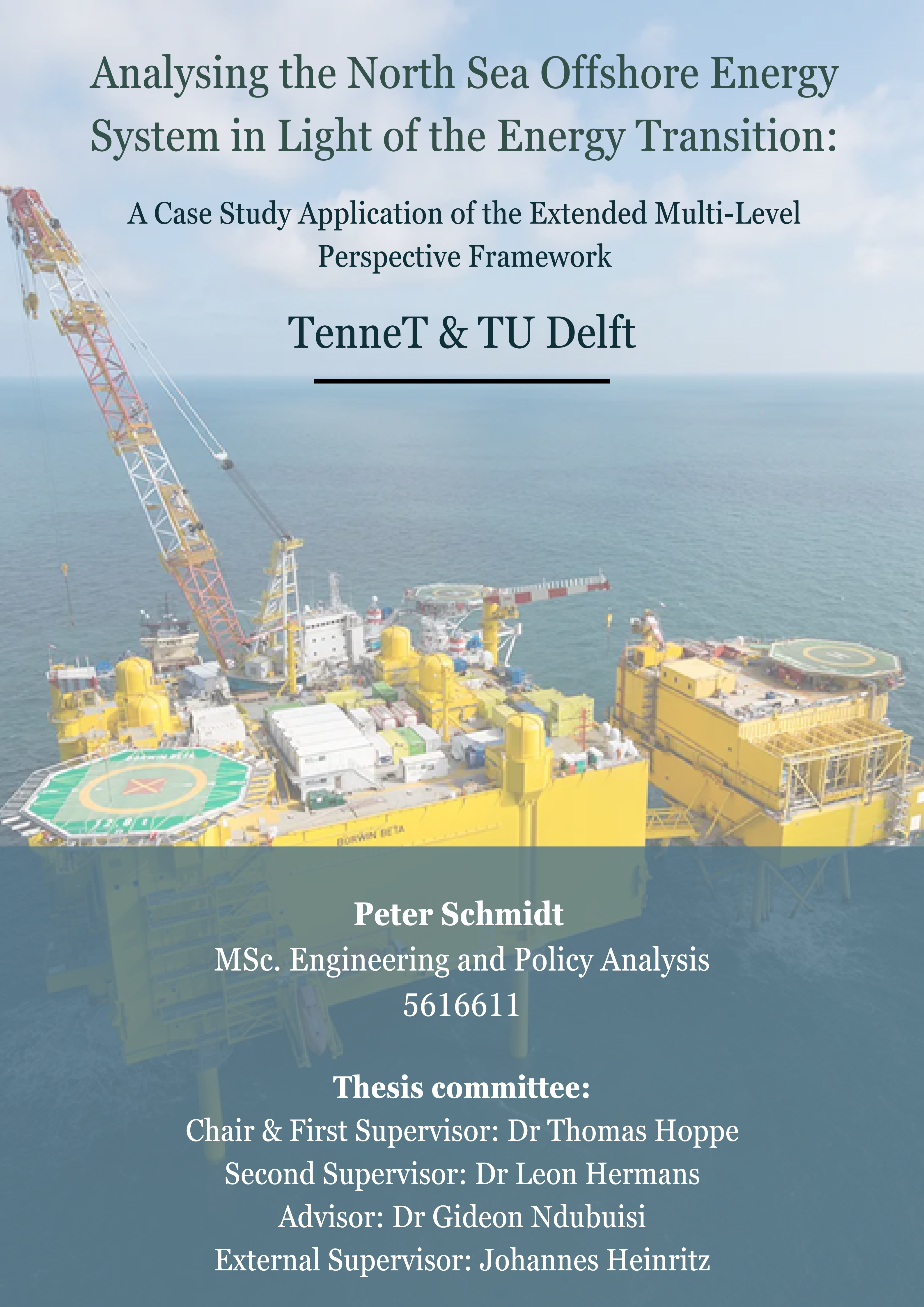


Analysing the North Sea Offshore Energy System in Light of the Energy Transition:

A Case Study Application of the Extended Multi-Level Perspective Framework

TenneT & TU Delft

Peter Schmidt
MSc. Engineering and Policy Analysis
5616611

Thesis committee:
Chair & First Supervisor: Dr Thomas Hoppe
Second Supervisor: Dr Leon Hermans
Advisor: Dr Gideon Ndubuisi
External Supervisor: Johannes Heinritz

Analysing the North Sea Offshore Energy System in Light of the Energy Transition: A Case Study Application of the Extended Multi-Level Perspective Framework

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Engineering and Policy Analysis**

Faculty of Technology, Policy and Management

by

Peter Schmidt

Student number: 5616611

To be defended in public on August 11th 2023

Graduation committee

Chairperson	: Dr. T. (Thomas) Hoppe, Section Multi-Actor Systems
First Supervisor:	: Dr. T. (Thomas) Hoppe, Section Multi-Actor Systems
Second Supervisor	: Dr.ir. L.M. (Leon) Hermans, Section Policy Analysis
External Supervisor	: Dr. G.O. (Gideon), Ndubuisi, Section Economics, Technology and Innovation
External Supervisor	: J. (Johannes) Heinritz, TenneT

Executive summary

The global warming target set by the Paris Agreement of 1.5°C is in danger of being exceeded, necessitating an energy transition for Europe with a particular role for offshore wind energy generated in the North Sea. The North Sea's offshore energy system is a complex socio-technical system; however, a holistic study of this system is missing in the literature. Particularly the transmission aspects, linking the onshore system to the offshore system and ensuring a connection between the rapidly increasing electricity supply and growing electricity demand, have been neglected in literature so far.

The multi-level perspective (MLP) framework is widely used to analyse transitions of complex socio-technical systems. However, no study has yet applied MLP to the North Sea offshore energy system.

This thesis extended the MLP framework with an actor analysis, including a social network analysis (SNA), PESTLE analysis, and scenario analysis to achieve a holistic understanding of the North Sea energy system. For this, a case study of the Dutch and German electricity transmission system operator, more specifically its department Grid Field Operations - Offshore (GFO-O), was applied to the North Sea offshore energy system to answer the following research question:

How does the application of an Extended Multi-Level Perspective (E-MLP) framework enhance the understanding of the complex socio-technical and uncertain dynamic nature of the North Sea offshore energy system, thereby informing GFO-O´s strategy to facilitate the energy transition?

A mixed method approach was chosen. For this, five different methods (MLP, actor analysis, social network analysis, PESTLE analysis, and Socio-Technical Scenarios) were incorporated and combined into the Extended Multi-Level Perspective framework whilst collecting and applying both qualitative and quantitative data. The application of E-MLP enabled a holistic understanding of the socio-technical system, accounting for its complex and dynamic nature.

The key findings of this research are that the North Sea offshore energy system is strongly influenced by onshore developments, supply chain, grid congestion, and demand flexibility. Reshoring the supply chain is costly and time-consuming. Grid congestion and demand flexibility are crucial, while AI enables niche innovations. Small nuclear reactors have limited impact. Offshore focuses on energy hubs, standardisation, and wind park expansion. Moving further offshore increases vulnerability. The future role of hydrogen in the energy system is uncertain. Cybersecurity and the multi-use of space are essential. Involving municipalities is vital for success in contrast to the current top-down approach by governments.
The following recommendations for GFO-O result:

- Plan reshoring of supply chain parts such as vessels or consider sharing concepts to mitigate uncertainties and reduce reliance on global supply chains.
- Attract digital talent through partnerships with universities, up-skill existing workers, invest early in AI capabilities and focus on automation for improved operations.
- Strengthen GFO-O's position through network leverage and drive standardisation discussions.
- Investigate the necessity of a 24/7 electricity supply and explore the possibility of rolling outages.
- Invest in maintenance robots and cargo drones to enhance the efficiency and safety of offshore operations.
- Investigate the potential of green hydrogen production on converter platforms and explore partnerships for hydrogen transmission.
- Monitor Orsted's development for potential impacts on GFO-O's transmission tasks.

Furthermore, policymakers should prioritise driving the multi-use of space and closely follow the valuable insights from the multi-frame project. Initiating pilot studies based on these findings can provide lessons learned about the multi-use of marine space. Establishing a dialogue with the military to address physical and cyber threats to the North Sea offshore energy infrastructure is essential, given its increasing relevance due to recent geopolitical developments. Additionally, incentivising demand flexibility on a consumer level through awareness campaigns and market incentives can further support renewable energy production in the North Sea and reduce the burden on the offshore system.

Moreover, a case study of a transmission system operator in the North Sea offshore energy system was added to the body of MLP studies, and E-MLP was successfully applied. Additionally, the landscape level of the MLP framework has been analysed in more detail than in previous studies by applying the PESTLE framework, as requested by previous research.

This thesis introduces the E-MLP research framework, applied to the case study of GFO-O, a transmission system operator in the North Sea offshore energy system. E-MLP enhances the understanding of the system by analysing factors affecting it and contributes to energy infrastructure design literature. Through actor analysis and SNA, the regime and niche levels are extensively studied, providing insights into actor interactions and informal institutions. The thesis presents a novel approach to scenario analysis, combining exploratory scenario planning and socio-technical scenarios, offering valuable contributions to scenario literature. Additionally, the study provides a holistic understanding of the North Sea offshore energy system and policy-relevant insights for future research and inclusive policymaking.

The selected approach for the thesis has potential limitations due to the use of multiple analysis tools with limited in-depth exploration. Publicly available data was used to ensure repeatability, but it restricted the pool of information. The semi-structured interviews and focus on specific experts may limit perspectives. The social network analysis was limited by undirected ties and unweighted nodes, potentially missing out on information. The inclusion of 50Hertz in the analysis could provide material for future studies exploring cooperation dynamics within the offshore energy system.

This research offers the starting point of more detailed analyses of different levels within the MLP framework for the North Sea offshore energy system or more detailed studies of specific relevant factors, such as the offshore supply chain. This thesis can be extended by adding political or economic weights to the nodes in the SNA. Future studies could explore a heterogeneous analysis of the oil and gas sector, study specific factors like the offshore supply chain in more detail, and apply E-MLP to other energy transition regimes. Furthermore, E-MLP should be applied to the Baltic Sea offshore energy system to test and refine it.

Acknowledgements

I sincerely thank my dear friends and family for all the love and support during my thesis. To give me the strength to continue in times of doubt. I also thank my thesis committee for the continuous support, for redirecting me when I went off track and having the patience to answer all my questions, as silly as they might have sounded.

Contents

Executive Summary **ii**

Acknowledgements **vi**

List of Figures **x**

List of Tables **xi**

Abbreviations **xii**

1 Introduction **1**
1.1 Motivation 1
1.2 Problem statement 1
1.3 Societal relevance 4
1.4 EPA relevance 5
1.5 Research objectives 6
1.6 Research outline 8

2 Theoretical background **9**
2.1 Multi-level perspective 9
2.2 Institutional theory 12
2.3 Energy infrastructure 12
2.4 Design of energy infrastructure 13
2.5 Interim summary 15

3 Research design and methodology **16**
3.1 Research design 16
3.2 Extended Multi-Level Perspective Framework 16
3.3 Relevance of GFO-O for MLP 17
3.4 Relevance of North Sea offshore energy system 19
3.5 Methodology 20
3.5.1 PESTLE Analysis 20
3.5.2 Actor Analysis 21
3.5.3 Social Network Analysis 22
3.5.4 Socio-Technical Scenarios 23
3.6 Research approach 26
3.7 Data Collection 29
3.7.1 Desk research 29
3.7.2 Actor analysis 29
3.7.3 Social Network Analysis 29
3.7.4 Expert interviews 29
3.8 Coding of interviews 32
3.9 Data Analysis 33

3.10 Research validity and reliability 33

4 Policy Analysis for the North Sea offshore energy system 35
4.1 Socio-technical system of the North Sea 35
4.2 Technological map of the North Sea 36
4.3 Actor analysis 37
    4.3.1 Value and Resource Analysis 38
    4.3.2 Social Network Analysis 41
    4.3.3 GFO-O as problem owner 47
4.4 PESTLE analysis 48
    4.4.1 Political 50
    4.4.2 Economic 54
    4.4.3 Social 58
    4.4.4 Technological 60
    4.4.5 Legal 64
    4.4.6 Environmental 65
4.5 Interim Summary 66

5 Scenario Analysis and Discussion 67
5.1 MLP Analysis of Future System 67
    5.1.1 Landscape 67
    5.1.2 Regime 69
    5.1.3 Niche 71
5.2 Scenario Analysis 72
    5.2.1 Scenario building 72
    5.2.2 Scenario 1 75
    5.2.3 Scenario 2 78
    5.2.4 Scenario 3 82
    5.2.5 Scenario 4 85
    5.2.6 Scenario Results 88
5.3 Discussion 90
5.4 Interim Summary 93

