundance they see for RES and offshore wind. These differing standpoints on how ‘scarce’ offshore wind is could be linked to the actors’ own national potential for offshore wind energy [Anonymous]. One could then conclude that the higher the perceived offshore wind potential, relative to a countries’ current electricity consumption, the higher the perceived potential for electrolyser capacity tends to be [Ørsted, 2020][P7][Anonymous][CCC, 2018].

The extent to which different actors consider electrolysers to be in competition with electricity consumption for offshore wind could be seen as a reason for incompatible visions on the role of electrolysers. They are incompatible as some actors envision a large installed electrolyser capacity in the NSR, and others envision a smaller installed electrolyser capacity in the NSR with more (green) hydrogen imports, blue hydrogen production etc. This incompatibility is rooted deeper than merely different offshore wind potentials seen for the NSR as a whole, as previously mentioned. Even if all actors in the NSR were to perceive the same offshore wind potential for the NSR as a whole, the envisioned national offshore wind potentials still remain different. Due to the national scope, some actors tend to take, visions on the role of electrolysers would probably also still differ.

National governmental actors want to provide the cheapest electricity to their own population. However, they also aspire to sell their offshore wind energy at the highest value when exporting their energy. Currently, one can get the highest value for offshore wind energy exports in the form of hydrogen and other e-fuels (produced from green hydrogen). For instance, if Danish actors export their offshore wind capacity on a windy day directly, they would often have to sell their electricity at low price points. This low price can be explained by the abundance of electricity on the grid on windy days. Therefore, if Danish actors could store their offshore wind energy, they could acquire a higher value for their energy source [P8][FutureGas, 2020][Energinet, 2019a].

The incompatibility of different actors’ visions increases when certain nationally based political stakes are at play. To summarise, the disagreement of actors is not only based on disagreement on the most logical or cost-efficient way to utilise offshore wind electricity in the NSR as a whole (e.g. offshore wind being either consumed directly or via electrolysers). The disagreement of actors is also based on what actors perceive is the highest export value of offshore wind. Currently, actors see the highest value can be obtained using hydrogen. However, this could change in the future, considering the pricing system of electricity, infrastructure, flexibility, etcetera.

This more national scope of actors could lead to a less technically efficient energy system arising because the offshore wind energy in the NSR that could have been ‘consumed’ as electricity directly is ‘consumed’ by an electrolyser to produce hydrogen. This becomes inefficient when such a considerable amount of offshore wind (and other RES) is collectively ‘claimed’ by electrolysers. As a result, renewable electricity demand would no longer be supplied entirely. This electricity would then have to be provided by fossil fuel based power plants, which is inefficient for the development of a decarbonised energy system. In addition, this electricity could also be imported, which is also inefficient as long-distance energy imports are currently done more technically efficient in gaseous forms. Both these inefficiencies could lead to a less efficient energy system arising, considering the scope of the whole NSR.

5.1.2. Different visions on the development speed of electrolysers

In addition to the aforementioned differences in perceived offshore wind potential, there are also differences in the speed that actors consider electrolysers should be installed [P18]. The next four paragraphs discuss this difference. This research defines an ongoing balancing act of actors, who either state relatively low targets for electrolyser capacity (possibly not creating the opportunity for the technology and market to develop quickly enough), or who state relatively high targets for electrolyser capacity (leading to increasingly competitive claims of offshore wind) [Anonymous][P18].

While hydrogen is seen by most actors as a crucial element in the long term (for flexibility), in the near future, newly installed electrolysers are considered likely to lead to an increase in emissions. This increase is expected because of the unlikeliness that in the short term there will be a sufficient increase in RES to supply the increase in electrolyser capacity. Therefore, fossil fuels (such as natural gas) are expected to be used increasingly to produce such electricity necessary for electrolysers [Anonymous].

Several consequences are seen when the development of electrolysers leads to an increase in GHG in the short term. Generally, such a development could make it difficult to maintain public acceptance of electrolyser technology. This public acceptance could decrease if a technology that is initially presented as a ‘carbon-free’ technology turns out to be a ‘carbon-based’ technology. Subsequently, investing in ‘too expensive’ technologies at the beginning of a transition could also undermine financial support in the longer term, where new necessary learning curves would have to be funded [P18]. This could block further electrolyser developments, making it difficult to develop an energy system based on both gasses and electricity infrastructure. Such a decrease in electrolysers could lead to the emergence of a more inefficient energy system, based on the normative standpoint mentioned in the introduction of this report that gaseous fuels are an essential part of a future decarbonised energy system.

In summary, for electrolyser technologies and corresponding green hydrogen applications to develop (faster), actors would have to accept an increase in GHG emissions in the short term, all while maintaining public acceptance for electrolyser technology. Maintaining such public acceptance for a future ‘green’ technology is a challenge.

This is challenging because most government actors from Belgium, the UK, Germany and the Netherlands mention that innovative funded technologies should contribute to the reduction of GHG’s. In other words, electrolyser technology should be economically and ecologically justifiable [Belgium Interfederal Energiepact, 2018][BE federal government, 2020][CCC, 2019][Gasunie,TenneT, 2020]. Considering these standpoints, one could expect it to be challenging for actors to justify a technology for the sustainable energy transition that emits GHG in the short term. The Danish council is the only actor to explicitly accept that electrolysers will probably not deliver real GHG reductions at affordable costs by 2030, focusing on the electrolysers’ necessity to achieve climate neutrality by 2050 [Danish Council on Climate Change, 2020].

Focused on this balancing act, there seems to be a certain incompatibility between different actors accepting or not accepting GHG emissions in exchange for faster development of electrolysers. Essentially, this is dependent on the expected role of electrolysers in the long term and what actors deem worthwhile in the meantime to reach this long-term goal.

These different visions are incompatible with each other because they lead to different envisioned speeds of electrolyser capacity being installed in the NSR. This entails differences in visions of TSOs, industrial and governmental actors within the same country and differences in visions between different countries. Although the exact differences between visions of actors are relatively uncertain as this topic is often not mentioned explicitly.

If these differences were aligned nationally, the system would become a lot more compatible. If these differences were not aligned nationally, such disagreement within a country could lead to increased debates to maintain public acceptance. This could lead to slower electrolyser development.

In contrast, different electrolyser development speeds within different countries could exist next to each other. Therefore, these differences are not as incompatible as misaligned insights within a country. Nonetheless, if different levels of public acceptance of electrolysers exist in the NSR, it could still be challenging. This challenge could remain because public opinions could influence each other and therefore influence electrolyser developments. The currently decreasing and fluctuating public support for biomass in the whole NSR is an example of different national public opinions influencing each other.

Such public acceptance is important to maintain. This is also mentioned in actors’ energy visions. Almost all actors agree that both consumer willingness, public acceptance and political support are an essential boundary condition for energy infrastructure developments, with support being necessary for many years and even decades [VARIO, 2020][DE BMWi, 2020a][Statnett, 2019b][Statnett & Fingrid & Energinet & SvenskaKraftnat, 2020][Statnett, 2019d][Drift, 2020][Anonymous][Drift, 2020][FNB Gas, 2018][APPG, 2020][P14][DENA, 2019]. When there is a lack of these three elements, the most technically and economically efficient technologies is considered to sometimes not be chosen [DENA, 2019].

5.2. Theme 2: Visions on the capacity operation of electrolysers

The capacity operation of electrolysers is also a topic discussed differently in various energy visions. The following paragraphs discuss three different flexibility roles envisioned for electrolysers; shaving or capping off the unused peaks of offshore wind (1), ramping up and down (2) or always running at full capacity (3). These envisioned roles are also illustrated in Figure 5.1. Lastly, concluding remarks are given on how (in)compatible these different visions on capacity operations of electrolysers are.

5.2.1. Peak load capping

This paragraph focuses on the first flexibility role actors envision. Due to the Danish offshore wind potential being higher than their own energy consumption, both the Danish TSO and government consider electrolysers to run on a surplus of offshore wind generation and other RES. This surplus is defined as the renewable energy that is not interconnected electrically with other countries, and the renewable energy that the Danes themselves do not consume [Energinet, 2020][P9].

Most other actors (including the UK government and NL/BE/DE electricity TSOs) mention that such a surplus of renewable electricity peaks is too scarce to meet the expected hydrogen demand [VARIO, 2020]. An energy expert mentions that only running electrolysers on a surplus of renewable electricity would lead to a negative business case; not at all being competitive with other electrolysers running at a higher capacity [Liebreich, 2020]. Quantitatively, research mentions that energy peaks are currently capped 100 hours a year (of the total 8765 hours) [VARIO, 2020] or 1.5-2.2% of total RES generation 2030 in Germany [Anonymous][P3][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019]. The net-zero scenarios in 2050 of the CCC also considered the use of electrolysers who are supplied by RES that would otherwise have been curtailed. This scenario analysis concluded that such electrolysers would have a relatively low annual load factor, as only 15-24% of full capacity all year round hydrogen production is expected in that case [NationalGrid ESO, 2020a]. Considering these small frequencies, most actors see the curtailment of a surplus of electricity to be a more cost-effective option [P3].

One could argue that actors, who foresee a use for peak capping electrolysers, might have to adjust their geographical scope to the North Sea region or Europe as a whole. Although in the competitive environment of the NSR, this expansion of scope is also likely to happen automatically, as hydrogen produced with ‘peak-capping electrolysers’ would have to compete with electrolysers optimally ramping up and down.

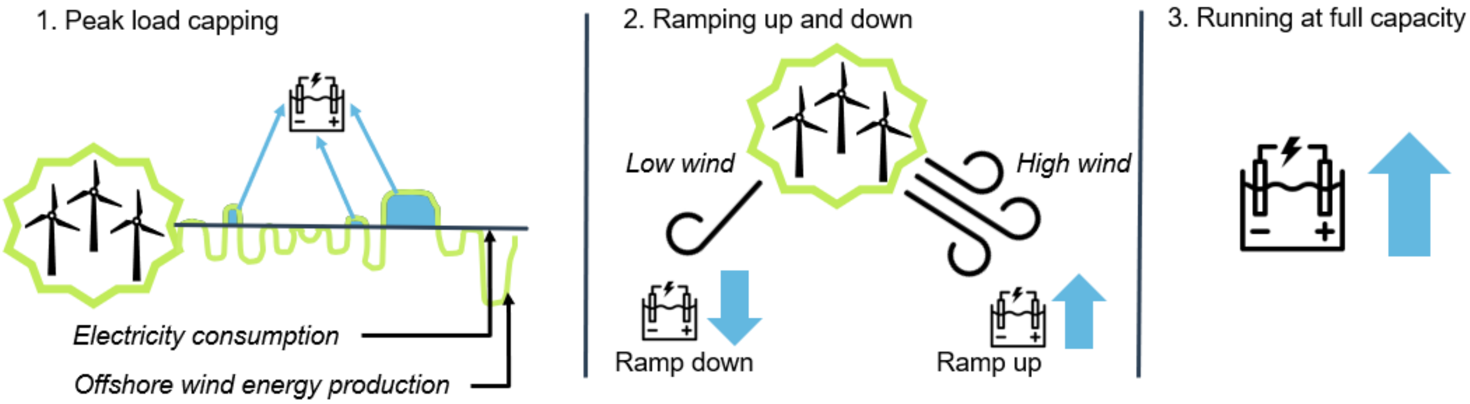


Figure 5.1: A simplified schematic illustration of the three capacity operation methods mentioned in this report. The option on the left shows peak capping, where if offshore wind energy production exceeds electricity consumption, the surplus energy supplies an electrolyser. The second option shows how an electrolyser ramps up and down at different wind speeds. The third option shows a capacity running at full capacity.

5.2.2. Ramping up and down

This paragraph presents a second option for the capacity operation of electrolysers. This option considers electrolysers being ‘ramped up’ when electricity demand and prices are low, and ‘ramped down’ when electricity demand and prices are high. Most actors consider this ‘ramping up and down’ to be a form of demand side response [NationalGrid ESO, 2020a][Energinet, 2020] [Ørsted, 2020][FNB Gas, 2018][TKI Nieuw Gas, 2019][P3][UK Oil & Gas authority et al., 2020][DENA, 2019][TenneT, 2020b][Energinet, 2020].

Some actors (mostly from Belgium) perceive this ramping up and down not to be ‘the’ business case for electrolysers, but more the cherry on top of an already existing business case. They also expect ramping up and down to become more important in the far future; when a larger fluctuation in electricity prices is expected due to, among other things, an increase in RES in the energy system [P4][P3][P13].

Furthermore, the Danish actor Energinet even considers ramping up and down of electrolysers to be beneficial on a timescale of seconds. However, most other energy experts interviewed deem this cost inefficient. Other technologies (e.g. batteries) are considered more cost efficient in such a timespan. They also mention that ramping up and down on such a small timescale reduces the efficiency and total lifespan of electrolysers [P9][P12][P13][CCC, 2018]. This last argument is not often explicitly mentioned in energy visions and only came up in interview discussions.

5.2.3. Always running at full capacity

Thirdly, other actors mention the necessity for electrolysers to always run at full capacity as a baseload. Actors reason this choice by mentioning the (currently) high capital expenditures (CAPEX) of electrolysers [VARIO, 2020][P7]. Due to this high CAPEX, the higher or lower operating expenditures (OPEX) of electrolysers, which are mostly driven by electricity prices, are deemed insignificant by actors. Only some industrial actors share this preference, as they focus on the expected short term profit from an electrolyser [Anonymous].

As currently electricity prices do not fluctuate as such, ramping up and down is deemed less necessary. However, running electrolysers at full capacity does result in an increase in peak electricity consumption. TSO and government actors mention this to potentially worsen infrastructural bottlenecks, which consequently increases the challenge of maintaining both network and generation adequacy [TenneT, 2020b][CCC, 2018].

The envisioned necessity for the capacity operation of electrolysers remains uncertain. Especially considering if it is necessary in the future to operate an electrolyser at full capacity in order to achieve a positive business case. Different actors envision different capacity operation of electrolysers, mostly due to the different expectations of the volatility of electricity prices [P3]. For instance, certain research concluded that a value is seen for electrolysers running on ‘shaved peaks’. In this case, it was concluded that, due to the high electricity price in times of scarcity, the benefits of ‘use of shaved peaks’ outweighed the CAPEX of electrolysers [Anonymous][P18]. Then again, other research envisioned electrolysers to run a higher amount of hours. For example, an energy expert from FutureGas expects electrolysers to run 4000-6000 hours, and not the full 8760 hours in a year, due to expected temporary high electricity prices in a future energy system [P8]. Similarly, in an interview with another energy expert 4000-5000 hours were deemed necessary to reach profitability [Anonymous].

Specifically, some power intensive industries are characterised as a large consumer with a consistent consumption profile with a high willingness to pay for power and fewer possibilities to offer flexibility at low prices. For instance, an industry that uses green hydrogen for steel production or to make green fuels is considered to not be able to stop production when the ‘wind is not blowing’. For such industries, it is necessary to either be able to store green hydrogen, if possible, or to keep on running an electrolyser at full capacity at high electricity price points [CCC, 2020]. This choice made for capacity operation is based on the willingness of industries to purchase electricity for their electrolysers at a high price in exchange for a consistent supply profile. A lack of such willingness could even in the long term result in hydrogen production moving to other regions where electricity is cheaper and less volatile.

At the same time, power-intensive industries are an important reserve for flexibility in situations of power shortages. Nordic Energy Research concluded with great certainty that some industry players would reduce consumption during periods of very high spot prices. Although it is uncertain how high prices must go before this would occur [Nordic Energy Research, 2020].

Therefore, this industrial potential for a reserve for energy flexibility might be a large opportunity for offshore wind integration. However, most energy visions of TSO and government actors currently do not mention this opportunity explicitly, which could lead to a lack of necessity seen for industrial players to experiment with this application. This lack of experimentation could prove problematic in the future when flexibility becomes necessary.

The previous paragraphs explained three different envisioned options for the capacity operation of electrolysers. Due to the differing costs actors consider in their business cases, it is likely that different electrolysers in the NSR will have different flexibility characteristics. One could reason that this depends on the specific actor. However, because not all actors envisioned a specific preference for capacity operation of electrolysers, an explicit conclusion cannot be made.

Nonetheless, using logical reasoning, one could conclude that TSO's would tend more to ramp electrolysers up and down. This preference seems logical because if electrolysers were to run at full capacity, TSOs would have to increasingly invest in expanding electricity infrastructure so that they could support a higher peak electricity demand. TSOs would also probably have to invest in technologies to better manage the increased generation adequacy challenge, which could occur when electrolyser run at full capacity. Additionally, industrial players could be expected to tend more to electrolysers running as a baseload; due to their focus on producing a steady load of hydrogen to provide for a steady amount of hydrogen consumption (necessary for certain industrial applications).

This difference between actors' preferences could be related to the dimensional scoping of operational expenditures (OPEX). Industrial actors consider an electrolysers OPEX to mostly consist of the electricity price. Furthermore, industrial actors could also include the benefit of a steady supply of green hydrogen when considering their OPEX. As an example, if hydrogen is not steadily supplied to a specific chemical plant, the whole plant could have to shut down its process. The costs of this shutdown would be enormous compared to the costs of a higher expected electricity price. Of course, the produced hydrogen could also be stored to maintain a steady supply of hydrogen for an industrial plant. Therefore, the costs of storing hydrogen would probably also be considered when envisioning ones' OPEX.

In contrast, compared to industrial actors, TSOs tend to consider different opportunity costs to be part of the OPEX. These opportunity costs include the amount of money a society would save on the otherwise necessary installed (renewable) electricity generation capacity and electricity network capacity if electrolysers were to ramp up and down efficiently.

Visions on the most optimal form of electricity capacity operation are partly dependent on how the future electricity price includes the value of flexibility services. Additionally, this is also dependent on a drive arising for electrolysers to become a source of flexibility [P7]. It could be concluded that different actors envision different forms of capacity operation because these actors have formulated a different business case. This emergence of different business cases (that do or do not consider societal costs), could then be considered to depend on the price valuation of flexibility characteristics. Indirectly, this depends on the percentage of electrolysers that are considered necessary to maintain flexibility in the energy system [P7]. How and possibly why actors differently approach such a business case is further discussed in section 5.9.

In the previous paragraphs, three different methods for capacity operation of electrolysers were defined. Subsequently, the underlying reasoning was explained for actors having a specific preference for one of these three methods.

One can conclude that different actors have different visions on the capacity operation of electrolysers. These different visions do not lead to an incompatible energy system because an energy system can exist with different electrolysers using different capacity operations.

The different visions only become incompatible with each other when different actors perceive a different capacity operation strategy for the same electrolyser. This would lead to discussion and, subsequently, slower developments of electrolysers as a whole. However, it is uncertain how often this would happen because it is uncertain in what future case multiple actors would be responsible for the capacity operation of one specific electrolyser.

The most significant incompatibility recognised is the risk that once there is a need and drive for flexibility services, the flexible characteristics of electrolysers are not developed sufficiently at that point. This could occur if all actors initially would have chosen to not ramp up and down electrolysers because this was not deemed cost-efficient. This constraint of technological development could occur because most actors currently seem to be driven by short-term cost-efficiency and short-term decarbonisation [P18]. In this case, the energy visions considering no need for capacity operation of electrolysers and the energy visions considering a large role for electrolysers to manage a flexible energy system would be incompatible. This could lead to increased challenges of maintaining generation and network adequacy in the NSRs energy system. However, this development (of electrolyser ramp up and down technology to not be ready) is unlikely to occur because when considering the different energy visions analysed, it is highly unlikely all electrolysers will always run at full capacity.

5.3. Theme 3: Vision on the optimal location of electrolysers

The different roles that actors consider for electrolysers also lead to differently perceived ideal locations for electrolysers; being connected directly to offshore wind turbines (to run at full capacity) or being integrated into the electricity grid (for a more flexible role) [P13]. The choice for electrolyser location is important, as for example, TenneT concluded in their model analysis that 9 GW of electrolysers at a 'suboptimal' location in 2035 could lead to additional costs of several hundred million Euros per year [TenneT, 2020c].

In an ideal case, electrolysers are located close to large scale renewable assets, to multi-connections to different markets, to strong connection points in the electricity transmission grid, to re-usable gas infrastructure, to existing hydrogen demand, to hydrogen storage opportunities, to access to CO2 for the production of green fuels and to a space with the ability to utilise surplus electrolyser heat [Energinet, 2020] [TKI Nieuw Gas, 2019][NL EZK, 2020b][FNB Gas, 2019][Gasunie,TenneT, 2020][DENA, 2019]. Unfortunately, this ideal case does not exist, and a choice has to be made for a less ideal location. This choice ranges between two extremes. Both of these extremes are illustrated in figure 5.2, and are discussed in the paragraphs below.

Figure 5.2: A simplified schematic illustration of two different locations for electrolysers. The left picture shows an electrolyser located nearby hydrogen consumption with, as a result, a larger dependence on an electricity grid for the transport of offshore wind energy. The right picture shows an electrolyser located nearby renewable energy production with, as a result, a larger dependence on a gas grid for the transport of offshore wind energy.

5.3.1. Locating electrolysers nearby hydrogen consumption hubs

The first extreme, illustrated in figure 5.2 on the left, would be to locate electrolysers as close to the location of hydrogen consumption as possible. This option is mostly envisioned by industrial actors, who tend to perceive hydrogen as a high-value raw fuel or feedstock consumed in transport, heating and industrial sectors [P9][Drift, 2020]. Especially in the first development phase of hydrogen technologies, this is seen as a good starting point; because a hydrogen network is still non-existent and electrolyser capacity is still relatively small [P7][P12]. As the Dutch government also states in the questionnaire: "the first electrolyser projects will most likely take place onshore and near the industry hubs where the demand for clean hydrogen is higher" [Questionnaire NL].

However, as electrolyser capacity grows, such a location could become challenging. For the more land inwards production, this would result in electrolysers tapping into an existing electricity grid (assuming not all hydrogen can be produced on-sight due to the space needed for RES) [P9]. This would put increasing pressure on the electricity grid. Such increasing pressure can best be exemplified with the example that an electrolyser could have the same capacity as the electricity demand of the city of Amsterdam [TenneT, 2020c].

5.3.2. Locating electrolysers nearby offshore wind production

The second extreme, illustrated in figure 5.2 on the right, is to locate electrolysers as close to renewable energy sources as possible. Hydrogen would then be transported using gas infrastructure.

Mostly Dutch, German, Belgian and Danish TSOs mention a preference for an electrolyser located nearby offshore wind production or other RES. These actors mention that adequately located electrolysers and gas storages could have the potential to reduce the need for additional electricity lines [TenneT, 2020b][Gasunie,TenneT, 2020][P4][P9][Energinet, 2020][Anonymous][TenneT, 2020c][Gasunie,TenneT, 2020]. These electricity lines would be necessary to supply electrolysers with electricity more land inwards. Furthermore, several actors consider the decreasing public acceptance of high voltage electricity transmission lines to be a driver for more use of gas infrastructure (given gas infrastructure is less visible) [IEA,BMWi, 2020][DE BMWi, 2020a][Anonymous][BE federal government, 2019b][Energinet, 2019a][Energinet, 2019b][Energinet, 2019d][Elia, 2018] [Elia, 2020].

These actors also mention that in the more extreme case, locating electrolysers nearby offshore wind production could relieve otherwise expected electricity grid bottlenecks. Bottlenecks could be relieved because, compared to the case where electrolysers are connected to the electricity grid, it is less likely that the electricity grid would reach its limit. It would be problematic if the electricity grid were to reach its limits. For instance, this could stall (local) RES growth and electrification developments, which is inefficient for the energy transition as a whole [Elia, 2020][DENA, 2019][TKI Nieuw Gas, 2019]. Surely, electricity grids could be expanded to support such an increase in the capacity of electricity lines. However, some also deem such expansions less cost-efficient, as some actors also assume that transport of gasses is more cost-efficient. This is reasoned due to the larger capacity of gas infrastructure and higher energy density of gas [Fluxys, 2019][TenneT, 2020c].

Such a strategic location nearby offshore wind production is deemed specifically important for the north to south connections across countries where power generation and consumption are divided. Otherwise, the electricity grid throughout the whole country would have to be strengthened to supply energy to the location of consumption in the South. This is mostly the case in Germany and to a certain extent in the UK (although UK actors focus on solving this problem with electricity reinforcements) [Gasunie,TenneT, 2020][TenneT, 2020a][TenneT, 2019a][DE BMWi, 2020a][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][NationalGrid ESO, 2019a][H-Alba][CCC, 2018][Frontier Economics, RWTH Aachen University, 2019][Crown Estate Scotland, 2018][TKI Nieuw Gas, 2019][DENA, 2019][FNB Gas, 2019].

5.3.3. Locating electrolysers offshore or onshore

The exact distance between electrolysers and offshore wind sources also depends on the decision to place them onshore or offshore.

As mentioned in chapter 4, most offshore wind parks are currently foreseen to be connected with electricity cables with mostly electricity TSOs responsible. Gas TSOs do not focus on connecting offshore wind parks in their energy visions, although they are involved indirectly in stakeholder meetings [Anonymous][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][P1].

There is a potential recognised for synergy of gas infrastructure, also between countries, as increasingly offshore wind projects are placed far into the sea nearby the national borders due to the stable wind speeds there. This presence of offshore gas pipelines is seen to be a driver for offshore electrolysers (in the Netherlands and the UK) [P14].

Such reuse of offshore gas pipelines is seen to be easier for spatial planning of the North Sea as no new permits are needed, compared to new permits being needed for installing new electricity grids. This is considered by some to also increase offshore RES developments [The Offshore Energy Platform, 2020]. In conclusion, the use of gas infrastructure when integrating offshore wind into the energy system could be beneficial because, in the future, TSOs expect that in some cases connecting offshore wind parks in time will be a bottleneck for installing more wind parks [P14].

The preference actors have for either locating electrolysers on or offshore is also related to the available space different countries have in their part of the North Sea.

For instance, previous research showed that the Scottish and Danish area of the North Sea is expected to be able to fit new corridors to connect offshore wind parks. Dutch actors are expected to prefer using existing gas infrastructure corridors due to the lack of space in their North Sea area. Furthermore, Belgian and German actors would probably have to consider different solutions for connecting offshore wind generation to an electricity or gas grid, as in their areas of the North Sea, there is neither space nor offshore gas infrastructure available for reuse [Anonymous][P14][Questionnaire][Crown Estate Scotland, 2018].

Due to the different space actors have in the North Sea and the different availability perceived for reuse of gas infrastructure, it is inevitable actors' preferences for the use of offshore gas infrastructure will also differ. This more local optimisation does not specifically lead to incompatibility between the local regions. Although, it could become more challenging if actors would want to collaboratively connect their offshore wind parks to the gas or electricity grid, as they perceive economic benefits to do so.

Although Danish actors do not have a lot of gas infrastructure offshore, Danish actors are most explicit on their vision of offshore electrolysers on an energy island. Although more actors do envision a certain energy island (e.g. the North Sea Wind Power Hub), Danish actors, and especially the TSO Energinet, envision the use of energy islands in a shorter term than other actors in the NSR [UK Oil & Gas authority et al., 2020][P9]. Their ambitions are high, despite the socio-economical value of such an island not yet being proven [Energinet, 2020]. These ambitions could create an interesting first-mover advantage for Danish actors, which, if successful, could be beneficial for energy island developments in the whole NSR. For instance, the collaborative North Sea Wind Power Hub (NSWPH), of which TenneT, Gasunie and Energinet are a member, also envisions an energy island [P9].

However, also in Denmark, onshore electrolysers are currently mostly preferred as this is currently considered to be cheaper. Danish actors, together with Dutch and UK actors, mention that placing electrolysers onshore is beneficial. This is argued as an electrolyser located onshore is considered less difficult to install. Furthermore, actors consider it easier to connect an electrolyser located onshore to nearby industrial hubs with a high hydrogen demand. Actors also perceive an onshore electrolyser to be beneficial as its residual heat could be used in (onshore) industrial clusters or district heating systems [Questionnaire DK][Provincie Groningen, 2019][NationalGrid ESO, 2019b][P7]. Another reason for placing electrolysers onshore is that an electrolyser can be supplied by several renewable energy sources (e.g. offshore wind, onshore solar energy). This is expected to increase the capacity operation of an electrolyser and to therefore increase the output (and economic profits) of an electrolyser [P9].

Nonetheless, a role for energy islands is expected in the future. This is expected to occur when offshore wind is installed farther out in the North Sea. In that case, hydrogen is expected to be a more efficient method for transporting energy due to expected electricity losses of electric cables and costs of having to install such long and high capacity electric cables.

Lastly, during these aforementioned discussions, one should also consider the effect of ‘wireless offshore wind parks’ running directly to an electrolyser. Such parks are not connected to the electricity grid. Estimates for annual load factors of wind turbines in the UK are seen to range from 32% to up to 55%. Electrolysers connected to ‘wireless offshore wind parks’ would only produce hydrogen 32% to 55% of the time at full capacity [CCC, 2018].

This could be seen as beneficial as these electrolysers could not use scarce electricity from the grid, otherwise leading to a larger increase in peak demand and a larger necessity for electricity grid reinforcements. However, ‘wireless offshore wind parks’ could also be seen as a missed opportunity. This is reasoned as, in times of electricity shortages, the electrolyser would not be able to ramp down and provide its offshore wind energy to the in-land (electric) baseload.

Different energy visions on the use of ‘wireless offshore wind parks’ could lead to incompatibilities in the energy system because the flexible character of electrolysers envisioned by some actors (e.g. TSOs) could not be present in the energy system if other actors only envision the use of ‘wireless offshore wind parks’. This topic is not discussed by many actors.

In summary, the preference for the location of electrolysers differs per actor, both dimensionally (TSO/industrial actors) and geographically.

Considering the dimensional difference, for one specific location, some actors benefit from a certain location, and some actors find hindrance in the same location [P14]. This can occur when considering the preference of industrial actors (nearby hydrogen consumption) and the preference of some TSOs (nearby location of offshore wind energy production).

Furthermore, there are several different geographical factors that determine a preference for a certain location of an electrolyser. These factors include the proximity to hydrogen consumers, the existence of nearby gas infrastructure, the extent to which electrolysers can help optimise electricity grid expansions and the presence of a strengthened electricity grid that has enough capacity to supply electricity to an electrolyser [P3][DENA, 2019][P16][CCC, 2018].

In conclusion, the different visions on electrolyser location are not seen to be incompatible with each other. They are not incompatible as different electrolysers can be located differently, existing together in one envisioned energy system.

The visions only become incompatible with each other if different actors envision a different location for the same envisioned electrolyser. However, it remains uncertain in how many cases several actors are responsible for the location of one electrolyser.

Lastly, incompatibility could also arise if TSOs do not have any control over the location of electrolysers, but do envision a certain specific location for electrolysers which is beneficial for the management of energy infrastructure. This could be problematic as poorly placed electrolysers could increase societal infrastructure costs, which are the responsibility of the TSO. As mentioned in the introduction, this could lead to high costs of several hundred million Euros per year for every 9 GW of suboptimally placed electrolysers [TenneT, 2020c].

5.4. Theme 4: Visions on the role of flexible power plants when integrating offshore wind

This section discusses what roles different actors perceive for gas infrastructure when there is a shortage of offshore wind energy (and other RES such as solar power) for days or weeks. Such a period of energy shortage is defined as a ‘dunkelflaute’ [Elia, 2019b][P2].

In the current energy system, power plants based on fossil fuels are used in such a period of renewable energy scarcity. A choice is made specifically for flexible power generation because such power plants have the ability to quickly ramp up and down [OFGEM, 2020].

In the future, shortages (and peaks) of electricity production are set to increase due to an increase of volatile RES in the energy mix, electrification and decommissioning of coal and nuclear baseload [Gasunie,TenneT, 2020]. As a result of these increasing peaks, actors envision a variety of solutions to maintain the generation adequacy of the energy system.

Some of these options to supply peak electricity demand are (peak) power plants based on fossil fuels (e.g. fuelled by natural gas, coal). This is not perceived by actors as a final solution because all actors aspire to decarbonise their energy system. For a decarbonised energy system, there are also several options. The following paragraphs described these options and the preference of different actors. Subsequently, it is concluded that most actors envision a certain role for the use of natural gas for managing a ‘dunkelflaute’ in their energy system. In a separate subsection, these different types of roles actors envision are further discussed, concluding if these different visions are compatible or incompatible with each other.

In almost all energy visions, actors perceive a role for battery storage, interconnection and demand side response to manage generation adequacy in an energy system. However, most actors consider these technologies to not be (technically and economically) sufficient for supplying flexibility on a weekly and seasonal basis [TenneT, 2020c][P3][EZK,CIEP, 2020][DE BMWi, 2020a][Gasunie,TenneT, 2020][Energinet, 2020][BP, 2020].

There are several other options that could provide decarbonised electricity in times of a shortage of renewable energy sources, in the timeframe of days, weeks and seasons. These options include compressed air storage, pumped hydro and nuclear generation. However, because these technologies are not deemed sufficient to maintain generation adequacy in the NSR, flexible power plants are considered a necessity. Specifically, actors consider a role for flexible power plants fuelled by hydrogen, natural gas use with CCUS and bio-energy with/without CCUS.

Before elaborating further on the role of flexible power plants, this paragraph first explains why actors do not deem compressed air storage, pumped hydro and nuclear generation sufficient to maintain generation adequacy in the NSR.