6 Conclusion and recommendations 94
6.1 Answering the research questions 95
6.2 Academic contribution 98
6.3 Recommendations for GFO-O 99
6.4 Recommendations for Policymakers 100
6.5 Limitations 101
6.6 Extensions and future work 102

Appendix 116

A Actor Analysis 116
A.1 Step by step guide: Actor Analysis 116
A.2 Actor Analysis Data 118

B Social Network Analysis 119
B.1 Step by step guide: Social Network Analysis 119
B.2 SNA Model 121
B.3 Scenario Analysis 176

List of Figures

1 System overview. Source: own elaboration 5
2 Transition process within the multi-level perspective. Source: Geels, 2004b 11
3 Socio-technical energy infrastructure. Source: modified after Scholten and Künneke, 2016 13
4 Design of energy infrastructure. Source: adapted from Scholten and Künneke, 2016 14
5 Extended Multi-Level Perspective framework for socio-technical systems. Source: own elaboration 17
6 Multi-level perspective on socio-technical transitions. Source: modified after Geels, 2002; Tenggren et al., 2016 18
7 Guide for the application of an actor analysis to the E-MLP. Source: modified after Hermans and Cunningham, 2018 21
8 Guide for the application of a social network analysis to the E-MLP. Source: modified after Hermans and Cunningham, 2018 23
9 Exploratory scenario planning framework and its application for this thesis. Source: modified after Enserink et al., 2022; Elzen et al., 2004a 26
10 Overview of data, methods and tools required to answer subquestions. Source: own elaboration 26
11 Codebook using the multi-level perspective. Source: own elaboration 32
12 Socio-technical system for North Sea offshore energy. Source: own elaboration based on Hafner and Tagliapietra, 2020; Scholten and Künneke, 2016; TenneT, 2023; Quirk et al., 2021; Schupp et al., 2021; Flynn, 2016; Gusatu et al., 2020 36
13 Technological map of the North Sea offshore system. Source: own elaboration based on uit het Broek et al., 2019; Riddick et al., 2019; Schupp et al., 2021; Liyanage and Bjerkebaek, 2006; Buck and Langan, 2017; Mathew et al., 2006; Li et al., 2022; Golroodbari et al., 2021; Spro et al., 2015; Martínez-Gordón et al., 2022; Goetz and Shenoi, 2007; Jaatun et al., 2020 37
14 Interconnector map of European offshore TSOs. Source: own elaboration using Gephi 38
15 Power-Interest matrix. Source: own elaboration 41
16 Social Network Graph based on connections of the key players in the North Sea offshore energy system. Source: own elaboration using Gephi and the Yifan Hu algorithm 42
17 Degree Centrality SNA. Source: own elaboration 43
18 Actor network of Orsted. Source: own elaboration using Gephi and the Yifan Hu algorithm 44
19 Betweenness Centrality SNA. Source: own elaboration 45
20 Closeness Centrality. Source: own elaboration 45

21 External factors resulting from literature review. Source: own elaboration . . . 49
22 Pricing zones in Europe. Source: modified after Nouicer and Meeus, 2019 . . . 50
23 Scenario cross. Source: own elaboration . . . 74
24 Future North Sea energy system. Source: own elaboration . . . 94
25 Actor network Energinet. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 121
26 Actor network National Grid. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 122
27 Actor network Amprion. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 123
28 Actor network Elia group. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 124
29 Actor network TenneT. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 125
30 Actor network Statnett. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 126
31 Overview actor network including labels for ties. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 127
32 SNA with visualisation of niche level developments. Source: own elaboration using Gephi and the Yifan Hu algorithm . . . 128
33 AI as an example topic for the niche level SNA . . . 128
34 2 GW program as an example project for niche level SNA . . . 129
35 Factor ranking based on uncertainty and impact . . . 176

List of Tables

1 Roles of the interviewed experts 31
2 Actor screening based on values 39
3 Actor screening based on resources 40
4 Niches identified by the SNA 47
5 External factors categorised using MLP framework 65
6 Factor ranking based on impact and uncertainty 73
7 Planned capacity from offshore wind in North Sea by country . 88
8 Comparison of capacity produced by offshore wind in the scenarios 88
9 Sources actor analysis 118
10 Centrality measures of most relevant nodes in SNA 129
11 Interconnectors between European offshore TSOs 130
12 Data for the SNA part 1 - key players, domain and connection type131
13 Data for the SNA part 2 - project topic and sources 147
14 Factor ranking based on impact 176
15 Factor ranking based on uncertainty 176

List of Abbreviations

DC	Direct current
E-MLP	Extended Multi-Level Perspective
EPA	Engineering and Policy Analysis
GFO-O	Grid Field Operations - Offshore
GW	Gigawatt
HSE	Health, Safety and Environment
HVDC	High-voltage direct current
LPO	Large Projects Offshore
MLP	Multi-level perspective
NGO	Non-governmental organisation
SNA	Social Network Analysis
TSO	Transmission System Operator

1 Introduction

1.1 Motivation

The world is currently on a trajectory to significantly overshoot the 1.5°C target for global warming agreed upon by 196 countries in the Paris Agreement in 2015 (Intergovernmental Panel on Climate Change, 2022a; United Nations, 2016). The consequences of exceeding 1.5°C global warming are predicted to be disastrous for the planet and life on Earth (Armstrong McKay et al., 2022). Tipping points will be reached, further exacerbating catastrophic climate impacts endangering the livelihoods of millions of people and threatening entire ecosystems to collapse (Armstrong McKay et al., 2022; Intergovernmental Panel on Climate Change, 2022b).

One of the main drivers of climate change is the CO2-equivalent- (CO2e) emissions resulting from inefficient and ecologically unsustainable activities such as the combustion of fossil fuels (Heubaum & Biermann, 2015). Modern life is based on energy consumption (Clemente, 2010). Hence, one grand challenge in the 21st century and beyond is how humans can utilise energy without exponentially fueling further global warming. A major trend in energy consumption is electrification due to the benefits of transportability, exchangeability, and low cost of electricity (Tsao et al., 2018). Especially in the Western world, electrification is strongly linked with decarbonisation to achieve climate targets (de Maere d'Aertrycke et al., 2020). Green energy sources such as solar and wind play an essential role in electrification and the European energy transition, while wind energy is heavily invested in by the Netherlands and Germany, among others (Koivisto et al., 2020; MacKinnon et al., 2022). Especially offshore wind from the North Sea is seen by many as key to the European energy transition (Tosatto et al., 2022; De Croo et al., 2023; Jansen et al., 2022).

1.2 Problem statement

Given the need for the energy transition, a significant body of research has been devoted to understanding it. Many studies have been conducted on the production (Díaz and Guedes Soares, 2020; Rentier et al., 2023; Kang and Guedes Soares, 2020; Fernández-Guillamón et al., 2019) or consumption aspects (Gea-Bermúdez et al., 2021; Hennig et al., 2020; Khan et al., 2022; Huber et al., 2014) of the European energy transition. However, these studies have neglected the transmission aspects, especially in the North Sea.

Governments from countries bordering the North Sea have set highly ambitious capacity targets for offshore wind production, considering it as the 'Green Power Plant of Europe' (De Croo et al., 2023). The build-out of offshore wind and supporting energy infrastructure is enormous. So is the growing demand for electricity by electrification of the industry onshore (Wei et al., 2019; Göransson et al., 2019). Without corresponding transmission developments, the offshore system would continue investing in new assets, increasing production, while the onshore system demands more and more energy, but the bridge between these two systems remains missing. That is why it is important to study transmission aspects as well for the European energy transition.

Considering the socio-technical, multi-actor nature of the North Sea energy system, deemed Europe's 'Green Power Plant' De Croo et al. (2023), an analysis across multiple dimensions is required. The multi-level perspective (MLP) is used as a multi-dimensional framework to analyse socio-technical transitions (Elzen et al., 2004b). MLP is dividing the socio-technical system into three dimensions. The landscape is comprised of slow-changing factors external to the regime level. The regime level entails the actors and their interactions, embedded in a set of rules and norms. From protected niches, innovations can spawn that have the potential to impact the regime level and landscape.

Out of the studies on the consumption and production aspects of the European energy transition, none have used the MLP framework despite complex socio-technical systems being best addressed by MLP. The research process yielded only two studies that apply MLP on the North Sea offshore energy system (Flynn, 2016; van Hoof et al., 2020). One is analysing the transition of Dutch fisheries, and the other focuses on a specific offshore grid initiative. A third one is applying lessons learned from the UK's energy transition to China, with a brief mention of North Sea gas (Yang et al., 2022). Given the societal relevance of the North Sea for the European energy transition, this creates a possibility of losing out on valuable scientific insights that can inform policies on a system level. Thus, the lack of applying MLP, a framework to analyse complex socio-technical systems, to this highly relevant offshore energy system is creating a scientific gap. Moreover, there has been no holistic study of the North Sea offshore energy system so far. Studies have either focused on specific aspects, such as emissions from oil and gas platforms (see Riddick et al., 2019 (2019)), the offshore wind energy sector (Künneke et al., 2015), or on a specific country (Denmark, see DAndrea et al., 2021 (2021)). A holistic analysis of the North Sea offshore energy system as a complex, socio-technical system is missing in the body of literature.

Furthermore, extensions of MLP to account for the multi-actor nature and inherent uncertainty of future developments in this rapidly changing system are not to be found in the existing body of MLP case studies. Even though Genus and Coles (2008) point to the added value of an actor analysis to MLP and Andrews-Speed (2016) stresses the need for more detailed analyses of the landscape level within MLP, there has been no systematic integration of an actor analysis, social network analysis, detailed external factor analysis and scenario analysis in MLP so far. In order to fully understand niches with the potential for system change, it is essential to achieve an overview of the social network of other actors on the regime level, and assess their partnerships, projects and consortia they are part of. Hence, a more holistic framework grasping the complexities, uncertainties and multi-actor nature of socio-technical systems such as the North Sea offshore energy system in the midst of the energy transition is needed.

Combining these insights, MLP is applied to a case study of a transmission system operator in the North Sea offshore energy system, combined with an actor analysis, a social network analysis, external factor analysis and scenario analysis to analyse this highly dynamic and relevant system for the European energy transition in a holistic way.

In the Netherlands and Germany, the Transmission System Operator (TSO) manages the electricity grid (Söder et al., 2020). TenneT is the only TSO in the Netherlands, one of four TSOs in Germany, and a major actor with significant market power in the electricity system of these two countries. TenneT's operations can be divided into onshore and offshore. While the onshore department mostly focuses on maintaining and operating the transmission grid on land, the offshore department builds offshore converter platforms, operates, and maintains them. More specifically, the department Grid Field Operations - Offshore (GFO-O) is responsible for operation and maintenance while the department Large Projects Offshore (LPO) builds the platforms and Asset Management is responsible for the operational readiness life-cycle management.

When looking at the path electricity takes from being created in offshore wind parks until it arrives in either industry or at the household level of end-consumers (Figure 1), offshore conversion and transmission to land forms a crucial bottleneck. Resolving this bottleneck is essential for Europe to accomplish the energy transition, given the planned rapid development of offshore wind generation in the North Sea (IEA, 2020; Díaz and Guedes Soares, 2020; Jansen et al., 2022; De Croo et al., 2023). Solving this bottleneck is not fully under GFO-O's control, resulting in a complex problem.

Due to the problem's multi-actor nature within a complex socio-technical system, a solution and successful performance of GFO-O hinges on a sophisticated understanding of the external factors that are impacting the transmission business. Additionally, the recent developments with Russia's invasion of Ukraine and the political scramble for energy security have re-emphasised the value of energy security and security of supply (Correljé and van der Linde, 2006; Kuzemko et al., 2022; Purvins et al., 2011). European politicians are scrambling to provide security of energy supply to their citizens amid increasing uncertainties. Thus, it becomes clear that GFO-O's role in enabling the security of supply as its core task is of immense societal value and of critical importance for the Netherlands and Germany. In order to mitigate their impacts and enable the security of the electricity supply on which the German and Dutch energy transitions depend, analysing the external factors affecting GFO-O is indispensable for dealing with them.

GFO-O's performance:

To understand what exactly GFO-O's performance is, a look at its vision is imperative. GFO-O aims to be the *leading offshore TSO in Europe*. In order to become this, safety for people, availability of the grid connection systems as well as technical and financial efficiency are key. For these areas, GFO-O has defined key performance indicators to ensure safe and reliable electricity supply.