Firstly, not all actors perceive compressed air storage and pumped hydro as a sufficient option to maintain generation adequacy because only some local areas in the NSR have the potential for these technologies. In other words, both technologies depend on geographical access to resources, which is not abundant in the NSR as a whole [Nordic Energy Research, 2020][NO ministry, 2020a][Questionnaire NO][Drift, 2020][DE BMWi, 2020a]. For instance, Norway has a large potential for pumped hydro, as was also mentioned in chapter 4. Nonetheless, the Nordic hydro capacity is not deemed to be sufficient to solve Europe's (and therefore the NSR's) challenges with long-term energy imbalances [Nordic Energy Research, 2020].

Aside from compressed air storage and pumped hydro, nuclear generation is also not seen as a sufficient option to maintain generation adequacy in the NSR. Technically speaking, an increase in baseload of nuclear energy could result in a smaller share of RES being needed, and therefore smaller energy supply peaks in an energy system arising. Large scale nuclear plants could therefore play a role in enhancing the flexibility of an energy system. Considering the different actors in the NSR, only UK actors consider nuclear plants a realistic decarbonised substitute for natural gas plants [CCC, 2019]. This can be explained by the currently negative public opinions on nuclear energy in the rest of the NSR. Therefore, the use of nuclear plants is also insufficient to provide the whole energy system of the NSR with enough flexibility on a weekly and seasonal timescale.

As other technologies are not deemed sufficient to guarantee generation adequacy, almost all actors mention flexible (thermal) power generation as a prerequisite to guarantee affordable system flexibility. Reasons that are often given for this conclusion is that alternatives that aim to enhance system flexibility are inadequate or too expensive [CCC, 2020][DE BMWi, 2020a][TKI Nieuw Gas, 2019][Nordic Energy Research, 2020][CCC, 2019][OFGEM, 2020][IEA,BMWi, 2020][DE BMWi, 2020b][Provincie Groningen, 2019][Fluxys, 2019][NationalGrid ESO, 2020a][NationalGrid ESO, 2019b][Nordic Energy Research, 2020][Gasunie,TenneT, 2020][Elia, 2017a][BE federal government, 2019b] [Elia, 2017b][TKI Nieuw Gas, 2019][Power Responsive UK, 2019][NationalGrid ESO, 2019c][P2][DE BMWi, 2020a]. Some Norwegian and, to a certain extent, Danish actors form an exception to this statement. This is reasoned as their energy systems rely mostly on Norwegian pumped hydro for flexibility and are therefore not in need of flexible power generation [NO ministry, 2020a][Gassco, 2019a][Nordic Energy Research, 2020].

In this research, flexible power plants are specified as power plants that are supplied with gaseous fuels that produce electricity. Additionally, such power plants also have a flexible character; being able to ramp up and down relatively fast in the role of a peaking plant. This section intentionally does not elaborate on the technical details of such flexible power plants, as this was also not done in the empirical data analysed and is therefore out of scope for this research.

5.4.1. The use of biogas and green hydrogen for generating peak electricity

Actors mention several carbon-neutral fuels to generate peak power with. Mostly, natural gas with CCS (i.e. blue hydrogen), green hydrogen, or biogasses are discussed as options. For the NSR, green hydrogen and biogasses are not deemed sufficient to maintain generation adequacy in the energy system. The reasons for this perceived insufficiency are discussed in the following two paragraphs.

Biogas, in the form of biomethane, can be used in existing gas-based turbines almost without modification [P4][NationalGrid ESO, 2020a]. Most actors perceive a small role for flexible use of biogas [NationalGrid ESO, 2020a][NationalGrid ESO, 2019b][Equinor, 2019][CCC, 2019]. The only exception to this rather small role considered for biogas to fuel flexible power plants are some Danish actors and, to a smaller extent, Belgian actors [NationalGrid ESO, 2020a][NL EZK, 2020a][Fluxys, 2019][Elia, 2017a][DE BMWi, 2020b][Danish Council on Climate Change, 2020][Energinet, 2019e][P2][P9] [FutureGas, 2020][Equinor, 2019][P4][FNB Gas, 2019][DE BMWi, 2020a][Elia, 2017a][BE federal government, 2019b] [Fluxys, 2019][FNB Gas, 2018]. This role is considered to a smaller extent by Belgian actors due to current insufficient public support for biogas [Anonymous].

The role actors envision for biogas does remain uncertain. Nonetheless, differing visions on the role of biogas does not necessarily lead to an incompatible energy system. This is reasoned because, considering cross-border infrastructure, biogas can be transported simultaneously in the gas grid together with natural gas.

The following paragraph considers the role actors envision for green hydrogen as a fuel for a flexible power plant. This role is also envisioned by some actors, although not in the near future. Most actors reason their disfavour by mentioning the large efficiency losses of using green hydrogen as a fuel for flexible power plants. Such efficiency losses are considerable, as a ‘round trip of electricity’ (of ‘electricity to hydrogen to electricity’) has an approximate efficiency of 35% [Kotowicz et al., 2018].

Actors also reason their disfavour by stating that it is inefficient to use a ‘scarce’ and ‘valuable’ product such as green hydrogen for an application that could also be executed with other fuels [P19][DE BMWi, 2020b][DE BMWi, 2020a][P3][Natuur en Milieu, 2020][FNB Gas, 2018].

In contrast, other actors do mention a possibility for green hydrogen to play a role in the far future. They reason this because, in the future, they expect green hydrogen to become cheaper or the pricing for flexibility to become extremely high, making green hydrogen a cost-efficient alternative [DENA, 2019][NationalGrid ESO, 2020a][Anonymous]. Therefore, the role of green hydrogen as a fuel for flexible power plants remains uncertain.

5.4.2. Envisioned use of natural gas & CCS or blue hydrogen for flexible power generation

Considering that the previously mentioned fuels are not expected to play a large role for balancing power, it seems evident that natural gas is expected to be used as a transition fuel [P16]. A role is seen for either natural gas, natural gas with CCS post-combustion or CCS pre-combustion (blue hydrogen) [Gassco, 2019b][KonKraft: A collaboration arena for the Norwegian Oil & Gas Association et al., 2020]. The differences in necessary infrastructure between natural gas with CCS post-combustion and blue hydrogen are illustrated schematically in figure 5.3. The left figure illustrates how blue hydrogen is first produced from natural gas. Carbon is then captured pre-combustion of natural gas. In this case, hydrogen is transported in a hydrogen network to different flexible power plants to create electricity. The right figure illustrates how natural gas is transported to flexible power plants to produce electricity. In this case, CO2 is captured post-combustion, and is transported from the power plant to a CO2 storage location.

Technically speaking, CCS pre-combustion is deemed more cost-efficient and easier than CCS post-combustion, although there are many different elements to consider which could change this narrative [P13][Natuur en Milieu, 2020]. This includes the costs for repurposing an existing flexible power plant stack or for a new hydrogen-fired flexible power plant. The latter is expected to be more expensive as technically speaking, repurposing is relatively simple [Gasunie,TenneT, 2020][Natuur en Milieu, 2020]. However, the technical details and developments are out of scope for this research.

Increasingly, turbine manufacturers are adjusting their products to meet a future where hydrogen operations may be relevant. For example, all the major manufacturers supplying gas turbines to the European market have jointly declared that all new turbines supplied from 2020 should be able to be operated with natural gas mixed up to 20% hydrogen, and with 100% hydrogen from 2030 [NO ministry, 2020a]

Nevertheless, this research focuses on the visions of different actors on flexible power generation, which has an effect on cross-border transportation of gasses. These choices are mostly perceived differently by national actors. They are considered to be dependent on the role actors consider for CCS, the current role of power generation, the actors’ need for natural gas imports/exports and the uncertainty actors consider of both CO2 and natural gas price [P1][Anonymous]. Based on these differences, it is deemed almost inevitable that a future energy system will have natural gas, hydrogen and CO2 pipelines, although this is not the most technically and cost-effective solution. The six paragraphs below elaborate further on the different geographical characteristics and preferences for each country, building on chapter 4.

In Denmark, the use of CCS and natural gas is not mentioned specifically in energy visions analysed. The Danish are not in need of as much flexible power generation, and quite a large role is seen for biogas [Energinet, 2020][Danish Council on Climate Change, 2020][P9]. In the transition period, some use of natural gas is expected to take place, although several actors in Denmark speak of trying to become independent of natural gas [P9].

The Norwegian energy system is only slighlty dependent on fossil fuel based flexible power plants (0.2 GW) and also has no intention to use hydrogen for such purposes [Gassco, 2019a][NO ministry, 2020a]. The Norwegian government sees an opportunity for exporting their natural gas supply, producing blue hydrogen and storing CO2 [Gassnova NO, 2020][Questionnaire NO].

The Norwegian hydrogen strategy states that in the development phase, hydrogen production is expected to be closer to the end-user. This location of blue hydrogen production is preferred because

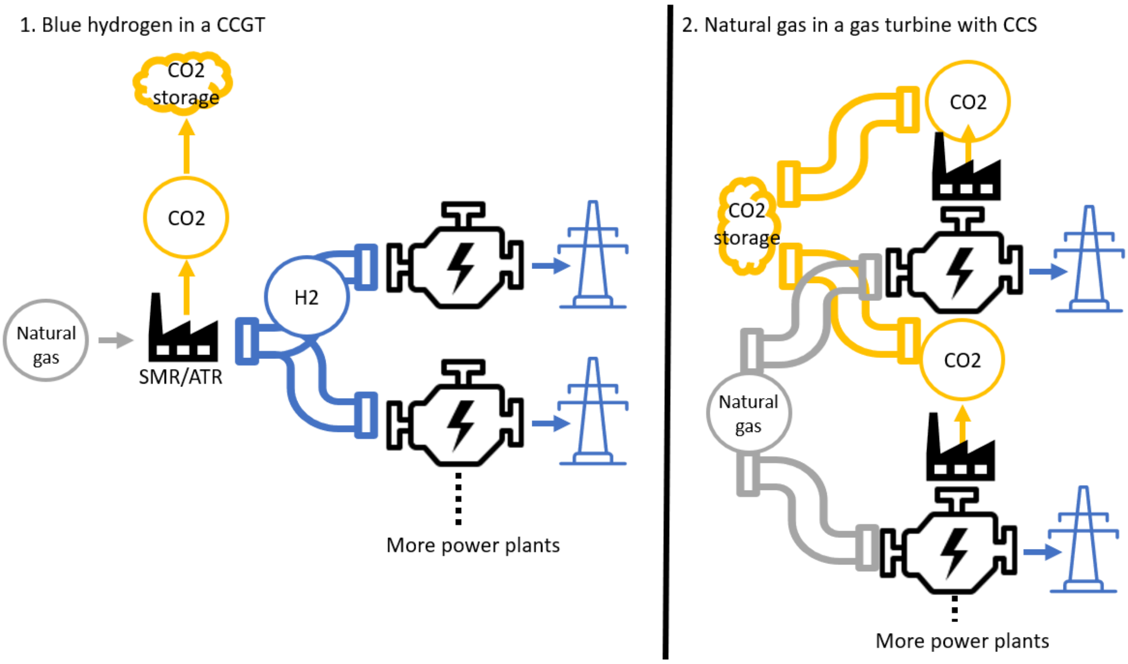


Figure 5.3: A simplified schematic overview of two different production methods for flexible power generation with CCS. For the left image, carbon is captured 'pre' natural gas combustion (CCS pre-combustion). Blue hydrogen is then distributed to power plants via a gas network. For the right image, carbon is captured 'post' natural gas combustion. Natural gas is then distributed to power plants via a gas network, and CO2 has to be transported from the power plant to a CO2 storage point.

of the higher expected investment and transport costs per delivered energy unit for hydrogen than for natural gas [NO ministry, 2020a][P16]. If and when a hydrogen market has matured, large scale (blue) hydrogen export is considered a realistic option in the future. In that case, hydrogen is considered to be transported in pipes or optionally on ships in the form of ammonia [Questionnaire NO][P16]. Blue hydrogen production in Norway is only perceived as an option if there is limited demand for natural gas without CO2-handling, if there are stricter requirements for GHG emissions and if there is a demand and willingness to pay for blue hydrogen. These requirements are seen to be necessary as a significant scale is needed to justify investment in new infrastructure (pipelines). Additionally, actors also want to prevent a lock-in of a hydrogen network, not being able to transport other gasses [P16][Questionnaire NO]. Ultimately, both the Norwegian ministry and Equinor conclude that it is up to the market to assess whether the export of blue hydrogen from Norway will become commercially attractive in the future. Comparing the different markets in the NSR, currently, there is already a lot of cooperation with UK actors (e.g. for blue hydrogen) [Questionnaire NO][P16].

In conclusion, Norwegian energy is expected to be exported in the form of natural gas and hydrogen, and CO2 is expected to be imported from other countries. It is unlikely a choice between different options will be made actively [P17].

UK actors envision natural gas to play a large role in flexibility; enabling flexible power system emissions to get close to zero by the 2040s, or in the case of Scottish energy visions by 2030 [CCC, 2018][CCC, 2019][H-Alba][P13]. To decrease emissions from natural gas-fuelled flexible power generation, UK actors are focused on the role of CCS [CCC, 2019] [UK Oil & Gas authority et al., 2020] [Savenkova, 2020] [NationalGrid ESO, 2020a][P17].

In their energy visions, UK actors mostly focus on CCS pre-combustion with a hydrogen-fuelled flexible power plant. This option is considered to have lower capital costs, making hydrogen-fuelled flexible power plants more economical when annual running hours are low. In contrast, post-combustion technology is deemed more expensive to run (even for limited hours), especially considering a potentially high carbon price and difficult to avoid residual carbon emissions of such power plants [NationalGrid ESO, 2020a][CCC, 2020].

UK actors also mention a preference for CCS pre-combustion because one could then avoid the need for building new onshore CO2 transportation infrastructure. This is avoided if hydrogen production is located in coastal areas, nearby CO2 storage facilities [CCC, 2018].

This preference for CCS pre-combustion is exemplified in the plans of UK government advisory board CCC. In these plans, they recommend that decisions to build gas plant during the 2020s (and beyond) should consider opportunities for fitting CCS technology or retrofitting to become 'hydrogen or ammonia ready' [CCC, 2019][CCC, 2018].

Most Belgian actors consider natural gas to be a 'transition fuel'. However, actors are uncertain of the decarbonisation route of natural gas for flexible power generation [P4][P2]. The Belgium energy system is dependent on RES imports and, due to no large CO2 storage being present, CO2 exports. Therefore, Belgian actors tend to be more anticipative of imports and exports in the form of natural gas or blue hydrogen [P4][P3].

Despite the situation in Groningen described in Chapter 4, in their Climate Agreement, Dutch actors foresee the necessity for a role for natural gas in a CO2-free energy system in 2050 [P12][Klimaatakkoord, 2020][TNO, 2020]. The advisory board for the Dutch government and Groningen government mention that natural gas power stations with CCS post-combustion seem less feasible or promising than hydrogen-fired power stations [TKI Nieuw Gas, 2019][Provincie Groningen, 2019]. Most projects and visions by Dutch actors also assume CCS pre-combustion and not CCS post-combustion [P13] [EZK,CIEP, 2020].

Advisory plans for the Dutch government consider it necessary that demonstration projects of controllable and flexible hydrogen-based power stations in large-scale practical projects are ready by 2030 [TKI Nieuw Gas, 2019].

German federal government and gas TSO conclude that gas is not expected to disappear any time soon (15 years) due to its flexible character, as it is deemed the green battery of the energy transition by government officials [DE BMWi, 2020a][FNB Gas, 2020][FNB Gas, 2019][Anonymous]. However, there is still uncertainty of the role of natural gas, driven by uncertainty in CO2 price and volatility of electricity price [50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][Anonymous]. Blue hydrogen is never really explicitly mentioned to be used in flexible generation. In their hydrogen strategy, CCS is only mentioned once, and the term "blue hydrogen" is only mentioned in the glossary [DE BMWi, 2020b]. Furthermore, a German TSO mentions that currently installed flexible power plants from the initial power plant stack are seen to have a cost advantage. Initial flexible power plants are considered to have a cost advantage because they already exist and can provide secured capacity in high load situations, while hydrogen-fired flexible power plants require new investments [Gasunie,TenneT, 2020].

In summary, the specific gas infrastructure actors deem necessary for flexible power generation remains uncertain. Generally speaking, CCS post-combustion is mostly not envisioned to be the best option. In contrast, CCS pre-combustion is increasingly seen as an option by different actors.

Although most actors envision a role for such hydrogen-fuelled flexible power plants, actors are uncertain of where and when blue hydrogen production will take place.

A diversity of options and arguments are given for different actors' reasoning, with the possibility of locations being both nearby the flexible power plants and nearby supply of natural gas production and CO2 storage options. This leads to either a more developed CO2 and natural gas network or hydrogen network, as both networks could be seen as complementary to each other [P4]. This is also illustrated in figure 5.3, where a more extensive hydrogen infrastructure is deemed necessary in the left image. In contrast, in the right image a more extensive CO2 and natural gas infrastructure is deemed necessary. Although it should be emphasised that this is a simplified image and the real energy infrastructure is far more complex and dependent on factors such as the locations of natural gas supply, blue hydrogen production, flexible power plants and CO2 storage.

Both CCS pre-combustion and CCS post-combustion are likely to occur simultaneously in the NSR due to the different infrastructural starting points in the area. These starting points include the currently present flexible power plants and the possibilities for such power plants to connect to CO2 transport and storage points [Anonymous][P18]. Due to these different starting points of actors in the NSR, it is likely there will be a necessity for natural gas, hydrogen and CO2 transport in the NSR as a whole

[NationalGrid ESO, 2020a][P17]. The visions of different actors on different infrastructures are not fully incompatible with each other because different infrastructures are able to exist in parallel with each other.

Although different infrastructures can exist in parallel with each other, there is still a degree of incompatibility between different energy visions. Due to different visions, more infrastructure would have to be added than if all actors had the same vision. This could then increase costs of infrastructure, without certainty that these costs are saved in other parts of the business case (e.g. costs to replace gas-fuelled flexible power plants with hydrogen-fuelled flexible power plants, costs of hydrogen infrastructure compared to CO2 infrastructure). For example, if blue hydrogen is produced in different locations, all these locations would need to be connected to a CO2 pipeline.

Such different energy visions become increasingly incompatible when different actors envision different reuse options for the same parts of gas infrastructure. For example, if ‘actor A’ envisions reuse of gas infrastructure for a CO2 backbone, and ‘actor B’ envisions reuse of the same pipeline for a hydrogen backbone.

Furthermore, there is also a timely element, as a gas plant built today may still be part of the energy system in 2050 [CCC, 2019][CCC, 2018]. Solutions that are currently deemed most efficient, based on the different starting points in the NSR, might not be representative of the most efficient energy system in 2050.

Lastly, there also seems to be a competing claim on storage options for gases in the NSR.

Hydrogen is considered to be an energy storage medium that allows for renewable energy to be stored in a flexible manner in gas pipelines and salt-caverns. It therefore helps balance energy supply and demand [DE BMWi, 2020b][NationalGrid ESO, 2020a][Energinet, 2019a][Energinet, 2019a][P9][P12]. However, CO2 also needs to be stored. Bigger fields are considered more suitable for CO2 than for hydrogen storage. Currently, CO2 storage is a bit further in development than hydrogen storage. Actors have a tendency to develop CO2 storage close from shore, where there are some small fields, although such locations could actually be better used for hydrogen. This might lead to an overlap between CO2 and hydrogen storage, with a need to assign the right fields for the right cause [WPC, 2020]. Such possible ‘competing claims on storage potential’ are especially of interest considering that certain actors (e.g. Belgian) are dependent of other actors’ storage potential [P1].

Again this could lead to incompatible energy visions if the same actors envision a different role for the same storage fields.

5.5. Theme 5: Visions on the (re)use of gas infrastructure when integrating offshore wind

When integrating offshore wind, two roles are seen for gas infrastructure. First, offshore gas platforms can be supplied with offshore wind energy to decarbonise the process of natural gas extraction. Such a process can be seen as a precursor of using gas platforms for placing electrolysers offshore. The produced hydrogen could then more easily be transported onshore because the existing gas pipelines are already in place. A second, more general, role for gas infrastructure is envisioned when transporting hydrogen-based gasses from locations of production and consumption. The following two subsections explain both roles for gas infrastructure, and whether the visions actors have on these roles are compatible or incompatible with each other.

5.5.1. Visions on the reuse of gas infrastructure offshore

Some actors consider the option to electrify oil and gas production platforms with offshore wind energy. Currently, most of these platforms use power generators that run on fossil fuels as an energy supply. The energy needed for the oil and gas production process can be decarbonised with offshore wind.

This technological option is not often mentioned in energy visions analysed in this research. Nonetheless, it is highly likely oil and gas industries will electrify their current energy demand. For instance, oil and natural gas industries are increasingly setting targets to reduce emissions to near zero in 2050 [KonKraft: A collaboration arena for the Norwegian Oil & Gas Association et al., 2020][Anonymous]. In some cases, this is expected to have quite an impact on how offshore wind is integrated into the energy system and what role is seen for gas infrastructure. The subsequent paragraphs explain two different functions different actors envision for this type of electrification.

Firstly, actors perceive the electrification of oil and gas platforms as a flexible energy source. These actors consider it as a type of demand side response because in times of scarcity of renewable electricity, due to peak demand or very low RES generation, the oil and gas platforms can be turned off. This could be beneficial for the energy system as it reduces the need for investments in networks and power plants for meeting peak demand [Danish Council on Climate Change, 2020][P16].

The development of platform electrification is mostly discussed by Norwegian consortia, Equinor, the UK oil and gas authority and to a smaller extent by the Danish Council. Although the latter only mentions a ‘medium’ probability to reach a sufficient stage of electrified platforms in 2030 without being unreasonably expensive [Danish Council on Climate Change, 2020]. Other actors, especially from Belgium and Germany, do not mention this development in their energy visions, and in interviews, some even tend to be against it. They consider the production of carbon-based fuels (natural gas/oil) not to be part of the necessary developments to achieve a net-zero GHG target, even if such a production process is decarbonised [Ørsted, 2020][Anonymous].

The large capacities necessary for electrification of oil and gas platforms and the consequences this has on integration of offshore wind should not be underestimated [Equinor, 2019][Statnett, 2019c][Statnett, 2019d] [Gassco, 2019b]. The electrification of this sector is seen by both Norwegian, UK and Danish actors as a driver for floating offshore wind in the future [Danish Council on Climate Change, 2020][Equinor, 2019][Gassco, 2019b][UK Oil & Gas authority et al., 2020].

For example, in the case of the UK, Rystad Energy expects that 60% of NCS production will come from electrified offshore platforms by 2025 [Savenkova, 2020]. The UK oil and gas TSO also approximate a currently required 21 TWh of electricity in 2018 to electrify the oil and gas electrification process. As a comparison, 21 TWh is about 6% of the current UK electricity consumption [NationalGrid ESO, 2020a]. Therefore, oil and gas electricity demand is seen by the UK Oil and Gas consortia to support wind power expansion in new areas, where sharing infrastructure is seen to improve project economics for both sectors [UK Oil & Gas authority et al., 2020].

As a second function, electrification of oil and gas platforms is seen as a step towards eventually installing electrolysers on gas platforms. Subsequently, the produced hydrogen could be transported onshore via the already existing gas pipelines, saving on costs for electric grid connections. Maritime ships could also consume the produced hydrogen directly offshore as a transport fuel.

Recommissioning of such gas platforms could lead to a larger role for gas infrastructure in integrating offshore wind [P14]. Although in a webinar by COGEN Europe (the European Association for the Promotion of Cogeneration) this specific function of electrifying oil and gas platforms is only seen to have a function for 10% of all platforms [Cogen, 2020][TNO, 2020]. This low percentage could lead to some incompatibility in energy visions as more actors envision recommissioning of their gas platform than essentially necessary. In other words, not all oil and gas platforms could be electrified and eventually be recommissioned for hydrogen production because such a large capacity is not needed.

This option for recommissioning gas platforms is most prominently mentioned in energy visions of Dutch actors [TNO, 2020][Anonymous][P16]. In contrast, in an interview, a Norwegian actor explicitly mentioned not to see such a large role for recommissioning previously electrified gas platforms into hydrogen producing platforms [Anonymous]. This standpoint is explained by the actors’ current strategy of specifically electrifying oil and gas platforms that are expected to have a long life-cycle. This way, one can profit as much as possible from the CAPEX investment of electrifying the platform [Anonymous]. With such a long life-cycle, hydrogen production is deemed an irrelevant option.

In conclusion, the electrification of oil and gas infrastructure could lead to a relatively simple opportunity to integrate offshore wind. Different visions on doing so are compatible with each other as some platforms can, and others cannot be electrified in parallel.

However, considering coordination between actors, the claims actors put on offshore wind to electrify oil and gas platforms is not recognised by many actors. This could lead to incompatible visions as different actors envision different uses for the same capacity of offshore wind. Such ‘competitive claims on offshore wind’ and their consequences were also discussed in section 5.1.

5.5.2. Visions on hydrogen gas transport in greenfield and brownfield pipelines

This subsection discusses how hydrogen-based gasses, produced from electrolysers using offshore wind energy, are envisioned to be transported throughout the region.

In general, actors in the NSR consider it likely that hydrogen transport will start within consumption and production hubs as this is deemed easiest. Subsequently, actors expect these hubs to be connected to each other throughout the region in a transnational hydrogen grid, as a 'European hydrogen backbone'. Such a vision on a 'European hydrogen backbone' was published in July 2020 by several European TSOs. Within the NSR, Energinet and the gas TSOs Fluxys and Gasunie were involved in this project [P13][Ørsted, 2020][P19].

Different visions on transportation methods for each individual 'hub' are effectively compatible with each other. Different hydrogen hubs, that transport their hydrogen within these hubs in a different way, are able to exist in parallel with each other. However, these visions do become incompatible when one starts to envision these hubs to be connected to each other and form a hydrogen backbone. In that case, actors envision different characteristics for the same hydrogen backbone, which is technically impossible to be executed. This section further discusses this (possible) incompatibility of different visions on hydrogen transport.

Hydrogen can be transported in ships, trucks or pipelines. Due to the high initial investment required for pipelines, hydrogen is likely to first be transported by ships or inland with trucks [Drift, 2020][P8].

This subsection focuses on hydrogen transport in pipelines (and not in ships and trucks) because different energy visions on pipeline transport are most likely to be incompatible with each other. Different visions on hydrogen transport in ships and trucks are naturally more compatible with each other, because specific ships and trucks could transport hydrogen differently. This is not the case for pipelines. Another reason for the focus on pipelines is that actors perceive a connected uniform hydrogen pipeline network most efficient to support the development of a large scale hydrogen market [Gas for Climate Enagás, 2020][CCC, 2018][TNO, 2020][P14]. Based on this conclusion, this research takes the normative position that a hydrogen backbone is necessary for a large scale hydrogen market to develop and that such a market is beneficial for the energy system.

One can consider several uses for pipelines. Firstly, hydrogen can be blended into the existing gas system. Secondly, a part of the methane grid can be converted to handle hydrogen. Thirdly, hydrogen can be methanised and lastly, hydrogen can be transported in new dedicated pipelines [Energinet, 2020][CCC, 2019]. The following three sections discuss actors' visions on either reusing or newly constructing gas infrastructure for hydrogen transport (1), the timing actors envision for gas infrastructure to be reused or newly constructed (2) and the forms in which actors envision hydrogen to be transported (3).

Visions on either reused or newly constructed infrastructure

The following paragraph discusses why specific actors do or do not envision the recommissioning of gas infrastructure for hydrogen transport. The subsequent paragraph discusses why specific actors explicitly do not envision such use.

Several actors are driven towards the reuse of gas infrastructure, with one of the reasons being the otherwise high decommissioning costs for gas infrastructure. Such decommissioning is obligatory, as is mentioned in the 'OSPAR convention Decision' [WPC, 2020]. As an example of the value at stake, the German gas TSO concluded that a total one-off expense of EUR 3.1 billion in dismantling costs could be assumed for dismantling or securing pipelines in the German transmission network (approximately 22,500 kilometres) [FNB Gas, 2018].

Actors have different starting points when it comes to recommissioning gas infrastructure, based on the current and expected use of natural gas in their national energy systems. Concluding from chapter 4, in the NSR, Dutch actors are the only actors to currently envision a large role for the reuse of gas infrastructure. Dutch actors mention such reuse as a driver for hydrogen developments because they consider themselves in the unique position to have an empty gas infrastructure available the fastest [Questionnaire NL][P14][EZK,CIEP, 2020]. In contrast, Belgian and Norwegian actors do not expect (significant) infrastructure to be available for reuse up until natural gas consumption decreases [P1]. An explanation for this development could be their current role as a natural gas transit hub (Belgium) and natural gas production hub (Norway) [P1]. Additionally, Denmark is claimed to not have a lot of natural gas demand, and therefore not a lot of gas infrastructure in general. This also leads to a relatively small perceived role for reuse of gas infrastructure [P9].

Some actors are still in the phase of transitioning their energy system to be dependent on an increased use of natural gas, and others are already thinking and setting up a hydrogen network. COVID-19 has made the process even more diverse and uncertain as recommissioning might be sped up due to the low oil and natural gas price, or slowed down as there is no capital present for recommissioning [The Offshore Energy Platform, 2020][WPC, 2020].

Belgian, UK, German, Danish and some Dutch actors' hydrogen developments are less driven by the recommissioning of gas infrastructure. These actors consider it irresponsible to make such a long term decision only based on the decommissioning cost of gas infrastructure [VARIO, 2020][Crown Estate Scotland, 2018][P5][FNB Gas, 2020][DNV GL, 2020][Fluxys, 2019][Energinet, 2019a]. For example, the UK CCC mentions that "the sunk costs of having an extensive gas grid do not automatically mean that it will be lower cost to switch it [heating applications] over to hydrogen and use it in boilers as we do with natural gas at the moment" [CCC, 2018](*Page 7*).

Other actors also mention that it is still uncertain if recommissioning is technically feasible. Furthermore, these also mention that the necessary additional recommissioning costs are also uncertain [Questionnaire][CCC, 2019]. This includes elements needed for a new coating, the need for suitable seals and the need to counter vibrations that occur when transporting hydrogen [TKI Nieuw Gas, 2019]. This topic is often not considered in energy visions that were analysed. Therefore, there seems to be a necessity for a more detailed balance between the costs of retrofitting gas infrastructure and constructing new infrastructure [P8].

In conclusion, different actors consider different options for recommissioning of gas infrastructure, mostly due to their different current energy systems. Therefore, transition management with "phased and balanced conversion and construction of [hydrogen] infrastructure" could be needed in the NSR, with both attention to the construction of hydrogen infrastructure and the reuse or phaseout of the current (natural gas) system [TKI Nieuw Gas, 2019](*Page42*).

Although, it is important to accept that the transition of gas infrastructure is unlikely to be optimal. This does not make the differing visions necessarily incompatible with each other. Such less optimal transport does not necessarily result in a non-operable energy system. It is likely that actors will always find a way to eventually transport hydrogen. For instance, German actors state that if their own gas infrastructure is not ready yet, they would consider consuming hydrogen via the Dutch hydrogen backbone [Anonymous][Anonymous].

Two other important themes are relevant to consider during the development of a hydrogen pipeline network. Firstly, it is important to consider what timing actors envision for a cross-border hydrogen pipeline network to develop. Secondly, it is important to consider the type of gas transported in such a network. Both considerations are further discussed in the next paragraphs.

Timing of gas infrastructure (re)use

The following paragraphs discuss the different timing actors foresee for the reuse of gas infrastructure. Firstly, a general overview is given on what options actors see for reusing their gas infrastructure. Next, an insight is given on the other uses actors envision for reused gas infrastructure and if this is competitive with the role seen for hydrogen transport. Lastly, the possible consequences of a time-gap between decommissioning of gas infrastructure and reuse of the same gas infrastructure are discussed.

In the short term, no actor within the NSR plans to cease natural gas transport and consumption as a whole. Although, in the longer term, there are differences due to the different timing envisioned for natural gas infrastructure to become redundant. This is linked to several topics, including the role foreseen for natural gas in flexible gas-fired power plants discussed in section 5.4.

Generally, EU wide infrastructure developments are currently discussed in the Ten Year Development Plan (TYNDP) of the ENTSO-E and ENTSO-G and in other collaborative organisations. The terms ENTSO-E and ENTSO-G are abbreviations for the European Network of Transmission System Operators for Electricity and Gas, respectively. In these documents, hydrogen infrastructure is not explicitly mentioned to play a large role in the next ten years.

Considering the timing of gas infrastructure reuse, UK, Belgian and German actors are first considering the renovation of their gas infrastructure to transport high calorific gas. Nonetheless, German gas

TSOs believe that reusing pipelines for a hydrogen net could start in 2030, which is identical to visions of Dutch and UK actors [P5][FNB Gas, 2019]. In contrast, Norwegian actors do not find this theme of gas infrastructure reuse relevant as of yet [P16].

The largest opportunities for reuse of infrastructure for hydrogen are seen for both the UK (with a focus on Scotland) and the Netherlands. UK actors mention they expect some elements of their gas infrastructure to become usable in the coming years. However, the assessment of what infrastructure will exactly become available is not yet certain [P14][NationalGrid ESO, 2020a]. Furthermore, Dutch gas infrastructure is expected to become available for reuse in the next decade because of the planned dismantling of various unnecessary pipes [DNV GL, 2020]. Actors also consider plans for the construction of a “hydrogen backbone” to connect the Netherlands’ major industrial clusters by 2030 and demo projects planned in the coming 3-4 years [P14][TKI Nieuw Gas, 2019][Questionnaire NL].