1.3 Societal relevance

GFO-O is of societal relevance not only for the offshore energy system in the North Sea but also as a key puzzle piece for the European energy transition. Its core task is to ensure the reliability of energy supply despite significant uncertainties. Navigating these uncertainties across multiple dimensions requires a system perspective to understand and identify relevant external factors. Furthermore, change at an unprecedented pace requires a robust and flexible strategy accounting for multiple future states of the world. Currently, there is no body of strategies available that helps TSOs and, hence, GFO-O to ensure the reliability of supply amid the various uncertainties by solving the transmission bottleneck in the offshore energy system to facilitate the energy transition.

Not least because of its predicted enormous economic potential, the North Sea offshore system is in the middle of rapid changes and seeing an unprecedented transition, with GFO-O in the midst of it, tasked with solving the offshore to onshore transmission bottleneck.

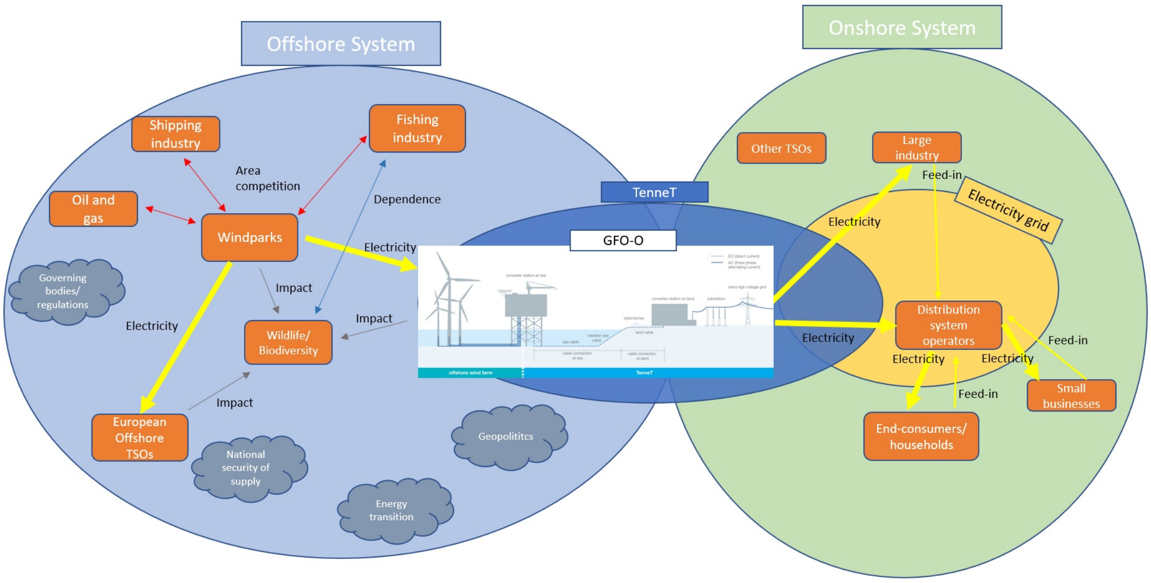


Figure 1: *System overview. Source: own elaboration*

The North Sea, due to its favourable wind conditions and relatively shallow waters, is seeing strong growth in offshore wind development and, hence, is a crucial arena for the energy transition in Europe (Jansen et al., 2022). However, it can be seen in Figure 1, that the offshore energy system in the North Sea is of complex socio-technical nature (Künneke et al., 2015).

To achieve an understanding of the offshore energy system in the North Sea, it is essential to analyse a broad range of factors. Moreover, the offshore system is only part of the larger energy system in the Netherlands and Germany, as there exists a strong and growing dependence of the onshore system to receive electricity generated offshore. For a better understanding, the way of electricity is illuminated in Figure 1.

1.4 EPA relevance

This thesis is conducted within the Master of Science degree in Engineering and Policy Analysis (EPA). Aligning with the objectives of the study program, a grand societal challenge, the energy transition, is analysed in a multi-dimensional way. Going beyond pure engineering and technical considerations, a socio-technical approach is taught within EPA and, hence, applied to this study. Thinking in systems, dealing with uncertainties and the multi-actor nature of systems is at the core of the EPA program.

Therefore, it is aimed to research the complexity of the system of interest with the methods of actor analysis and social network analysis (Hermans & Cunningham, 2018), scenario analysis (Enserink et al., 2022), and policy analysis (Enserink et al., 2022), which were learned in the courses EPA1144 Actor and Strategy Models and EPA1124 Policy Analysis of Multi-Actor Systems. PESTLE is a method that is not part of the EPA-curriculum but highly aligned because it enables multi-dimensional analysis of factors in a system (Perera, 2020; Soares et al., 2023). Similarly, the MLP framework is not explicitly taught within EPA but allows the analysis of a socio-technical system on multiple levels and, thereby, contributes to understanding and mitigating grand societal challenges.

The interdisciplinary nature of societal challenges often requires the combination of different methods into a framework that is able to analyse a system holistically. This has been done for this thesis with E-MLP, combining all methods mentioned above to achieve a holistic understanding of the system and inform policy-makers and decision-makers within TenneT's GFO-O on how to best deal with the insights arising from the study of the North Sea offshore energy system. Thus, this thesis fulfils another onjective of the EPA program, the relevance for decision-making both in the industry and in the public sector.

1.5 Research objectives

Using the lense of the extended MLP framework, the main characteristics of the North Sea offshore energy system are analysed. To account for multiple dimensions within the three levels of the socio-technical system, a PESTLE analysis is performed. PESTLE is an external factor framework, considering political, economic, social, technological, legal, and environmental factors (Sharmina et al., 2019). Political factors encompass the national energy policies. Economic factors range from workforce to resource interest and demand for raw material, for instance by the wind parks, TSOs and the shipping industry. Furthermore, the European energy transition is not merely of technical nature but clearly involves social and environmental factors (Acosta et al., 2018; Tenggren et al., 2016). National regulation is an example of a legal factor. To account for the dynamics of the European energy transition, an exploratory scenario analysis will be integrated within the E-MLP.

As a result, this thesis aims to analyse the North Sea offshore energy system using the E-MLP framework in a holistic way. Following the call by Andrews-Speed (2016) for case studies with particular focus on the landscape within MLP, a complementing PESTLE analysis will be performed to identify and analyse relevant external factors for GFO-O's performance (defined above). Based on the most relevant factors identified, a qualitative scenario analysis will be conducted to evaluate the factors' impact on GFO-O's performance within the future uncertain landscape of the European energy transition. The final goal is to add an E-MLP case study within the North Sea offshore energy system to the body of literature and give policy recommendations for the strategy process to the management and policy makers Thereby, a starting point for MLP studies on the North Sea offshore energy system will be created and a new, less studied system will be added to to the growing body of MLP case studies. Another contribution of this thesis is the extension of the MLP framework by an actor analysis, providing a more holistic understanding of socio-technical systems in transitions. Moreover, niches are uncovered within a system that has not intensively been studied with MLP, which adds value to the literature and future scholars studying the North Sea energy system under the light of socio-technical transitions. Not only the offshore perspective can be useful but also insights into this case study of a transmission system operator are relevant for scholars in every country to understand and improve the scientific body of MLP to contribute to the security of energy supply as a bottleneck of international energy transitions.

Consequently, the following main research question was drafted.

Main research question

How does the application of an Extended Multi-Level Perspective (E-MLP) framework enhance the understanding of the complex socio-technical and uncertain dynamic nature of the North Sea offshore energy system, thereby informing GFO-O´s strategy to facilitate the energy transition?

To answer the formulated main research question, the sub questions below are deemed most relevant and suitable to guide the process of this thesis.

Sub-questions

1. **What is an Extended Multi-Level Perspective framework?**
2. **What are the main characteristics of the North Sea offshore energy system captured by the use of the extended multi-level perspective framework?**
3. **What are the relevant actors in the North Sea offshore energy system?**
4. **What are plausible socio-technical scenarios capturing the evolution of the North Sea offshore energy system in the next 15 years?**
5. **Taking into account the static and dynamic characteristics of the North Sea offshore energy system, how can GFO-O adapt its strategy in the face of uncertainty to perform its core tasks and facilitate the energy transition?**

1.6 Research outline

Chapter 2 introduces the theoretical background of MLP and elaborates on the location of this research within MLP and the energy infrastructure domain. Chapter 3 explains the chosen research approach in more detail. Chapter 4 provides an understanding of the socio-technical North Sea offshore energy system, analyses the relevant actors, introduces TenneT's and GFO-O's position and objectives within this system and entails the PESTLE analysis based on the literature research. Furthermore, it contains a map of technological innovations impacting the system resulting from the social network analysis and PESTLE analysis. In chapter 5, the results of expert interviews on external factors will be compared with the literature research of the PESTLE analysis. Based on these factors, exploratory scenarios will be created, discussed and the implications for GFO-O analysed. This will then be used to give policy recommendations to GFO-O and policymakers in chapter 6. Furthermore, a conclusion will be drawn and limitations and potential extensions of this research discussed.

2 Theoretical background

This thesis is positioned within the European energy transition. To understand the body of transition literature, a first understanding is required of what a transition is.

"The term transition is broadly used in many scientific disciplines and refers to a nonlinear shift from one dynamic equilibrium to another." (Loorbach et al., 2017). According to Elzen et al. (2004), transitions can be envisioned as long-term processes within systems that provide ’basic societal functions’ such as energy. Furthermore, transitions are described to bring about ’drastic change of the technical as well as the societal dimensions of such a system’ (Elzen et al., 2004a).

Looking at transitions from a scientific perspective, a large body of literature focuses on energy systems transitions (Demski et al., 2015; Leal Filho et al., 2020; Kern and Smith, 2008; Acosta et al., 2018). The supply side aspects (particularly offshore wind generation) and demand side aspects are well covered in literature (Tenggren et al., 2016; Perveen et al., 2014; Díaz and Guedes Soares, 2020). A lot of research can be found on energy production and the environmental impact of various renewable energy sources, however, there is not much focus on the transmission as a critical aspect of energy provision as a bottleneck between generation and supply of energy (Tenggren et al., 2016; Edomah et al., 2017). Moreover, because this thesis is focusing on the North Seah offshore energy system, the relevant literature domain energy systems transitions is part of the body of research on ’socio-technical transitions’ (Geels and Schot, 2007; Leal Filho et al., 2020; Geels, 2004a). The following chapter is setting the scene for the scientific background and introduces the main theoretical framework for this thesis.

2.1 Multi-level perspective

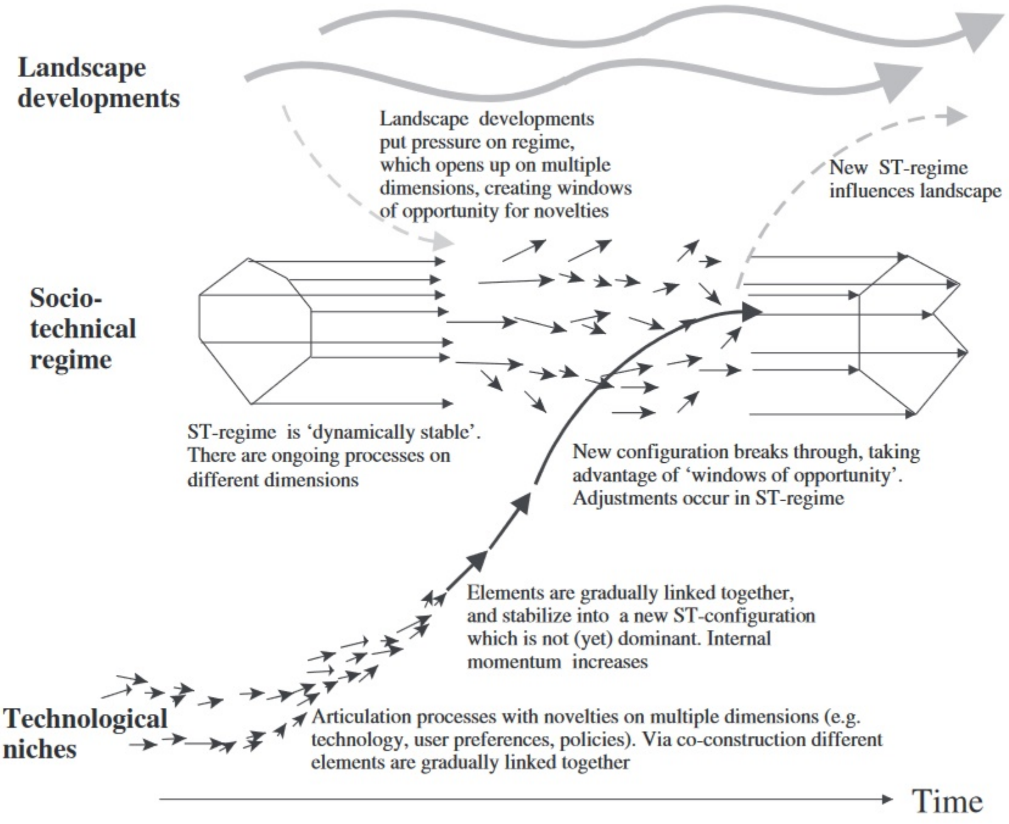
To analyse socio-technical transitions, the multi-level perspective is widely used and successfully applied (Andrews-Speed, 2016; Jehling et al., 2019; Elzen et al., 2004b; Fuenfschilling and Truffer, 2014). "The so-called ’multi-level perspective’ has been developed to analyse and explain transitions and system innovations." (Elzen et al., 2004a). According to Geels and Schot (2007), within socio-technical transitions, three levels are of significance when considering socio-technical systems (Figure 6). These three levels are the landscape, regime and niches. It should be noted that the different levels are not a mere depiction of reality but concepts to analyse and simplify ’complex dynamics of sociotechnical change’ (Geels, 2002). Furthermore, the levels are linked and this linkage enables an explanation of the dynamics of a transition. MLP depicts transitions in the light of dynamic interaction between different levels and their structuring (Fuenfschilling & Truffer, 2014). The structuring is hierachical, with the landscape being the most structured level and the niche level the least structured (Fuenfschilling & Truffer, 2014).