Differently, Norwegian actors, and also some UK and Belgian actors, present the option of recommissioning gas infrastructure for CCS processes [BE federal government, 2019a][CCC, 2020][CCC, 2019][UK Oil & Gas authority et al., 2020][Savenkova, 2020]. Explicitly, the UK Oil and Gas Consortia estimates such recommissioning of gas infrastructure for CCS could lead to 20-30% CAPEX savings of CCS processes in the UK [UK Oil & Gas authority et al., 2020].

Reusing the gas infrastructure for CO2 transport could possibly become competitive with the role other actors recognise for reusing gas infrastructure for hydrogen transport [Questionnaire]. Such different visions could be incompatible with each other as different actors envision a different purpose for the same piece of gas infrastructure. This incompatibility and its consequences were already further explained in section 5.4.

Furthermore, a time gap could occur between the current use of gas infrastructure and future use of that same infrastructure for alternative energy purposes. Such a time gap is defined as the gap between planned decommissioning of gas infrastructure and planned reuse of the same gas infrastructure. If this gap is too large and developments of hydrogen infrastructure are not yet deemed necessary, obligated by law, gas infrastructure would have to be decommissioned. In that case, a lot of potentially reusable infrastructure is likely to disappear [DNV GL, 2020][Drift, 2020].

One would expect that such a time gap would often be mentioned in energy visions analysed. Nonetheless, this topic is not mentioned often in analysed energy visions, in contrast to the topic often being mentioned by the Dutch gas TSO, and in more industrial-focused webinars and interview discussions. The phrase “mind the gap” is often mentioned in such webinars [WPC, 2020]. Why such a time gap is not often mentioned remains unclear. It could be that actors deem the reuse of gas infrastructure for hydrogen highly uncertain and too far into the future to explicitly consider. For instance, actors mention that more research is necessary on the suitability and modification of natural gas infrastructure for the transport of hydrogen [Questionnaire].

Nonetheless, it could also be the case that TSOs and government actors are aware of such developments, but do not relate them explicitly to hydrogen transport developments. One could understand the challenge of including such considerations in their energy visions. For instance, some gas TSOs are almost in conflict with themselves as they perceive a longer and larger role for natural gas but also envision ambitious roles for hydrogen to secure their position in the energy system in the long term. Furthermore, most (electricity) TSOs focus on electricity grid reinforcements and envision gas infrastructure more as a future option.

In conclusion, comparing different visions on the timing of reusing gas infrastructure remains difficult because not all actors (e.g. electricity and gas TSOs) explicitly mention this topic. Some of the visions, that do explicitly mention this topic (e.g. gas TSOs, industrial actors and some governments), tend to have differing visions on the timing of reuse. Nonetheless, different timing is deemed inevitable, because of the different starting points and geographical factors of various countries’ energy systems [P3].

These differing visions are not explicitly incompatible with each other because different timing of recommissioned gas infrastructure can exist in parallel with each other. This is the case, presuming that actors who consider the same piece of gas infrastructure do have identical visions. However, visions do become incompatible when a specific actor envisions and bases their own individual energy vision on the assumption of a future large scale European hydrogen backbone. Therefore, to increase the compatibility between energy visions, one could argue that it is important that the timing of such a backbone is envisioned the same way by all actors. Although, the type of infrastructure, be it with reused gas infrastructure or newly constructed gas infrastructure, is not as important.

Type of gas transported and blending opportunities
As previously mentioned in the introduction of this section, different distribution grids are expected to be interlinked with each other in the far future to create a hydrogen network. The moment this interlinking occurs, it would be beneficial if the same type of renewable gasses is already transported in individual grids. Otherwise, these grids are difficult to interconnect with each other. More effort would be needed to alter either the production process or consumption process of individual grids to align them into a 'backbone'.

The type of gas transported in individual grids is an important discussion topic. The forms hydrogen could be transported in include ammonia, biomethane, pure hydrogen or hydrogen blended into natural pipelines. Differences in envisioned transportation forms tend to occur due to the different applications and production methods envisioned by different actors [Drift, 2020].

Transporting hydrogen in the form of ammonia is considered to be out of scope for this research. Furthermore, the topic of biomethane has previously been discussed in section 5.4. Therefore, this section focuses on the discussions between either transporting hydrogen in its pure form or blending it into the natural gas grid. The following three paragraphs elaborate on the current state of visions on blending, what advantages actors present and subsequently, what disadvantages actors present in their energy visions.

Currently, there are different national limits for blending, which include a minimum of 2% blending of hydrogen into the natural gas grid in Belgium and 0.1% in the UK [Questionnaire][TKI Nieuw Gas, 2019][VARIO, 2020][H-Alba][CCC, 2019][Crown Estate Scotland, 2018]. As a reference point, blending up to 20% is stated as a safe limit in various technical studies. Such a percentage is said to also be tolerated by domestic appliances [Crown Estate Scotland, 2018].

Currently, actors do not have a unanimous preference or disfavour for blending, while a certain shift is recognised away from blending [P9][Anonymous]. However, the gas TSOs of Germany have recently (Dec. 2020) released a public vision on blending and in the UK Chancellor's Spring Statement, there was a commitment to accelerate the decarbonisation of natural gas supplies through blending [Anonymous][H-Alba][FNB Gas, 2019][P5][Power Responsive UK, 2019]. Most Belgian actors also seem to consider blending hydrogen an option [Elia, 2017a][BE federal government, 2019b][Fluxys, 2019]. In addition, on a European level, the EU is researching ways to stimulate sustainable gasses with an obligatory blending percentage of 10% [Elia, 2017a][BE federal government, 2019b].

This diversity of visions on blending could be considered quite logical because developments for hydrogen transports are still in the experimental beginning phase [Anonymous]. However, it is important to understand the arguments made on both sides to gain insight into how different actors consider different advantages and disadvantages of blending.

Currently, many actors from the NSR (BE/DE/UK/DK/NL) are researching the limits and possibilities of blending [VARIO, 2020][BE federal government, 2019b][Fluxys, 2019][DE BMWi, 2020a][FNB Gas, 2020][FNB Gas, 2020][CCC, 2018][H-Alba][Energinet, 2019a][Energinet, 2019d][Energinet, 2019e] [Ørsted, 2020][NL EZK, 2020b]. Different actors mention that blending hydrogen could manage off-take risks. In this case, off-take risks are defined as the risk of not making a profit on investments for new energy production. Actors consider the off-take risk to be more manageable when blending. They reason this by stating that ,with blending, one could easily scale up hydrogen demand in the transition phase and reduce emissions without needing significant (costly) infrastructure changes and investments [GL, 2020][Crown Estate Scotland, 2018][DENA, 2019][H-Alba][UK Oil & Gas authority et al., 2020] [Questionnaire][NO ministry, 2020a][EZK,CIEP, 2020]. Specifically, both the Dutch hydrogen strategy and UK Crown Estate energy vision mention that a blending obligation could be beneficial for speeding up developments for offshore (floating) wind energy [NL EZK, 2020b][Crown Estate Scotland, 2018]. Blending is also considered a more flexible option because one can increase blending percentages throughout the decade. Blending could then providing a route for constrained (floating) wind energy [Crown Estate Scotland, 2018][CCC, 2018].

Actors also consider blending to allow the spreading of costs, either through regulation or consumer choice. Costs are spread when blending hydrogen because many consumers would pay a small premium instead of concentrating costs on only several consumers [Drift, 2020][Crown Estate Scotland, 2018]. Although this benefit could also be achieved through ‘virtual blending’, where physically no hydrogen gas is blended but virtually several actors pay for the hydrogen use of one actor and share the benefits of the GHG decrease [Anonymous].

Actors opposed (or indecisive) to blending state that hydrogen is best transported in its pure form, as one loses the value of hydrogen if it is blended with methane [P2][P10][P8]. For example, e-fuels based on pure hydrogen are deemed more valuable. Furthermore, blended hydrogen is not able to supply fuel cells, which could be problematic for certain applications [P5][Crown Estate Scotland, 2018][Drift, 2020].

In addition, actors also consider blending to lead to a lock-in of certain applications, which could only run on certain blending percentages. This is considered to be problematic because these applications would not likely be relevant in a fully decarbonised economy [Ørsted, 2020].

From a more short term point of view, hydrogen applications are also challenged because the admixture percentage is likely to be unstable due to flexible hydrogen production [Anonymous][P10].

Another disadvantage for blending are the high capital costs for upgrading the transmission network to prevent embrittlement and gas losses. Furthermore, actors mention that if one was to blend hydrogen into a certain gas grid, all connected industries to this grid that are unable to switch to such a blended gas would lose their piped natural gas supply. Subsequently, these industrial facilities would need to use other natural gas delivery methods [UK Oil & Gas authority et al., 2020]. As a consequence, consumers that share the same natural gas grid would be dependent on what blending percentage an individual consumer can handle [Anonymous].

In summary, one could expect hydrogen to both be transported in a pure and in a blended form under different circumstances, based on the advantages and disadvantages mentioned above [VARIO, 2020]. Actors that consider a scarcity of gas infrastructure could tend more to blending than other actors. In addition, actors that envision the need to transport a relatively low capacity of green hydrogen could also tend more to blending. One could reason this by concluding that a smaller amount of hydrogen is seen to be transported more easily in an existing natural gas grid [P9].

Such different visions could become increasingly incompatible with each other if actors differently envision a blended or not blended interconnected natural gas or hydrogen backbone [P13]. This could lead to slower development of a hydrogen backbone, which could be less beneficial for the development of a decarbonised energy system.

Additionally, differing visions could also lead to a lock-in of hydrogen applications based on blended hydrogen. Such applications could either slow down the development of pure hydrogen-based applications and hydrogen transport. On the other hand, if a European hydrogen backbone would arise, transporting pure hydrogen, such applications could then not be fuelled accordingly. The application would have to be dependent on a different type of infrastructure. Having these two different infrastructures exist in parallel, one for pure and one for blended hydrogen, would not lead to a cost-effective energy infrastructure.

In conclusion, of the previous three subsections, hydrogen produced from renewable energy sources such as offshore wind can be transported both in reused pipes or new pipes and can be transported in the form of pure hydrogen or blended hydrogen.

Considering the different timing of hydrogen transport envisioned, one could assume a theme of ‘first come, first lock-in’. Here, the Netherlands could have an advantage because of their early opportunity to reuse their gas infrastructure they seem to be one of the first to start transporting hydrogen. However, it is more likely that this competitive advantage is not strong enough to counter international cooperation wherein a certain uniformity arises [P13].

Currently, actors are in an experimental phase, working from different starting points. For instance, different actors have to deal with different demanded forms of hydrogen, and have to build their hydrogen systems based on different existing gas infrastructures and storage capacities [P4][Drift, 2020].

Eventually, a shift will occur from actors individually experimenting with hydrogen transportation options towards actors coming together to agree on a uniform transport methodology for cross-border transport. This is a more collaborative phase, which is already ongoing in small collaborative groups.

For instance, on a European level, there are already several projects which focus on the EU regulatory framework, including the EU working group Hydrogen Energy Network (HyENet) [BE EWI, 2020]. Furthermore, there are committees on standardisation work of "Hydrogen in energy systems" (CEN-CLC/TC 6) and "Hydrogen Technology" (ISO/TC 197), of which non-EU members (NO, UK) are also part [Questionnaire NO].

The question remains when a shift will occur from actors individually experimenting with hydrogen transport towards actors coming together to agree on a uniform transport methodology for cross-border transport [Anonymous]. This gradual collaborative approach might be best taken as soon as possible to prevent future incompatible energy visions. Especially because a full European backbone is expected to take 10-15 years to be constructed [Gas for Climate Enagás, 2020]. In this case, alignment is deemed beneficial as a uniform transport good is easier to be traded and leads to more compatible energy systems. One could try to align hydrogen transport methods in different hubs where possible before hubs are physically connected to each other [P13]. The risk of not aligning energy visions in time is that actors would have to change their hydrogen transport methods to connect their individual hydrogen hubs to a hydrogen backbone. It could be quite costly to switch to a different transport method, especially considering the production and consumption settings that an actor has already invested in.

5.6. Theme 6: Visions for hydrogen consumption

Chapter 4 concluded that actors envision most offshore wind energy being consumed either in the form of gasses (primarily hydrogen) or in the form of electricity. All actors also agree to a mixture of both greater electrification (with necessary electricity grid reinforcements) and a low carbon gaseous energy carrier.

If the energy application allows it, direct electricity use is preferred over hydrogen use due to the energy losses of green hydrogen production [TenneT, 2020b] [DE BMWi, 2020b][NO ministry, 2020a][Fluxys, 2019][Energinet, 2020] [Questionnaire][P16][P9][Statnett, 2019c][NO ministry, 2020a][P3]. Although a role is seen for low carbon gasses by all actors, the ratio or extent of the role of gas as an energy carrier is still uncertain. As is stated by the EU commission, "while gaseous fuels are expected to continue to play an important role in our energy mix, the mix of gaseous fuels will highly depend on the chosen decarbonisation pathways [of current carbon-based consumption]" [European Commission, 2020](*Page 15*). EU Scenarios project a share of 18-22% for gaseous fuels in the EU energy mix by 2050, compared to 25% today [European Commission, 2020]. Other percentages of gaseous carriers in 2050 include 21-59% by the UK TSO, 30-50% by the Dutch government and 50% by both Dutch and Belgian TSOs [NationalGrid ESO, 2020a][EZK,CIEP, 2020][Anonymous][P4][P3]. This uncertainty in envisioned ratios and timing of developments leads to future gas and electricity infrastructure being difficult to plan collaboratively. Effectively, these different ratios are dependent on what specific applications are envisioned to use electricity or gaseous fuels as an energy carrier.

The planning of infrastructure is considered to be dependent on the specific hydrogen applications and their consequent infrastructure needs and timings. Appendix figure A.4 illustrates the differences seen for applications, based on the information given in chapter 4. The information is ordered per country as actors within a country envision (almost) the same applications.

Four different types of hydrogen applications are identified: hydrogen used as raw material and for heating in industry, hydrogen used for heating of the built environment, hydrogen used in heavy mobility (e.g. trucks) and hydrogen used in personal vehicles (e.g. residential cars).

Most actors have similar visions on hydrogen applications, although there are some differences. However, if such visions differ, they are largely still compatible with each other. This could be reasoned as different hydrogen applications are able to exist in parallel with each other.

Nonetheless, some different energy visions of hydrogen applications are, to some extent, incompatible with each other. If such energy visions were to be executed, they could lead to infrastructure challenges arising. The following subsections discuss three of these challenges that could arise. The first section discusses the increased challenge of maintaining network adequacy on a local level when different applications are envisioned (5.1.1). Furthermore, the second section discusses the increased challenge of maintaining generation adequacy (5.1.2). The third section discusses the challenges that could occur when hydrogen applications are not explicitly linked to either blue or green hydrogen production (5.1.3).

5.6.1. Differing hydrogen infrastructure needs in the same local area

From chapter 4, it can be concluded that different actors have different visions of using either electricity or renewable gasses for certain applications. It becomes challenging when actors who envision the same local area have these different visions. In this case, a local area, or local scope, is defined as being within national borders. Essentially, these different energy visions for one local area could result in more infrastructure being installed than necessary [Anonymous]. This would lead to incompatible energy visions for one local area because such an overcapacity of infrastructure could be more costly.

After analysing the different visions on hydrogen applications, it can be concluded that local actors mostly differently envision the role of hydrogen in heating the built environment.

Considering hydrogen use for heating the built environment, this is to some extent considered an option by several UK, German, Dutch and Belgian actors. Within these countries, actors mostly mention the uncertainty of the decarbonisation pathways of heat and also tend to see different potentials for hydrogen use in the built environment [VARIO, 2020][FNB Gas, 2018][TKI Nieuw Gas, 2019][DE BMWi, 2020b][DENA, 2019][EZK,CIEP, 2020][NationalGrid ESO, 2020a][CCC, 2018][OFGEM, 2019][APPG, 2020]. Therefore, actors deem more local coordination between actors key to maintain network adequacy [CCC, 2018].

As such, these differing visions are not considered to be fully incompatible with each other, as different heating networks based on gas or electricity infrastructure can exist in parallel with each other. However, these visions are not fully compatible with each other as an overcapacity of infrastructure is not deemed the most cost-effective route.

5.6.2. Generation adequacy needs due to envisioned hydrogen applications

The choice for either electricity or gaseous fuels as an energy carrier could also lead to a larger or smaller challenge of maintaining generation adequacy. As previously mentioned, generation adequacy is defined as “the presence of sufficient generating capacity to meet demand on baseload and peak periods” [Zupančič et al., 2017](*page2*). For an energy system to always be able to meet energy demand, also in times of renewable energy scarcity (e.g. when the sun is not shining and wind is not blowing), many actors consider (hydrogen) gas advantageous as it can easily be stored [VARIO, 2020][Fluxys, 2019][DENA, 2019][TKI Nieuw Gas, 2019][EZK,CIEP, 2020][Nordic Energy Research, 2020][CCC, 2018][CCC, 2019][CCC, 2018][H-Alba][NationalGrid ESO, 2020a] [APPG, 2020][FNB Gas, 2020][FNB Gas, 2020][FNB Gas, 2018][FutureGas, 2020][Ørsted, 2020][Energinet, 2020][Energinet, 2019d][Energinet, 2019a]. Especially on a seasonal scale, a gaseous energy carrier can more easily be stored than an electric energy carrier (as also previously explained in section 5.4) [Anonymous].

Maintaining generation adequacy is especially a challenge when considering the decarbonisation route for heating in the built environment. This challenge is not relevant in Norway and Denmark because heat demand is often electrified or supplied with CHP’s [Statnett, 2019c][NO ministry, 2020a][DK Klimaaftalen, 2020]. In CHP’s (Combined Heat Power), surplus heat from electricity production is utilised, and gas generators produce electricity and heating alternately.

This challenge of maintaining generation adequacy, whilst decarbonising heat, is especially relevant in Germany, the Netherlands, the UK and Belgium due to their current use of gaseous fuels for heating [Fluxys, 2019][Questionnaire][P9][OFGEM, 2019][GL, 2020]. If actors from these countries choose to electrify their heat demand, this will probably result in an increased electricity peak demand in winter (as heating demand is highest in winter) [Energy futures lab, 2018][P12]. Furthermore, the electricity system could be overloaded in the summer if an energy system would have enough RES capacity (e.g. offshore wind) installed to cover the heat demand in winter with direct electrification [P5].

The difference between peak energy demand in winter and summer is considerable. As an example, figure 5.4 illustrates the difference in peaks for the Belgian energy system [Fluxys, 2019]. Considering the aforementioned challenges of electrifying heat, German, Dutch, UK, and Belgian actors recognise an opportunity for using hydrogen for heating. Some of these actors are also driven by the potential to reuse existing local natural gas infrastructure [TKI Nieuw Gas, 2019][EZK,CIEP, 2020][Provincie Groningen, 2019][DENA, 2019][OFGEM, 2019][GL, 2020][Anonymous].

The extent to which the advantages of gas use for generation adequacy (mostly mentioned by gas TSOs) outweigh the efficiency advantages of electrification of heating or storage is still uncertain [Anonymous]. For example, the Belgian government and electricity TSO deem direct electrification of heat demand more cost-effective [VARIO, 2020][BE federal government, 2019b][P3]. Contrarily, the UK's government advisory board (CCC) concludes that economically, hydrogen is able to provide the greatest value in meeting these peaks in winter months. This is also recognised in the visions of the gas TSOs of Germany and the UK government [FNB Gas, 2018][CCC, 2018][CCC, 2020][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019].

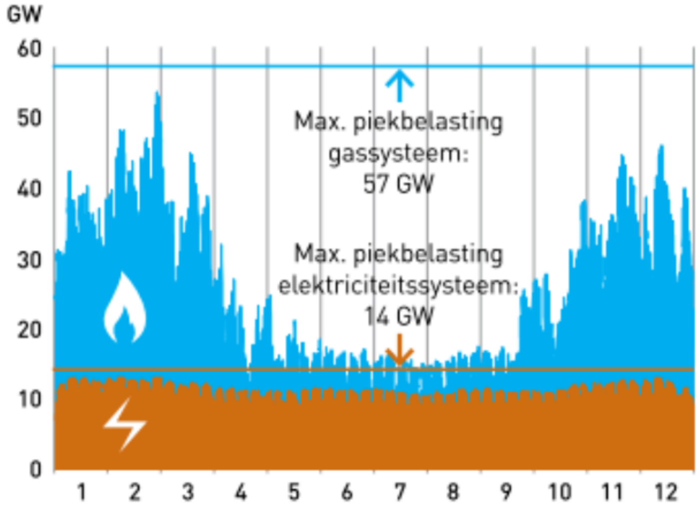


Figure 5.4: Electricity and gas consumption per month in Belgium in 2018. Gas use throughout the year is shown in blue and electricity use in orange. This graph also includes two lines that illustrate the maximum peak capacity available in infrastructure (57 GW for gas and 14 GW for electricity) [Fluxys, 2019].

Actors could opt for electrification of heating instead of using hydrogen due to the later expected technology readiness of this hydrogen application, mentioned by Belgian, German and Dutch actors to be around 2030 [BE EWI, 2020][VARIO, 2020] [DE BMWi, 2020b] [Provincie Groningen, 2019] [EZK,CIEP, 2020] [TKI Nieuw Gas, 2019]. The UK government deems a commitment necessary for the scale of hydrogen deployment in heating in the mid-2020s [CCC, 2018]. This is an earlier and larger commitment compared to the other actors.

A large electricity consumption peak in winter could lead to increased generation adequacy challenges. Such challenges are recognised by actors to be important to coordinate within the NSR as a whole, both considering timing and the size of its role. The option of Combined Heat Power (CHP's) or hybrid heat pumps is also mentioned as an option to manage flexibility [CCC, 2018][DENA, 2019][DE BMWi, 2020a][Elia, 2019b][Energinet, 2020].

The most important conclusion of this section is that effectively different actors have different visions on supplying decarbonised heat with either electricity or hydrogen as an energy carrier. There remains a lot of uncertainty on how actors envision to decarbonise heat consumption. This also leads to a lot of uncertainty on the extent to which generation adequacy challenges are to arise. Different envisioned heating systems could exist in parallel with each other and could therefore be perceived as compatible. However, if actors envision the electrification of heating demand, such individual visions could become incompatible if no actors deem themselves responsible for managing and compensating for the related generation adequacy challenge. Decarbonising heat demand with gaseous could play a role in solving such challenges.

5.6.3. Visions on specific green or blue hydrogen-based applications

Aside from the two other challenges previously mentioned, there is one general notable sub-theme for all envisioned hydrogen consumption. This sub-theme focuses on the specific sources hydrogen actors consider when envisioning a specific hydrogen application. Currently, in the analysed energy visions, most actors do not explicitly mention if the envisioned hydrogen application is supplied with green or blue hydrogen [P16]. This exclusion is relevant because it is rational to believe that some hydrogen applications will only be supplied with green or blue hydrogen due to the difference in cost structures between both [EZK,CIEP, 2020].

NationalGrid ESO and the Scottish government are some of the only actors to explicitly focus on what applications can or can not be considered in the case of different hydrogen production [EZK,CIEP, 2020][Arup, 2020][NationalGrid ESO, 2020a]. For instance, the Dutch, Norwegian and German national hydrogen strategies do not explicitly mention certain applications being supplied specifically by green or blue hydrogen. An example of the Scottish Government Hydrogen Policy Statement is illustrated in figure 5.5. This figure shows eight different scenarios, with different green and blue hydrogen production ratios in the second row. Subsequently, the other rows show what applications for hydrogen are then considered in that case. For example, one can recognise that in the 'Big green hydrogen' scenario with only green hydrogen production, use is only seen for hydrogen in the transport sector.

If actors do not explicitly mention an application to be supplied by either blue or green hydrogen, it is unclear if energy visions are incompatible or compatible with each other. The demand for green hydrogen is currently unclear as no insight is given into what specific application is expected to be supplied by green hydrogen. A challenge could arise if ambitious energy visions unintentionally stimulate the demand for green hydrogen due to this uncertainty and subsequently, green hydrogen production is not scaled appropriately. This puts pressure on the production of green hydrogen and its competitive claim on offshore wind [P13]. This theme of 'competing claims on offshore wind' has already been discussed in section 5.1.

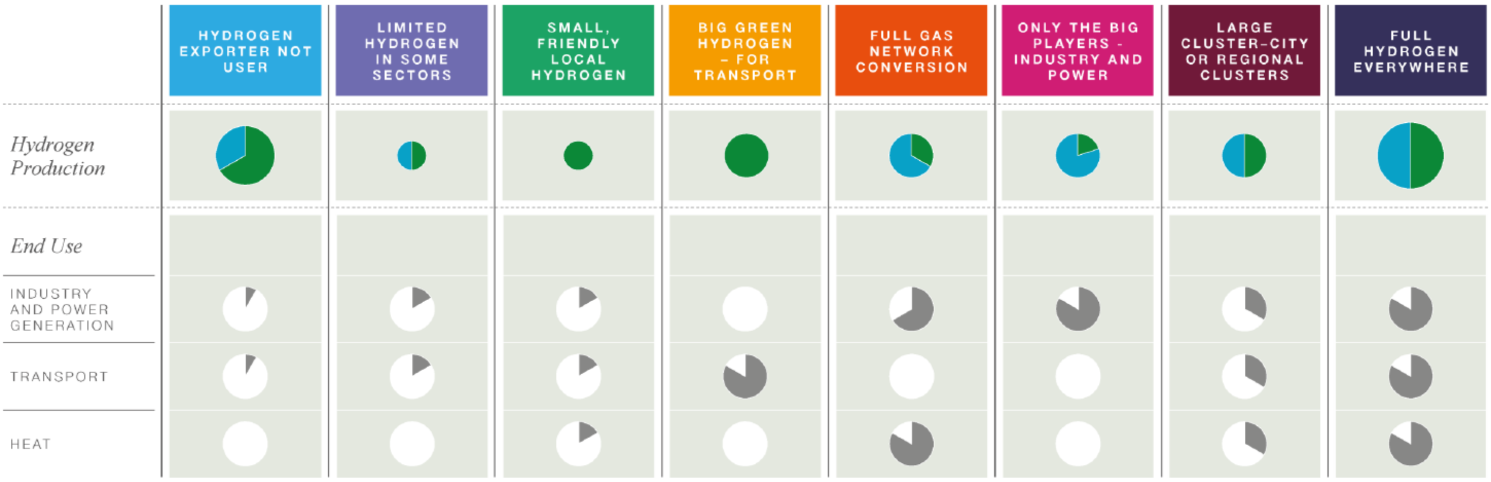


Figure 5.5: Longlist scenario's for Scottish hydrogen assessment [Arup, 2020]. The envisioned ratio of blue and green hydrogen production is illustrated in the first row. In the next three rows, the expected end-use application of hydrogen is illustrated in pie charts where the 'pie' is represented in grey.

In summary of section 5.6, most different visions on hydrogen applications are compatible with each other as such visions are able to exist in parallel with each other. Nonetheless, such visions are, to some extent, incompatible with each other. These incompatibilities arise when actors consider different options for hydrogen use in the built environment in local areas. Incompatibilities also arise considering the generation adequacy challenges that could occur when decarbonising a peak heat demand in winter. Lastly, incompatibilities could arise when actors do not explicitly consider an envisioned hydrogen application is supplied by green or blue hydrogen.

5.7. Theme 7: Visions on attaining a hydrogen hub function

Envisioned hydrogen developments of actors are not only driven by achieving GHG reductions and decarbonising the energy system. There is also an economic argument for actors positioning themselves in hydrogen developments [Anonymous][VARIO, 2020][BE federal government, 2020][P2][DK Klimaaftalen, 2020][DE BMWi, 2020a][APPG, 2020][Provincie Groningen, 2019][Energinet, 2019a] [Norwegian Embassy The Hague, New Energy Coalition, Enterprise Europe network, Royal Danish Embassy,

Embassy of Finland The Hague, TKI Nieuw Gas Topsector Energie, 2020]. Due to the foreseen opportunities in the North Sea Region for hydrogen, all actors in the region want to gain economically by becoming a hydrogen production, consumption or transit hub [Anonymous]. This theme is important to consider, as it impacts the size of the role gas infrastructure could play when integrating offshore wind.

The initial development of hydrogen production and consumption is likely to be in regional clusters, driving geographical differences in energy use, which could remain local or could scale up to widespread change across the NSR [NationalGrid ESO, 2020a]. Figure 5.6 shows a Venn diagram that illustrates the different roles envisioned by different actors, based on Chapter 4. In the figure, five different icons can be recognised, representing the visions of gas TSOs, industry actors, electricity TSOs, combined gas and electricity TSOs and government actors. All these different actors can be illustrated in six different colours, representing the countries these actors come from.

In the Venn diagram, three different circles can be recognised. Actors' icons are placed into the left circle if they are aspiring to become a hydrogen production hub, possibly exporting the produced hydrogen. The terms blue H2 or green H2 are added if actors specifically aspire to become either blue or green hydrogen production. Actors' icons are placed in the right circle if they are aspiring to become a hydrogen consumption hub. Lastly, actors' icons are placed in the circle above if they mention aspiring to become a hydrogen trading or transit hub, as be it a 'backbone'. The terms H2 and CO2 are specifically mentioned if actors mention becoming either a hydrogen or CO2 'backbone'. If actors' icons are placed in locations where the circles overlap, the respective actors are aspiring to become both the hubs in both circles. For example, Dutch government actors aspire to become a hydrogen transit, production and consumption hub.

The figure shows that there are not only differences between countries in envisioned roles but also between dimensional actors. For instance, TSOs mostly aspire to a role as a trading hub and most industrial actors (depended on their role) aspire to a role as consumption and/or production hub.

Four sub-themes are distinguished when analysing these different hub characteristics. These are discussed below.

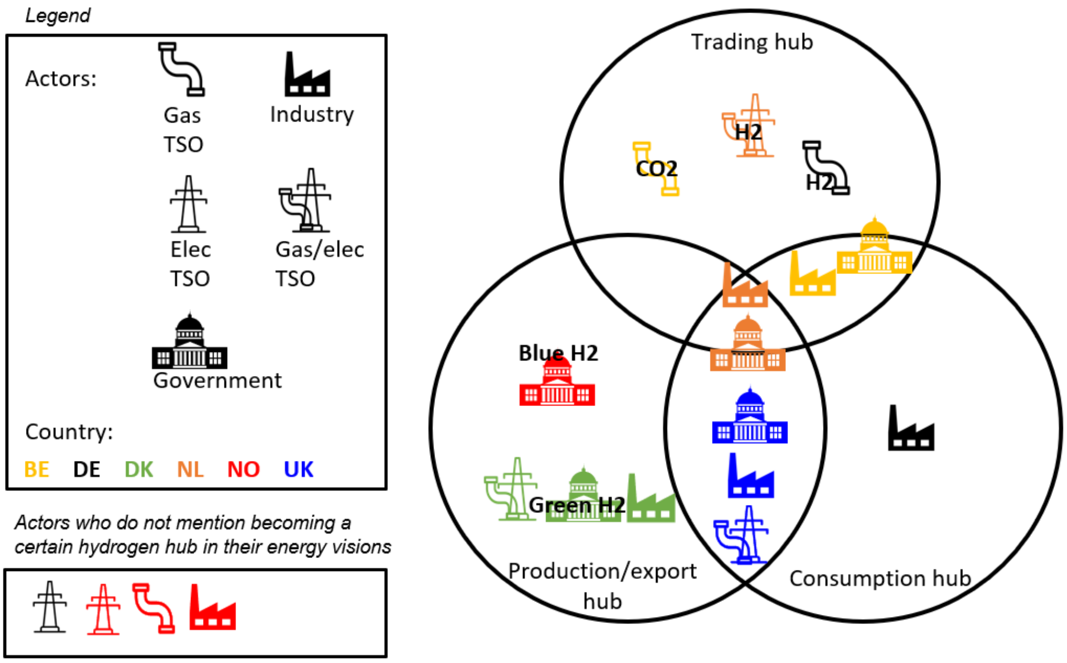


Figure 5.6: A Venn diagram of the different hydrogen hub functions different actors aspire. These include aspirations for becoming a hydrogen trading hub (top circle), production hub (left circle) or a consumption hub (right circle). The different types of actors are illustrated by using different icons. The different colours of the icons illustrate the country an actor comes from. In the box left below, icons are noted of actors that did not mention a specific role. This figure was made by the researcher. The information used to compose this illustration originates from the information given in chapter 4.

5.7.1. Shared and exclusive characteristics for hydrogen hubs

Table 5.1 illustrates the different characteristics actors consider themselves to have. Actors use these characteristics as reasoning for becoming a hydrogen (production, consumption or transit) hub. Such characteristics can also explain an actors' drive towards either blue or green hydrogen production, hydrogen transport and consumption. For example, chapter 4 concluded that Norwegian actors saw a role in blue hydrogen production. This could be linked to Norwegian actors mentioning their energy system to have CO2 storage possibilities, gas infrastructure present, knowledge and experience and a presence of a large natural gas supply for export. Another example would be Danish actors who envision a role for green hydrogen production. This could be linked to Danish actors mentioning their offshore wind potential, hydrogen storage availability, knowledge and experience and subsequently, opportunity to produce e-fuels from green hydrogen due to their access to carbon from bio-resources.

The following two paragraphs discuss what consequences there are for the differences and similarities one can recognise for different actors in the NSR.