The landscape level entails factors external to the regime level that impact the regimes over a long period of time, while change is only occurring slowly at the landscape level (Geels, 2004b). These factors are multi-dimensional and range from economics, politics, cultural, and societal to environmental factors (Geels, 2004b). There is almost no possibility to change the landscape factors from the regime level (Geels, 2004b). As the top level, the landscape sets the context for the regimes and therefore the niches. Even though the process is slow, changes in the landscape occur and these changes put pressure on the regime level to adjust (Geels, 2002). Pressure can result from changing regulation or policies, but also from a changing macroeconomic environment.

Socio-technical regimes can be considered the backbone of the system due to interaction of the actors (Fuenfschilling & Truffer, 2014). They are the set of rules that govern behaviour of social groups and therefore provide an inherent stability for a multi-dimensional, socio-technical system (Geels, 2004b). This stability still enables innovation but slows down the process and all but prevents radical disruptions (Geels, 2004b). In case of pressure from landscape and niches, the regimes can be weakened, enabling radical transformations and transitions from one system state to another. Regimes can be understood as actors and institutions that provide societal functions such as electricity and infrastructure (Tenggren et al., 2016). The regimes interact and are maintaining system elements, such as energy infrastructure.

The niche level is less institutionalised, meaning they are subject to less rules than the regime level and therefore more free to innovation (Fuenfschilling & Truffer, 2014). From niches, rapid and often radical innovations originate that have the potential to disrupt the system (Tenggren et al., 2016; Geels and Schot, 2007). These disruptions can result from new business models or technological development. Niches can be thought of as a fertile breeding ground for ideas that is protected from strong impacts of regimes and the landscape. Niches enable learning processes, experimenting with new technologies or other aspects potentially impacting the entire system in a protected environment (Geels, 2004a). Learning processes within niches are protected from selection forces such as market pressure (Geels, 2004b). This gives room for the development of radical innovations that would otherwise not succeed as they are too expensive in their development or their development process might take too long to survive under the competitive pressures on the regime level. Another aspect of niches is the fostering of network effects that can feed into innovations, such as supply chain connections (Geels, 2004b). Furthermore, niches can quite literally provide the space for actors to connect, exchange ideas, knowledge, and best practice in a protected environment which can stimulate innovation and, consequently, disrupt the previously stable regime level (Geels, 2004b). Niches differ in their maturity, while some innovations are almost ready to be scaled up, others are far from it (Elzen et al., 2004a).

Transitions result from shifts in regimes. An old, highly structured regime gives way to a new one, where the structures are yet to establish (Fuenfschilling & Truffer, 2014). New laws, regulations, business and business models are drivers for such a transition (Fuenfschilling & Truffer, 2014). An example to illustrate the dynamics within MLP are negative externalities such as environmental impact. At first, they might be ignored by the the regime level as the effects are not immediate. However, if they are picked up by other actors, for instance an environmental Non-governmental organisation (NGOs) , they can rise to the landscape level and manifest as environmental regulation. This regulation will have a direct impact on the regimes (Geels, 2004b). This dynamic can be seen in Figure 2. For actors in the regime level, there is an incentive to identify relevant niches and factors while they are not yet in the landscape and therefore the immediate influence on the factor is lost. Thus, strategic and competitive games on regime level between actors result (Geels, 2004a). Investing in the right niche can pay of in the long term as the (radical) innovation makes its way to the regime level and may result in policy changes on the landscape level, potentially causing system change (Geels, 2004a).



Landscape developments put pressure on regime, which opens up on multiple dimensions, creating windows of opportunity for novelties

New ST-regime influences landscape

ST-regime is 'dynamically stable'. There are ongoing processes on different dimensions

New configuration breaks through, taking advantage of 'windows of opportunity'. Adjustments occur in ST-regime

Elements are gradually linked together, and stabilize into a new ST-configuration which is not (yet) dominant. Internal momentum increases

Articulation processes with novelties on multiple dimensions (e.g. technology, user preferences, policies). Via co-construction different elements are gradually linked together

Figure 2: *Transition process within the multi-level perspective. Source: Geels, 2004b*

2.2 Institutional theory

The domain of institutional theory aligns with MLP, it investigates the interdependence between actors, rules and technology (March & Olsen, 1983). Institutional theory is looking at organisations and how they can provide their core tasks to society, which is located in the regime level within MLP. Institutional theory specifically focuses on the interaction of organisations with their environment, taking into account competitors but also social rules and norms - institutions (Edomah et al., 2017). Two kind of institutions can be distinguished. Informal institutions encompass intangible concepts such as norms, traditions, or values, shared among different groups and communities (Scholten & Künneke, 2016). These are often not stated explicitly, but rather implicitly shared as ’culture’ (Andrews-Speed, 2016). They are results of countless interactions and emerge spontaneously rather than that they are created (Scholten & Künneke, 2016). In contrast, formal institutions are officially stated and actively rule interactions as laws or regulations, formulated by authorities (Scholten & Künneke, 2016). Examples are market design or environmental regulations. Actors in the regime level and their interactions are governed by such formal institutions.

2.3 Energy infrastructure

An energy transition is not possible without physical assets, the energy infrastructure. Energy infrastructure ranges from the production, over the transmission to the consumption of energy (Scholten & Künneke, 2016). Part of the energy infrastructure considered in this research are the wind parks offshore, the onshore grid, but also converter stations offshore and subsea cables, among many other assets. With the focus on the North Sea offshore energy system, this thesis can be located within the body of literature on offshore as part of the energy infrastructure domain (Garg et al., 2015; Edomah et al., 2017; Scholten and Künneke, 2016). Scholten (2016) emphasises the importance of operation and maintenance as a critical part for adaptive socio-technical systems. This validates GFO-O’s relevance and the purpose of this thesis not only from a societal but also from a scientific perspective.

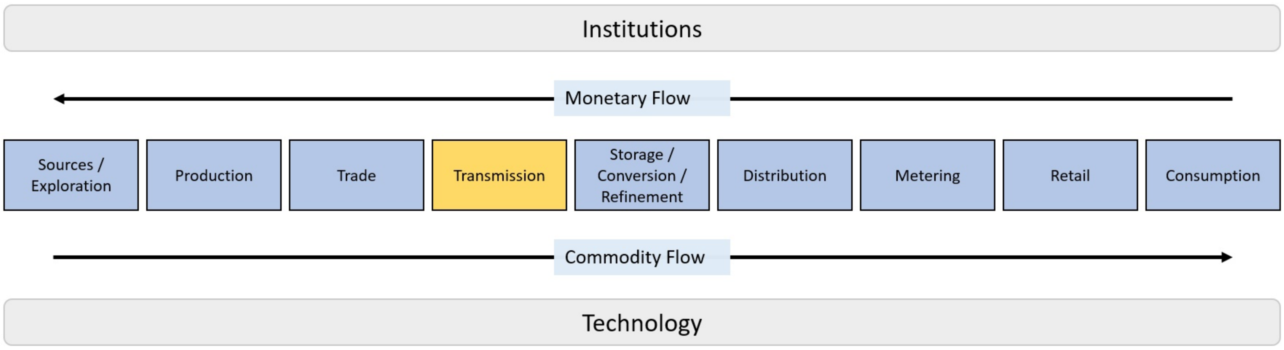


Figure 3: *Socio-technical energy infrastructure. Source: modified after Scholten and Künneke, 2016*

According to Scholten (2013), energy infrastructure can not be reduced to physical infrastructure anymore. Due to the complexities and interconnections of actors, technology and institutions, the perspective on energy infrastructure changed towards that of a socio-technical system (Scholten, 2013). The operation of energy infrastructure is reliant on humans, which shapes the notion of reliability as it moves beyond a purely technical dimension. Interdependence and relations among actors are highlighted and particularly actor networks require special attention (Scholten and Künneke, 2016; Scholten, 2013). The development of decentralised and spatially distributed energy infrastructure is further contributing to the complexity. In Figure 3, this complexity is depicted. While the flow of energy (the commodity of consideration) and the monetary flow are linear in opposing directions, energy flows from source to consumption and the monetary flow proceeds from the consumption to the source, institutions and technology encompass the entire energy infrastructure value chain. The concrete dynamics and interactions are too complex to depict in one figure and further emphasise the need to consider energy infrastructure as a socio-technical system. The part within energy infrastructure that this research focuses on is the transmission, as highlighted in Figure 3.

2.4 Design of energy infrastructure

Building upon the concept of energy infrastructure as a socio-technical system Scholten and Künneke (2016) go a step further and argue for the need of a comprehensive design approach that combines the technological and economic dimension of energy infrastructure. For the design of a system, not only components of this system need to be chosen carefully, but also the way of connecting these to fulfil the system's objective (Waldo, 2006). In case of energy infrastructure, this objective is security of energy supply (availability) in an affordable and acceptable way (European Commission, 2000). Availability, affordability and acceptability are considered to measure the performance of energy infrastructure (Scholten & Künneke, 2016). Looking at the socio-technical system of energy infrastructure, this raises the question of how to select and connect these components - how to design energy infrastructure.

Scholten and Künneke (2016) criticise, that the separate design of energy infrastructure and electricity market design led to contradicting outcomes in the example of liberalising energy markets, enabling a decentralised structure operated by multiple actors while the operation of the physical infrastructure remained firmly in the hands of one single actor. Hence, the design of energy infrastructure should entail the economic and technological dimension in one comprehensive design. The benefit of such a design can best be explained with the words Scholten and Künnecke: "It enables us to adequately identify, interpret and address operational and market challenges to energy infrastructure performance." (2016).

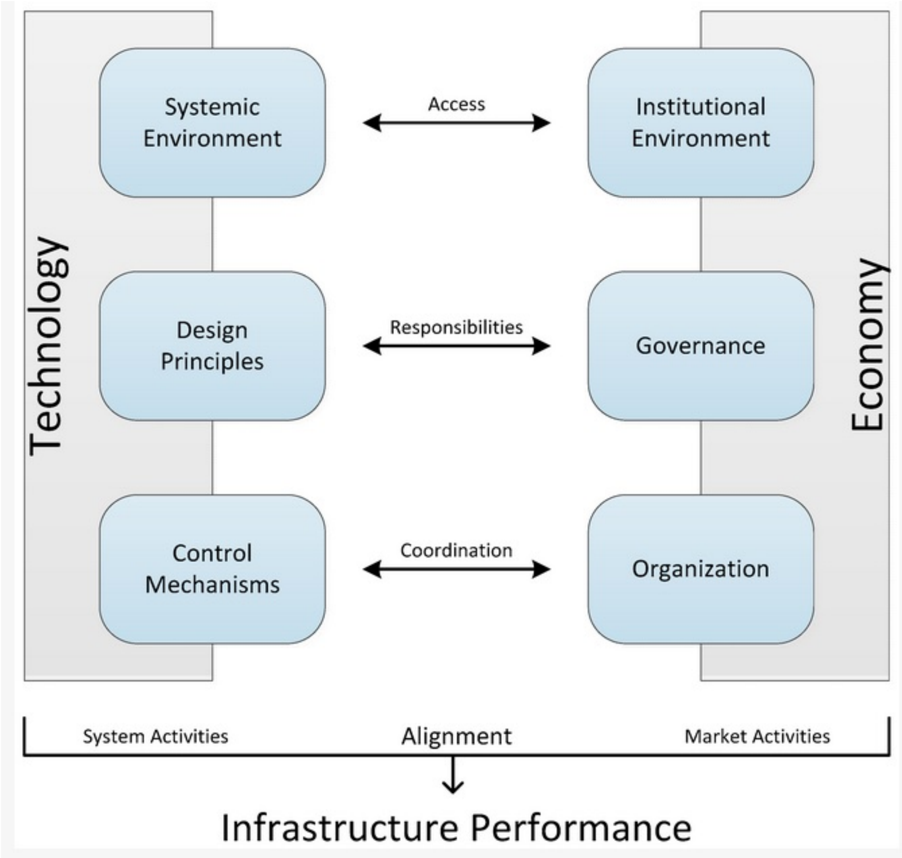


Figure 4: *Design of energy infrastructure. Source: adapted from Scholten and Künneke, 2016*

Figure 4 shows the proposed design, which can be separated in three levels. The systemic environment is linked to the institutional environment via the concept of "access", which can be broken down in open and closed access to infrastructure. Open access allows different actors to access the infrastructure and provide services based on standards and protocols. This pool of actors is significantly reduced and the services are of limited nature for closed access in the technical dimension. Economically speaking, governments control and regulate the market in case of closed access, while functions and services are opened up for competition and liberalised in the case of open access.