Table 5.1: Qualities actors mention as drivers for becoming a hydrogen 'hub'. Dark grey means actors within a country mention this as a very important characteristic. Grey means actors within a country mention this as an important characteristic. White means the characteristics is not mentioned by actors or not mentioned to be important. The UK also includes Scotland. This figure illustrates that many countries in the NSR share the same beneficial qualities for becoming a hydrogen production, consumption or transit hub. This table was made by the researcher and is based on information presented in chapter 4 and [Provincie Groningen, 2019][EZK,CIEP, 2020][TKI Nieuw Gas, 2019] [CCC, 2018][Energinet, 2020][H-Alba][KonKraft: A collaboration arena for the Norwegian Oil & Gas Association et al., 2020][APPG, 2020][DNV GL, 2020].

Quality perceived present for becoming a 'hub'	**BE**	**DK**	**DE**	**NL**	**NO**	**UK**
Availability of offshore wind in landing spots		▓	▒	▓	▒	▓
Hydrogen storage availability (salt caverns)		▒	▓	▓	▒	▒
CO2 storage possibilities					▓	▓
Presence of ports and its coastal hydrogen demanding industrial clusters	▓	▒		▓		
Presence of in-land hydrogen demanding industrial clusters			▓	▓		
Gas infrastructure present	▓	▒	▓	▓	▒	▓
A geographical location for import and export	▓			▓		▒
Knowledge and experience in the role want to play (CCS, trade, imports)	▓	▓	▓	▓	▓	▓
Presence of a large natural gas supply for export					▓	
Access to carbon from bio-resources for e-fuels		▓				

Table 5.1 shows that some qualities are specific in certain countries, leading to specialistic hub-functions of actors. This includes the presence of a large natural gas supply and of CO2 storage possibilities leading to actors aspiring to become a blue hydrogen production and trading hub (Norway). Furthermore, the presence of a large offshore wind potential leads to actors aspiring to become a green hydrogen production and trading hub (Denmark). Additionally, the presence of large industrial clusters leads to actors aspiring to become a consumption hub (mostly in the Netherlands and Germany). Lastly, actors who consider themselves to have a central geographical location and a port, aspire to become a transport hub (mostly the Netherlands and Belgium).

Due to these different nationalistic characteristics, different energy visions of actors define a 'hub'-role in different ways. These roles include actors envisioning themselves as a hydrogen user, producer, importer, exporter and trader. They are compatible with each other as different hydrogen hubs are able to exist in parallel with each other. Although, these visions could become incompatible with each other, once actors depend on other hubs without coordinating this in their energy visions. For example, an actors' ambition to become a hydrogen consumption hub is nothing without a vision of how hydrogen will be supplied (produced or imported). In the NSR, most actors do tend to coordinate such relevant necessities to a certain extent. Examples of such collaborative projects and groups are further described in Appendix D.

Such different ambitions for becoming different types of hydrogen hubs rather strengthens the development of hydrogen because different actors would possibly be able to pursue different roles and combine these goals to achieve a strengthened whole energy system [Anonymous].

In energy visions, most actors mention becoming a role model due to their 'specific characteristics'. However, some qualities which actors perceive as specific for them are not as special in the NSR [*Based* *on information from chapter 4*]. This is illustrated in Table 5.1, as one can recognise that there are almost always several actors that mention having a certain characteristic. The only ‘original’ characteristics are the Danish access to carbon from bio-resources for e-fuels and the Norwegian presence of a large natural gas supply for export.

Focused on these ‘specific characteristics’: if actors do not recognise their competitors around them or are ‘bluffing’ about their qualities to attract investments, this could lead to aims and targets being too ambitious. This leads to the risk of other actors building upon these too ambitious energy visions which could be problematic for predictions and expectations for maintaining system adequacy.

Furthermore, because of these shared characteristics, some competition is evident between specific actors (e.g. between German and Dutch actors for hydrogen consumption). In a certain way, energy visions where actors have a shared ambition to become a first-mover are incompatible with each other. Such visions on specific parts of the hydrogen chain (production, consumption, transport) are not able to exist in parallel with each other because only one actor can essentially become a first-mover or role model.

However, such competitive elements are not as problematic for hydrogen development. One could argue that competition for a frontrunner position puts pressure on other countries and actors to also increase development speeds; due to competitive targets and goals, different countries are ‘inspiring’ others to do more [Anonymous][P13]. This has been the case in the increasingly ambitious Dutch, German and French targets, which had publishing dates that all succeeded each other.

However, a great risk of competition between actors is protectionism, with the risk of every national government funding their own actors and assuming a protective approach [Drift, 2020]. This could lead to a decrease in collaboration of actors and hindrance of actors for other actors. This could decrease the speed of hydrogen developments because of avoidable reasons. Therefore, there seems to be a large role for the EU commission and other collaborative groups to counter protectionism and to coordinate critical aspects, while also including non-EU members.

In conclusion, taken together, the NSR offers a large range of necessary characteristics for PtX technologies. Actors could increasingly collaborate to make use of all these qualities together, also increasing the compatibility of their energy visions. This is specific for hydrogen to become successful, as no actor has all the characteristics to become a fully self-sufficient hydrogen production, consumption and transit hub. Additionally, a large international scale is deemed necessary for a thriving hydrogen market [RLI, 2021], whilst for example for CCS technology could thrive on a more local scale, as verified in interviews [P14].

However, such energy visions are also slightly incompatible as not all actors can essentially become a first-mover and role model in the same technology. Although, due to the scale at which hydrogen is expected to operate, it is technically feasible (and even necessary if one wants a large scale hydrogen market to develop) for all actors to attain a role in the hydrogen cycle.

5.7.2. The chicken and egg dilemma

This section discusses the challenge of developing hydrogen demand, supply and infrastructure in parallel. It is important these three elements develop in parallel because all three elements cannot exist without one another. For instance, hydrogen demand cannot develop further without transportation methods or a hydrogen supply. This necessary (parallel) development makes it more difficult for developers to invest and for projects to be coordinated. It is recognised as the ‘chicken-and-egg’ dilemma by many actors both in published documents and in all interviews [TKI Nieuw Gas, 2019][NationalGrid ESO, 2020a][CCC, 2019][P1-P19].

Considering this dilemma, non-TSO actors often tend to put an emphasis on hydrogen production and consumption. The infrastructure element is often overlooked and sometimes not even mentioned [Anonymous]. However, hydrogen infrastructure elements are extremely important because the construction of grid infrastructure often has a longer lead time than the realisation of renewable energy projects. Additionally, the (consumption) market is also not expected to ‘take off’ if there is no reliable infrastructure [BE EWI, 2020][Elia, 2019a].

The ‘chicken-and-egg’ dilemma could lead to both incompatible and compatible energy visions. Both options are discussed in the next two paragraphs.

Some actors could consider the necessary developments for hydrogen transport, and others could only focus on either hydrogen consumption or production. Such energy visions could be seen as incompatible with each other. In that case, actors have a narrow geographical and dimensional scope which could lead to unexpected developments if their energy visions are executed. As an extreme example, a disconnected energy vision fully focused on hydrogen production (and not on where hydrogen is consumed and how it is transported) is probably not compatible with another disconnected energy vision fully focused on hydrogen consumption. Such a narrow scope could be explained by the different roles and responsibilities certain actors (e.g. TSOs) have in the NSR. This is further discussed in section 5.9.

However, different visions, focused on either hydrogen consumption, production and transport, could also be perceived as compatible with each other. This could be the case if actors consider their neighbouring actors and combine their separate energy visions on the perceived timing of large-scale hydrogen production, transport and consumption into a combined vision on a full hydrogen system. Actors could widen their geographical and dimensional scope to essentially ‘solve’ the chicken-and-egg problem. They could do so by combining different starting points of different actors in the NSR; coupling energy visions where there is more production with ones where there is more demand.

Figure 5.6 shows what possibilities there are for collaboration between actors combining visions of a production, trading and user hub. For instance, this illustration shows that Danish actors (illustrated in green) do not aspire to become a hydrogen consumption hub but do aspire to become a hydrogen production hub. In contrast, German industrial actors aspire to become a hydrogen consumption hub. Both actors could collaborate with each other; Danish green hydrogen could supply German industrial consumption hubs.

5.7.3. Existing grey hydrogen demand as a driver

As a third sub-theme, industrial hubs already consuming (grey) hydrogen are seen as a shared driver for hydrogen developments. This characteristic was also previously illustrated in table 5.1.

This is an important characteristic of the NSR, given the current presence of grey hydrogen demand in industries is 18 TWh in Belgium, 55 TWh in Germany, 49 TWh in the Netherlands, 40 TWh (4.6 GW) in Norway and 27 TWh in the UK [Nordic Energy Research, 2020] [DE BMWi, 2020b][EZK,CIEP, 2020]. This is excessive, as a quick calculation concludes that if one would want to replace this grey hydrogen (189 TWh) with green hydrogen, one would need 30.8 GW of installed electric capacity considering an electrolyser efficiency of 70%. If offshore wind energy would provide all of this green hydrogen, a capacity of 79 GW installed offshore wind would be needed. For this calculation, a capacity factor of 39% is used, which is the average UK load factor for offshore wind over the last five years (*although one should consider that this load factor is set to increase in the future due to technological improvements of offshore wind turbines*) [NationalGrid ESO, 2020a]. As a comparison, at the moment, the amount of installed offshore wind is 9.9 GW in the UK, 7.4 GW in Germany and 1.1 GW in the Netherlands, as mentioned in chapter 4.

In conclusion of this quick calculation, there is a substantial amount of grey hydrogen currently being consumed in the NSR. This example is merely to show the order of scale of current grey hydrogen consumption. One should keep in mind that most actors consider it highly unlikely that such a large grey hydrogen demand is replaced with green hydrogen from offshore wind [P13]. The next paragraphs further elaborate on how this characteristic could be a driver for future hydrogen developments.

Aside from the current use of grey hydrogen, an increase in general industrial use is also expected by all actors. This increase is expected in sectors that are hard to further abate with without any gaseous fuels such as hydrogen [DE BMWi, 2020b][Energinet, 2019a][FNB Gas, 2020][Frontier Economics, RWTH Aachen University, 2019][NL EZK, 2020a][Fluxys, 2019][P13][FNB Gas, 2019][DE BMWi, 2020b].

In general, one could propose that the larger the current consumption of grey hydrogen in countries, the larger the trigger is for actors to develop green and blue hydrogen consumption hubs. The hydrogen demand in industrial sectors, and especially industrial ports, are well-placed to become one of the main factors to speed up the market roll-out of hydrogen [DE BMWi, 2020b][DENA, 2019][EZK,CIEP, 2020][Drift, 2020][BE EWI, 2020]. Therefore, location and installed capacities (investment decisions) of energy intensive industries have a high impact on where hydrogen hubs arise and where hydrogen infrastructure develops [Gasunie,TenneT, 2020][P4].

In the past couple of years, one could recognise an increase in hydrogen developments for industrial clusters [Anonymous]. For instance, the CCC is already recommending that significant volumes of low-carbon hydrogen should be produced at one or more industrial clusters by 2030 [CCC, 2019].

Such an increase in hydrogen developments could also translate into an increase in competition between different aspired hydrogen consumption hubs. In such a case, it is unclear if current industrial hubs remain the most beneficial locations. Therefore, industrial actors could lose out to newly developed hydrogen industrial clusters [Drift, 2020]. For instance, the Norwegian electricity TSO states that Norwegian general industry growth could be triggered because Norway is “well placed to deliver emission-free and cheap power” [Statnett, 2019c](*Page12*)[Statnett, 2019d]. This risk of losing out to new industrial clusters can be seen as a driver for fast hydrogen developments in existing clusters. This driver is mentioned explicitly in the ambitious energy vision of the Port of Rotterdam [Drift, 2020].

In conclusion, the existing grey hydrogen demand in the NSR is considered to be a beneficial driver for hydrogen developments. This is the case as long as infrastructure necessities are coordinated accordingly between the different actors. However, due to this increase in development speeds, competing ambitious visions of industrial clusters could become increasingly incompatible with each other. This is the case as different actors, envisioning to be a hydrogen consumption hub, are competing for the same hydrogen produced. This topic is discussed in more detail in the next paragraph.

5.7.4. Competition for hydrogen in industrial hubs

Focusing on the geographical scope of hubs, actors also aspire to become a production hub for nearby countries outside of the NSR (DK/NO) or mention the need for hydrogen production outside of the NSR as complete European energy independence is not perceived as achievable (UK/BE/NL/DE) [TenneT, 2020b][P12][DE BMWi, 2020b]. Combined with the development of import and export inside of the NSR, such export and import developments outside of the NSR could have consequences for the current consumption hubs now envisioned and, therefore, the (gas) infrastructure now envisioned.

In the following paragraphs, competition between hydrogen production and consumption hubs are further described, inside and outside of the NSR. These sections also describe how compatible or incompatible differing visions on these topics are with each other.

In the case of production hubs, there is such a need for both blue and green hydrogen envisioned that no real competition is expected [P9][P7][P17]. Although currently from a regulatory point (e.g. subsidies in the EU), there is increasing competition for financial aid for blue and green hydrogen, so that actors can speed up their developments [P7].

Furthermore, competition with cheaper imported hydrogen from outside of the NSR is expected but still uncertain as the costs of transporting hydrogen over long distances are unknown.

Furthermore, several actors also aspire to become a hydrogen consumption hub. As explained in the previous section, actors increasingly envision a faster development speed of hydrogen consumption hubs. This ‘rush’ could be explained by the fact that the consumption hubs to first acquire hydrogen are expected to develop a competitive advantage. Such a ‘first-mover advantage’ could be beneficial due to these regions becoming the initial actors to become part of a ‘hydrogen backbone’. If such a ‘first-mover’ region is one of the firsts to have hydrogen supply available, the region could possibly attract hydrogen-based industries. This could be beneficial for economic development in such a region [P16][Leporini et al., 2019]. Due to this competition, certain actors could also lose out on hydrogen developments. For example, if hydrogen is mostly imported (via ships), industrial ports such as the Port of Rotterdam could be cut-off [Drift, 2020][CCC, 2019].

These different envisioned development routes are important for actors to consider because they also lead to different views on the gas infrastructure necessary to transport energy carriers. Essentially this is then related to the way offshore wind energy is eventually integrated into the energy system. However, this topic is not mentioned as such in energy visions by TSOs and governments.

Differing energy visions of actors wanting to become a consumption hub are incompatible with each other to a certain extent. This is the case as, due to the currently expected lack of green and blue hydrogen in the development phase, a scarcity of hydrogen is expected. It is likely that some actors who aspire to become a hydrogen hub will initially lose out on a hydrogen supply [Drift, 2020], which also has consequences for the use of gas infrastructure different actors envision.

Additionally, there could also be certain specific competition for hydrogen importers as to the origin of the hydrogen (inside/outside of Europe) and the production method. Such hydrogen import is especially relevant considering the expected blue hydrogen production in Norway (where Equinor states mostly seeing a current market in the UK) and the expected green hydrogen production in Denmark (with a large focus on export to Germany) [P16][P9]. This could be problematic for the Dutch and Belgian actors, who could miss out on opportunities and, therefore, security of supply in times of hydrogen shortages. Although actors within both these countries are also developing strategies to secure hydrogen imports, as also mentioned in chapter 4 [Questionnaire BE][Questionnaire NL]. In general, there is a large chance of a European hydrogen commodity market arising, with import and local renewable production combined [P3].

In summary, most actors in the NSR have a vision on attaining a hydrogen production, consumption or transport hub. Both competition and a need for collaboration are identified, as most actors in the NSR have both shared and specific characteristics that could help them realise their ambitions. In short, the NSR consists of actors aspiring to become hydrogen production (DK/NO/NL/UK), transport (NL/BE) and large consumption hubs (NL/DE). As a concluding remark, both competition and collaboration could be expected between different actors.

Lastly, different actors also have different visions and ambitions to become a role model in Power-to-Gas knowledge. The main benefit of becoming a ‘hydrogen expert’ mentioned by actors includes the economic benefits and potential job creation (as a leverage for the oil and gas industry). Another reasoning that has gained importance during the Covid pandemic is the benefit actors recognise of being independent of others’ international industries. As our research scope does not focus on this theme specifically, this theme is further discussed in Appendix chapter E.

5.8. Theme 8: Visions on the timing of technological developments of electrolysers

Increasingly, the technological development of electrolysers is transitioning from a focus on innovation to a focus on upscaling. When focused on upscaling, actors are pursuing a higher technical efficiency and lower costs of an electrolyser [TKI Nieuw Gas, 2019][Drift, 2020][BE EWI, 2020][NO ministry, 2020a][NL EZK, 2020b]. Various national and international studies have shown that significant cost savings of around 50-60% can be achieved for electrolysers in the next ten years, partly due to the use of cheaper materials [NL EZK, 2020b][Anonymous].

There are two commercially available technologies on the market today; alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis. Both technologies are relatively mature, although PEM electrolysis is more expensive than alkaline electrolysis and behind in (industrial) scale of use [NO ministry, 2020a][Liebreich, 2020][VARIO, 2020][Anonymous]. European actors mostly focus on PEM electrolysis. Actors reason this preference because PEM electrolysis technology is easier to ramp up and down more frequently than alkaline electrolysers [Liebreich, 2020][CCC, 2018].

The theme presented in this section focuses on the technological development of electrolysers. Some actors recognise a gap between the envisioned technological maturity of electrolysers and the envisioned necessary upscaling of the production technology to match the ambitions for green hydrogen production [VARIO, 2020][Equinor, 2019][CCC, 2018]. These different visions could be seen as incompatible because they cannot exist in parallel with each other. One can not simultaneously envision an electrolyser to not yet be technologically mature enough for large-scale operation, and also envision an electrolyser to be ready to supply a large demand of green hydrogen. Such a gap between these visions could become problematic for the energy system. When actual technological developments are slower than expected, the large role for electrolysers to help maintain system adequacy when integrating offshore wind could not be executed efficiently (as also verified in an interview) [Anonymous].

This gap between energy visions is explained in the following two subsections. The first subsection further explains the different visions on the technological maturity of electrolysers. The second subsection explains the different visions on the large scale use of electrolysers in the nearby future. Lastly, this section concludes how incompatible both types of visions are with each other.

5.8.1. The envisioned technology readiness levels of electrolysers

Most actors' visions on the expected technology readiness levels (hereafter TRL) for electrolysers seem to be aligned to a certain extent. Nonetheless, this uniformity remains uncertain because some actors do not mention specific expectations due to the uncertainty they envision for electrolyser developments.

Norwegian, Belgian, UK and to some extent German actors seem to be uncertain of the speed of development, emphasising the current starting phase of the electrolyser technology [VARIO, 2020][P19][NationalGrid ESO, 2020a] [P5][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][P2][H-Alba]. Actors explain this uncertainty by mentioning the long lead times of electrolyser projects and lack of available expertise on electrolysers [VARIO, 2020][NationalGrid ESO, 2020a][H-Alba][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019]. Nonetheless, Danish, German and Dutch TSOs and governments envision the development of demonstration projects by 2023, large-scale hydrogen production on a Gigawatt scale and cost-efficient market ramp-up around 2030, and towards 2035 a reasonable level of market maturity with an increase of end-user applications [DE BMWi, 2020b][DENA, 2019][Energinet, 2019a][TKI Nieuw Gas, 2019][DNV GL, 2020][Provincie Groningen, 2019][Energinet, 2020][Ørsted, 2020][FNB Gas, 2020][50Hertz Transmission GmbH Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH, 2019][NL EZK, 2020a][Gasunie,TenneT, 2020][NL EZK, 2020b][Energinet, 2019f].

Differences and uncertainties in visions on the TRL of electrolysers could be explained by considering the different futuring techniques used by actors. Some actors tend to consider what timing is deemed possible, using a forecasting approach that includes envisioned challenges that have to be overcome. Other actors consider what timing is deemed necessary, backcasting towards the current affairs. In the case of backcasting, economic analysis is preferred over credible deliverable actions [Equinor, 2019].

The different futuring techniques used could be part of the reason for the existence of slightly different energy visions on the TRL of electrolysers.

The different actors' visions on the TRLs of electrolysers also seem to be related to the actors' vision on the TRLs of blue hydrogen production technologies. One could argue that the longer the technological development takes for green hydrogen, the longer blue hydrogen would have to be produced to meet the demand of decarbonised gasses [P16][P1]. Therefore, actors for whom blue hydrogen developments are beneficial could benefit from a vision of slow development of the TRL of electrolysers.

For instance, actors that would benefit from a large green hydrogen market envision a slower development for blue hydrogen production. For example, Ørsted mentions that "CCS is still an immature technology at scale, and the cost advantage to other technologies is unproven" [Ørsted, 2020](*Page5*). In contrast, actors who benefit from both a longer use of natural gas and CCS opportunities, often envision blue hydrogen technologies developing faster than electrolysers. This is for instance the case for actors from the Norwegian government and UK actors [KonKraft: A collaboration arena for the Norwegian Oil & Gas Association et al., 2020][CCC, 2019][Northern Gas Networks, 2019][APPG, 2020][NO ministry, 2020a]. However, these actors are not unrealistically optimistic about the TRL of blue hydrogen. For instance, actors do mention they expect the deployment of large-scale CCS solutions to progress slowly [NO ministry, 2020b][NO ministry, 2020c][NO ministry, 2020a][Northern Gas Networks, 2019]. Dutch actors are a more neutral example because they do not have a specific (one-sided) preference for either blue or green hydrogen production. Several Dutch actors envision blue hydrogen developing faster than electrolysers [Provincie Groningen, 2019][NL EZK, 2020b][DNV GL, 2020].

Intended or unintended, these actors have a certain bias towards the TRL of blue hydrogen production and the TRL electrolysers. This bias leads to slightly differing visions on the TRL of electrolysers. Although, the exact TRL envisioned by actors does not differ as much. Nonetheless, there is a difference in how beneficial actors deem a certain TRL for electrolysers. This could be the case because actors have different starting points and geographical characteristics that influence the TRL (and subsequent pricing) they deem appealing.

5.8.2. An envisioned 'hydrogen hype'

Despite the (small) differences in TRLs mentioned above, our analysis showed that the TRLs envisioned are becoming increasingly uniform. This development could be linked to a particular 'hydrogen hype', of actors increasingly recognising the opportunities of hydrogen and even aspiring to become a first-mover [P7]. Interviewed actors and analysed documents mentioned such a hype to be beneficial for creating a self-fulfilling prophecy and aligning the different TRLs perceived [Energinet, 2019a][P9][TKI Nieuw Gas, 2019].

Although actors use the term 'hype', this might not be the best description of the current developments [Anonymous]. The term hype assumes that the increasing enthusiasm, strategies, and developments for hydrogen will eventually pas. Due to the fact that actors are currently envisioning a systematic role for hydrogen in the energy system, one could conclude that many actors do not expect this so-termed 'hydrogen hype' to pass.

The fact that most actors envision almost the same TRL for electrolysers means that these visions are compatible with each other. However, these compatible energy visions could still become incompatible with themselves if the TRL envisioned eventually proves to be unrealistic and unreachable. The 'hype' bringing actors together might lead to unrealistic goals. As an example of the possible unrealistic nature of the envisioned TRL, the paragraphs below mention two key aspects that are only mentioned by a few actors in their energy visions.

Firstly, the enormous growth necessary for electrolysers is often not explicitly considered by actors in their energy visions. Currently, installed electrolyser capacity is still relatively small at 50 MW in the whole world. Therefore, it is likely that it will take time to develop electrolyser technology on a large scale [Anonymous]. Most visions do not explicitly mention the enormous growth necessary to meet their ambitious electrolyser targets. The question then remains if such actors underestimate the development that still needs to happen or if they really do recognise an option for installed electrolyser capacity to grow rapidly.

Secondly, the supply speed of electrolysers is also often not explicitly considered by most actors in their energy visions. Energinet is one of the only actors to mention that there will probably not be enough supply of electrolysers for all (European) actors to satisfy their hydrogen strategies in 2030 [P9]. At present, the electrolyser production capacity in Europe is less than 1 GW per year [Oxford Institute For Energy Studies, 2020]. This production capacity speed is relatively low compared to the combined electrolyser target of all NSR countries. Quantitatively, the targets of the NSR region approximate a total 20 GW in 2030/2040 [VARIO, 2020][Energinet, 2020][KAPSARC, 2020][TenneT, 2020c](*capacities on which this is based can be found in the Appendix table A.1.* An additional comparison is the EU target of having 40 GW of electrolysers installed by 2030. Therefore, the difference between these values and the size of electrolyser capacity targets is massive and should not be underestimated.

In conclusion, both the necessary growth of electrolyser installation and supply speed of electrolysers are not explicitly mentioned in most energy visions. Therefore, it is uncertain if actors do or do not consider these two aspects when forming their vision on the TRL level of electrolysers.

It could be the case that actors do not consider such aspects and are taken by the 'hydrogen hype'. For instance, they could even be basing their own assumption for a TRL on ambitious TRLs mentioned in previous energy visions. This could be problematic, especially if these actors are not aware of such a presumed TRL being ambitious and not realistic, as this is not explicitly mentioned. With such an unrealistic TRL of electrolysers, actors could envision a larger supply of green hydrogen than actually will be available in the future. Such a lack of green hydrogen production could put pressure on meeting the expected demand for green hydrogen, which was able to arise due to the (too high) expectations of green hydrogen production. This gap between green hydrogen production and demand could lead to losses of public support of hydrogen developments because the possibly faster-developed demand for green hydrogen would have to be met with either blue or grey hydrogen.

However, it could also be the case that actors do implicitly consider the two aspects (the necessary growth of electrolyser installation and supply speed of electrolysers) when forming their vision.

The 'hydrogen hype' is not necessarily a bad development, as long as one recognises these two aspects, accepts the 'risks' of setting unrealistic targets and does not see hydrogen as a 'silver bullet' but also considers other low-carbon alternatives [P13]. Considering interviews and vision documents, most actors at the core of hydrogen developments are aware of the high level of ambition in energy visions [P7]. Such actors often mention they expect a mix of different technologies and that they do not define hydrogen technology as a 'silver bullet' [DE BMWi, 2020a][TenneT, 2019a][P13][P7].

The positive effects of a 'hydrogen hype' should not be underestimated. A hype can also lead to hydrogen gaining more attention and investments, increasing its trajectory on becoming a viable option.

It could almost become a self-fulfilling prophecy. Such an increase in consideration of hydrogen could possibly lead to a larger role for hydrogen by 2050 if actors deem this efficient for the energy system [CCC, 2018][NationalGrid ESO, 2020a].

As a last comment, this section focuses on the TRL of electrolysers specifically. However, actors also mention that technology development and innovation in a value chain perspective can also help to exploit potential synergies between industries [Questionnaire][NO ministry, 2020a]. These synergies with electrolyser technology include hydrogen applications, e-fuels (such as methane, methanol and jet fuels) production, transport and storage infrastructure, CCS, offshore wind and other renewable energy technologies [NationalGrid ESO, 2019b][Ørsted, 2020][Energinet, 2019a][Energinet, 2020][VARIO, 2020].

For a hydrogen value chain to thrive, different technologies are expected to be deployed and scaled simultaneously, preferable with almost identical TRLs. In such a case, different actors need to respond adaptively, fast, and flexibly [TKI Nieuw Gas, 2019]. The next section (5.9) further discusses the extent to which actors consider such a whole system approach and what consequences this has.

5.9. Theme 9: Visions on the roles and responsibilities for integrating offshore wind into the energy system

When envisioning the most economically and technically efficient approach for system integration, the outcome differs if one takes an approach with the focus on one's individual electricity system, gas system or industry hubs, or if one takes a 'whole system approach'. The latter is an approach where heat, electricity, natural gas and hydrogen networks and their producers and users are considered as one system [NationalGrid ESO, 2020a]. Not considering such a whole system approach leads to different perceived roles for gas infrastructure when integrating offshore wind.

To emphasise, in the introduction of this research, the normative position has been taken that a whole system approach to offshore wind integration is beneficial for the energy system as a whole, including the consideration of gas infrastructure. This approach does not entail that offshore wind should always be integrated with gas infrastructure, but merely that one should consider the use of gas infrastructure. Whether gas infrastructure is the most efficient way to integrate offshore wind differs per region because it depends on the geographical characteristics and starting points of the different energy systems within the NSR [Bolton et al., 2019].

In this section, the extent to which actors take a whole system approach is discussed. Differences in actors' scopes lead to a certain incompatibility between energy visions. Due to their different scopes, actors could differently define the most optimal energy system. Therefore, they could disagree on the correct vision to create the most efficient energy system. In order to be able to make recommendations on how this scope could be changed to increase compatibility between energy visions, it is important to have an understanding of the current scopes actors take.

This difference of scope is explained in three different subsections. First, different geographical scopes are defined. Second, the different approaches of different types of actors are defined (e.g. industrial, government and TSOs). The last section defines the different business cases actors have because of their different scopes.

5.9.1. A national responsibility for an international energy system

Part of the whole system approach is an international scope. Such a scope is considered beneficial, as previous research states that the most efficient and least expensive energy system is achieved when managed internationally [Gea-Bermúdez et al., 2020][Kristiansen et al., 2018][Wieczorek et al., 2015][Bolton et al., 2019]. In Europe, and the NSR, aside from optimisation on a national and local level, the energy system is also optimised on an international scale by TSOs in the European electricity market [Anonymous]. Such infrastructure is also planned in the ENTSO-E/ENTSO-G infrastructure Ten Year National Development Plans (TYNDP's) [ENTSO-E, 2019a].

Although optimisation is increasing on a more international level, the responsibility of system integration is scoped nationally. National governments are ultimately responsible for the integration of RES. Due to this national responsibility, politicians are said to rather choose a nationally regulated option, than an internationally regulated option. For example, if for a nationally regulated option a fault would occur three times in ten years, one would still prefer this option, even though the internationally regulated options would lead to a fault occurring one in ten times (concluded in PWC research) [P12]. Therefore, one could conclude that there is a mismatch between national powers and responsibilities (politics) and the area that a grid operator can cover, leading to sub-optimal solutions in terms of policy [P12]. It is unlikely that national governments will fully 'hand over' their responsibilities for maintaining the security of supply to an international party who would be able to optimise it more efficiently for the region as a whole. This could make collaboration increasingly challenging in the NSR.

In the analysed energy visions, and even within one actors' energy vision, the scoping of system adequacy differs between being nationally focused, Nordic focused, and EU focused [DE BMWi, 2020a]. Based on the information given in Chapter 4, UK actors are recognised to be the most nationally focused in their energy visions compared to the other NSR actors. Furthermore, Danish and Norwegian actors are initially quite Nordic focused in their energy visions, although they also do maintain an international scope. For instance, the Danish TSO Energinet mentions the North Sea could be considered as a power system for the whole of Europe [Nordic TSOs, 2020]. Belgian actors are considered to be the most (explicitly) European focused in their energy visions. For instance, Elia and Belgian governmental actors mention the "development of strategic and interconnected European energy networks to [lead to] a greater flexibility potential within the energy system" [BE federal government, 2019b](*Page11*)[Elia, 2019b]. Additionally, German actors explicitly mention their international focus outside of the NSR (e.g. to import hydrogen) [DE BMWi, 2020b]. Lastly, Dutch actors are not really characterised by a specific geographical scope taken in their energy visions [Nordic TSOs, 2020][P1][Statnett & Fingrid & Energinet & SvenskaKraftnat, 2020][P9][VARIO, 2020][Elia, 2017a][Nordic Energy Research, 2020][NationalGrid ESO, 2020b][Elia, 2020][P2].

A North Sea approach is never really taken when the security of supply is considered, which could be explained as the North Sea is mostly seen as a power system for the whole of Europe [Nordic TSOs, 2020]. Therefore, a North Sea approach is often expanded towards a more European approach.

In conclusion, a whole geographical system approach could be considered most beneficial when optimising system adequacy within the NSR. However, responsibilities for maintaining this system adequacy are on a national level. Due to this misalignment and the tenacity of governments to keep control of maintaining the security of energy supply, one might argue that the most optimised system is not achievable. For example, Nordic Energy Research mentions that as price volatility is higher in the power markets outside the Nordic region, they expect the solutions to take place where the challenges are greatest [Nordic Energy Research, 2020]. This conclusion is important to consider when defining the most optimal route for managing generation adequacy when integrating offshore wind. Energy visions might be incompatible with each other if they maintain a different geographical scope and therefore consider different technological options to create the most optimised energy system. In other words, actors could disagree on what the most optimal energy system is due to the different geographical scope they take. Although scopes differ, actors' visions are compatible to a certain extent as all actors agree that the responsibility of maintaining system adequacy lies on the national level.

5.9.2. The different approaches taken by industrial players, governments and TSOs

This section considers the different approaches for offshore wind integration taken by industrial players, government actors and TSOs, and to what extent these actors envision a role for gas infrastructure.

This paragraph focuses on the specific role industrial players consider for gas infrastructure when integrating offshore wind.

After analysing different energy visions and interview discussions, this study concludes that industrial players find themselves to be responsible for either the production or consumption side of hydrogen. They mostly aspire to a positive business case [P4][P7]. These actors tend to focus less on the transport of energy and integrating aspect of offshore wind, as these are seen to be socialised costs and therefore a role for the TSOs and governments [P7][P13]. Maintaining system adequacy only becomes part of their 'duties' if a business case to do so arises, driven by either market incentives or governmental financing, rules or regulation [P7][P16].

Currently, national governments are ultimately responsible for maintaining security of supply [P12]. They often give a mandate to a certain TSO to integrate offshore wind and maintain system adequacy.

The next paragraphs describe the different types of roles and responsibilities governments and TSOs consider for themselves in maintaining system adequacy. These roles and responsibilities are then linked to what role these actors subsequently envision for gas infrastructure when integrating offshore wind into the energy system. This combined information could be seen as one of the explanations why actors' visions on the role of gas infrastructure for integrating offshore wind differ from each other.

The proposition of this research is that the extent to which actors are well coordinated (with coordinated responsibilities for both gas infrastructure and offshore wind integration) is related to the extent actors consider a whole system approach (and subsequently a role for gas infrastructure when integrating offshore wind). This proposition is tested and further discussed for each national group of actors. In other words, the following paragraphs analyse if the responsibilities of actors (for integrating offshore wind) are related to the extent to which actors take a whole system approach.

These paragraphs are structured in three different subsections, one for each different TSO organisational structure categorised [P12].

An organisational structure with several TSOs with different owners

There are different organisational structures of TSOs. Firstly, there could be several TSOs with different owners. Due to a variety of TSOs having their own individual responsibilities, these TSOs could be less driven to cooperate [P12].

Such an organisational structure of TSOs is the case in Germany. Network operation and expansion is organised privately between many TSOs. Several actors mention that such an organisational structure increases the challenge to coordinate plans using a whole system approach when compared to other countries around them [P12][P5].

Currently, in Germany a larger focus (by the government) is put on the installation of electricity lines than on gas infrastructure to integrate offshore wind [DE BMWi, 2020a][Gasunie,TenneT, 2020]. This is expected to change, as the German government plans to have a joined grid planning for electricity and gas infrastructure from 2020 onwards and an integrated infrastructure planning across all sectors from 2030 onwards [DENA, 2019][P5]. In addition, the new "Third Act revising Energy Industry Rules" contains rules on improving security of supply, ensuring that an integrated view is taken of the gas and electricity systems [DE BMWi, 2020a].

Focusing on the regulation of hydrogen, the German government currently plans for an opt-in framework. Such a framework leaves the decision to hydrogen network operators whether they want to be regulated or not [Lohmann, 2020].

Possibly due to the current larger focus on electricity grids to integrate offshore wind by government actors, electricity TSOs also focus less on the role of gas infrastructure than gas TSOs in their energy visions. However, in an interview, this conclusion was contradicted. In this interview it was concluded that, due to the limitations of timely electricity grid expansion, electricity TSOs do recognise a large role for gas infrastructure [Anonymous].

The proposition of well-coordinated actors (with coordinated responsibilities for offshore wind integration) being related to the whole system approach actors take can be considered to slightly hold in the case of the German energy system. The previous paragraphs explained that because several private actors (coordinated by the federal government) are responsible for integrating offshore wind, a whole system approach is only taken to a certain extent. The federal government is trying to increase coordination between these private actors, which they expect could increase the whole system approach taken.

An organisational structure with two separate TSOs who have the same stakeholder

A second organisational structure of TSOs is that there are two separate gas and electricity TSOs, who do have the same stakeholder (the government). This stakeholder could then optimise the roles between both TSOs. For instance, a smaller return on investment for an electricity TSO could then be compensated by a larger return for a gas TSO [P12]. This seems to be the case in both Norway, Belgium and the Netherlands. The three paragraphs below explain the different responsibilities TSOs have and the related role they see for gas infrastructure when integrating offshore wind.

The Norwegian government perceives hydrogen developments as more of a business opportunity than a necessity to maintain system adequacy [NO ministry, 2020a]. The government, and not the TSOs, play a large role in hydrogen visions. Firstly, the electricity TSO deems that "the future is electric" [Statnett, 2019d](*Page2*). Secondly, The gas TSO mentions their only responsibility is to be the operator of the Norwegian transport system for natural gas, developing both regional and transnational infrastructure, where in their Annual report of 2019, the term 'hydrogen' is not mentioned once [Statnett, 2019c][Gassco, 2019a][Gassco, 2019b]. They also do not perceive it to be their role to discuss where or how blue hydrogen may or may not be produced [P17]. Both TSOs are, however, in good dialogue with each other to ensure to get the most optimal development both on and offshore [P17].

As can be concluded from chapter 4, Norwegian actors all see no large role for gas infrastructure when integrating offshore wind. The proposition, of well-coordinated actors (with coordinated responsibilities for offshore wind integration) being related to the whole system approach actors take, can be considered to hold in the case of the Norwegian energy system. This can be concluded because Norwegian TSOs are not very well-coordinated, and also do not explicitly maintain a whole system approach.

In Belgium, the federal government is responsible for security of supply and for regulating the development of offshore wind farms, which are currently all connected electrically [P1][P2]. With the exception of one future project (ONSHORE), which is planning to convert offshore wind into hydrogen [P2].

The TSOs Fluxys and Elia are private parties where the government has an interest [P3]. Here, Elia has a legal obligation to plan and expand the transmission network. In their offshore wind federal development plan, they do not include a role seen for gas, blue hydrogen, sector coupling or PtG [Elia, 2019a][Elia, 2019b][P1][P4].

The gas TSO Fluxys is more focused on hydrogen, stating that gas and electricity infrastructure should complement each other optimally in a sustainable, affordable and reliable energy system [Fluxys, 2019][P1].

Currently, the hydrogen network in Belgium is privately managed by Air Liquide. However, Fluxys is strategically trying to get a role in hydrogen transport as they recognise a decreasing transport of natural gas in their large transport hub Zeebrugge [P1]. In their energy vision, Fluxys presents themselves as a "market-neutral operator, who can use its technical know-how to execute its role in the energy transition, by integrating green gas and innovative gas technologies into their infrastructure" [Fluxys, 2019](*Page5*)[P4]. Fluxys also mentions to "work on the complementarity between the gas and electricity systems by letting the Fluxys gas infrastructure play a key role in the transportation and storage of (green) energy" [Fluxys, 2019](*Page5*). Furthermore, Fluxys and Elia are in discussion together, considering a whole system approach, although the interaction is expected to become more important up to 2040-2050 when decarbonisation of hard to electrify applications is said to arise [Anonymous][P4].

The proposition of well-coordinated actors (with coordinated responsibilities for offshore wind integration) being related to the whole system approach actors take, tends to apply to the Belgian energy system. Belgian actors can be considered to be less coordinated (only one actor is deemed responsible for integrating offshore wind), and the energy visions of Belgian TSOs do not take a whole system approach.

In the Netherlands, the government is responsible for integrating offshore wind, and has mandated the electricity TSO TenneT to be the operator at sea [NL EZK, 2020b]. In TenneT's view, the best way to currently connect wind farm areas, currently located relatively close to the Dutch coast, is to use electricity lines [TenneT, 2020b].

TenneT also has a collaborative energy infrastructure outlook with the Dutch gas TSO which concluded, firstly, that an energy system based on domestic RES will rely on coupled electricity and gas grids and, secondly, that adequately located PtG units and gas storages have the potential to reduce the need for additional electricity lines [TenneT, 2020b]. This could be a reasoning behind the relatively larger role seen for the use of gas infrastructure when integrating offshore wind.

Gasunie is both a TSO and an infrastructure company. The law prohibits them from producing energy, but Gasunie could also deploy transport projects not regulated by law [Anonymous].

As indicated in the Growth Strategy for the Netherlands, the government intends to play a key role in the development of the hydrogen infrastructure, reviewing whether and under which conditions part of the gas infrastructure can be used for the transport and distribution of hydrogen [NL EZK, 2020b].

The proposition of well-coordinated actors (with coordinated responsibilities for offshore wind integration) being related to the whole system approach actors take, can be considered to not exactly hold in the case of the Dutch energy system. The electricity TSO TenneT is mandated by the government to integrate offshore wind. Together with Gasunie, TenneT published a collaborative infrastructure outlook for 2050 [Gasunie,TenneT, 2019b]. Possibly stimulated by both this vision and government actors, TenneT takes a whole system approach to their strategy for integrating offshore wind into the energy system. If the proposition were to hold, a more electrical focus should be considered by TenneT.

An organisational structure with one management or owner of one TSO

A third option is that there is one management and owner of a TSO responsible for both electricity and gas. This seems to be the case for the Danish Energinet and NationalGrid in the UK, although this organisation of TSOs in the UK is slightly more complex [P12].

In the UK, the government is responsible for maintaining system adequacy. Ofgem acts as the independent energy regulator, answerable to the UK Parliament and UK Government. They manage the competitive tender process through which offshore transmission licences are granted, appointing different Offshore Transmission Owners (OFTO's) [OFGEM, 2020]. Ofgem is a strong financial regulator to the network sector, ensuring that network companies deliver a safe and reliable service [H-Alba]. According to interview discussions, Ofgem is deemed more market-focused compared to regulators in other countries. Ofgem is increasingly driven by cost-efficiency [P14][OFGEM, 2020]. This is also proven by the governments and Ofgem's choice to over-size electricity network infrastructure as financially, this is a low-regrets option [CCC, 2020]. This could also be a reason for the small role seen for gas infrastructure for integrating offshore wind, as in the short term this is not deemed the most cost-efficient solution.

The National Grid, the TSO for most of the country, produces Future Energy Scenarios (FES) for the next 30 years annually where a whole system approach is considered [NationalGrid ESO, 2020a][NationalGrid ESO, 2019b]. The FES is an analysis of potential credible futures produced by National Grid ESO. National Grid ESO is not legally allowed to build or run any energy generation. Similarly, National Grid Gas is not allowed to own any gas production facilities. Furthermore, these two companies are legally separate and can only collaborate as they would do with any other third party [P19].

The Northern Gas Network and Scottish government also mentions the importance of interaction between Ofgem, UK and Scottish government due to the "growing inter-dependencies between different parts of the energy system" [H-Alba]Page35][Northern Gas Networks, 2019].

The proposition of well-coordinated actors (with coordinated responsibilities for offshore wind integration) being related to the whole system approach actors take, can be considered to hold in the case of the UK energy system. A technology independent energy regulator is responsible for integrating offshore wind, and a whole system approach is taken when envisioning ways to integrate offshore wind.

Energinet is a public TSO owned by the Danish Ministry of Energy, Climate and Utilities. They take a whole system approach, combining responsibility for electricity, gas and heat networks [P12][Energinet, 2019a][P9].

In Denmark, the government seems to be the main actor responsible for maintaining system and network adequacy, with a new agreement on offshore wind in 2020, which stated that offshore integration is included in offshore tenders [Energinet, 2019a][P7]. Governed by objectives based on the Danish State's ownership strategy, Energinet focuses on energy transport. Energinet is given the responsibility of balancing the grid but does not find itself to be responsible for 'producing' the flexibility [Energinet, 2019a][P9].

The TSO mentions that they will not produce any hydrogen or green fuels directly but that they must avoid 'getting in the way' and be ready to integrate hydrogen into the energy system [Energinet, 2019a][P9]. Energinet is actively contributing to the designation of suitable electrolyser locations, because they consider such locations to establish hydrogen clusters and ensure system development (for e.g. hydrogen infrastructure). Nonetheless, Energinet does consider the performance of electrolysers to be out of their scope of influence [Energinet, 2019a][Energinet, 2020]. The TSO is very ambitious and sometimes perceived as unrealistically ambitious by anonymous Danish energy experts [Anonymous]. This can be exemplified in Energinet's idea (and now governmental plan) to develop an energy island, which by some is seen as a very large project with a lot of untested technology [Anonymous].

The proposition of well-coordinated actors (with coordinated responsibilities for offshore wind integration) being related to the whole system approach actors take, can be considered to hold in the case of the Danish energy system. A whole system approach is envisioned for integrating offshore wind, and Energinet is both responsible for gas and electricity infrastructure developments.

One last type of organisational structure for TSOs can be defined. In this case, there is one asset management department for gas, electricity and heat infrastructure [P12]. In this case, investments are made collectively for gas, electricity and heat infrastructure leading to full technological neutrality of such investments. Such a structure is not the case for any TSO in the NSR.

In conclusion, focused on the role of TSOs and government actors, most governments have mandated electricity TSOs to integrate offshore wind. Depending on the whole system approach of these TSOs, a certain role is currently envisioned for gas infrastructure when integrating offshore wind. The electricity TSOs mostly seem to mention integration solutions within the electricity network. Due to their shortcomings and grid bottlenecks arising faster than they can solve, electricity TSOs then see necessity to make use of gas infrastructure to integrate RES [Elia, 2020][Energinet, 2019a]. Contrarily, gas TSOs mention the role of gas infrastructure for green gasses as this is seen as a viable replacement for reducing natural gas currently transported through the grid. Although differently motivated, one could conclude that these actors are starting to find each other [P12].

Effectively, this study concludes that the larger the cooperation and coordination between a gas and electricity TSOs, the more a whole system approach is envisioned. For instance, the combined gas and electricity TSO seems to increasingly take a whole system approach, focused on both electricity and gas infrastructure. This proposition holds for the UK, Belgian and Danish actors and to a certain extent for German and Dutch actors. Norwegian actors are a more diverse exception, possibly due to the role of natural gas in the Norwegian energy system.

The information in this section could be seen as one of the explanations why actors' visions on the role of gas infrastructure for integrating offshore wind differ from each other. A certain relation can then be defined between who is responsible for integrating offshore wind and to what extent a whole system approach is taken. Gaining more knowledge on this relation could also further explain the incompatibility between energy visions with or without a whole system approach.

However, it is uncertain if the relation is a cause or an effect. In other words, does the system work more collaboratively because actors are collaborating, or do actors collaborate because the specific energy system already works more collaboratively? Considering actors' different energy systems, it remains difficult to answer this question.

Nevertheless, how these scopes could possibly be expanded or altered is discussed in the next chapter.

5.9.3. The scope of hydrogen business cases

All actors, and especially TSOs, mention cost-efficiency to be an important driver for flexibility technologies [Energinet, 2019d]. However, in the business cases envisioned by actors, a whole system approach is often not taken. Such a whole system approach considers all different opportunities and societal costs. This leads to large differences on what is and is not considered between different actors. Subsequently, this is also a cause of incompatibility of different energy visions on the role of gas infrastructure. If actors use different business cases to determine what technology they envision to be beneficial to integrate offshore wind energy, their visions are likely to also be incompatible.

A perfect 'whole system approach' business case, for the use of gas as opposed to electricity infrastructure for system integration, does not yet exist. Furthermore, an interviewed expert expects the development of such a business case to be challenging because of the current uncertainty on future costs and actors' lack of awareness on all different aspects [P3]. Absolute prices will never completely be the same, but it is important for actors to at least recognise the different elements. Examples of these different elements include the capacity factor of electrolysers, transport costs (which include the distance and the percentage of pipes utilised), the cost of reusing or newly constructing gas infrastructure, the CO2 price, the cost of gaseous storage, the primary electric or gaseous fuel costs, additional costs related to conversion and costs for modifying applications to accommodate new fuels and the opportunity cost of having to otherwise decommission gas infrastructure and further reinforce electricity grids and storage [TenneT, 2020b][NO ministry, 2020a][Equinor, 2019][Energinet, 2020][VARIO, 2020][P3].

The financial benefits of gas as opposed to electricity infrastructure for integrating RES should also be considered in actors' business cases. The way flexibility is expected to be valuated in the electricity markets is out of scope of this research, as all different competing flexibility technologies effectively use the same prices. However, one should still consider the scope when determining these benefits. As in the case of hydrogen, direct users of hydrogen do not only benefit financially, but the whole system benefits from a balanced energy system [Drift, 2020].

5.10. The state of (in)compatibility of the nine themes

The following section concludes this chapter by answering the second sub-question of this research: To what extent, and based on what underlying reasoning, are energy visions compatible or incompatible with each other? This chapter defined nine overarching themes on which actors had visions that were compatible or incompatible with each other. In every subsection, the extent to which these themes are (in)compatible was discussed, with the subsequent reasoning for this (in)compatibility and possible consequences of this (in)compatibility on the energy system as a whole.

The themes defined in this chapter can be categorised into four different groups with varying (in)compatibility levels. This is done to provide a better overview of the extent to which actors' energy visions are (in)compatible. These groups were termed 'Group A. Celebrated themes', 'Group B. Themes where actors envision the same approach', 'Group C. Themes with competition between different types of approaches' and 'Group D. Themes where there is no co-existence possible'.

These groups are informatively composed by the researcher. This was done by combining the theoretical futuring framework from chapter 2, with insights from both interviews and previous research on *Social innovation in energy transitions* [Wittmayer et al., 2020]. To emphasise, these groups were designed to make it easier for the researcher to structure all the different themes defined. The goal of these groups is by no means to be restraining for the researcher.

In the paragraphs below, the nine themes characterised in this chapter are categorised into four different groups. The themes are referred to as (**5.1 till 5.9**). This gives an overview of the current (in)compatibilities between actors' energy visions in the NSR.

A. Celebrated themes

The first group contains themes on which actors have identical visions, which are collaborated upon (celebrated) in groups and associations. This is the most compatible group, as when actors already collaborate with each other, their visions are able to be executed together without problems or conflict. Most themes that are part of this group were defined in chapter 4.1. This includes the shared potential of offshore wind all actors in the NSR recognise.

B. Themes where actors envision the same approach

The second group contains themes on which actors also have identical visions but which are not collaborated upon explicitly. In this case, there is a possibility of competition between actors, as they all aspire to gain a first-mover advantage. This group is relatively compatible because, compared to a more collaborative approach, more regional competitive action could also allow more rapid experimentation and tailoring of policies and thus developments in general. However, the group is not as compatible as more collaborative actions at an (inter)national level could also provide better coordination which leads to an increase in efficiency of a system [Dedecca et al., 2019]. This is further explained in the next chapter. Two themes defined in this research are considered to be part of this group.

A first theme considered part of this group is the role actors see for becoming a production, consumption and transit hub of hydrogen. Both competition and need for collaboration are identified, because together the NSR consists of hydrogen production (DK/NO/NL/UK), transport (NL/BE) and consumption hubs (NL/DE) (**5.7**).

A second theme considered part of this group is the technology readiness level (TRL) of electrolysers. Most actors share the same insight into the TRL of electrolysers. Although, sometimes, there is a lack of insight if a certain goal is considered a technological probable target or an ambitious aspiration (**5.8**).

C. Themes with competition between different types of approaches

The third group contains themes that are also relatively compatible, because actors have different co-existing visions and are in competition on the approach. Previous research concluded that a competitive approach allows for technological and regulatory experimentation, does not constrain ambitious front runners, is more robust to regulatory design errors, and is more adapted to the different preferences of actors. However, previous research showed there is a risk that actors do not consider the externalities they inflict on the whole system by optimising their own sub-system, leading to incompatibility [Dedecca et al., 2019]. This is further explained in the next chapter. Five themes defined in this research are considered to be part of this group.

A first theme is the consideration of ratios of gas and electricity consumption. Different consideration of this ratio leads to different visions actors have on the infrastructure deemed necessary. Although different consumption patterns in industry, mobility, and heating are identified between national regions, this research does not consider it problematic for infrastructure alignment due to most consumption differences occurring within a national scale (**5.6**).

A second theme is the role of flexible (gas-based) thermal power plants. In times of a shortage of wind energy, most actors see a role for thermal power plants. However, there are different visions on the exact process being CCS pre- or post-combustion. Consequently, the form in which gasses would have to be transported, to fuel these power plants, is uncertain. Due to these differences in visions, a parallel pipeline network for hydrogen, natural gas and CO2 is likely to develop. This development of competing pipeline networks is not considered to be the most efficient system. However, it is also not considered to be completely incompatible because the co-existence of different gas infrastructures is possible (**5.4**).

Lastly, three themes focus on the role of electrolysers envisioned for integrating offshore wind energy into the energy system. Differing visions on this theme leads to actors seeing a different role for electrolysers in both flexible uses of electrolyser capacity (ramping up and down or running at full capacity) and electrolyser location (nearby offshore wind production or hydrogen consumption). This co-existence of different ideas can be regarded as beneficial because, in this research, we expect this competition of different approaches to eventually lead to a good combination of different uses for electrolysers. Although, one must be mindful of the competing claims of offshore wind that could arise as it would be impossible for both electrolysers and direct electricity consumption to 'claim' the same offshore wind capacity (**5.1, 5.2 and 5.3**).

D. Themes where there is no co-existence possible

The fourth group contains themes on which actors also have different visions, but where co-existence of ideas is not possible; if energy visions were to be executed, there would be a conflict of interests between actors. In this case, different actors seize a role for the same elements and envision different functions and developments for it. By definition, this is an incompatible group. Two themes defined in this research are considered to be part of this group.

The first identified theme considered part of this group is the form in which gaseous fuels are envisioned to be transported in. Problematic is that both modes of transport of pure hydrogen and blended hydrogen with natural gas are discussed in different energy visions. Also of interest is the role seen for the reuse of gas infrastructure currently used for natural gas. Mostly Dutch actors currently see the economic benefit of reusing gas infrastructure, leading to possible misalignments on the timing of hydrogen pipeline transport. As any part of a gas infrastructure can only transport a single gas, conflicting visions on timing of infrastructure repurposing could be problematic (**5.5**).

A second identified theme considered part of this group is the theme of differing visions on the roles and responsibilities for integrating offshore wind into the energy system. This theme and its state of incompatibility are defined in chapter 6 (**5.9**).

In conclusion, there are several compatible and several more incompatible themes in the NSR that can be divided into four different groups. Together, these four different groups compose a 'collaboration framework', which is explained in the next chapter.

The specific descriptions of these themes in the subsections also concluded that some themes are incompatible due to some undynamic characteristics of actors' energy systems. To what extent such themes can be made more compatible is also discussed in the next chapter.

6

How could energy visions be made more compatible

This chapter discusses how, with the help of futuring theory, one can optimally consider a 'whole system approach' (e.g. where gas infrastructure is considered) within the NSR as a whole. In the introduction of this research, the normative position has been taken that a whole system approach to offshore wind integration is beneficial for the energy system as a whole, including the consideration of gas infrastructure. This approach does not entail that offshore wind should always be integrated with gas infrastructure, but merely that one should consider the use of gas infrastructure. Whether gas infrastructure is the most efficient way to integrate offshore wind differs per region and is based on the different energy systems within the NSR [Bolton et al., 2019].

Based on the pattern model of the previous chapter, the third sub-question is answered in this chapter (How could these energy visions be made more compatible to improve international system integration in the North Sea region?). This question is reflected upon by considering the themes presented in chapter 4 and 5 and discussions from interviews. This chapter can be seen as a discussion on the use of the concept of energy visions to make the NSR more compatible, it therefore also builds upon the academic review on energy visions in chapter 2.

First, in this chapter, the benefits and necessity of both competition and collaboration of actors are presented. This is done to determine to what extent both competition and collaboration could make energy visions more compatible. This section (6.1) concludes that a combination of competition and collaboration is beneficial for the energy system of the NSR. This combination is elaborated upon in section 6.2, which also discusses the concept of a 'Collaboration framework' which was introduced in the previous chapter (5.10). Based on this 'Collaboration framework', four recommendations are subsequently presented that increase compatibility in the NSR considering the role of gas infrastructure when integrating offshore wind.

6.1. Competition versus collaboration

Actors could be hesitant to collaborate when their ideas are different due to different starting points. They could also be hesitant to collaborate when they want to maintain a competitive advantage over the other. To be able to recommend what collaboration or competition is most efficient for the NSR, it is important to first have an understanding of the current collaborative or competitive nature of actors. Therefore, the next three paragraphs discuss the current competitive or collaborative nature of industry (1), government (2) and TSO (3) actors in the NSR.

Firstly, in most energy visions from industrial players, a more competitive culture is detected. In such a culture, there is much hesitation to share and widely collaborate among industrial partners. Although, as the Port of Rotterdam mentions, there is currently a shift towards a focus on the joint challenge of industrial players to create societal support and policy conditions together [Drift, 2020]. As this research focuses less on industrial players, less focus is also put on their collaborative role. This is supported by the fact that industrial actors are not seen (to become) responsible for integrating offshore wind and maintaining system adequacy.

Secondly, considering the competitive or collaborative nature of governmental actors, there is a balance between collaboration on infrastructure plans and competition for first-mover advantage. Government actors are responsible for maintaining system adequacy in their country and are, as previously mentioned in section 5.9, not inclined to 'hand over' part of this responsibility. This is also the case if an energy system is more efficiently optimised on an international scale, saving costs and increasing security of supply. The actor is not likely to do this as it takes away their independence, which could be hard to justify to their 'voters' [Anonymous].

Thirdly, currently, both electricity and natural gas infrastructure are seen as a public good with different regional actors (TSOs) being responsible. Therefore, infrastructure could more easily be coordinated as there is no regional competition; everyone has their own assigned area [P1][Anonymous]. This explains their less competitive nature, also detected in TSO energy visions.

Although if two different entities are responsible for gas and electricity infrastructure, a slight competition could be defined between these TSOs. These actors would compete for transporting the same energy in either electric or gaseous form. This competitive behaviour is not deemed efficient for the energy system. This inefficiency is reasoned because, in such a case, choices for technologies are not based on what is most beneficial for the system but are based on an actors' assets being included in the solution. Such competition is also of interest considering hydrogen infrastructure. This is discussed in detail further on in this chapter.

6.1.1. Advantages and disadvantages of a competitive or collaborative approach

After analysing different actors' energy visions in both document form and interviews, one can conclude that most actors tend to sometimes take a more competitive and sometimes take a more collaborative approach. There are no actors that exclusively take a collaborative approach or exclusively take a competitive approach. There are advantages and disadvantages to a competitive or more collaborative approach. These are discussed in this paragraph.

On the one hand, actors deem it essential to hold on to one's individual perspectives, as more competitive regional action can allow for more rapid experimentation and tailoring of policies. On the other hand, action at an (inter)national level can provide better coordination [Dedecca et al., 2019]. Previous research showed that a competitive approach allows for technological and regulatory experimentation, does not constrain ambitious front runners, is more robust to regulatory design errors, and is more adapted to the "heterogeneous contexts and preferences of actors" [Dedecca et al., 2019](*Page 56*). In the case of a competitive approach, different ideas are able to exist and are demonstrated where evidently the ideas could converge into the main development path, often driven by governmental actors [P16][P8].

The same research mentions three disadvantages of a competitive approach. Firstly, a competitive approach is said to include the duplicated use of resources in the system. In this case, several actors competitively claim the same resources. Secondly, a competitive approach is considered to make coordination of decentralised and heterogeneous system elements more complex. Lastly, a competitive approach could lead to decentralised systems not internalising the externalities inflicted by one system element to another (being prone to free-riding of actors) [Dedecca et al., 2019]. In other words, there is a risk that actors do not consider the effect their actions, to optimise their own sub-system, have on the part of the system that is outside of their scope. This could lead to actors profiting from their actions without fully expending effort or paying for it.

The themes defined in chapter 5 illustrate that there are differences between actors based on unchangeable geographical and historical characteristics. For example, the large Norwegian gas supply will not change. This proposition, combined with the fact that competition is sometimes deemed advantageous for an energy system, results in the conclusion that an energy system with only identical energy visions is impossible and undesirable to achieve. Therefore, this research recommends that actors do not pursue one collaborative uniform (heavily detailed) energy vision, but that both (local) competition and (international) collaboration are developed in parallel with each other (as supported by [Anonymous][P10]).

As also stated in previous research, collaboration between visions is not always necessary, as cooperation at the regional level is simpler, centralisation could hinder experimentation and hold back ambitious front runners and decentralisation is “more robust to design errors and accounts for heterogeneous national characteristics” [Dedecca et al., 2019](*Page 60*)[Hyysalo et al., 2014]. A “mix of top-down and bottom-up elements” [Dedecca et al., 2019](*Page 60*) is recommended (by both the author Deddecca and the ENTSO-E). In this case, flexible implementation is considered beneficial when combined with rigid obligation [Gephart et al., 2015][Dedecca et al., 2019].

In conclusion, the energy system as a whole has never been the most efficient, and neither should one expect it to become this way in the future. Therefore, it is essential to determine where alignment is needed and where different actors can have different energy visions. Of course, it is possible to have one (be it vague) unanimous vision, but there will always remain difficult to change certain geophysical, political or infrastructural factors that lead to different visions. Actors will always tend to first consider their own needs and what is the cheapest route for their own industry or region [Anonymous].

This leads to the term ‘collaborative futuring’, previously presented in chapter 2, which is defined as maintaining one’s own vision whilst considering other existing visions within the same envisioned geographical and dimensional scope.

6.2. The ‘Collaboration framework’

Collaborative futuring can best be explained by considering the distinctive groups that this research divides different themes into. As a recap, these themes were categorised on a scale of incompatibility and whether actors had shared or different views on these themes. The ‘collaboration framework’ is illustrated in figure 6.1. In the middle of this figure, a scale is shown from compatible to incompatible themes. The farther to the right the themes are placed, the more incompatible the themes are. This makes group A themes the most compatible themes, group B and C themes equally ‘relatively’ compatible, and group D themes the most incompatible themes. Furthermore, groups that are placed above the scale depict themes on which actors have identical visions. In contrast, groups that are placed below the scale depict themes on which actors have different visions.

In this research, compatible sub-systems are defined as a group of energy sub-systems that are able to exist or occur together without problems or conflict. Group ‘A. Celebrated’ themes are seen as most compatible, because the envisioned themes in this group are identical and are already collaborated upon in projects and collaborative groups. Therefore, it is highly unlikely such themes are unable to exist together with conflict.

Next, group ‘B. Same approach’ and group ‘C. Different approach’ themes are considered to range from being relatively compatible or relatively incompatible. All themes within these groups could be both relatively compatible or relatively incompatible. This differs per specific theme. An example of a group B theme could be that two actors could both envision to become a ‘first-mover’ for a specific technology. This is relatively incompatible as these visions are not able to occur together. Only one ‘firs-mover’ is possible. Nonetheless, another group B theme could me more compatible. For example considering when different actors both envision to become a green hydrogen production hub. In this case, both actors would be in competition with each other, but it is likely both green hydrogen production hubs are able to exist in parallel with each other, although they would not be fully compatible as actors are in competition with each other and could try to obstruct one another.

An example of a group C theme could be that actors envision different optimal locations for electrolysers. Such ideas are different but are relatively compatible as different electrolysers could be placed in different ‘optimal’ locations. Although this theme is not fully compatible as different infrastructure is needed for facilitating both electrolyser locations. Therefore, this is not deemed the most cost-efficient solution.

Lastly, group ‘D. No co-existence’ themes are considered to be the most incompatible, because in this case different envisioned themes are considered impossible to be executed together. An example of such a theme would be if different actors envision different locations for the same specific electrolyser.

Generally speaking, ‘collaborative futuring’ does not aspire to get all themes in group ‘A. Celebrated’, as this is neither deemed possible nor beneficial for the system as explained in section 6.1. However,

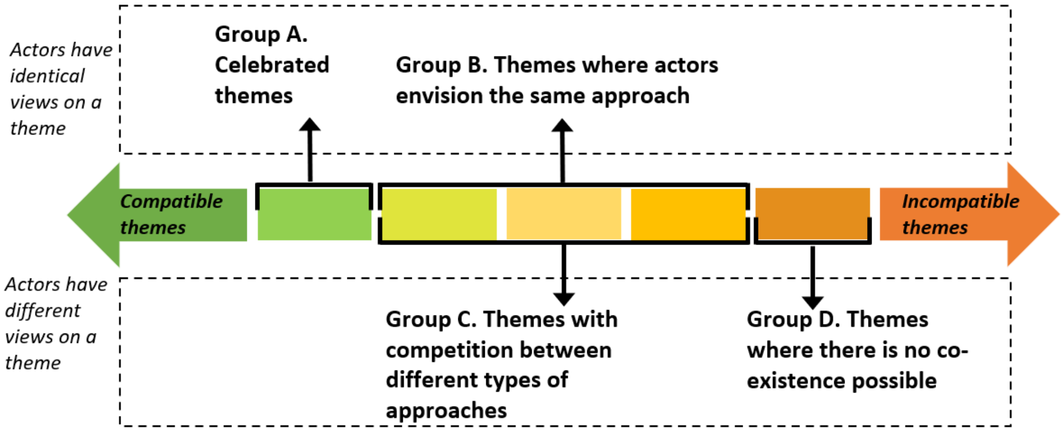


Figure 6.1: A ‘collaboration framework’. In the middle of this figure a scale is shown from compatible to incompatible themes. The farther to the right the themes are placed, the more incompatible the themes are. This makes group A themes the most compatible themes, group B and C themes equally ‘relatively’ compatible, and group D themes the most incompatible themes. Furthermore, groups that are placed above the scale depict themes on which actors have identical visions. In contrast, groups that are placed below the scale depict themes on which actors have different visions. This framework was specifically designed by the researcher.

one should aspire to at least prevent the development of group ‘D. No co-existence’ themes, as this leads to incompatible sub-systems.

The exercise of an independent observer filling in the aforementioned framework could be seen as an important part of collaborative futuring, as also verified in interview discussions [P18]. Subsequently, one can use the framework subdivision as an instrument to initiate a discussion and possibly collaboration. There is no ‘one size fits all’ for making energy visions more compatible with each other, as mentioned in the previous section. Therefore, categorising different themes into different groups is helpful to distinguish the different developments necessary to make specific themes more compatible. What these specific elements are for making energy visions more compatible is discussed in the next section of this chapter.

6.3. Recommendations for collaborative futuring

In this section, four recommendations for collaborative futuring are presented. These are recommendations from the author that build further on the ‘Collaboration framework’ previously presented. Specific recommendations are proposed to be most beneficial for specific groups of the ‘Collaboration framework’. It is important to emphasise that this does not mean that recommendations are only specifically relevant for specific groups. One of the reasons for this is that all recommendations are considered to be dynamic. For instance, throughout time, the themes that are currently characterised as group ‘C. Different approach’ could migrate to group ‘D. No co-existence’. Therefore, the exercise of placing different themes in the framework is of great importance and should be repeated throughout time periods. By using this framework, a specific actor in a specific niche can develop “reflexively and strategically in accordance with global challenges and themes” [Dignum et al., 2018](*Page 202*). Which previous research concluded is beneficial for the energy system [Dignum et al., 2018].