In the second level, design principles are linked to governance of markets via the concept of "responsibilities". In the technical dimension, this entails the assignment of infrastructure operation and maintenance tasks to different actors. In the economic dimension, the objective of service provision enabling security of energy supply is achieved by assigning "ownership and decision rights" to market participants. This can be done by privatisation, liberalisation, regulation and introducing competition where it is effective to achieve the above stated objective. Responsibility allocation should align between market functions operation tasks of actors (Scholten & Künneke, 2016).

The third level links control mechanisms and organisation with the concept of "coordination". The first two levels need to be established in order for the third level to function effectively. The third level focuses on actor interactions. In the technical dimension, these interactions take shape in more (centralised) or less (decentralised, almost autonomous) "coordinated" form to perform operation tasks. From the economical perspective, the interactions in different kinds of market, for example spot markets, are of relevance. Moreover, the organisation types and their level of regulation are of key importance to prevent inefficiencies such as centralised control and highly privatised market transactions.

Such coherent design is not only relevant for each level but across all levels for a successful application of this framework to challenges like the large-scale integration of wind as a variable renewable energy source and the consequent challenges for energy infrastructure and market design (Scholten & Künneke, 2016). Thus, potential lock-ins and path dependence due to thinking along merely one dimension could be potentially avoided.

2.5 Interim summary

MLP is used to analyse socio-technical systems in the context of transitions and splits up these systems into the landscape, regime and niche level. The landscape and niche level apply pressure on a weak regime, when it develops cracks and tensions, opportunities arise for niche developments to rise to the regime level and disrupt the system. Institutional theory applies to the regime level of MLP and institutions can be divided into informal and formal. Design of energy infrastructure is accounting for the change in function and treats energy infrastructure as a socio-technical system, encompassing the technical and economic dimension and their interaction. Availability, affordability and acceptability are used to measure performance of energy infrastructure.

3 Research design and methodology

In this chapter, sub-question 1 will be addressed by presenting the E-MLP and elaborating on its components as well as motivating their choice.

3.1 Research design

This thesis operates on the intersection between MLP, institutional theory and the design of energy infrastructure within socio-technical transitions. Within the domain of energy systems change, it particularly focuses on the transmission process instead of the well-covered demand- or supply-side aspects. Andrews-Speed (2016) stresses the need for case studies that go beyond a general application of MLP and institutional theory to the energy sector. He emphasises a lack of detailed analyses of socio-technical systems within energy where particular attention is paid to the landscape within MLP (Andrews-Speed, 2016).

Thus, a case study using E-MLP is adopted. Case studies are beneficial for studying socio-technical transitions as they allow insights into complex, multi-dimensional situations (Agency, 2018). Moreover, case studies can be used to analyse non-linear processes over a certain time, which is particularly valuable to study the complex nature of the energy transition, per definition, a process spanning over a significant period of time. To account for the need for case studies with a focus on the landscape, stressed by Andrews-Speed (2016), an extended MLP framework and PESTLE are applied to the North Sea offshore energy system, studying the case of TenneT's GFO-O as a TSO with offshore transmission business with its core task being the provision of crucial societal reliability of energy supply.

3.2 Extended Multi-Level Perspective Framework

A mixed method approach is chosen. For this, 5 different methods (MLP, actor analysis, social network analysis, PESTLE analysis, Socio-Technical Scenarios) were incorporated and combined into the Extended Multi-Level Perspective framework, whilst collecting and applying both qualitative and quantitative data.

The composition of the Extended Multi-Level Perspective framework can be seen in Figure 5. A socio-technical system of interest, in case of this thesis the North Sea offshore energy system is chosen. Next, MLP is used to decompose the system into the landscape, regime and niche level. Building on top of MLP, a PESTLE analysis is used to identify relevant factors in all three levels that are affecting the system. Furthermore, the actors in the regime level within the socio-technical system and their interactions are studied by an actor analysis, while a SNA is conducted to identify cooperations on the regime level but also technological innovations and business models spawning from the niche level.

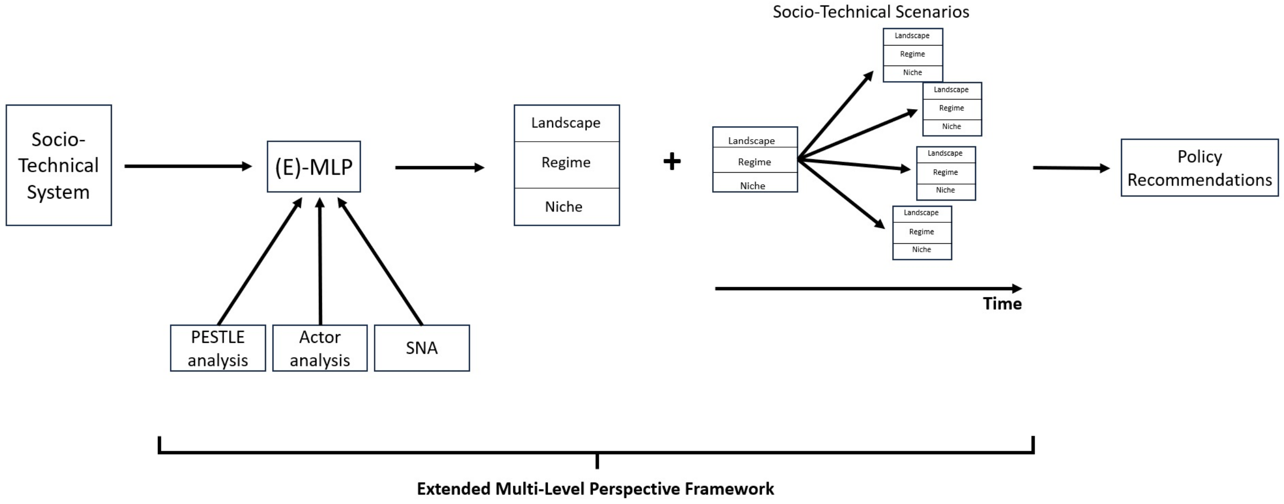


Figure 5: *Extended Multi-Level Perspective framework for socio-technical systems. Source: own elaboration*

Given the uncertainties particularly of socio-technical systems in the energy transition, Socio-Technical Scenarios are created to understand possible future developments and capture dynamics that are missed by a static consideration. Especially for the rapidly changing North Sea offshore energy system, the study of the systems' dynamics is essential. By designing four different scenarios, an understanding of the static and dynamic nature of the socio-technical system of interest is achieved. At this point, the holistic understanding, gained by applying the Extended Multi-Level Perspective framework enables the formulation of policy recommendations.

In section 3.5, the different methods combined for the E-MLP framework are elaborated on and motivated.

3.3 Relevance of GFO-O for MLP

Having introduced the multi-level framework and argued for its applicability to socio-technical transitions, the question might arise: what is the benefit of using E-MLP for this particular thesis, and where is the connection to GFO-O?

First of all, Europe is in the middle of an energy transition as a result of climate change and accelerated by the Russian war on Ukraine. Next to the technical aspects of scaling up renewable energy production and the grid accordingly, this transition goes far beyond the technological realm. It concerns the European society on multiple dimensions and, hence, must be considered a socio-technical transition. As described above, GFO-O is tasked with providing security of energy supply by transmitting energy produced offshore to shore. Offshore energy production is part of a larger socio-technical system, the North Sea offshore energy system. Hence, multiple developments in different dimensions lead to mutual reinforcement and disrupt the system's stability. Examples on the landscape level are regulatory changes and new, even more ambitious governmental policies (see De Croo et al., 2023), which bring about regime change (Geels, 2004b). A regime change might eventually lead to system change, which is highly relevant for GFO-O and the way it operates. In case of a GFO-O pushing for the change or enough time in which the effect can be anticipated, the consequences do not have to be of negative nature for GFO-O.

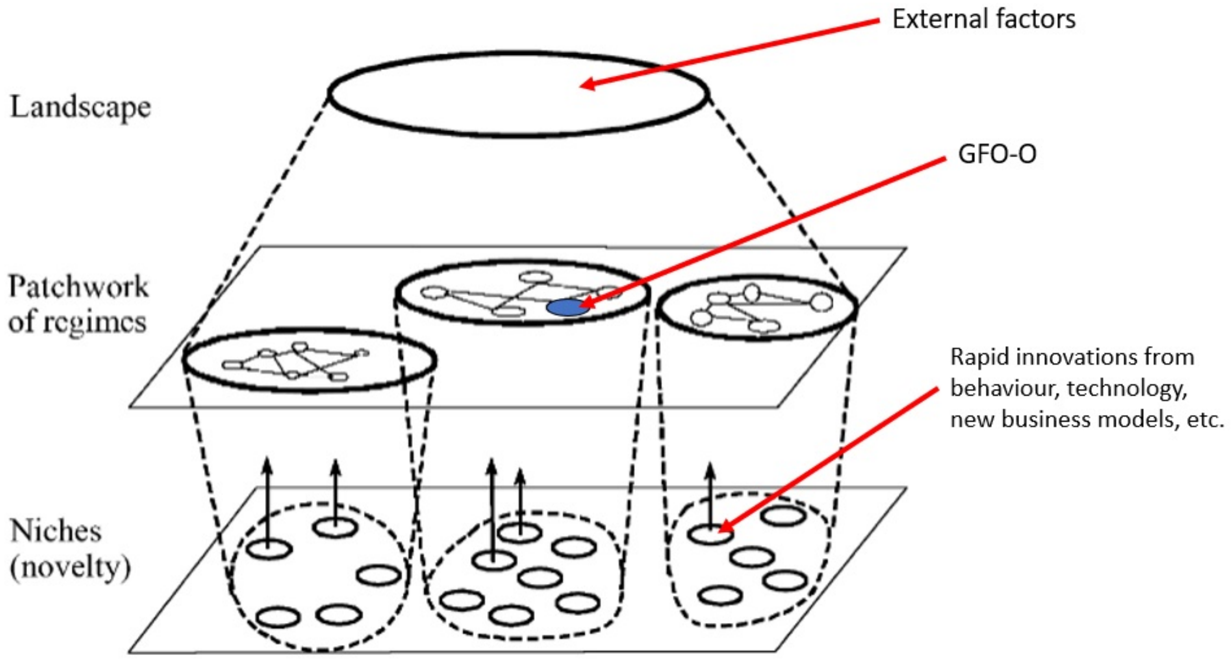


Figure 6: *Multi-level perspective on socio-technical transitions. Source: modified after Geels, 2002; Tenggren et al., 2016*

Taking a step back, GFO-O can be positioned within the regime level in the multi-level perspective, as shown in Figure 6. Maintaining the system element of critical converter platforms and subsea cables (infrastructure), it is providing energy to society. Hence, the existing set of rules governs its interaction with other actors within the regime level. The landscape level is consistent of factors external to GFO-O's influence. Subsequently, GFO-O's position is reduced to a reactionary one. Understandably, this is everything but advantageous when operating critical infrastructure and providing security of energy supply.

Concrete examples of landscape pressures on GFO-O are the evolving regulatory landscape or European ambitions for the North Sea energy system to be the 'Green Power Plant' of offshore wind, as decided at the North Sea Summit (De Croo et al., 2023). Additionally, rapid offshore wind park developments require workforce growth that is beyond the existing capacities to maintain and operate an increasing number of assets. Environmental regulation and societal pressure for environmental protection affect GFO-O's operations as well. Besides immediate impacts on the operations, this also affects the supply chain, and determines which contractors can be chosen and which are not acceptable. European policy regarding domestic supply chains with fewer ties to China significantly furthers the supply chain pressure and impacts GFO-O significantly, without much room to change it.