All four recommendations are further defined in the next subsections of this chapter.

6.3.1. Recommendation 1: Increased consideration of different actors in individual energy visions

This section focuses on building a shared frame of reference around data in order to enhance communication between actors [Dignum et al., 2018][Turnheim et al., 2015]. Themes that especially benefit from this recommendation are themes that differ significantly per actor due to geographical and historical factors of the energy system. These themes are categorised into group ‘C. Different approach’ of the ‘Collaboration framework’. Other themes, that are prone to miscommunications, could also profit from this recommendation.

After analysing different energy visions from different actors, it can be concluded that several actors use different timing and definitions. This makes it very difficult for actors to compare and consider each others' visions. Additionally, actors often do not consider how their planned actions relate to their geographically and dimensionally (e.g. gas infrastructure, electricity infrastructure, hydrogen production) 'neighbouring' actors. Actors also often do not consider what assumptions they make about the role and behaviours of their neighbouring actors, also referred to by Moriarty [Moriarty et al., 2005]. Both these two 'considerations' are focused on in this section. First, a general recommendation is given to try to increase actors 'considering' their neighbours. Secondly, more detailed recommendations are given on how to align the structure and language in different actors' energy visions.

One could consider energy visions to always be uncertain because nobody knows what essentially will happen till it has happened. Actors are often also not yet certain of their own standpoints in an energy vision. Due to this uncertainty, actors could be hesitant to cooperate with others. For example, governments are seen to be cautious 'demanding' things from their neighbours unless they are completely certain of their needs [P13][Anonymous]. This lack of cooperation could result in actors becoming increasingly 'stuck' in their own ideas. This could become problematic when neighbouring actors are actually not doing what is implicitly expected of them in an actors' energy vision.

To prevent this, it could be beneficial for actors to consider other (dimensionally and geographically) neighbouring actors' energy visions in their own energy visions [Anonymous]. This would prevent actors from producing an infeasible energy vision. Furthermore, it is also important for current developments and discussions that actors better consider other actors' energy visions. This importance is based on the performativity of an energy vision (discussed in chapter 2).

As a solution, a certain 'consideration-paragraph' could essentially present what one needs from other actors, within other geographical regions and sectors, in order for their own energy vision to become compatible with other energy visions. This is sometimes done (unconsciously) by political actors, industrial associations and TSOs. Examples include the chapter on 'Supporting and flanking policy: international strategy' in the Dutch hydrogen visions [NL EZK, 2020b] and the chapter on 'International collaboration on hydrogen' in the Norwegian hydrogen strategy [NO ministry, 2020a]. Other governmental actors did not include such chapters in their hydrogen strategies (e.g. France) [P13]. Nonetheless, it is recommended such chapters become a fundamental aspect of energy visions and include all relevant actors.

Some actors might be hesitant at first to include a 'consideration-paragraph', because they do not want to 'hand over their trumps'. Nonetheless, this recommendation is deemed essential for maintaining a whole system approach. Another reason for actors being hesitant is that one simply does not know or understand what is needed from others due to the complexity of the energy system [Anonymous]. Therefore, an idea could be that a group of actors agree on a certain framework they can use. This could be based on the 'Collaboration framework' previously presented. Such an exercise does not have to be perfect and complete; even a thought exercise would be beneficial for developing an increased whole system approach in an actors' individual energy visions.

Aside from considering one's 'neighbours', it is also important that different actors understand each other when they are considering and comparing their own visions with other actors' visions. This understanding can be improved if actors include the same time frames (1), use the same approach to consider uncertainty (2) and use the same terms for the same concepts. All three elements are discussed below.

Firstly, considering the different time frames currently used for reaching certain targets, it would be more beneficial to align these to increase comparability of energy visions [Anonymous]. This also includes the moments new targets are set by different governments/TSOs. For example, if targets are set annually or every five years. However, aligning time frames might be more difficult to integrate than expected due to the differing political cycles in the NSR. Nonetheless, it is important to aspire this alignment and let actors be aware of their choice for a time frame, considering the other time frames used around them. This could be of interest, as possibly certain time frames are not as fixed as initially thought.

Secondly, it can be concluded that different energy visions consider uncertainty either implicitly or explicitly. To increase the comparability of energy visions, it is deemed helpful to add probabilities as to how likely something is currently deemed to occur. For instance, a low, medium and high probability were assigned to envisioned developments by the Danish council on climate change in their Klimateredet [Danish Council on Climate Change, 2020]. This could create a better understanding of what ‘dynamic certainty’ currently exists, as there are always some themes one can give certainty on and other themes that are more likely to adapt [P18]. Even the thought exercise for actors of defining the probability, forcing to search for certainty, is seen as an important starting point.

Thirdly, there is a necessity to “bridge language problems across a lay/expert divide or between different professional knowledge cultures” [Späth and Rohracher, 2010](*Page 450*). In other words, currently different energy visions sometimes use different words that define the same principle. This includes the words ‘grid balancing’ and ‘power system flexibility’ [Cao et al., 2016][Grunwald, 2011][Anonymous]. Aligning these terms is important because if actors use different terms in their energy visions, they could be more prone to miscommunications and more difficult to compare with each other.

It is important to bridge these language problems as soon as possible, considering some terminology can otherwise become politicised and embedded in policy and law. Therefore, one should try to ‘force’ certain terminology before it is differently embedded into national rules and regulations [Anonymous]. Although considering the rapid developments in the niche hydrogen sector, it might already be too late for the wording of some concepts.

Examples of definitions that are insightful to discuss in the NSR, include:

- The different definitions of the terms system integration, sector coupling, Power-to-Gas (PtG) and Power-to-X (PtX). Where PtX is mostly used by Danish and Belgian actors. UK actors use this term to a smaller extent. For instance, in a webinar UK actors had to verify the definition of PtX [EZK,CIEP, 2020]
- The terms low carbon, clean, blue, green, orange, turquoise etc. hydrogen. All are differently defined types of hydrogen production. Some terms are subjective and becoming politicised. For instance, ‘low carbon’ hydrogen is a more politicised term than blue or green hydrogen. An example is that the Norwegian Government defines *clean hydrogen* as hydrogen produced with low- or zero emissions and Danish actors mostly perceive green hydrogen to be the only ‘clean’ option [Questionnaire NO].
- Terms used when describing the role of flexible power plants. In some energy visions it is not distinguished if the (natural gas) power plants are expected to be used for baseload or for flexibility purposes balancing volatile RES generation.
- If actors deem the terms goal, ambition, target etc. equal, or see a different degree in probability between these developments actually happening.

In conclusion, as discussed in interviews, it is necessary to understand that the NSR consists of several strong actors who all perceive themselves to be a front-runner and expert, and therefore mostly ‘accept’ their own vocabulary and structure of energy visions [Anonymous]. Therefore, achieving 100% comparability should not be pursued, but the alignment of the most important terms should be strived for.

In other words, one should pick their battles wisely to align the formatting of energy visions in both time frames, explicit consideration of uncertainty and use of terms.

6.3.2. Recommendation 2: A mandate for TSOs

Different mandates of TSOs are expected to have an effect on the extent to which actors maintain a whole system approach. This recommendation focuses on the different envisioned responsibilities of TSOs and how these responsibilities relate to the envisioned role of gas infrastructure when integrating offshore wind. This recommendation builds on the themes discussed in sections 5.3 and 5.9, which are both themes on which actors currently have different visions (part of group C and D of the ‘Collaboration framework’).

A small side note should be mentioned before focusing further on this recommendation. The topic of issuing a mandate is very complex and depends greatly on the current organisational structures of TSOs in the NSR. The details of this topic were not part of the scope of this research. However, as the topic of issuing a mandate for hydrogen has big consequences for the compatibility of different energy visions, a recommendation is formulated.

In the NSR, gas and electricity infrastructure are perceived as a public good, and this research argues that this should also be considered for hydrogen. This standpoint is not self-evident, as currently hydrogen transport is mostly privatised [P14]. Hydrogen is advised to become a (partially) public good, considering its envisioned role and impact when maintaining both network and generation adequacy of the energy system.

Furthermore, if hydrogen were to be a public good, it would be openly accessible for different actors. This could lead to fairer competition between industrial actors because an 'outsider' could more objectively decide what locations for hydrogen production and transport are most beneficial for the energy system and (national) economic development.

Public use of hydrogen is also recommend as the development of hydrogen is, and in the nearby future will remain, dependent on government funding [P5] and therefore it could be seen as logical that governments can (indirectly via TSOs) regulate the social (infrastructure) costs linked to hydrogen for maintaining system adequacy.

Currently, TSOs are mandated for transporting gasses and electricity. Considering the reasons above, one could argue for an assigned expansion of a mandate for TSOs, to coordinate both hydrogen infrastructure and, in some specific circumstances, the placement of electrolysers.

Expanding this mandate as soon as possible is important as the development of hydrogen infrastructure is crucial for the development of a hydrogen market. Furthermore, the mandated actor could then be present in the increasing amount of discussions and collaborations on future hydrogen and offshore integration developments.

Expanding the mandate of the current TSOs, and not setting up a new one is also an important part of this recommendation. By doing so, a balance can be made between the value of old natural gas infrastructure and new hydrogen/electricity infrastructure. This balancing is extremely important as, in the future, it could be the case that only a small amount of natural gas will be necessary to be transported in the future [FutureGas, 2020]. Using the current valuation system, transporting a small amount of natural gas is not seen to have much value. However, in reality, its value could be enormous due to its role for maintaining generation adequacy.

However, there is also an accompanying risk with expanding the mandate instead of making a new actor responsible for hydrogen transport. One could argue that someone who already has a certain responsibility, will continue to maintain the largest focus on this old instead of their new responsibility. In other words, actors could have difficulties to balance different incentives. For instance, there is a reason that the UK's Ofgem aspires to maintain the most technically neutral role possible [OFGEM, 2020].

Aside from a mandate on hydrogen infrastructure, one could also experiment with giving TSOs the obligation to approve the location electrolysers are planned to optimise the locations of electrolysers for system balancing. This would prevent electrolysers from being placed in locations that result in electricity and/or gas grid congestions. If TSOs would not have this responsibility, the societal costs of grid constraints would probably not be considered (unless such societal costs would be depicted in the electricity price in a different way). This responsibility is important, as for example, TenneT concluded with their energy model that 9 GW of electrolysers at a 'suboptimal' location in 2035 can lead to additional costs of several hundred million Euros per year [TenneT, 2020c].

As this mandate is given to a certain actor, this might also initiate the discussion for government actors if an electricity and gas TSO should be combined into one TSO [P12]. Combining or not combining TSOs into one organisation has different advantages and disadvantages that are based on a countries' specific organisational structure of TSOs and their energy system. The question of which TSO should get the mandate for hydrogen and electrolyser locations could be a natural driver for a discussion on the general organisational structure of TSOs within a country.

This section focused on issuing a mandate for hydrogen to increase how actors consider a whole system approach and are forced to communicate with each other. This then drives the need for integrating previously mentioned (recommendation 1) collaborative parts in one's own individual energy visions. As these individual energy visions develop on a collaborative basis, the question remains how discussions about these collaborative themes should be conducted. This is elaborated on in the next section.

6.3.3. Recommendation 3: Discussion groups with a whole system approach

Collaboration between different energy visions is all about acknowledging that there are different truths and to search for what part of the total energy future could and must be executed together [Braunreiter and Blumer, 2018][Longhurst and Chilvers, 2019]. Relating this to the framework previously presented, especially the themes presented in the framework group 'D. No co-existence' are topics that should be discussed between different actors, both dimensionally and regionally. It is important to emphasise that in this section, it is not advised to discuss and align every single theme present. However, it is advised to align the necessary "joint elements" in visions, as is mentioned by Turnheim [Turnheim et al., 2015](*Page 246*). These discussions also force different actors to consider other perspectives, making 'Recommendation 1' easier to execute. Additionally, discussion groups do not have the formal aspect of a uniform energy vision. This could be beneficial as during a more informal "continuous dialogue" actors could be more collaboratively minded [P1].

There are many different existing collaboration and discussion groups, elaborated on in Appendix D. Considering these existing groups, this study would not advise an additional discussion group is set up to discuss several themes. Instead, this research recommends altering such groups in two different ways discussed in the two paragraphs below.

A first alteration of discussion groups focuses on the 'dimensional diversity' of actors within the groups. Currently, most collaborative groups focus specifically on electricity infrastructure, gas infrastructure, hydrogen and its applications, offshore wind, etcetera. In this case, the different actors in the discussion groups represent different countries. In order to strengthen a whole system approach in these discussion groups, this study proposes the alteration of creating overarching discussion groups where one focuses on one discussion point. In this case, the different actors would represent different dimensional sectors (e.g. electricity infrastructure, gas infrastructure, hydrogen), and the standpoint from the whole region.

A second alteration of discussion groups focuses on the regional scope of discussion groups.

Effectively speaking, the North Sea is so important for its surrounding countries, it is seen as a socio-technical energy system (as was elaborated upon in chapter 2). Therefore, one could deem it important to involve a large group of (European) actors when envisioning the NSR. However, for some specific themes, it is important to specifically involve different actors from the NSR in these discussion groups. This could be important as this research concludes that most actors around the NSR have differing specific characteristics and stakes due to their challenge of integrating offshore wind and their tradition of using gas infrastructure.

There are a lot of discussion groups on a European level, which is beneficial for the system. However, a narrowed down scope should be put on the specific role gas infrastructure has when integrating offshore wind in the NSR. These topics are highly unlikely to specifically be discussed in larger discussion groups with all countries involved. Such cooperation groups are recommended to start with a small group of actors. Possibly, these groups could be used as a steppingstone to develop into larger multilateral alliances. These steppingstones put less pressure on collaborative groups having to be perfect from the first initial meeting.

6.3.4. Recommendation 4: An overarching universal energy vision for the NSR

Although actors within the NSR do not have to agree on everything and have different starting points [P18], a wide overarching vision (or policy agenda) can enhance mutual communication. It can also "acknowledge North Sea countries' common interests in safeguarding the long-term viability of shared North Sea resources (via multi-use)", which is also mentioned to be important in other research [Dignum et al., 2018][Onyango et al., 2020](*Page 92*)[Anonymous]. In other words, an overarching vision can stimulate actors to recognise their shared North Sea resources and benefit from them collaboratively.

An overarching vision is deemed important as it could create a common frame of reference and guidelines that individual actors can use themselves for their individual energy vision. Although one should prevent to aim to align actors on too many (premature) details [Anonymous]. This could lead to a hollow and generic vision that prevents meaningful intervention [Dignum et al., 2018].

The timing of this official uniform vision is essential. If one attempts to publish a vision too soon, this could create tension between actors. A tension could arise because if actors themselves do not yet know how they would want to act, they could be hesitant to openly publish their insights. What actors consider a beneficial timing for publishing a uniform vision still has to be aligned. For instance, in different interviews, different actors recommended that the phase of a uniform vision has arrived, or contrarily, recommended that it is better to 'wait and see' for a bit longer, letting actors act individually first [P10][Anonymous](*More than one anonymous interviewee*).

Topics that could be included in these visions should be part of group 'A. celebrated themes' of the 'Collaboration framework'. Additionally, themes where actors envision the same approach, but there is possible competition on the approach (group B), could also be considered. In this transitioning case of group B themes, collaboration must be deemed more beneficial by actors than competition between themselves.

Considering the already existing regional and European energy visions mentioned in Appendix D, the researcher recommends at least two kinds of overarching energy visions. A first overarching vision focuses on the topic of actors accepting a role for gas infrastructure when integrating offshore wind. A second overarching vision focuses on a detailed integrated infrastructure planning vision for (reuse) of gas infrastructure. Such visions are deemed useful to improve compatibility within the NSR.

A first theme that deserves a uniform overarching vision is the uniform acceptance of a role for gas infrastructure when integrating offshore wind and other RES. Such a vision would also consider the importance to decarbonise not only the electricity but the full energy system with offshore wind. In this vision, the main message would be that all actors recognise the NSR to be a region with a large energy potential, and all actors want to work together to smooth out any incompatibilities that might arise in the future to make the most beneficial use of the whole NSR. Actors could then possibly accept to sometimes give up a regional technical optimisation to get a more efficient international technical optimisation (spreading the costs accordingly) [P12].

An important element would be the acceptance of actors that to integrate this offshore wind energy, a whole system approach is the best approach to take. Therefore, a role should be accepted for gas infrastructure in the net-zero energy system of the future.

To counter the feeling of 'political obligation' for actors to join this uniform vision, it is recommended that the vision is not labelled 'The NSR vision', but it is labelled as 'a shared vision by actors within the region'. Bringing together these governmental actors could be seen as a point of departure to possibly develop more detailed energy visions with more actors.

For instance, in the more distant future, one could think of a more detailed vision on the regional challenge of how countries can support each other in situations of scarcity and abundance. For instance, this is already done on a Nordic scale in a 'mid-term adequacy forecast 2017' [Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019]. Here, specific computational scenarios of what energy shortages or abundance could happen are not necessary. A discussion on who is able to aid who and who is not interested in 'helping' if different situations occur in the future could already prove useful for increasing the compatibility of energy visions. This gives a larger sense of security of supply and stimulates a thought process of the different scenarios that could occur. It also prevents actors from mentioning the role of another region to solve their system adequacy problems, whilst this region is actually not able to guarantee this.

Secondly, a detailed integrated infrastructure planning vision is recommended with the geographical scope of the NSR. Such integrated infrastructure planning is key. For instance, if actors would collaboratively consider build-out rates and large investments costs, actors could collaboratively save on necessary infrastructure costs. This is especially of interest if one considers that most infrastructure installed now is expected to have a function in the coming 40 to 60 years [P1]. Inefficient choices now for the infrastructure system as a whole could lead to undesirable lock-ins.

Such a uniform vision could mention all possibilities for integrating offshore wind energy, and not try to force one uniform route to be taken. This vision could build upon the already existing Ten Year National Development Plan (TYNDP) of the ENTSO-E and ENTSO-G, looking even farther into the future in 2050/2060.

Building upon the information in the TYNDP's, it is advised to focus on the North Sea and how offshore wind is expected to be integrated, considering the choices made between electricity and gas infrastructure and coordinated planning of reused gas infrastructure. Furthermore, the different considerations of a timeline are also important to determine when certain gas infrastructure is available for reuse and how this relates to other actors regarding the same North Sea area.

Considering the different boundaries sometimes seen for the North Sea region, it is advised to first determine a vision with a few national TSOs and not specifically profile it as ‘the’ North Sea region vision. The uniform vision can then slowly expand remaining in a dynamic state, for example, from actors such as the Netherlands, UK (focused on Scotland) and Denmark, driven by reuse of gas infrastructure and a large build-out of offshore wind respectively, to other actors such as Germany and Belgium.

As a concluding remark for both these uniform energy visions, it is important to consider that once these visions are published, they will not bring complete certainty. It is inevitable actors will have to act with uncertainty, where energy visions merely provide a framework within which people can cooperate with each other [P18][P13][Equinor, 2019].

7

Conclusion and recommendations

This chapter provides conclusions derived from the pattern modelling process conducted in this thesis, answering the main research question; Focused on gas infrastructure as a solution for integrating offshore wind, how can the co-existing energy visions in the North Sea region be made more compatible?

This research assumes that the use of a whole system approach is beneficial for the economic and societal efficiency of an energy system. This assumption leads to the assumption that it is beneficial to consider (but not to directly prefer) gas infrastructure as an option to integrate offshore wind.

It can be concluded that currently, to a certain extent, some actors' energy visions are incompatible with each other. This research illustrates this by defining several themes and how (in)compatible these differently envisioned themes are with each other. These differences are dependent on certain geographical, economical and political starting points of both dimensionally and geographically different actors. Therefore, it is deemed impossible for all actors to have a uniform energy vision on some specific themes. This acceptance of diverse energy visions within a region leads to the conclusion that 'collaborative futuring' is an important element of making the NSR more compatible.

This chapter firstly presents a summary of the different energy integration themes at play in the NSR as a whole. Secondly, the concept of 'collaborative futuring' is further described. Finally, different recommendations for collaborative futuring are summarised, which could increase the compatibility of energy visions to further international system integration in the NSR.

7.1. Themes within the NSR

This section summarises the answer to the first sub-question of this research (*Focused on the interplay between electricity and gas infrastructure, what energy visions for system integration currently co-exist in the North Sea region?*).

In the first paragraph, several shared themes of the Transmission System Operators (TSOs), governments and industrial associations in the NSR are presented. The second paragraph presents more diverted and characteristic themes of different regions.

7.1.1. Shared themes in the NSR

All actors within the NSR expect to make use of their offshore wind potential and expect to integrate this energy efficiently into their energy grid. Nonetheless, the exact offshore wind potential does differ between countries. Belgian actors seem most realistic of their (lack of) offshore potential. Dutch and Danish actors recognise a large offshore wind potential, also compared to their domestic energy demand. German actors recognise a large offshore wind potential. However, relative to German energy consumption, this potential is not as large. Lastly, Norwegian actors and increasingly active UK actors are deemed a bit modest of their offshore wind potential in their energy visions. This modesty could be the case as both the Norwegian and, to some extent, the UK North Sea areas are quite deep. Therefore, an option is seen for floating offshore wind, which is less developed than offshore wind.

In addition to the offshore wind potential actors envision in the NSR, all actors also have the ambition to develop a net-zero decarbonised energy system by 2050 or earlier. Furthermore, most actors in the

NSR also present certain identical developments in their national energy systems. Such developments include the increase in decommissioning of both nuclear and coal power generation, an increase in electrification of certain sectors and an increase in volatile renewables energy sources. These developments are considered to make it increasingly challenging to maintain system adequacy of the actors' energy systems. System adequacy is defined as the ability of a power system to cope with its load in all different circumstances (e.g. in times of peak load and peak demand).

7.1.2. Unshared themes in the NSR

Different actors sometimes envision different roles for a certain theme. These differences are sometimes unchangeable because actors' visions are based on unchangeable geographical and technical characteristics of their energy system. The following list shortly summarises themes that actors in the NSR countries envision differently.

- Actors in Belgium recognise themselves to be dependent on surrounding countries for (renewable) energy sources. They, therefore, envision a large role for electricity and gas infrastructure interconnection. The Belgian energy system is also characterised by their plans for decommissioning their nuclear power plants, which entails approximately half of their current electricity consumption.
- The Danish energy system does not have as much gas infrastructure in place as other NSR countries. However, they do see a certain necessity for hydrogen production to expand on their offshore wind potential. A role for gas infrastructure is seen as Danish actors envision the use of offshore energy islands with offshore electrolysers.
- In the current German energy system, a lot of natural gas is consumed. Natural gas is also seen as a future transition fuel for the energy transition. German actors' energy visions also consider a role for hydrogen developments. The necessity for hydrogen, and therefore hydrogen infrastructure, is mostly driven by the need to decarbonise the relatively large German industrial energy demand.
- Dutch actors are the only ones to mention the availability of decommissioned gas infrastructure to be a driver for hydrogen developments. This is due to their expected decommissioning of their natural gas supply in Groningen in the nearby future (2030). Furthermore, they also notice a role for gas infrastructure to expand on their offshore wind potential.
- The Norwegian energy system is characterised by its large natural gas supply and large exports of natural gas. Such exports are expected to be relevant now and also in the future. Norwegian actors do not recognise a large role for gas infrastructure when integrating offshore wind in the nearby future. Existing and new gas infrastructure is expected to be used for natural gas, blue hydrogen or CO2 transport. In the far future, some actors mention that gas infrastructure could be used for integrating floating offshore wind. Nonetheless, the large capacity of Norwegian hydro power is expected to play the largest role in maintaining system flexibility.
- Lastly, UK actors mostly mention electricity-based solutions to integrate offshore wind (e.g. batteries and demand side response). Nonetheless, they also recognise a slight role for using gas infrastructure. A role for gas infrastructure is especially recognised in the northern part of the country where the UK's largest potential (and of Europe) for offshore wind is located.

7.2. Collaborative futuring

Building upon the information mentioned above in this section and the previous chapters, this research defines different themes. These themes are used to define the degree of (in)compatibility of the actors' different energy visions. These energy visions focus on the role of gas infrastructure when integrating offshore wind. Effectively, the description of these themes gives an answer to sub-question 2 (*To what extent, and based on what underlying reasoning, are these energy visions compatible or incompatible with each other?*). The levels of (in)compatibility of these themes can be categorised into four different groups. These groups are termed:

- Group A. Celebrated themes.
- Group B. Themes where actors envision the same approach.
- Group C. Themes with competition between different types of approaches.
- Group D. Themes where there is no co-existence possible' (if the energy visions were to be executed).

These different groups are illustrated in a 'Collaboration framework', in Figure 7.1. The horizontal access of this figure ranges from compatible to incompatible themes. The farther to the right the themes are placed, the more incompatible the themes are. This makes group A themes the most compatible themes, group B and C themes equally 'relatively' compatible, and group D themes the most incompatible themes. Furthermore, groups that are placed above the horizontal scale depict themes on which actors have identical visions. In contrast, groups that are placed below the horizontal scale depict themes on which actors have different visions. This framework was originally designed during this study by the researcher.

In this research, compatible sub-systems are defined as a group of energy sub-systems that are able to exist or occur together without problems or conflict. Group 'A. Celebrated' themes are seen as most compatible because the envisioned themes in this group are identical and are already collaborated upon in projects and collaborative groups. Therefore, it is highly unlikely such themes are unable to exist together with conflict.

Next, group 'B. Same approach' and group 'C. Different approach' themes are considered to range from being relatively compatible or relatively incompatible. All themes within these groups could be both relatively compatible or relatively incompatible. This differs per specific theme. An example of a group B theme could be that two actors could both envision to become a 'first-mover' for a specific technology. This is relatively incompatible as these visions are not able to occur together. Only one 'firs-mover' is possible. Nonetheless, another group B theme could me more compatible. For example considering when different actors both envision to become a green hydrogen production hub. In this case, both actors would be in competition with each other, but it is likely both green hydrogen production hubs are able to exist in parallel with each other, although they would not be fully compatible as actors are in competition with each other and could try to obstruct one another.

An example of a group C theme could be that actors envision different optimal locations for electrolysers. Such ideas are different but are relatively compatible as different electrolysers could be placed in different 'optimal' locations. Although this theme is not fully compatible as different infrastructure is needed for facilitating both electrolyser locations. Therefore, this is not deemed the most cost-efficient solution.

Lastly, group 'D. No co-existence' themes are considered to be the most incompatible, because in this case different envisioned themes are considered impossible to be executed together. An example of such a theme would be if different actors envision different locations for the same specific electrolyser.

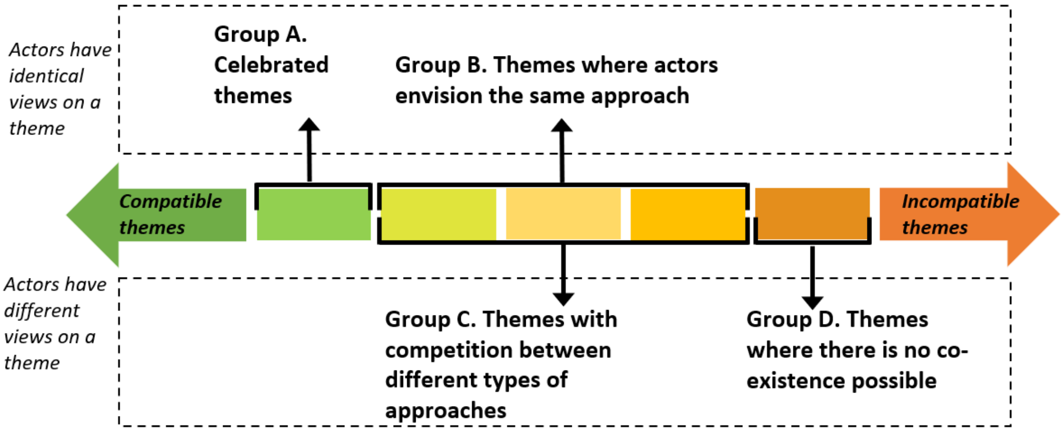


Figure 7.1: A schematic overview of the 'Collaboration framework'. In the middle of this figure, a scale is shown ranging from compatible to incompatible themes. The farther to the right the themes are placed, the more incompatible the themes are. This makes group A themes the most compatible themes, group B and C themes equally 'relatively' compatible, and group D themes the most incompatible themes. Furthermore, groups that are placed above the scale depict themes on which actors have identical visions. In contrast, groups that are placed below the scale depict themes on which actors have different visions. This framework was specifically designed by the researcher.

This research uses this 'Collaboration framework' to gain insight into how different themes, characterised into different groups, can be made more compatible. Different approaches to increase the compatibility of envisioned themes are needed. For instance, some themes are envisioned differently because of fixed underlying societal and geographical characteristics of an actor or a country. In this case, it is therefore impossible for actors to collaboratively pursue one uniform compatible energy integration vision, with the exact same details envisioned by every actor in the NSR.

Therefore, this research recommends maintaining one's own vision whilst considering other existing visions within the relating geographical and dimensional (e.g. gas, electricity, hydrogen, offshore wind) scope. This process is defined as 'collaborative futuring'. Considering the 'Collaboration framework' presented above, when one is 'collaboratively futuring', one accepts that not every theme can develop into a group 'A. Celebrated' theme. Additionally, one also aspires to prevent any themes from being or becoming a group 'D. No co-existence' themes.

7.3. Recommendations to increase the compatibility of different energy visions in the NSR

This research has four universal recommendations to improve compatibility between the existing energy visions in the NSR. These recommendations give an answer to sub-question 3 of this research (*How could these energy visions be made more compatible to improve international system integration in the North Sea region?*). By answering this question, the main research question is also answered.

Specific recommendations are proposed to be most beneficial for specific groups of the 'Collaboration framework'. It is important to emphasise that this does not mean that recommendations are only specifically relevant for specific groups. Certain recommendations are merely increasingly beneficial for certain groups.

In this section, all four recommendations, based on chapter 6 of this research, are presented. In addition, specific recommendations are also given on how to increase the compatibility of the themes defined in chapter 5. The characterised group of a theme has been used as a tool to determine which of the four recommendations is most beneficial to increase the compatibility of this differently envisioned theme.

7.3.1. Recommendation 1: Increased consideration of different actors in individual energy visions

This research recommends that in their energy vision documents, actors better consider other actors' perspectives around them, both geographically and dimensionally (e.g. gas infrastructure, electricity infrastructure, hydrogen transport, consumption or production focused). It is deemed important to build a shared frame of reference around data and explanation to enhance communication between actors. Specifically, this entails two specific considerations. Firstly, actors could attempt to use the same planning time frames in their energy visions. Secondly, actors could attempt to use the same choice of terms in their energy visions. Themes that especially benefit from this recommendation are themes that differ significantly per actor due to geographical and historical factors of the energy system. These themes are categorised into group 'C. Different approach' of the 'Collaboration framework'. Other themes, that are prone to miscommunications could also profit from this recommendation.

This recommendation can be applied to two of the themes defined in this research. These two themes are discussed in the following paragraphs.

Explicitly mention to what extent GHG emitting electrolysers are accepted

The first theme to which this recommendation can be applied focuses on the role envisioned for electrolysers to integrate offshore wind into the energy system. In several energy visions, most actors do not relate the electricity demand of electrolysers to the installed capacity of offshore wind within the NSR. This lacking relation leads to competing claims on offshore wind. Some actors consider a use for offshore wind energy for electricity consumption directly. In contrast, others consider a use for the same installed capacity of offshore wind energy to produce green hydrogen with electrolysers. The competition between both envisioned uses could lead to electrolysers effectively running on non-renewable energy sources because all renewable energy source (e.g. offshore wind energy) is already 'claimed' for direct electricity consumption. This could then decrease public acceptance of electrolysers as a 'green technology'.

It is recommended that actors are open about the extent to which they accept an increase in greenhouse gas (GHG) emissions in the short term, in exchange for faster development of electrolysers in the long term, to achieve a (possibly) more considerable decrease in GHG emission. Such open communication could counter a decrease in public acceptance of electrolyser technology, as the public does not feel a sense of betrayal when 'green hydrogen' from electrolysers turns out to not be as 'green'.

Furthermore, it is recommended that actors explicitly communicate in their individual energy visions where they expect the electricity supply for the envisioned electrolysers to come from. Mentioning this relation could stimulate the development of both offshore wind and electrolyser capacity in parallel. Relating the envisioned capacities of installed electrolysers to the (necessary) envisioned capacities of renewable energy sources could also decrease the number of competing claims on offshore wind.

Explicitly mention an envisioned hydrogen application is envisioned to be supplied by green or blue hydrogen

The second theme to which this recommendation can be applied focuses on the visions on hydrogen applications. Currently, actors have some similar and some different visions on the possible applications for hydrogen. If energy visions are different, they are not necessarily incompatible with each other as they can often exist in parallel with each other.

However, it is sometimes uncertain if the capacities of hydrogen applications envisioned are in line with the expected capacity of green or blue hydrogen production envisioned to be installed simultaneously. This is difficult to check because the specific type of hydrogen (blue or green) envisioned to be consumed is not explicitly mentioned. If not all envisioned applications could be supplied with their (implicitly) aspired form of hydrogen, this could lead to a certain form of incompatibility. Especially considering the 'competing claims on offshore wind' mentioned earlier.