On the regime level, there exists strong competition due to multiple actors in the North Sea offshore energy system. Varying interests further complicate the situation; one of many conflict zones is area competition. Military, the fishing and shipping industries, as well as wind park operators and oil and gas companies, compete for the restricted space in the North Sea. Moreover, operators of wind farms could change their core business and potentially start transmitting electricity from the sea to shore themselves, with high implications for GFO-O.

Niche developments have the potential to disrupt GFO-O's core business and therefore need to be accounted for in the strategy. Spawning business models that might require adaption of the core business need to be closely monitored; an example would be hydrogen production on the offshore platform using electrolysis. In this case, GFO-O is required to refocus on how to operate the converter platforms and needs new skills within the workforce. Also, facilitation of operations is possible as the result of radical niche innovations, examples range from automation to robotics and innovative software developments. For GFO-O, there exists a huge opportunity to learn from other actors' niches but also to grow its own innovative business ideas in niches protected from market forces. Lacking awareness from GFO-O of potential cooperations on projects or within consortia which GFO-O is currently not part of, results in missing out on the sharing of lessons learned and valuable knowledge about disruptive business ideas or innovations (Geels, 2004a). This is one of the reasons for performing a Social Network Analysis, introduced below. Another reason is the concept of learning by doing. Working with new technology leads to a better understanding of technology; hence an actor becomes more effective in using it (Storm, 2012). Resulting is an advantage for those actors experimenting with the technology in niches before innovations move up to the regime level.

By using MLP, an understanding of factors that could be internalised by co-operation or adaption of niches before they rise to the landscape level can be achieved. The nature of social-technical systems due to the presence of physical infrastructure makes it difficult to change in the face of a transition and quickly adapt; a strong path dependence is limiting actors (Geels, 2004a). MLP is a framework to help with that. If GFO-O would only be reactionary and not observe the socio-technical system utilising MLP, it is hard to enable a successful transition and provide its services to society.

3.4 Relevance of North Sea offshore energy system

The North Sea offshore energy system can be considered one of the main drivers to successfully achieve a European energy transition. As the 'Green Power Plant of Europe' and one of the most crowded seas in the world, wind energy production is set to rapidly increase to reach up to 300 Gigawatt (GW) capacity by 2050 (De Croo et al., 2023). Thus, this complex socio-technical, multi-actor system is of particular significance for Europe. Despite this, few studies have applied the multi-level perspective to this system to understand its role in the energy transition and analyse landscape factors and niche innovations and their impact.

3.5 Methodology

In the following, the different methods used in this study are presented and a rational for choosing each one for the construction of the Extended Multi-Level Perspective framework is given.

Due to the long-term horizon of landscape factors such as national energy policies and the long term investment that energy infrastructure requires, focusing only on factors currently influencing the North Sea offshore energy system and analysing the static system within which GFO-O operates would not be sufficient to understand the socio-technical system and solve the bottleneck of security of energy supply. Instead, a certain level of anticipation but also foresight into future developments is essential to account for critical future impacts that might be already visible on the horizon.

3.5.1 PESTLE Analysis

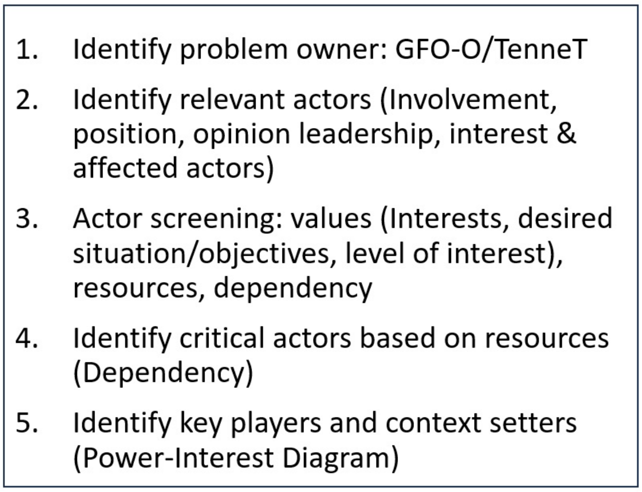
As a first step to understanding the future, we need to observe and understand current developments and trends. Thus, extending the MLP framework with the PESTLE analysis is a combination of PESTLE and MLP is a great tool for this. MLP's layered perspective complements the multi-dimensional radar of a PESTLE analysis. This way, not only immediate impacts on GFO-O in terms of external factors are analysed, but also the understanding is acquired where these factors originate and what their potential level of influence is. Structuring these factors into landscape, niche and regime developments enables an assessment of potential risks or opportunities, also based on a time dimension, with niche developments bearing the potential of rapid system disruption.

PESTLE is the chosen framework for analysing factors impacting the North Sea offshore energy system because of its multi-dimensional scope. PESTLE is a framework for external factor analysis that is frequently used in the energy domain (de Andres et al., 2017; Soares et al., 2023; Borges Posterari and Waseda, 2022; Cholewa et al., 2022; Demirtas et al., 2021). Areas of application range from Poland, Azerbaijan to the Pacific Islands (Borges Posterari and Waseda, 2022; Cholewa et al., 2022). PESTLE ensures a broad scope for the analysis to identify and analyse the most relevant factors without limiting the analysis (Achinas et al., 2019; Cholewa et al., 2022). Not only ensures PESTLE the right scope for the desired purpose of analysing the most relevant external factors in the offshore energy system in the North Sea, it also adds value as an established tool used as an input to build exploratory scenarios (Borges Posterari and Waseda, 2022; Demirtas et al., 2021; Wade, 2012; Enserink et al., 2022). This flexibility enables the integration of PESTLE within the E-MLP framework.

3.5.2 Actor Analysis

An actor analysis is performed to understand the interests and resources of the different actors and, hence, their position in the system. Clearly, GFO-O is the problem owner. For comparison purposes, an organisational level of aggregation is chosen for the actor analysis. Hence, not the Department GFO-O is considered as the problem owner, but TenneT as a whole. This choice is made due to the availability of aggregated public data on projects companies are conducting but the inaccessibility of department-level data, which is often only internally available to organisations. Relevant actors are identified because they are either strongly involved in the North Sea offshore energy system, have a strategic position, have an influence on the opinion of other actors, are highly interested in or strongly affected by developments within the system.

The identified actors are screened based on their interests, level of interest, their objective, resources and whether they are critical actors. Afterwards, critical actors are identified and in a Power-Interest Diagram the distinction between crowd, subjects, context setters and key players is drawn. This procedure was adopted from Hermans and Cunningham (2018) and slightly modified, as can bee seen in Figure 7. In the appendix, the procedure is described in more detail in subsection A.1.



1. Identify problem owner: GFO-O/TenneT
2. Identify relevant actors (Involvement, position, opinion leadership, interest & affected actors)
3. Actor screening: values (Interests, desired situation/objectives, level of interest), resources, dependency
4. Identify critical actors based on resources (Dependency)
5. Identify key players and context setters (Power-Interest Diagram)

Figure 7: *Guide for the application of an actor analysis to the E-MLP. Source: modified after Hermans and Cunningham, 2018*

3.5.3 Social Network Analysis

Given the analysis of a system, not only the analysis of each individual actor but also the interactions between the actors is of great importance to arrive at a holistic understanding of this system. Therefore, an analysis of interactions between actors, their social network, provides insights on actors' behaviour and relations to understand their strategies (Hermans & Cunningham, 2018). By visualising these otherwise hidden aspects and drawing conclusions, this method allows a unique perspective on a socio-technical system.

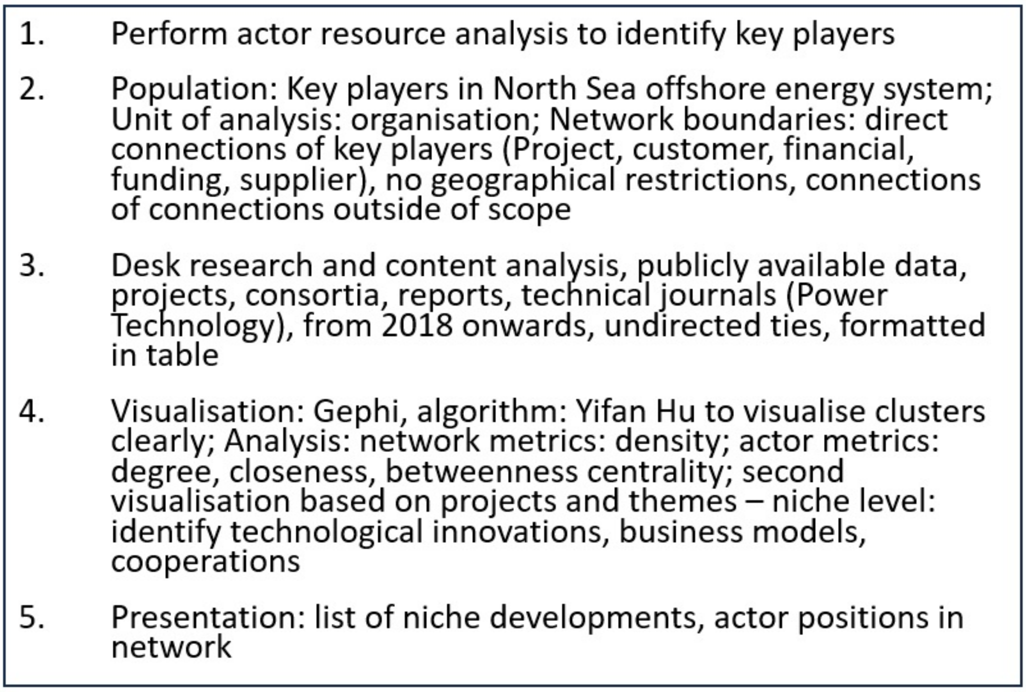
Conducting an actor analysis and performing a social network analysis of relevant actors on the regime level will result in an understanding of the interactions of actors, cooperations and the respective position in the network. This goes beyond the analysis of rules that govern the interactions of actors in the regime level of MLP and adds value to the E-MLP framework and, therefore, to a holistic understanding of the North Sea offshore energy system.
Furthermore, niche level developments can be identified in the SNA from projects between actors that are not covered by academic literature. These niche developments can contain innovative technology pilots or business models with the potential to disrupt the entire system and drive the transition towards a new regime.

By using the combination of an actor analysis and a social network analysis, two levels within MLP can be analysed. The actor analysis looks at resources, power and interests of the actors, therefore focuses on the regime level. Due to a small tweak in the visualisation of the social network analysis, creating a second network graph that is clustered based on themes and projects, both the niche and regime level can be analysed with one method.

For this thesis, two different networks have been analysed. The network of European TSOs with offshore business to understand their interconnections. For this analysis, attention was only paid to the physical connections, electricity interconnectors. These are electricity cables, mostly high voltage, linking electricity systems of different countries (National Grid, 2023). As interconnection is a relevant feature of future European electricity grid and necessitates collaboration between countries and, therefore, their TSOs, it gives a first indication of relevant actors. Moreover, the type of connection, either HDVC or AC is relevant for the energy system, as long distances, crossing water bodies are more economic using HVDC interconnectors (Wang & Redfern, 2010). The data for this SNA can be found in Table 11.

The second network that was analysed is that of the key players in the North Sea offshore energy system. Taking into account the results of the actor analysis and power-interest diagram, a set of key players should emerge that are of particular relevance for this thesis. Starting with these key players, connections are identified with other key players, but also with supplier, project partners, customers, financial connections (shareholders) and funded ventures. Hereby, connections between the connections of key players were considered out of scope due to the already large size. Even though this thesis analyses the North Sea, no geographical boundaries were applied to the SNA as for example customers such as Microsoft or project partners like the WorldBank are not only operating in the North Sea.

The procedure applied to perform the SNA in this thesis can be seen in Figure 8 and in more detail in the appendix in subsection B.1. The software Gephi is leveraged for the visualisation. For a layout that identifies clusters in a clear to understand way, the Yifan Hu algorithm was chosen, because of the large size of this social network and emphasis on the key players, a clear presentation was focused on.



1. Perform actor resource analysis to identify key players
2. Population: Key players in North Sea offshore energy system; Unit of analysis: organisation; Network boundaries: direct connections of key players (Project, customer, financial, funding, supplier), no geographical restrictions, connections of connections outside of scope
3. Desk research and content analysis, publicly available data, projects, consortia, reports, technical journals (Power Technology), from 2018 onwards, undirected ties, formatted in table
4. Visualisation: Gephi, algorithm: Yifan Hu to visualise clusters clearly; Analysis: network metrics: density; actor metrics: degree, closeness, betweenness centrality; second visualisation based on projects and themes – niche level: identify technological innovations, business models, cooperations
5. Presentation: list of niche developments, actor positions in network

Figure 8: *Guide for the application of a social network analysis to the E-MLP. Source: modified after Hermans and Cunningham, 2018*

3.5.4 Socio-Technical Scenarios

Socio-technical scenarios account for the dynamic aspects that influence the system and provide further insights. They enhance MLP's abilities to account for potential rapid change and uncertainty of the energy transition by drawing the development of potential futures for the North Sea offshore energy system, emerging from interactions of the current system.