Therefore, it is recommended for all energy visions to specify if either blue or green hydrogen or a mix of both is envisioned for a specific application. Increasing this focus could also invite more specific visions on infrastructure choices specific for blue or green (from offshore wind) hydrogen.

Furthermore, it could also urge actors to not think of hydrogen as a raw material that can simply replace natural gas, but as an energy carrier that either has to be imported or has to be produced from RES or natural gas with carbon capture and storage (CCS). With such a mindset, actors could possibly better consider the necessary price and bulk of hydrogen they would need for a certain application. For instance, considering the difference between the need for cheap and bulk blue hydrogen (often envisioned for industrial use), opposed to the acceptance of more expensive green hydrogen fuels and less bulk (often envisioned for use as high-value fuels in the transport sector).

7.3.2. Recommendation 2: A mandate for TSOs

A second recommendation is that actors should consider the option to widen mandates of (gas) TSOs for both transporting hydrogen, and for installing electrolysers in specific locations. This mandate would essentially make hydrogen transport a public affair, which would increase the consideration of societal infrastructure costs. Therefore, including the scope of a TSO when deciding on these topics could decrease societal costs of transporting energy. This discussion could also function as a starting point for discussing whether it is (currently) necessary for electricity and gas TSOs to merge specific activities.

Building on two themes, there are two mandates recommended for the TSOs. A mandate is recommended for both transporting hydrogen and for determining locations of electrolysers.

A mandate for transporting hydrogen

Firstly, in the NSR, gas and electricity infrastructure are perceived as a public good, and this research argues that this should also be considered for hydrogen. This standpoint is not self-evident, as currently hydrogen transport is mostly privatised.

Expanding the mandate of the current TSOs, and not setting up a new one is also an important part of this recommendation. By doing so, a balance can be made between the value of old natural gas infrastructure and new hydrogen/electricity infrastructure. For instance, the societal value of a small amount of gas necessary to be transported should not be underestimated for maintaining system adequacy.

However, there is also an accompanying risk with expanding the mandate instead of making a new actor responsible for hydrogen transport. One could argue that someone who already has a certain responsibility, will continue to maintain the largest focus on this old instead of their new responsibility. In other words, actors could have difficulties to balance different incentives.

A mandate for appointing electrolyser locations

Secondly, societal costs can also be better balanced if TSOs are mandated to appoint or have to grant permission for certain electrolyser locations. Determining an optimal location for electrolysers is important because sub-optimally located electrolysers could lead to additional infrastructure costs. Effectively, if one were to maintain a whole system approach, electrolysers are expected to be located in various places. Case by case, the most cost-efficient approach would then be chosen considering the existing gas and electricity infrastructure already present and the cost and efficiency of transporting renewable energy in the form of either electricity or gas.

If electrolyser locations were to be appointed by a TSO, the TSO could situate electrolysers near strong points in the transmission grid. The implications of giving TSOs a mandate for locations of electrolysers should not be underestimated. If one would choose to make this a public affair, it would likely be a difficult discussion as restrictions would have to be imposed on free-market parties.

When TSOs are responsible for determining electrolyser locations, one should be aware that such locations could likely become part of a political debate. This is reasoned as an electrolyser placement could indirectly determine the (hydrogen) consumption hubs that are bound to arise. Such a decision could therefore create either an international or national competitive advantage for such an (industrial) hub. Although challenging, TSOs could use its collaborative and non-competitive TSO network to optimise electrolysers locations across geographical borders.

7.3.3. Recommendation 3: Discussion groups with a whole system approach

This research recommends that actors better maintain a whole system approach in (already existing) discussion groups, primarily focusing on themes in group ‘D. No co-existence’. Additionally, it would also be beneficial to discuss some themes from other groups, such as from group ‘C. Different approach’. Including such themes in discussion groups could prevent themes to otherwise eventually develop into group D themes, as energy visions become more specific in time.

This recommendation can be applied to three of the themes defined in this research. These three themes are discussed in the following paragraphs.

Discussing visions on the capacity operation of electrolysers

The first theme to which this recommendation can be applied focuses on the different visions on capacity operation of electrolysers. The flexibility role of electrolysers is still up for discussion as different actors consider a role for either peak shaving (mostly Danish actors envisioning to supply electrolysers with a surplus of offshore wind electricity that is not domestically consumed or exported), ramping up and down according to electricity price (most actors) or running at full-time capacity (mostly industrial actors envisioning electrolysers in the near future due to the high CAPEX costs). It is recommended to discuss these different capacity operation options of an electrolyser and stimulate or keep track of the current technological developments for the future use envisioned. Such discussions are especially important when actors perceive a different capacity operation for the same electrolyser.

Discussing visions on the role of net-zero hydrogen or natural gas-based flexible power plants

The second theme to which this recommendation can be applied focuses on the role of flexible power generation when there is a shortage of offshore wind to meet electricity demand. Most actors perceive a role for natural gas in net-zero emitting flexible power plants. In this case, CO2 can be captured both post and pre-combustion. In the case of CCS post-combustion, natural gas would be transported to a power plant, and CO2 would be transported from a power plant to a CO2 storage location. In the case of CCS pre-combustion, blue hydrogen would be produced from natural gas and would be transported to hydrogen-fuelled power plants. Blue hydrogen could then be produced nearby a natural gas supply and CO2 storages.

Different actors envision different CO2 capture routes and even different locations for pre-combustion CCS (nearby power plants or nearby natural gas supply and CO2 storage). Therefore, there is a necessity considered in the NSR for both natural gas, CO2 and hydrogen infrastructure. This ‘three-piece necessity’ is inevitable; the different actors’ choices for either pre or post-combustion CCS are dependent on the currently existing infrastructure, power plants that can be renovated and acceptance of CCS technology.

However, within discussion groups for specific regions, this could be further discussed. In that case, different actors are recommended to consider the (economic) effect their choice has on their neighbouring actors, especially considering cross-border infrastructure. For example, such discussions include the dependence of actors on the decision of Norwegian actors to export their domestic natural gas supply as either blue hydrogen or natural gas. It also includes the necessity for Belgian actors to find a location to store CO2 outside of their own borders, as they do not have much natural storage potential.

Considering all this uncertainty and diversity in energy visions, it is also proposed that visions to develop and deploy CCS and hydrogen for flexible power plants are joined up with broader visions focused on CCS, hydrogen and maintaining generation adequacy. These two different types of visions are recommended to be discussed both within and between countries. This international focus is important as large national backbones are expected to be connected with each other. Differences are already arising as in Belgian actors' visions a CO2 backbone is envisioned, and in Dutch actors' visions a hydrogen backbone is envisioned.

Discussing visions on transporting hydrogen in pipelines

The third theme to which this recommendation can be applied to focuses on how gaseous renewable energy carriers (e.g. hydrogen) are transported. Among other things, this can be done with both newly constructed gas infrastructure and reused gas infrastructure. In the NSR, Dutch actors are the only ones driven to hydrogen use and production due to their gas infrastructure becoming available for reuse in the nearby future. Other actors do not mention this or notice a smaller role for (partly) reusing gas infrastructure.

Most actors envision gasses to be produced, transported and consumed in (industrial) hubs initially. Hydrogen transport is subsequently expected to be expanded to hydrogen backbones throughout the region. The timing of this alignment is an important discussion point between TSOs. It is recommended that the benefits of recommissioning gas infrastructure should be considered increasingly by electricity TSO and government. This is important, especially considering the expected gap between obligatory decommissioning of gas infrastructure if out of use. There seems to be a necessity for a more detailed discussion on the balance between the costs of recommissioning gas infrastructure, constructing new hydrogen infrastructure and the costs of having to decommission gas infrastructure at its end of life that will not be reused.

In addition, it is also recommended to already align the hydrogen transport methods in different individual hydrogen hubs, if circumstances allow this. Elements that could already be discussed include the form hydrogen is transported in, if it is blended and at what pressure it is transported. In such discussion groups, one should focus on the quick wins and accept the differences due to the current experimentation phase and different starting points of different actors. For instance, these different starting points include actors who have the opportunity to reuse gas infrastructure (Dutch actors) and for who it is necessary to invest in a whole new grid (Danish actors).

Such discussions, could build upon the discussions on the Ten Year Development Plan (TYNDP) of the ENTSO-E and ENTSO-G.

7.3.4. Recommendation 4: An overarching universal energy vision for the NSR

This research recognises a necessity for an overarching NSR vision for themes in group 'A. Celebrated', and for other themes that are deemed beneficial to include to create a more stable investment environment. Furthermore, such topics could be considered as 'need to haves' to prevent certain technological lock-ins.

Considering the current developments in the NSR, this could result in an overarching vision recognising the importance to decarbonise the full energy system with offshore wind energy (and not only the electricity system). Furthermore, this overarching vision could also recognise that gas infrastructure should be considered by all actors when integrating offshore wind energy.

Initially, bringing together several governmental and TSO actors in a uniform vision is a start to possibly more actors joining later on. A more detailed uniform energy vision on for instance integrated gas infrastructure planning, could then arise. In these more detailed visions, one could, for instance, discuss the regional challenge of how countries can collaboratively develop the recommissioning of their gas infrastructure and support each other in situations of scarcity and abundance of electricity and energy.

Aside from the two themes mentioned in the previous paragraphs, this research recommends actors develop an overarching vision on one more theme. This recommended overarching vision is mentioned in the paragraph below. As the same actors would probably be included in the the development of such an overarching visions, all topic discussed in this section could be combined into one overarching vision. Although in that case all actors would have to agree on all topics, which could make it a more time consuming (but evidently compatibility increasing) process.

An overarching vision on a hydrogen production, consumption and transport hub

This theme focuses on the shared visions on attaining a hydrogen hub function. As hydrogen infrastructure is seen to connect initial hydrogen hubs, it is important to consider where these hubs are currently envisioned. Most actors envision becoming either a hydrogen production, transport (transit, import or export) and consumption hub.

These different visions could be explained by the different characteristics of different actors. For instance, TSOs mostly mention their role as a transport hub due to their responsibility for energy transport. Danish, Dutch, UK and Norwegian actors mention a role as hydrogen production hubs, mostly focused on either green (NL/DK/UK) or blue (NL/NO/UK) hydrogen. Furthermore, German and Dutch actors mention a role as hydrogen consumption hub due to their industrial hubs. Belgian actors strongly aspire a function as a transit hub, also due to their current role as a natural gas transit hub.

Collaboration within a uniform vision would strengthen all actors together, combining the actors' shared and specific characteristics. Such collaboration could also stimulate competition with actors outside of the NSR.

In conclusion, there are still several energy visions incompatible with each other in the NSR. There will always be differences in actors' energy visions because of the different actors and their characteristics in the NSR. Therefore, one should find the right balance between collaboration and uniformity and maintaining different standpoints whilst considering and understanding each other. It is important that all actors accept that the future will always remain uncertain. Therefore, it is still important to act whilst considering these uncertainties.

The energy system is not perfect, and it is too optimistic to wait for the energy system to ever become perfect. Therefore, the 'Collaboration framework' tool is beneficial for the NSR to make use of its full potential; where all actors agree to make the most optimal use of gas infrastructure when integrating offshore wind in the region as a whole.

8

Discussion on methodology

This chapter critically discusses the methodological framework of this research in three different sections. First, the research methodology is critically evaluated, focusing on the advantages and disadvantages of the pattern modelling methodology and its combination with inductive coding. The same section also discusses the scoping of this research. The second section of this chapter focuses on the new innovative methodological elements and tools created in this research. Lastly, recommendations for further research are presented.

8.1. Critical evaluation of research methodology

Throughout this research, the pattern modelling approach has been proven useful. Its holistic approach was especially advantageous in understanding how all the different elements of an energy system were cross-related and dependent on each other.

According to literature, pattern modelling is characterised as successful if a certain theoretical saturation is reached [Wilber and Harrison, 1978]. This theoretical saturation is defined as a state of the analysis, where adding more empirical data does not lead to new defined themes. Finding this balance is deemed a challenge. One could either analyse too little data, which could lead to false or premature assumptions. On the other hand, one could also analyse too much data, where the researcher risks that the data can not be effectively processed [Bhattacherjee, 2012].

Considering the different energy visions analysed in the latest part of the research and interview discussion held, only details of themes were added. No large new developments arose from this new empirical data. Therefore, one could conclude the pattern modelling exercise to be successful for the scope of this research. This research's scope is defined as the 22 actors whose energy visions were analysed and not as the NSR as a whole. Whether the correct scope was taken to gain a general understanding of the NSR is further discussed in section 8.1.3.

Another way to determine if this research has reached theoretical saturation is to compare the themes defined in this research with the themes defined in previous literature. If no similar themes could be found, this could be a signal that no theoretical saturation was achieved. On the other hand, this could also be a sign that this research found many innovative themes. However, this is deemed less likely because specific themes are inevitable when analysing an energy system.

Themes present in energy visions mentioned earlier in chapter 2.3, include general economic drivers, geographical drivers (which include dependency on fossil fuels and potential for RES deployment), technological drivers and policy-based drivers [Weimer-Jehle et al., 2016] [van Asselt et al., 2000][Obrecht and Denac, 2016][Kühnbach et al., 2020]. In general, most themes distinguished in this research via pattern modelling were also mentioned in previous literature.

As a pattern modelling approach was used, it was possible to distinguish certain themes and their relations as focal points. This is an advantage of the pattern modelling methodology as otherwise, all these different themes would have had to be coded and focused on in detail. Now, for example, almost no focus was put on environmental restrictions and energy efficiencies.

The themes analysed in this research can also be compared to the themes defined in the ENTSO-E's 'Regional insights report on the North Sea region of 2019'- report [ENTSO-E, 2019c]. This report defines three themes; decommissioning, geographical change and security of supply. These themes were also mentioned in this research. In comparison, the themes presented by the ENTSO-E were more general than the specifics presented in this research for the NSR.

The previous paragraphs concluded that the pattern modelling methodology was successful for this research. Nonetheless, there are also still some shortcomings of the combination of methodologies used in this research. In the next four subsections, four different shortcomings are further characterised.

8.1.1. The detail considered in this research

One of the shortcomings of the pattern modelling approach was that due to the large and holistic scope of this research, there was less time to discuss and research certain specific themes in more detail. This was a critical balancing act for this research because the larger scope, considering several countries in the region, was essentially a strong and original element.

This shortcoming has two causes. First, during the inductive coding exercise, one does not yet know which exact details should be collected as at that stage, the themes are not even defined.

Secondly, some of the details of the themes eventually defined were often not presented in the analysed energy visions. Due to this lack of empirical data, and difficulty collecting the right details, themes in chapter 5 could sometimes not be described in full detail. Although, occasionally, other detailed reports were analysed when specific information was deemed essential for the storyline as a whole.

Considering this lack of detail in the used empirical data, it would have been better to first focus on pattern modelling and determine the different themes, as presented in chapters 4 and 5. Secondly, once the overarching themes were formulated, these themes could have been researched more in-depth by specifically analysing and searching for strategies, research articles, news articles and consultancy reports about this theme. These specific documents could come from new actors in the NSR or from the actors' energy visions who were already analysed (because for this research, only documents of actors were analysed that focused on the role of gas infrastructure when integrating RES). This information could have strengthened claims on how incompatible or compatible certain energy visions were with each other, as in the current research, such analysis was sometimes too simplistic.

There are several examples of details that were not elaborated upon in the used empirical data, but that could have been informative for this research. Examples include the role of large oil and gas companies, finance constructions for infrastructure development (subsidies, fiscal structures, European Union subsidies of for example HEAVENN and the value of the oil and gas sector decommissioning knowledge and experience as a future export product. The time gap between the current use of gas infrastructure and the future use of that same infra for alternative energy purposes was also expected to be a more explicit part/challenge. This topic was not mentioned explicitly in many energy visions, and therefore an expansion of documents would have been helpful to provide better insights into the topic. However, it is definitely a valuable conclusion that such topics of gas infrastructure are not yet discussed in detail in TSOs and governments' energy visions.

8.1.2. The researchers' bias

A second shortcoming of this research is the bias of a researcher throughout the process. Considering the analysis done, one can conclude that the main insights taken from the empirical data were constant throughout the research. Nonetheless, after reviewing the coding pf the empirical data in the first and last months of this research, one could conclude that certain emphasis on details had sometimes been shifted. This shift entailed some slight differences between the labelled details of certain themes. For example, the theme coded as 'electrification' was initially sub-coded per sector (e.g. electrification of industry, electrification of vehicles). In the last phase, as it became clearer that such information was not necessary for the research, only general statements on electrification were coded as 'electrification'. Details of these developments mentioned in the data were then not coded.

Such development of coding could be seen as inevitable and also efficient when one tries to work towards a general conclusion. Nonetheless, throughout this process, the researcher risks such an inductive coding exercise to become subjective, leading to an inevitable reader bias. Generally, previous research mentions that interpretive research is always open to one's preconceptions and biases [Bhattacherjee, 2012].

Six potential effects of this readers (or researchers) bias are presented for this research.

Firstly, due to a readers bias, one risks using a too pragmatic approach. This is defined as dealing with things sensibly and realistically in a way that is based on practical rather than theoretical considerations. In this study, such a pragmatic approach was rarely the case. The researcher retained herself first to define a theme and subsequently searched for information to verify this theme and find their interrelations.

Secondly, the researcher could risk basing conclusions on information that was not thoroughly verified. This was sometimes the case in this research, as concluding elements were occasionally based on the fact that some themes were not mentioned by actors. In other words, ‘unobserved parts’ in specific energy visions were also considered to be information. An example of such an unobserved part would be to conclude that an actor does not envision a role for hydrogen production because this actor does not mention anything about hydrogen production in the analysed documents. Basing conclusions on such information could be seen as risky. However, one could also argue that a topic that is so hard to find would probably not be such a vital part of an actors’ energy vision.

Thirdly, due to a readers bias the researcher could risk automatically putting more focus on searching for incompatibilities instead of compatibilities because the researcher subjectively deemed incompatibilities more interesting for the research than compatibilities. For this research, this was sometimes the case. Therefore, (unintentionally) less focus was put on group ‘A: celebrated’ of the ‘collaboration framework’. In hindsight, some of the compatible themes of energy visions were taken for granted and therefore not explicitly mentioned as an overarching theme. This could result in a biased image that there are only a few compatible themes in the NSR. This is not the case as underlying themes part of the main themes presented in chapter 5 are compatible and celebrated with each other in several collaborative groups mentioned in Appendix chapter D.

Fourthly, almost all documents were analysed in Dutch or English. Documents in other languages were only translated with Google Translate when they were deemed essential to gain an understanding of the actors’ energy vision. Not searching for and including documents in other languages could have resulted in a certain readers bias because documents (possibly mentioning more recent developments) might not have yet been translated into English. However, such a bias was prevented by combining the analysed documents with interviews. Additionally, the CIEP/IEA questionnaire also included a question on the documents that actors recognised to be important for hydrogen developments in the country. All documents that these actors recommended were then added to the empirical data (if deemed relevant for the scope of this research).

Fifthly, all interview participants or data sources may not be equally credible, unbiased, or knowledgeable about the phenomenon of interest, or may have undisclosed political agendas, which may lead to misleading or false impressions. Here, it was the job of the interpretive researcher to “see through the smoke” (hidden or biased agendas) [Bhattacherjee, 2012]. Considering that most interview discussions were in line with the documents analysed of the same actors, this was not the case for this research. The use of both written energy visions and interviews is concluded to be beneficial for the research. However, some detailed information of interviewees could not be verified as these details were not mentioned in the written energy visions.

Executing interviews near the end of the research was also beneficial to verify certain propositions and gain more in-depth insights. These interviews also verified the inductive coding exercise of different published energy vision reports as a strong foundation.

Unfortunately, some interviews only had a duration of half an hour. In that case, not all relevant questions could be asked. The researcher had to make a selection of the most relevant topics, which could have resulted in biased interview results. However, there was no way for the researcher to prevent such a bias because interviewees were only sometimes available for half an hour.

Lastly, this research initially set out to define the incompatibilities between both different geographical energy visions (differences between countries) and different dimensional energy visions (differences between TSOs, governments and industrial actors). However, possibly due to a readers bias, differences characterised often focused on geographical differences, and to a lesser extent, on dimensional differences. This could be the case as most actors within a country, to a certain extent, build their visions upon the same existing energy system. It could also be the case that such a focus occurred due to a readers' bias, where documents of different actors within the same country were analysed together and increasingly linked.

To counter such a readers bias, all analysed documents were coded and listed in one large document. Therefore, when analysing the data together, comparisons could easily be made between both different countries and different actors (TSOs, governments and industrial actors).

8.1.3. Shortcomings of the 'narrow' scoping of this research

As was previously mentioned, the large scope taken in this research was disadvantageous for the amount of detail that could be considered. Contrarily, the scope taken can also still be seen as too narrow, considering that several actors and topics relevant for the NSR energy system were not considered. In this section, five of these shortcomings are elaborated upon further.

Firstly, a risk of this research is readers seeing this study as a comparative national policy analysis, which it is not, as not all actors within a country were considered. In this research, a focus was put on governments and TSOs as main actors. Here, the hypothesis was that energy visions of these actors would be largely representative of the main narrative of all actors within the region. This was reasoned as industrial actors mostly lobby governmental actors, and infrastructure is often not seen as the responsibility of industrial actors but of TSOs. After also analysing and interviewing some large industrial actors and consortia, this hypothesis is validated. One could conclude that the large developments were essentially recognised within the region.

Although energy visions of already collaborative groups were not analysed, which would have been beneficial for this research, especially considering the last sub-question of this research (*How could these energy visions be made more compatible to improve international system integration in the North Sea region?*). This would have been beneficial because, in order to determine how compatibility between energy visions could be improved, it is important to be aware of all the existing collaboration groups and their energy visions in the NSR. However, an argument in favour of the used approach is that an analysis of individual energy visions does give an honest image of how individual actors are still misaligned to each other, despite the collaboration groups they are in together.

Additionally, some topics could also have been considered to a greater extent. This includes the role of existing oil and gas infrastructure for integrating offshore wind. This topic was only elaborated upon in more detail by some industrial players, and not necessarily by governments, apart from the Dutch government.

To increase the focus on these topics, other actors' energy visions could have been considered. An example is Nexstep, which is a national platform for e-use and decommissioning in the Netherlands. In interviews, other actors such as Vestas and Siemens were also mentioned to be important, as they have their "own specific insights into PtX" [P8]. Also, on a DSO level there are interesting developments considering our research scope. The insights of DSOs could be important for the larger transmission developments eventually because they form the base of infrastructural plans that could evidently be connected across-borders.

Furthermore, the energy system of the NSR is also related to the developments of nature conservation, recreational activities, fishers, areas used for defence and marine transport [TNO, 2020]. However, actors focusing more on these specific elements were considered to be out of scope for this research.

A last critical note considering the actors considered in this research is that a focus was mostly put on the historically more national character of industrial players. Although, most industrial players are more intra-nationalistic.

A second weak element of the scoping of this research is the current definition of the NSR as being six countries. This region was initially scoped due to the uniformity of all these countries envisioning to make use of the North Sea for offshore wind production. Nonetheless, in interviews, other countries that neighbour the defined NSR, were also mentioned to be of interest. For example, in an interview, the role of Ireland and the specific role of Scotland were also mentioned [P13]. France could also have also been a country of interest for the NSR, due to its current hydrogen alliance with Germany and characteristic use of nuclear power and biomass as energy sources [Amelang, 2020].

Thirdly, the market mechanisms of both the electricity and gas market and the pricing expected for flexibility services have only slightly been considered in this research. However, this element could have been of interest to this research as it would have been helpful when comparing different offshore wind integration technologies. For example, a separate debate is currently ongoing as to whether costs of maintaining system adequacy can be avoided by simply re-configuring bidding zones within Europe. This way, specific market mechanisms would help deal with congestion and integration [P18].

However, this research assumes that regardless of the pricing mechanisms to stimulate flexibility technologies, all technologies remain equally competitive with each other as they consider the same pricing. Although for this conclusion to hold, it is important that within this market mechanism discussion, the pricing need not discriminate certain technologies and maintains a whole system approach (where gas infrastructure is also considered to play a role).

Fourthly, a choice was made to analyse energy vision documents ranging from 2018 till mid November 2020. Energy visions and especially hydrogen developments in the North Sea region are currently very dynamic, resulting in the fact that visions and strategies analysed at the beginning of this research could almost already be outdated by the end of this research. However, one could argue that new developments do not often 'turn 180 degrees' within a year, and older documents also give a reasonably good insight into the developments.

An example of where insights were drastically different within a year is the difference between the Future Energy Scenarios report of the UK TSO in both 2019 and 2020. This was a drastic change as in 2019, almost no attention was paid to hydrogen, and in 2020 hydrogen was part of one of four key recommendations [NationalGrid ESO, 2020a][NationalGrid ESO, 2019b].

This dynamic character of developments is both an advantage for the energy system as a whole, as this increases discussions and slowly results in gas infrastructure already becoming part of the sociotechnical imaginaries in the NSR. However, it is a disadvantage for this research specifically as it is difficult to consider the 'analysing phase' of a study done, when every week new visions are published by different actors. Therefore, the interviews at the end of this research provided good verification to be aware of all the different energy visions currently present in the region.

Lastly, the scope of this research was sometimes unintentionally forced to be narrowed down to the role hydrogen plays in the NSR, although the research topic was the integration of offshore wind and the role of gas infrastructure. As hydrogen is currently seen as *the* energy carrier of choice, there is a large focus on this energy carrier in this research, as most energy visions analysed presented hydrogen developments.

Within the research, care was taken to open the scope to more than hydrogen. Nonetheless, due to this current great enthusiasm, the large role for hydrogen was inevitable in the empirical data analysed. Only time can tell if these current energy futures will predict the future or that the developments be such that larger roles are eventually seen for biogasses, biomethane, e-fuels etc.

In conclusion of this section, the scope of this research could have been widened to gain a greater and especially more detailed insight into actors' energy visions on the NSR. However, as section 8.1.1 concluded, with the current scope, it was already increasingly challenging to maintain an overview of all different actors and analyse the information correctly. Considering the workload broadening the scope of this research would not have been beneficial for the accuracy of this research.

Widening the scope with the five different groups of actors and topics mentioned above could be an option for further research.

8.1.4. The bias of different actors' energy visions

This section further describes the bias of specific actors' energy visions and how the researcher has recognised this bias throughout the research.

In the analysed energy visions, often a limited variety of futures are envisioned. Previous research also concluded this by stating that, in most energy visions, current themes are extrapolated and assumed to continue for decades [Weimer-Jehle et al., 2016][van Asselt et al., 2000][Obrecht and Denac, 2016].

This inconsideration of innovative developments, as they are not in the actors' scope or part of the 'mainstream narrative', are called **black swans**. They are defined as unforeseen events, typically with extreme consequences but low probability, that challenge conventional assumptions about future developments [Equinor, 2019][DE BMWi, 2020a][Turnheim et al., 2015]. The concept of ‘black swans’ is only explicitly described in energy visions of Equinor and the German government [Equinor, 2019][DE BMWi, 2020a]. Examples of black swan technologies mentioned by different actors are listed below. These specific black swan technologies could lead to radical changes in the role of gas infrastructure when integrating offshore wind and maintaining system flexibility.

- Innovative renewable energy production technologies that balance out the volatility of offshore wind (e.g. floating solar, tidal etc.) [Anonymous][The Offshore Energy Platform, 2020][CCC, 2019].
- The occurrence of a ‘supergrid’. This grid ranges from North to South Europe, using ultra-high voltage DC networks [Equinor, 2019][NO ministry, 2020a].
- Entirely new ways to produce hydrogen in the future, be it directly from solar energy, with microwaves (EM-waves), pyrolysis, with nuclear energy or as a combined ‘Battolyser’ [TKI Nieuw Gas, 2019][RLI, 2021].

Such visions of black swans were not considered specifically in this research. As only some actors mention them, they could be deemed incompatible with other visions. However, all actors consider such black swans to be highly uncertain if they were to occur. Therefore they were taken out of scope.

However, when analysing and comparing different energy visions it is important to consider how innovative different actors are by nature.

The fact that so few actors mention these different black swans could be explained by the necessity seen to provide suppliers, consumers, investors and policymakers with security to plan ahead [DE BMWi, 2020b][Anonymous]. Uncertainty leads to industrial actors not wanting to invest as there is no certain long term investment profit foreseen; a business case is not formed on speculation alone [P14][P16][Ørsted, 2020][KonKraft: A collaboration arena for the Norwegian Oil & Gas Association et al., 2020][TKI Nieuw Gas, 2019].

Based on the different energy visions analysed, this study concludes that industrial associations and consortia are often more innovative and daring than governments and TSOs. Previous research by Cambini also recognised this lack of incentive for (German) TSOs to engage in activities with uncertain benefits and a long payback period. This lack was even recognised when such activities were riskier but also less costly [Cambini et al., 2020]. Additionally, research by the Oxford Energy Forum also concluded that “innovation in the electricity industry has generally been sluggish, (...) even more so when it comes to the network segment” [Oxford Energy Forum, 2020](*Page38*). Considering the TSOs themselves, the demand for a more dynamic approach is only recognised by some, including the Danish and British TSOs [Energinet, 2019a].

To gain insight into the most recent developments in energy visions in the NSR, the energy visions of both industrial were added to the empirical data in this research.

8.2. The new tools developed during this research

Often in interpretive research, the “heavily contextualised nature of inferences” does not lend itself well to “replicability or generalisability” [Bhattacherjee, 2012](*Page 114*). However, in the case of this research, one can build upon two methodological elements that could also be used in other future research. The researcher specifically created and thought of these methodological elements for this research. However, these elements could be reused in future research. The following paragraphs explain to what extent this could be done.

Firstly, the innovative combination of both inductive coding and concept mapping with pattern modelling could be used in other research. This could be beneficial as the researcher experienced the pattern modelling methodology to be a bit unstructured and philosophical [Wilber and Harrison, 1978]. Both inductive coding and concept mapping were tools that gave more ‘concreteness’ to the method. Although, one should not go to any extreme to try and structure the research fully. It is important to also be accepting of the subjective and difficult to influence elements in this research.

Furthermore, the codes now inductively composed, could be used in further research as a foundation for a scope similar to the scope of this research. These concrete labels and their descriptions can be found in Appendix A.

Secondly, the 'Collaboration framework', as presented in chapter 5 and 6, is a new tool designed during this research. In summary, this 'Collaboration framework' distinguishes four different groups; where themes are divided into (A) envisioned themes that are collaborated on and where shared ideas are celebrated with one another, (B) themes on which actors envision the same approach, although possibly aspiring to maintain a competitive advantage, (C) differently envisioned themes, being in competition on approach where co-existence is possible and (D) having a conflict of interest between actors where (if the energy visions are executed) co-existence would not be possible. Categorising different themes within these groups can help define the level of (in)compatibility between different sub-systems. Additionally, it can also be used as a basis for determining how such themes can be made more compatible through collaborative futuring because different recommendations are better suited for specific groups.

As previously explained in Chapter 6, this framework could be reused for collaborative futuring exercises. Additionally, this exercise of creating a 'Collaboration framework' could also be done with other topics aside from the energy system, as this characterisation holds for other topics as well. This tool can be used in a condition where actors agree that futuring in a uniform manner is not always the solution when different actors have starting points that are too different from each other. Therefore, this research defines collaborative futuring as a process where one aspires to prevent any themes from being and becoming group 'D. No co-existence' themes and one accepts that not all themes can become group 'A. celebrated' themes.

8.3. Recommendation for further research

Many previous studies had taken a whole system integration approach, leading to their necessity for a smaller geographical scoping, as otherwise their research would become infeasible. In this study a larger geographical scope was taken, in combination with a holistic whole system approach, leading to not much detail being defined.

Finding the right scope is therefore a balance in geographical scope, dimensional scope and the details considered in the research.

This section recommends four different options for further research.

Firstly, considering the current increase in geographical scope for the energy system and the demand for the type of research which has a larger geographical scope (according to interview discussions), it is recommended that additional studies are done with a dimensional scoping and a large set of actors from different countries (geographical scoping). A starting point for such a research could be one of the nine themes identified in chapter 5 of this research. By focusing on a specific topic, future research can maintain an increased level of detail what was sometimes lacking in this research.

Secondly, it would also be of interest to analyse energy visions throughout the years. One could then possibly conclude under what circumstances these energy visions have changed and if such a change could also be expected in the future. This could give a description of the "temporal patterns regarding ambition, exposure, and decline over time" [Dignum et al., 2018](*Page 197*).

Additionally, more research could also be done on the differences between the performativity of different individual energy visions on the whole socio-technical imaginary in the NSR. This is also linked to the question of how energy futures are integrated into current government policy. This leads to questions such as how different visions come to exist, as within the NSR, energy visions are never born in isolation, and there are always other actors involved. As was argued in chapter 2 of this report. This research could lead to recommendations on how this performativity can be optimised, considering the time it takes for an energy vision to develop itself in relation to becoming a guiding vision, technological expectation or a sociotechnical imaginary.

Thirdly, regarding the recommendations done in chapter 6, one could argue for more research into the current collaboration discussion groups and collaboratively published energy visions of actors. Considering these groups, it is of interest to research how these collaborative discussion groups affect ones' individual energy future. This could be a good addition to the current research because during this research, mostly the individual energy future's were analysed.

Additionally, as there are many different discussion groups, one could opt for further research into these groups and where they overlap and how these can prevent incompatibilities between them. This could possibly increase the performativity of collaborative groups.