Resulting from the uncertainties and complexities of a transition is the need of a vision to successfully steer into a desirable direction. To develop and formulate a vision, scenarios are a suitable tool (Elzen et al., 2004a).

> "*It is precisely in such times of uncertainty that people most want to know, what's next. The best we can do, however, is scenarios*" - Parag Khanna, Connectography

Socio-technical scenarios are part of the mehtod of scenario analysis. According to Fahey (1998), scenario analysis is valuable for any strategic process that involves external factors in an environment deemed to be 'complex, changing and uncertain'. Huss (1988) agrees and adds the benefit of applying it in long-term analyses with a macro-level perspective. He describes scenario analysis as a bridge between forecasting and planning (Huss, 1988). Due to the inherent long-term nature of strategy processes and the rapidly changing offshore system with various uncertainties, scenario analysis is deemed a useful tool going forward (Dedecca et al., 2016; Meeus, 2014; Fahey, 1998).

Moreover, a large body of research for scenario analysis in the energy sector exists (Höjer et al., 2008; Luukkanen et al., 2015; Schmidt-Scheele, 2020). The authors mostly focus on the applicability of scenario analysis for the energy sector and socio-technical systems, aligning well with the intent of this thesis (Weimer-Jehle et al., 2016; Witt et al., 2020; Elzen et al., 2004a). The North Sea offshore energy system is highly dynamic and entails a significant deal of uncertainty due to its dependence on geopolitics, technological innovation and party politics (Koivisto et al., 2020). The forecasted exponential increase in offshore wind capacity places a significant burden on GFO-O to maintain and operate the converter platforms in a rapidly changing landscape to ensure the reliability of supply (Mytilinou et al., 2017). As a result, an exploratory scenario analysis approach is identified as suitable to deal with the described level of complexity and uncertainty (Riddell et al., 2019). Particularly for regimes such as GFO-O within socio-technical transitions, especially in the energy sector, this uncertainty hampers the operation and endangers the societal goal of a successful energy transition (Andrews-Speed, 2016).

The benefit of using socio-technical scenarios can be found in its scope, analysing the micro, meso and macro level based on the MLP and, hence, its compatibility with socio-technical systems and MLP (Elzen et al., 2004a). Furthermore, socio-technical scenarios are not limited based on one emerging technology but rather focus on the development of a system, considering both the technical as well as the social dimensions. Moreover, as a theoretically informed method, socio-technical scenarios use MLP to create a coherent story, directing the focus to the process and therefore enabling an understanding of the transition instead of merely focusing on the output of scenarios (Elzen et al., 2004a). By focusing on the process, the story evolves and logically links different niche developments and landscape factors that apply pressure on the regime. Tensions and cracks in the regime are becoming visible as a result. Moreover, the exploratory nature of socio-technical scenarios allows detachment from linear extrapolation of current developments into the future but rather enables the understanding of radical changes as the result of niche developments that are otherwise hard to integrate in scenarios (Elzen et al., 2004a).

Elzen et al. (2004a) mention patterns and mechanisms upon which the scenarios are built. Even though there is a lot of freedom for creativity content-wise, these should be integrated in order to ensure plausibility. On a broad picture, mechanisms for socio-technical scenarios can be divided into substitution, including disrupted regimes directing the focus on niche developments, or transformation, where current issues exacerbate in the future on many dimensions in the regime level and lead to a disruption of the system on all levels.

One example of a pattern are niche accumulations, where separate developments in niches are linked and building on top of each other to generate a new development. Another example is the interaction of the technological with the social domain and the impact of technological developments on social developments. An example is the usage of new technology. Furthermore, dynamic elements need to be included, such as niche developments and learning processes. This ranges from innovations to learnings by actors, society or new rules and regulations. Moreover, the development of innovations needs to be displayed in a system context by showing hybrid developments or reinforcing effects of different innovations. Niche proliferation entails niche developments into different regimes or other locations. Developments should also not be restricted to either the niche or landscape level but rather encompass all levels of the socio-technical system (Elzen et al., 2004a).

Socio-technical scenarios always start with a so-called ’pre-history’, to give context and show the development of current dynamics to a certain point in the future.

In socio-technical systems, complexity and uncertainty are all but preventing planned steering of transitions (Elzen et al., 2004b). Elzen et al. (2004a) emphasise the importance of driving forces when creating scenarios. Based on the concept of exploratory scenario planning in Enserink et al. (2022), these driving forces are determined based on impact and uncertainty of the identified factors. With these, the two most relevant factors are used to create a scenario cross. Resulting are four different scenarios, where the driving forces are used to create plausible storylines using the method of socio-technical, presented by Elzen et al. (2004a). The exploratory scenario planning method by Enserink et al. (2022) is used as the framework. It sets the boundaries for applying socio-technical scenarios and the consistent stories about future developments, that make them a well-suited method for E-MLP and, therefore, this thesis. The procedure of how the socio-technical scenarios are developed can be seen in Figure 9.

1. Formulate research questions
2. Literature research & PESTLE
3. Most relevant and uncertain factors as key drivers (literature+experts)
4. Generating socio-technical scenarios from uncertainties & impact
5. Implications for GFO-O
6. Validate with experts
7. Policy recommendations

Figure 9: *Exploratory scenario planning framework and its application for this thesis. Source: modified after Enserink et al., 2022; Elzen et al., 2004a*

3.6 Research approach

Combining the arguments above, the following research approach, outlined in Figure 10, is chosen to answer the main research question and sub-questions.

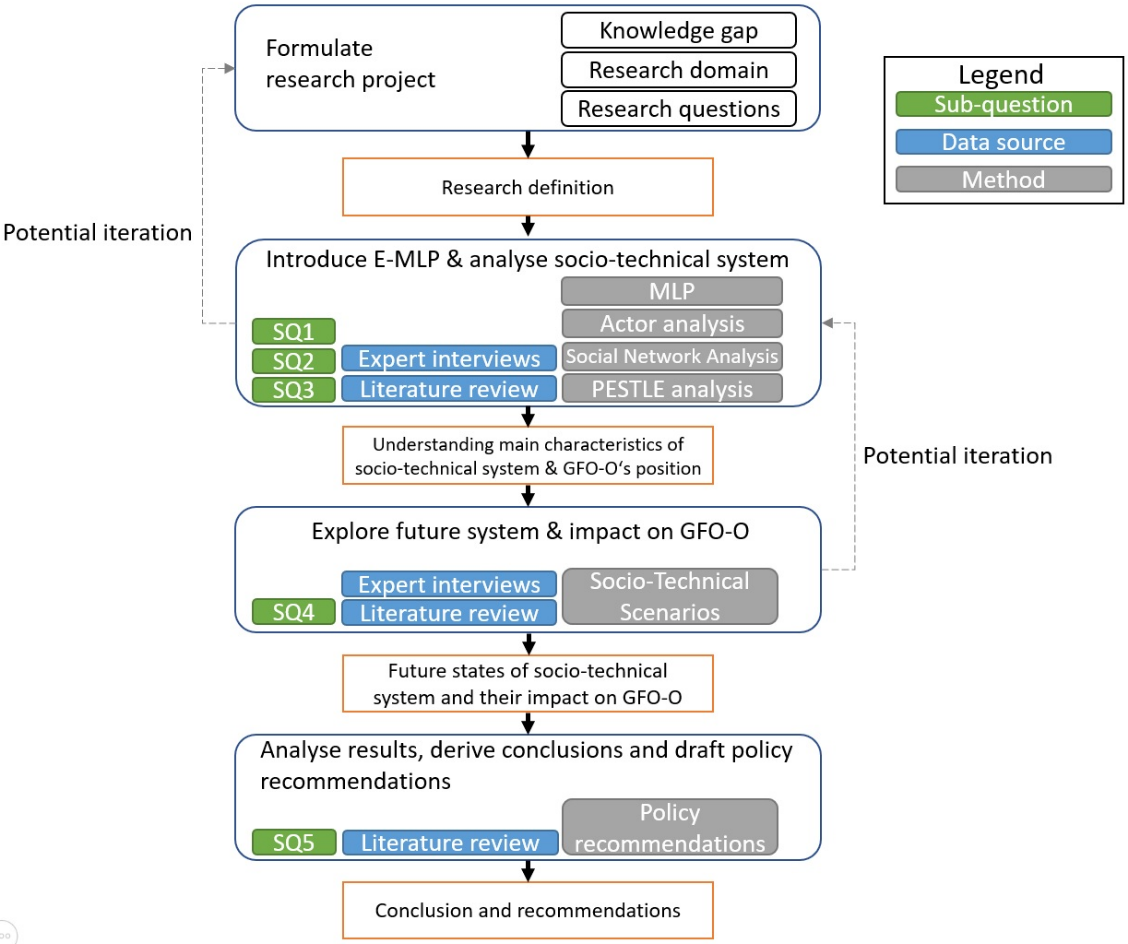


Figure 10: *Overview of data, methods and tools required to answer sub-questions. Source: own elaboration*

Sub-question 1

What is an Extended Multi-Level Perspective framework?

Following the explanation of the different methods and their combination above in the method section, the E-MLP framework is laid out and in the following will be applied to the North Sea offshore energy system for a holistic analysis of this socio-technical system.

Sub-question 2

What are the main characteristics of the North Sea offshore energy system captured by the use of the extended multi-level perspective framework?

To answer the second sub-question, an extensive literature review will be conducted to identify the main characteristics of the North Sea offshore energy system based on the MLP levels. This is complemented by an actor analysis, including a social network analysis to assess niche developments within the actor network and understand the position of the key players in the system. The combination between the multi-level perspective, actor analysis, and PESTLE enables an in-depth understanding of the interdependence between actors, landscape factors, niche, and regime developments within the North Sea offshore energy system. Thereby, the pressures that the landscape as well as the niches apply to the regime and, consequently, to GFO-O, can be discovered. Furthermore, relevant consortia can be identified, in order to enable GFO-O to learn and gain from knowledge sharing between regime level actors.

A first understanding of the North Sea offshore energy system is reached by drawing the socio-technical system and analysing the main technological components of the current system in a technological map.

For the actor analysis, a social network analysis using Gephi will shed light on the inter-dependencies of the different actors and embed them into the patchwork of regimes within the multi-level perspective framework. Moreover, disruptive business models or radical technological innovations emerging from niches can be identified. Next, a PESTLE analysis will be conducted. The factors identified by the literature-based PESTLE analysis are complemented by the factors resulting from the expert interviews. It was decided to first identify the factors, list them and then the factors based on MLP. This choice was made as a full PESTLE analysis of each individual MLP level was not feasible due to the lack of factors. Moreover, the chosen approach matches well with the design of the MLP-based interview guideline, where factors are identified first.

Sub-question 3

What are the relevant actors in the North Sea offshore energy system?

From the actor analysis and SNA, the position of the actors in the network will be assessed and relevant actors identified by analysing values, resources, power, and position. This is complemented by a network analysis using centrality measures to understand the social network and critical actors in the North Sea offshore energy system.

Sub-question 4

What are plausible socio-technical scenarios capturing the evolution of the North Sea offshore energy system in the next 15 years?

Building upon the insights from the actor analysis, PESTLE and semi-structured expert interviews, the resulting factors will be used to identify driving forces for dealing with the system's inherent uncertainty. These driving forces are used to construct socio-technical scenarios based on uncertainty and impact in an exploratory manner. Each scenario will be examined on the implications for GFO-O.

The identified main characteristics factors from sub-question 1 are used to identify 2 core uncertainties. These will be used to create a scenario cross with critical either/or uncertainties. As a result, four distinct scenarios are created. Within these scenarios, the implications for GFO-O are assessed (see Figure 9). Afterwards, the scenarios are translated into storylines that are presented to experts within TenneT and one external expert to verify the validity of the designed scenarios. Based on the experts' input, the scenarios are either confirmed or modified to form plausible future states of the world.

Sub-question 5

Taking into account the static and dynamic characteristics of the North Sea offshore energy system, how can GFO-O adapt its strategy in the face of uncertainty to perform its core tasks and facilitate the energy transition?