Fourthly, also based on the recommendations done in chapter 6, one could further research the most optimal organisation of TSOs considering hydrogen developments. This would be of interest to determine with what organisation structure, specific for every country, planned infrastructure developments could maintain a whole system approach and technology-neutral mindset when considering the different options for infrastructure developments. This could especially be of interest when considering the role of gas infrastructure when integrating RES.

In this research, one could also dive into the historical developments of TSOs and their differing responsibilities. Such research could give an insight if the different roles of TSOs led to different infrastructure developments (e.g. a focus on gas infrastructure or a focus on only electricity infrastructure to integrate RES), or if the energy system itself determined the different roles of TSOs.

A

Additional figures and tables

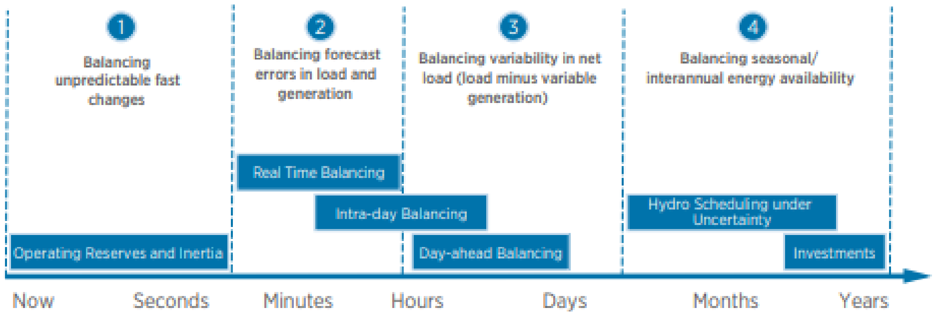


Figure A.1: The different time spans of maintaining a balanced system, in this study focus is put on the balancing of the energy system from an hourly basis [Allard et al., 2020].

Figure A.2: Picture of brainstorm executed to find different themes, where yellow notes were more technical oriented themes and orange notes more underlying economical, political and social themes. In pink different more overarching themes were defined, which were eventually combined into 9 overarching themes.

Table A.1: Table with an overview of electrolyser targets and ambitions of different actors in the NSR.

	Approximate target 2040 [GW]	**Where is ambition mentioned?**
BE	-	
DE	10	National hydrogen strategy: one of the objectives of this strategy is to increase capacity to 5 GW in 2030 and 10 GW in 2040 [DE BMWi, 2020b].
DK	8	Energinet: A massive build-out of offshore wind may require 5-8 GW of electrolysis in DK around 2035 [Energinet, 2020]. Green Fuels for Denmark project: Vision to scale up to 1.3 GW by 2030 [Ørsted, 2020].
NL	4	Climate agreement: ambition is mentioned to scale up to 3-4 GW installed electrolyser capacity in 2030 [Klimaatakkoord, 2020].
NO	-	
UK	-	
EU	40	2x40 GW green hydrogen initiative: EU has a roadmap for a 40 GW electrolyser capacity in the EU by 2030 [Oxford Institute For Energy Studies, 2020].

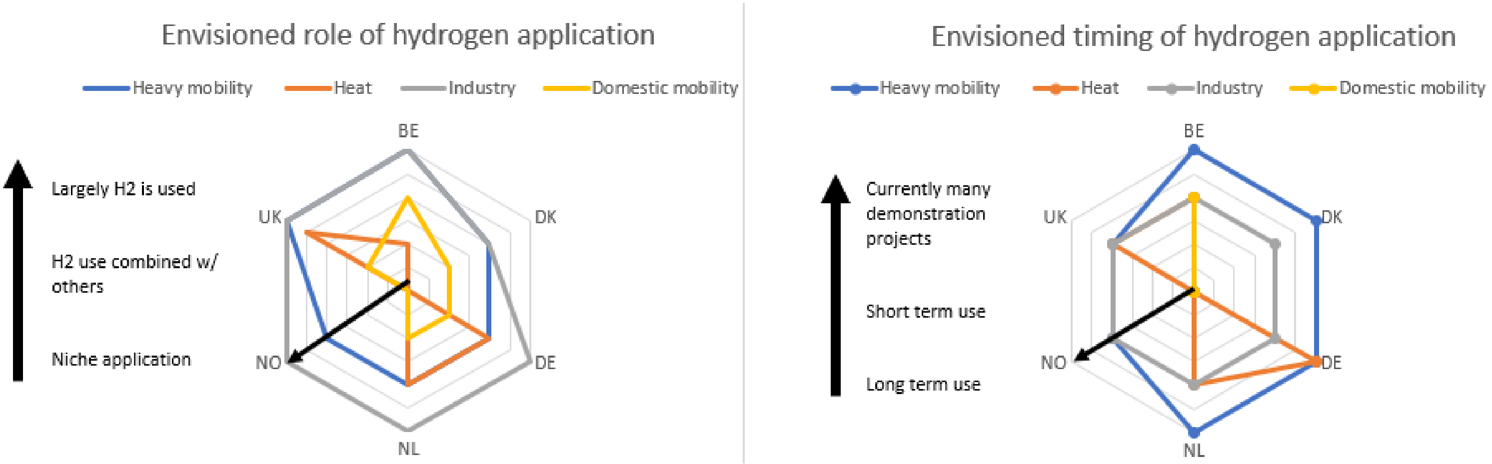
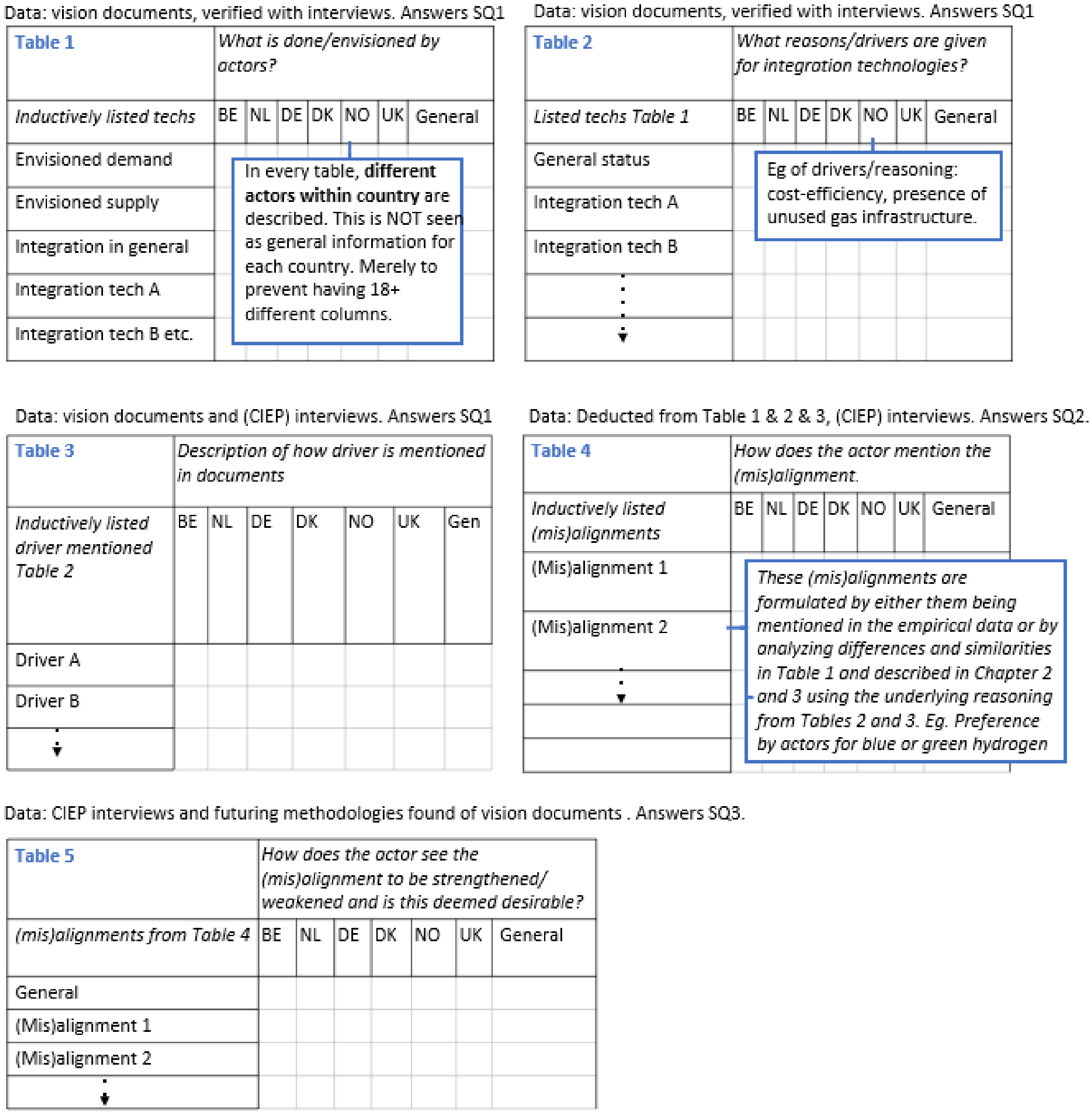


Figure A.4: A schematic summary of the perceived roles for hydrogen per actors within one country (based on TSO and government strategies mentioned in chapter 4). Some of the lines overlap with each other. The figure on the left shows the envisioned roles of the hydrogen application. A line further to the outside, corresponds to a larger envisioned use of the hydrogen application. The figure on the right shows the envisioned timing of the hydrogen application, where a line placed further to the outside means the application is currently already being used in demonstration projects. In contrast, applications that remain in the centre of the grid are envisioned to be used in the long term.



Data: vision documents, verified with interviews. Answers SQ1

Table 1	*What is done/envisioned by actors?*						
Inductively listed techs	BE	NL	DE	DK	NO	UK	General
Envisioned demand							
Envisioned supply							
Integration in general							
Integration tech A							
Integration tech B etc.							

In every table, **different actors within country** are described. This is NOT seen as general information for each country. Merely to prevent having 18+ different columns.

Data: vision documents, verified with interviews. Answers SQ1

Table 2	*What reasons/drivers are given for integration technologies?*						
Listed techs Table 1	BE	NL	DE	DK	NO	UK	General
General status							
Integration tech A							
Integration tech B							
⋮							
↓							

Eg of drivers/reasoning: cost-efficiency, presence of unused gas infrastructure.

Data: vision documents and (CIEP) interviews. Answers SQ1

Table 3	*Description of how driver is mentioned in documents*						
Inductively listed driver mentioned Table 2	BE	NL	DE	DK	NO	UK	Gen
Driver A							
Driver B							
↓							

Data: Deducted from Table 1 & 2 & 3, (CIEP) interviews. Answers SQ2.

Table 4	*How does the actor mention the (mis)alignment.*						
Inductively listed (mis)alignments	BE	NL	DE	DK	NO	UK	General
(Mis)alignment 1							
(Mis)alignment 2							
↓							

These (mis)alignments are formulated by either them being mentioned in the empirical data or by analyzing differences and similarities in Table 1 and described in Chapter 2 and 3 using the underlying reasoning from Tables 2 and 3. Eg. Preference by actors for blue or green hydrogen

Data: CIEP interviews and futuring methodologies found of vision documents . Answers SQ3.

Table 5	*How does the actor see the (mis)alignment to be strengthened/ weakened and is this deemed desirable?*						
(mis)alignments from Table 4	BE	NL	DE	DK	NO	UK	General
General							
(Mis)alignment 1							
(Mis)alignment 2							
↓							

Figure A.3: Overview of the specific tables made to structure the information from empirical data, for the researchers own understanding themes were ambiguously divided into more driving themes (eg. cost-efficiency, codes from Appendix B4) and more technical energy system integration themes (eg. pumped hydro, codes from Appendix B1, B2 and B3).

B

Coding scheme used in research

In the following list the codes that were inductively defined are presented. The empirical data was categorised according to these codes. New codes that were recognised in newly analysed documents were subsequently added to the list. After inductively defining the different codes, they were categorised into four different categories. These four different groups are presented below.

B.1. Category 1: How much flexibility is needed?

The following topics were labelled:

- **Flexibility necessary:** when in documents an insight is given into the future and current necessity for both generation and network adequacy. This includes developments in electrification, natural gas use, hydrogen use and nuclear power generation are mentioned.
- **More in detail: hydrogen applications foreseen** when in documents an insight is given into the envisioned hydrogen applications. This code was divided into vision on hydrogen use for heating the built environment, personal vehicles, heavy transport (e.g. trucks) and industrial processes. This includes current and future projects and existing government legislation.

B.2. Category 2: Flexibility technologies: generation adequacy

If the technologies are mentioned below, information is coded on specific details given on what is expected of these elements and how this fits into the energy system as a whole. Specific projects and time frames expected are also labelled. The following topics were labelled:

- **Gas storage:** when it is described how gasses can be stored in salt caverns, the linepack etc. and how this is beneficial for generation adequacy.
- **Gas imports:** when importing gasses in time of low RES production being available is given as a solution for maintaining generation adequacy.
- **Combined Heat Power (CHP):** when using CHP's is seen as an option to give more flexibility to heat consumption.
- **Thermal generation with natural gas:** when natural gas power plants are mentioned to be an option in times of electricity power shortages due to low wind or solar.
- **Thermal generation with electrolysis:** when green hydrogen is mentioned to be an option in times of electricity power shortages due to low wind or solar.
- **Thermal generation with blue hydrogen:** when blue hydrogen is mentioned to be an option in times of electricity power shortages due to low wind or solar.
- **Electricity storage (battery):** when batteries and other storage methods such as compressed air storage are presented as an option to give flexibility to the energy system.
- **Pumped hydro:** when pumped hydro is presented as an option to maintain generation adequacy. Both information on visions on pumped hydro within and outside of an actors' regional border is included.
- **Interconnection:** when interconnection with other countries nearby or far away is seen as an option to maintain generation adequacy in one's own region.

- **Electrolysis:** when electrolysers are mentioned to play a role in integrating renewables. This also includes what detailed (flexibility) role electrolysers are expected to play and at what capacity they are expected to run throughout the years.
- **Demand Side Response (DSR):** when demand side response, which also includes a role presented for electric vehicles (EV's), are said to play a role in maintaining flexibility of the energy system.

B.3. Category 3: Flexibility technologies: network adequacy

The following topics were labelled:

- **Electricity grid reinforcements:** when plans are given or envisioned to reinforce the electricity grid due to an expected increase of volatile RES. This includes labelling of the time scales presented.
- **Energy islands:** when considering offshore integration of offshore wind, both electricity and gas infrastructure on an island is envisioned to be used.
- **Gas grid reinforcements:** when plans are given or envisioned to reinforce the gas grid. This includes labelling of the time scales presented.
- **Re-use gas grid:** when plans are presented of the time scale gas infrastructure can be re-used, and what future role is seen for this gas infrastructure.
- **Offshore oil and gas industry electrification:** when plans are presented for electrifying oil and gas industries offshore. This includes the relation these developments have with integrating offshore wind nearby.

B.4. Category 4: Reasons given for the system integration choices made: both electricity and gas infrastructure based

The following topics were labelled:

- **Government targets:** when specific government targets in the far future are mentioned as a reason. Mostly about GHG reduction targets.
- **RES increase:** when an increase in volatile renewable energy sources is given as a reason for certain system integration technology developments.
- **Role of TSOs:** when it is implicitly or explicitly mentioned that TSOs see themselves to have a more active role in deciding what system integration choices should be made.
- **Urge to be role model:** when actors mention themselves to want to become a role model (in certain hydrogen expertise) and therefore reason the necessity for certain choices.
- **Urge to be hub:** when actors mention they aspire themselves to have a hub function in the hydrogen energy system and therefore see a necessity for certain system integration choices.
- **Role importer/exporter:** when actors mention wanting to become an importer or exporter of hydrogen, leading to specific developments being envisioned.
- **Security of supply:** when actors mention seeing a certain system integration technology to be more beneficial for security of supply than others. Or when actors generally mention the importance of security of supply and how this is related to their envisioned role as an energy importer and exporter.
- **(Inter)national scope:** when actors prefer certain system integration choices because they (implicitly or explicitly) use a certain specific regional scope of the energy system. Eg. as a nordic scope is taken, one sees the possibility that hydro power can help in maintaining generation adequacy.
- **Whole system approach:** when actors reason for certain system integration choices as they see the importance of maintaining a whole system approach of the energy system as a whole.
- **Cost efficiency:** when actors mention a certain choice for a certain system integration technology as this is seen to be the cheapest option.
- **CCS role:** when a choice is made for a certain system integration technology as a certain role is seen for CCS. Additionally, general topics that describe the CCS developments are also labelled.
- **Public acceptance:** when a choice is made for a certain system integration technology because (only) specific technologies are (explicitly or implicitly) accepted by the public/political environment. Or when certain technologies are explicitly mentioned not to be preferred due to a lack of

public/political support.

- **Natural gas supply present:** when actors mention that a natural gas supply is/is not/is in the future not expected to be present a certain choice is made for system integration technologies.
- **Experience gas :** when actors mention ‘their’ experience with handling gas consumption, transporting gas or gas production, and this is mentioned to be a reason for specific envisioned hydrogen or natural gas developments.
- **Presence industry:** when having a large energy intensive industry in the region is given as a reason to integrate more renewable energy sources in a specific way beneficial for this industry.
- **Existing gas infrastructure:** when existing natural gas infrastructure is mentioned to be a reason for integrating RES with gas infrastructure, because the infrastructure is already present in the region and therefore cost efficient to be re-used.

C
Interview questions and groups interviewed

C.1. Interview questions

Interviewees were asked the following questions, where often not all question were asked but only the questions aligned to their personal expertise. Furthermore, the formulated themes based on published energy vision documents were verified during the interview. Therefore, these questions are mostly in line with the nine themes defined in chapter 5.

Topic

The interplay between electricity and gas infrastructure when integrating renewable electricity, especially offshore wind, in the North Sea area (BE, DEU, UK, NO, DK, NL). Simply put, this interplay considers gas power plants (gas to electricity) and electrolysers (electricity to gas).

(Mis)alignments and themes seen

Review of (in)compatibilities between energy visions of gas and electricity TSOs, governments and large industrial players and consortia. Do you recognize these points of discussion and what are the consequences if different actors within the region approach these topics differently?

1. When considering different envisioned uses of hydrogen (in transport, heat, industry) compared to electrification of the same applications, do these different visions cause problems for infrastructure planning within the North Sea countries and for interconnection in the North Sea area?
2. What are the consequences of the different envisioned ratios of ”electricity: gases” energy carriers on the reuse of gas infrastructure within the North Sea region? Or is the re-use of gas infrastructure only a large topic in some countries and is hydrogen expected to be transported with new pipelines? Considering:
   (a) The question if hydrogen infrastructure is brownfield or greenfield.
   (b) Different timing of re-use of gas infrastructure due to the use of the infrastructure for natural gas, also necessary in power plants for flexibility in the energy system.
   (c) Different perceived options for blending of hydrogen into the gas grid.
   (d) The role energy islands and platforms are considered to play.
   (e) The drive for cross-border uniform green gas transportation rules and regulations
3. There seems to be disagreement in energy views about the role of an electrolyser for flexibility, either ramping up and down electrolysers or electrolysers always running at full capacity. Where does this disagreement come from? Are these differences due to the costs of flexibility and reuse of gas infrastructure (not) being sufficiently included in a business case for electrolysers? Does an ideal location for electrolysers exist?
4. What effect does it have that different actors see different roles for blue hydrogen in the energy system? Within and between countries? What role does import play here and the use of blue hydrogen in gas-fired power stations (for flexibility)?

5. Many actors would like to become a role model when it comes to hydrogen technology. Is this competition between actors beneficial? Or is there a risk that this protectionist attitude will result in northern Europe being overtaken by other major global players?
6. Different actors within the North Sea region envision a role as either a production, storage and/or consumption hub. Within the region, do different envisioned roles reinforce each other? Or is there competition? Is this beneficial for the overall system?
7. There are sometimes differences perceived between actors in their views on the speed of hydrogen production developments in the future. Is there currently a ”hydrogen hype” among some players, and is this something beneficial? Or are other innovative technologies therefore forgotten that may also play a role for system integration? Eg. Energy interconnections from North to South Europe, hydro.
8. What different scopes do you see of maintaining flexibility of the energy system for security of supply? Be it national, Nordic, North-West European or European. Does a different scope lead to a different importance seen for using gas infrastructure to maintain security of supply?
9. Within the North Sea region, what other (in)compatibilities do you see between the energy visions of grid operator and governments and industrial actors?

How should energy visions be better aligned?

1. What roles and responsibilities do you see for different parties when it comes to integrating renewable sources in the gas and electricity grid and guaranteeing the flexibility of the energy system? Will this be organised publicly or privately? Are there different roles for gas and electricity TSO’s?
2. Is it necessary for all actors in the North Sea region to have a uniform vision when it comes to the role of the gas infrastructure when integrating renewable sources?
3. Do some actors act more from competition than coordination, within a country and between countries? What is desirable? Is there a preference for cooperation and coordination or more for competition between different actors? What does this look like between TSOs, considering the ENTSO-E TYNDP?
4. Which themes currently presented in energy visions would you expect to change (drastically) throughout the years? In what manner do you expect these to change?
5. Which question did you expect me to ask, that I did not ask during this interview?

C.2. List of interviewees

A list of interviewed experts, giving a good mix between countries and type of actors: TSOs, government, industry, collaborations and researchers who are more observers of the situation. If more people are mentioned in one name section this entails an interview where all people were present together in a more discussion format. All references made in this report have been verified after the interview with the interviewee via email.

Referred to in text as	Name	Type	Country	Company name	Function
P1	Annelies Wastyn; Adwin Martens	Industry	BEL	Vario; Waterstofnet	Senior beleidsadviseur; Director waterstofnet
P2	Anonymous	Gov	BEL	Federal planning bureau	Energy expert
P3	Jan Voet	TSO	BEL	Elia	Group Head of System of the Future
P4	Thierry Deschuyteneer	TSO	BEL	Fluxys	Strategic & Prospective Studies Manager
P5	Malte Grunwald	TSO	DEU	Gasunie DE (FNB Gas)	Hydrogen Team
Anonymous					
P7	Magnus Horno Gottlieb	Industry	DK	Orsted	Senior Global Public Affairs Advisor
P8	Marie Munster	Collab	DK	FuturgeGas	Professor (MSO)
P9	Tor Alexander Elmelund	TSO	DK	Energinet	Engineer gas system innovation
P10	Dionisis Tsimis	Collab	na	Anonymous	Project manager
Anonymous					
P12	Paul Nilessen	Research	na		author OIEP article Hydrogen and the Emergence of the Energy System Operator (ESO)
P13	Noé van Hulst	Gov	NL	Gasunie/IPHE/CIEP	International Hydrogen Advisor Gasunie/ Chair IPHE/CIEP senior fellow
P14	René Peters	Research	NL	TNO	Business Director Gas Technology, North Sea Energy programme
Anonymous					
P16	Alexander Jongenburg; Matei Negrescu	Industry	NO	Equinor	Business Development Manager; Head of Area Development North Sea New Energy Solutions
P17	Svein-Erik Losnegard; Elisabeth Alen Hendriks; Ola Nestaas	TSO	NO	Gassco	Program Manager Sustainable Development; Department engineer Gassco; Advisor Gassco and Board member European Research Institute for gas and energy Innovation and NCCS
P18	Katja Yafimava; Martin Lambert; Anupama Sen; Anouk Honore; Alex Barnes	Research	UK	Oxford Institute for Energy Studies	Senior Research Fellow; Senior Research Fellow; Executive Director of the Electricity Programme; Senior Research Fellow; Independent consultant
P19	Robert Gibson	TSO	UK	National Grid gas	Whole system and gas supply manager

C.3. Questionnaire questions

In a parallel project of CIEP and the International Energy Agency (IEA), ministries of the Netherlands, Germany, France, the UK, Scotland, Belgium, Denmark and Norway were asked to answer the following questions in a questionnaire. This information was used as empirical data for verifying the already defined themes.

1. In preliminary research, we have identified the following list of documents as important contributions for the national policies/vision/approach to hydrogen in the Dutch part of the North Sea. In your opinion, should there be documents added or omitted from this list to provide a complete overview?
2. Next to the shared objectives of meeting the targets as set by the Paris agreement, the EC and the Pentalateral Energy Forum, which national factors or objectives is hydrogen intended to help achieve? (Limited to 5 most important, ordering is not required, and preferably more than three objectives) *For example, hydrogen can be applied to help meet climate targets in industry or the residential sector, to integrate renewables in the power system or to create energy exports.*
3. What is the current drive for the market development in your country? *For example, is it focused on import or export of clean hydrogen (longer term objective), create markets beyond the traditional industrial market (mobility, low temperature heating) or replacing grey hydrogen (shorter term objective), what is more important market push or pull or other?*
4. What infrastructure options, technologies and innovations are interesting to pursue on a collaborative basis that can help upscaling clean hydrogen in the region? *For example, these can*

be production of hydrogen on offshore platforms, artificial islands, combined electrolysers inside windmills, offshore hydrogen pipelines, among others.

5. Given the rapid developments, complexity and currently still large uncertainties surrounding low carbon hydrogen demand and supply, which policy instruments are crucial in meeting your country's objectives and create resilience for a successful implementation? *For example, subsidy schemes, contracts for difference, value chain development, regulation.*
6. Which policies of neighbouring countries support or conflict with the policies and instruments of your country in building the new value chains or develop new markets for hydrogen? *For example, competing subsidy schemes, safety regulations, definition of what is low carbon hydrogen and the role of TSO's and DSO's?*
7. Energy transport in the North Sea region is bound to see significant changes in the future. What is the approach to infrastructure (electricity, natural gas, hydrogen, carbon dioxide) on the North Sea, and what is (an indication of) the timeline and how important is it to create a regional marketplace? *For example, will hydrogen be created on- or offshore, shipped or piped and which infrastructure will be available first, will gas infrastructure be refurbished?*
8. In your opinion, which question should have also been in this questionnaire?

D

Existing collaborative groups and collaborative energy visions

Currently there are already several existing discussion groups on the topic of hydrogen and the use of gas infrastructure when integrating offshore wind, which are already quite beneficial for energy system integration [TKI Nieuw Gas, 2019]. Important discussion groups include:

- Pentalateral Energy Forum (PLEF): a cooperation between the Netherlands, Germany, France, Belgium, Luxembourg, Switzerland and Austria, for development of a common view on hydrogen regulation. Their goal is also focused on market integration for electricity to achieve improved security of supply and an optimisation of electricity trade and the use of the existing infrastructure through extensive market coupling [BE federal government, 2019b][Questionnaire].
- Gas for climate: Gas for Climate was established in 2017 to research and highlight the role of renewable and low-carbon gas in the future energy system. Gas for Climate is formed by ten leading European gas transmission companies (Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, Ontras, OGE, Snam, Swedegas and Teréga) and two organisations representing renewable gas producers (European Biogas Association and Consorzio Italiano Biogas)[Consortium Gas for Climate, 2020].
- TSO collaboration groups: European Network of Transmission System Operators for Electricity (ENTSO-E) and European Network of Transmission System Operators for Gas (ENTSO-G) [ENTSO-E, 2019a]
- Hydrogen council [Questionnaire]
- Cooperation specifically oriented towards the government level are Mission Innovation (MI), Hydrogen energy ministerial meeting (HEM) and Clean energy ministerial (CEM) [Questionnaire]
- International Partnership for Hydrogen and Fuel cells in the Economy (IPHE) [Questionnaire]
- Hydrogen Europe [Questionnaire]
- European Clean Hydrogen Alliance (ECHA) [Questionnaire]
- North Seas Wind Power Hub (NSWPH) [Energinet, 2020]
- North Seas countries Energy Collaboration (NSEC) [NorthSEE, 2020a]
- North Sea Countries' Offshore Grid Initiative (NSCOGI) [NorthSEE, 2020a]
- Fuel Cell and Hydrogen Joint Undertaking (FCHJU) [TKI Nieuw Gas, 2019]

Recently published energy visions are included in the list below, these were not all analysed in this research:

- "Nordic perspectives on mid-term adequacy forecast 2017", a regional report that analyses what potential there is for countries to support each other in situations of scarcity [Statnett &Fingrid & Energinet & SvenskaKraftnat, 2019].
- All TSOs publish a Ten Year Network Development Plan (TYNDP) which is obligated by the ENTSO-E (European collaboration of TSOs), based on their defined recent themes and national policy. These TYNDP do tend to go a bit further than 10 years in futuring energy visions. These

TYNDP’s are combined into a broad TYNDP for the whole region, also NSR specific published in 2018 [DE BMWi, 2020a].

- In December 2019, ENTSOG launched its 2050 Roadmap for Gas Grids, which identified the central role that gas grids will play in delivering the Green Deal objective of a carbon-neutral energy system by 2050 [ENTSO-E, 2019a].
- Oct 2020 *Power to Gas - A Sector Coupling Perspective* by the European TSO associations for electricity and gas ENTSO-E (electricity) and ENTSO-G (gas) [Energinet, 2019f].
- In the EU SET Plan (European Strategic Energy Technology Plan) hydrogen, electrolysis, fuel cells and hydrogen production from natural gas combined with CCS are identified as important energy technologies for the energy transition [Questionnaire]. The EU has also recently published “A hydrogen strategy for a climate neutral Europe” [Oxford Institute For Energy Studies, 2020].
- European Hydrogen Backbone, how a dedicated hydrogen infrastructure can be created published in july 2020. From Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgas, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga [Gas for Climate Enagás, 2020].

E

Out of scope theme for this research: shared ambitions to become a role model in Power-to-Gas knowledge

Especially national government visions and industrial consortia and associations mention the importance and aspiration to become a key leader in hydrogen expertise [DE BMWi, 2020a][P16]. This could also include exporting grid technologies, although no TSOs mention this explicitly in their energy visions, with Energinet as exception [P19][Energinet, 2019a].

The main benefit of becoming a 'hydrogen expert' mentioned by actors includes the economic benefits and potential job creation (as a leverage for the oil and gas industry) [VARIO, 2020][BE federal government, 2020][P2] [DK Klimaaftalen, 2020][DE BMWi, 2020a][APPG, 2020][Provincie Groningen, 2019][Energinet, 2019a] [Norwegian Embassy The Hague, New Energy Coalition, Enterprise Europe network, Royal Danish Embassy, Embassy of Finland The Hague, TKI Nieuw Gas Topsector Energie, 2020]. Another reasoning that has gained importance during the Covid pandemic is the benefit of independence of others' international industries [Norwegian Embassy The Hague, New Energy Coalition, Enterprise Europe network, Royal Danish Embassy, Embassy of Finland The Hague, TKI Nieuw Gas Topsector Energie, 2020].

This 'hydrogen expert' aspiration is important as it is a driver for the growth of an actors' home market, as this market is seen as an important showcase for their expertise [VARIO, 2020] [DE BMWi, 2020a][DE BMWi, 2020b]. Increasing ambitions for becoming a hydrogen expert therefore lead to increasing use of hydrogen in ones' home market, and therefore an increasing or different need for gas infrastructure.

Three categories of 'hydrogen expertise' are distinguished: hydrogen applications on the consumption side, hydrogen production and CCS technology necessary for blue hydrogen. Different actors envision various roles. These differences seem more nationalistically driven than dimensionally driven. This diversity is seen to be dependent on specific local circumstances, availability of resources or presence of particular companies and/or knowledge institutions. Furthermore, this geographical scope is of interest as effectively countries will never be a 'hydrogen expert' but companies will, which are not bounded by national borders [P10].

These roles mentioned above could be beneficial for aligning the different technology developments into one successful hydrogen chain in the areas of research, development, demonstration and implementation of hydrogen technology [TKI Nieuw Gas, 2019][P10]. This could be stimulated on either a collaborative or competitive basis. In the current energy visions some actors (Belgian, UK, Dutch) tend to present a more competitive approach than others, for example with a Flanders strategy mentioning that the Netherlands "regarding hydrogen technology does not have the same high level of expertise as Flanders does" [VARIO, 2020]Page62][BE federal government, 2019a][APPG, 2020].

However, the need for cooperation is nevertheless recognised, brought forward from every countries' own individual ambitions. Considering the size of the challenge, there is no individual country that is able to make the major necessary investments, that has the knowledge and expertise needed and that is willing to individually take the risk; the NSR is therefore doomed to work together [TKI Nieuw Gas, 2019][P1].

Another (yet underestimated) driver towards cooperation in the NSR are the larger competitors all over the world, as individual actors in the NSR would never be able to compete with a massive actor such as China. However, in almost all energy visions actors do not mention competition from outside of the NSR, apart from the UK government lobby group mentioning that "the UK missed the boat on wind technology and missed the boat on battery technology [where China now holds 73%, and rising, of the world's lithium cell manufacturing capacity]. We cannot afford to miss the boat on hydrogen" [APPG, 2020]Page28][DENA, 2019].

It is therefore recommended actors that when actors consider highly ambitious goals for becoming a 'hydrogen expert', they also widen their scope to the outside of the NSR. Thereby preventing too ambitious targets.

This aforementioned collaboration between countries in the NSR to collaboratively become a 'hydrogen expert', could be stimulated by creating barriers to entry for other actors outside of the NSR [P1][DENA, 2019] and by opting for cross-border funding; forming international coalitions of both government and industry to fund such investments considering both EU and non-EU countries [P11]. Forming international coalitions of both government and industry to fund hydrogen investments becomes increasingly logical when international hydrogen chains start to arise and the benefits of investing in green hydrogen becomes international [Drift, 2020].

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