Up to this point, the most relevant niche, regime and landscape characteristics of the North Sea offshore energy system have been identified, an understanding of the actor network was reached and potential future states of the world were developed as well as validated in the socio-technical scenarios. Furthermore, external factors and niche developments have been placed in these future states of the world. To answer the fifth sub-question, the insights from the scenarios and the extended MLP analysis are used to design policy recommendations to GFO-O's management. These policy recommendations are based on GFO-O's key performance indicators stated above and aim to aid the strategy process for the next five years and enable the energy transition with GFO-O as the leading offshore TSO.

3.7 Data Collection

3.7.1 Desk research

The necessary data will be acquired using desk research, literature reviews, and conducting stakeholder interviews. The data is available in various databases, such as the ones stated above, online or offline in various libraries. To broaden the perspective and ensure an unbiased result of the interviews, experts from TenneT as well as experts working outside of TenneT on the North Sea offshore energy system have been invited. ATLAS.ti will be used as software to code and interpret the interviews in order to reduce subjectivity and bias (Buckendahl et al., 2015). It is chosen because of the available license for TU Delft students and its intuitive user interface.

3.7.2 Actor analysis

For the actor analysis, data was used from different sources such as companies' strategies, annual reports or newspaper articles. The latter was chosen especially if there was a suspicion of strategy greenwashing, where words were deemed to be too far away from the actual actions. The sources for each actor can be seen in Table 9.

3.7.3 Social Network Analysis

Data will only be considered for the SNA dating back until 2018 to maintain a realistic scope for this thesis as well as prevent completely outdated information. The detailed data sources can be found in the appendix, but overall only publicly available data was considered, coming from the key players' website such as annual reports, press releases, project reports, financial reports. Other sources were technical journals such as 'Power Technology' or the websites of consortias, which listed all project partners. Consortia such as Eurobar have or 'The Offshore Coalition for Energy and Nature' have their own websites, from which all the members could be gathered.

3.7.4 Expert interviews

A qualitative content analysis approach is chosen in order to answer the research questions and arising questions during the literature research. Because of the highly dynamic nature of the North Sea offshore energy system, it is considered important for this study to acquire additional information from the expert's knowledge that is not attainable using a quantitative approach. The dynamic nature of the system is best evidenced by the drastic policy change from last year's Esbjerg declaration, aiming for 65 GW capacity offshore wind in the North Sea by 2030 to the North Sea Summit declaration, almost doubling these targets to 120 GW by 2030 only one year later (WindEurope, 2022a; De Croo et al., 2023). Hence, the perspectives of experts working in this highly dynamic environment might provide insights that cannot be found in papers due to the fast pace of offshore developments. According to Kaiser (2014), qualitative expert interviews are defined as a process of data collection that is systematic and theoretical and guided by theory, first and foremost. Experts are chosen because of their novel or unique knowledge about processes, systems, policies or companies that are not or are differently to be found in literature (Kaiser, 2014). Differing from the quantitative approach, qualitative interviews are not necessarily repeatable with the exact same outcomes if performed by another scientist due to the lacking inherent nature of standardisation. That is the main reason why it is highly relevant to transparently document and extensively describe the procedure of expert selection, development of the interview guideline and process of coding and finding categories for the transcribed statements to ensure the highest possible reproducibility (Kaiser, 2014).

An expert is defined by Kaiser (2014) as a person who is qualified by the role in a system or process and bears a responsibility or a person that has relevant knowledge about a system or process. An expert can also be both. On a less abstract level, the described system is a company and the expert is the CEO of this company or an analyst of or for this company (Kaiser, 2014). It is important that the experts are in possession of knowledge that can not or not entirely be found in the literature to obtain unique information enhancing the information gathered in the literature research (Kaiser, 2014). In the context of this thesis, experts are chosen who predominantly have a responsible role within TenneT or in institutions relevant to the North Sea system and, furthermore possess relevant knowledge about external factors, the offshore energy systems or regulations.

The experts were selected based on a minimum duration of employment in offshore-related activities in the North Sea for two years to ensure the presence of sufficient expertise which goes beyond the literature. Acquisition of the interview partners was conducted via LinkedIn, telephone and e-mail. The interviews were held entirely online, with Microsoft Teams as the platform of choice due to its automatic transcription capabilities. In an attempt to diversify the group of experts and broaden the perspective towards a holistic view on the North Sea offshore energy system, experts from three different countries, Germany, the Netherlands and Sweden, were interviewed. Moreover, the field of work of the experts ranges from ministries, environmental research institutes, the maritime industry, an independent offshore advisory, the offshore wind sector and different departments within TenneT. The roles of the interview partners can be seen in Table 1. A particular focus was paid to interview experts with technical expertise but also with an understanding of the overall system to provide the most valuable insights for this thesis. The given range for the number of interviews was 10 - 15, in the end 13 interviews were conducted and recorded.

Table 1: *Roles of the interviewed experts*

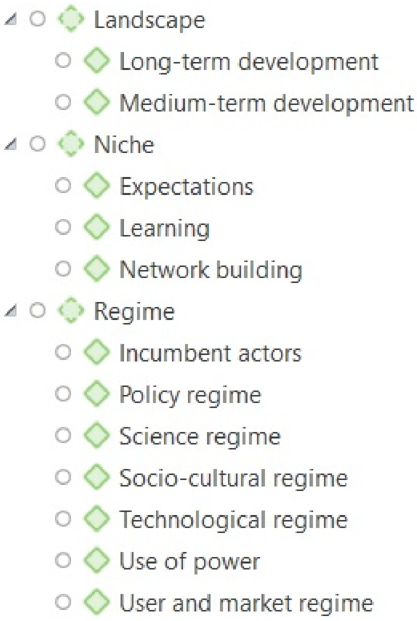
ID	Role
1	Policy Advisor
2	Engineering Manager
3	Strategist
4	Advisor
5	Operational Consultant
6	Senior Researcher
7	Director
8	Offshore Advisor
9	Policy Officer
10	Analyst
11	Business Development Manager
12	Offshore Wind Advisor
13	Strategy Advisor

After identifying the interview partners, the next step in the process is the development of an interview guideline, to be found in the appendix. For this thesis, the main purpose of the interviews was one the one hand to verify external factors that have been identified by the literature or add new ones that has not been considered so far. On the other hand, the aim was to get insights into the experts' perspectives on the potential futures of the North Sea offshore energy system. Outlooks into the development of the North Sea offshore energy system were not hard to identify and mostly rather case specific but not holistic, considering the entire system. Moreover, if using only one or two papers as input for future scenarios, might result in a strong biased. Therefore, all interview partners were asked to provide possible scenarios and pathways while describing key drivers or actions required in order to inform the scenario planning later in this thesis in a scientific way. Scientific in the sense that it can be repeated based on the same input. The interview style was chosen as semi-structured as choosing open questions presents opportunities for the experts to add aspects that has not been discussed at this point and thus potentially acquire unique information.

In this context, it is emphasised that within the qualitative approach used for this thesis, deviations from the interview guideline are possible depending on the interview situation. This can result in less reproducibility but on the other hand, enables the acquisition of information that cannot be collected with a quantitative approach and is therefore chosen due to the presumed lack of data for some factors (Kaiser, 2014). The interview guideline can be found in the appendix.

3.8 Coding of interviews

The transcribed interviews are coded with the Software ATLAS.ti. In a first step, the categories from the question sets were chosen as categories, so-called codes. Deductive coding was be applied using the research questions and the multi-level perspective as a framework to create a codebook and match the data to the predefined codes (Kaiser, 2014). Furthermore, applying the multi-level perspective to the acquired interview data gave it a structure and enabled a contribution to science as the codebook could be applied to further projects within the multi-level perspective and the body of research on socio-technical transitions. The coding process was started by using individual codes such as 'hydrogen' for factors identified by the experts. These individual codes were grouped using axial coding based on MLP into the three levels. Within each level, further distinctions have been made. These different layers enabled the grouping of codes into top- and subcategories, creating theoretically informed codes.



- Landscape
  - Long-term development
  - Medium-term development
- Niche
  - Expectations
  - Learning
  - Network building
- Regime
  - Incumbent actors
  - Policy regime
  - Science regime
  - Socio-cultural regime
  - Technological regime
  - Use of power
  - User and market regime

Figure 11: *Codebook using the multi-level perspective. Source: own elaboration*

In the multi-level perspective, the regime level can be differentiated into 5 different regimes, the science regime, policy regime, socio-cultural regime, technological regime and the user and market regime (Elzen et al., 2004b; Geels, 2005). Furthermore, incumbent actors and the use of power are important aspects of the regime level, that were included in the codebook (Figure 11). Within the landscape level, long-term (everything above 15 years) and medium-term developments (5-15 years) were distinguished. The niche level codes were informed by the concept of strategic niche management, which emphasises expectations, niche learning and network building (Hoogma, 2002).

3.9 Data Analysis

The E-MLP framework segments the North Sea offshore energy system based on niche, regime and landscape level and analyses its level to provide a holistic understanding of the overall system and identify cracks and tensions on the regime level resulting from landscape and niche pressures. Based on the relevant literature, the PESTLE analysis provides an understanding of relevant niche, regime and landscape factors that impact the system. These are complemented by insights from the expert interviews.

For the socio-technical scenarios, the content is based on the findings of niche developments in the actor analysis, factors from the PESTLE analysis and factors as well as descriptions of the future system resulting from the expert interviews. As the literature is not sufficient in terms of the impact and uncertainty of the individual factors of the North Sea offshore energy system, these are determined by asking the experts to provide a ranking of the most important factors based on impact and identify key uncertainties. The evaluation of factors based on impacts was done by assigning points in descending order. Factor number one received 3 points, factor number two received 2 points and factor number three received 1 point. As asking the experts to rank the key uncertainties was considered a rather hard task, each uncertainty was assigned 1 point. These were then added together and the two most important factors were used to span the scenario cross. This procedure is described in more detail in subsection B.3.

3.10 Research validity and reliability

Research validity is ensured by informed choices based on available literature. The choice of GFO-O as a case study is due to the relevant position of TenneT as one of the major TSOs with offshore transmission business in the North Sea and its unique position as a cross-border TSO in Germany and the Netherlands. This allows an enhanced perspective from two of significant countries in the European energy transition, providing relevant insights for the MLP perspective. Moreover, the findings of the literature analysis on external factors were validated and enhanced by the expert interviews. Not presenting the experts with the literature results beforehand reduced the introduction of potential bias in their answers. The scenarios were sent to two experts outside of TenneT in written form for validation and feedback and presented to three people within TenneT for validation purposes.

Research reliability is achieved by transparently documenting the individual steps for the PESTLE analysis, the actor analysis, interviews and socio-technical scenarios and providing relevant data in the appendix, where it was deemed necessary to reliably reproduce the achieved results. Moreover, another person working with GFO-O would be able to achieve the same results as for the PESTLE and actor analysis only publicly available data was used. The expert interviews might vary slightly due to the semi-structured nature, but the interview guideline and codebook are provided to reach similar results.

4 Policy Analysis for the North Sea offshore energy system

In this chapter, the North Sea offshore energy system will be analysed to gain an understanding of the socio-technical system, the actor network and the factors affecting the system on all three levels within MLP. The sub-question 2 is addressed by analysing the socio-technical system, its components and the factors influencing it based on PESTLE. Sub-question 3 is addressed by examining the actors, their values, resources, , power, position, and social network.

4.1 Socio-technical system of the North Sea

The socio-technical system for North Sea offshore energy is leaning on the description of socio-technical systems by Geels (2004). The technological elements and social elements interact and form a system that is providing functions for society and can be seen in Figure 12. Particularly relevant is the concept of affordability, availability and acceptability after Scholten and Künneke, 2016, introduced in the theoretical background. For the North Sea, the concept of sustainability is added, due to its position in the European energy transition. Regulations are spanning from national to EU level, with environmental regulations being formed on both levels.

It should be noted, that within this thesis, sustainability is used in the context of environmental sustainability. Spatial planning on a national level encompasses shipping routes, fishing areas and safety zones around oil and gas platforms or offshore wind parks. User practices mainly depend on the preference for energy, whether it is electricity, oil or gas, with the price of energy playing a significant role for these preferences. Demand by industry and consumers can be more or less flexible. Supply networks are mostly global, with international supply chains for materials such as vessels, steel or specific magnets for the wind turbines (Hafner & Tagliapietra, 2020). The supply of labour is another relevant aspect of supply networks with implications for the entire system. A particular feature of this socio-technical system is maintenance, requiring either special maintenance vessels, adapted to the rough conditions offshore or helicopters to transport people and cargo to offshore assets. The subsystems ‘User practices and markets’, ‘Regulation’, ‘Supply networks’, ‘Cultural meaning’ are entailed in factors within the PESTLE analysis. The technical aspects of the system, including the subsystems ‘Infrastructure’, ‘Technology’, and ’Maintenance networks’ are elaborated on below.

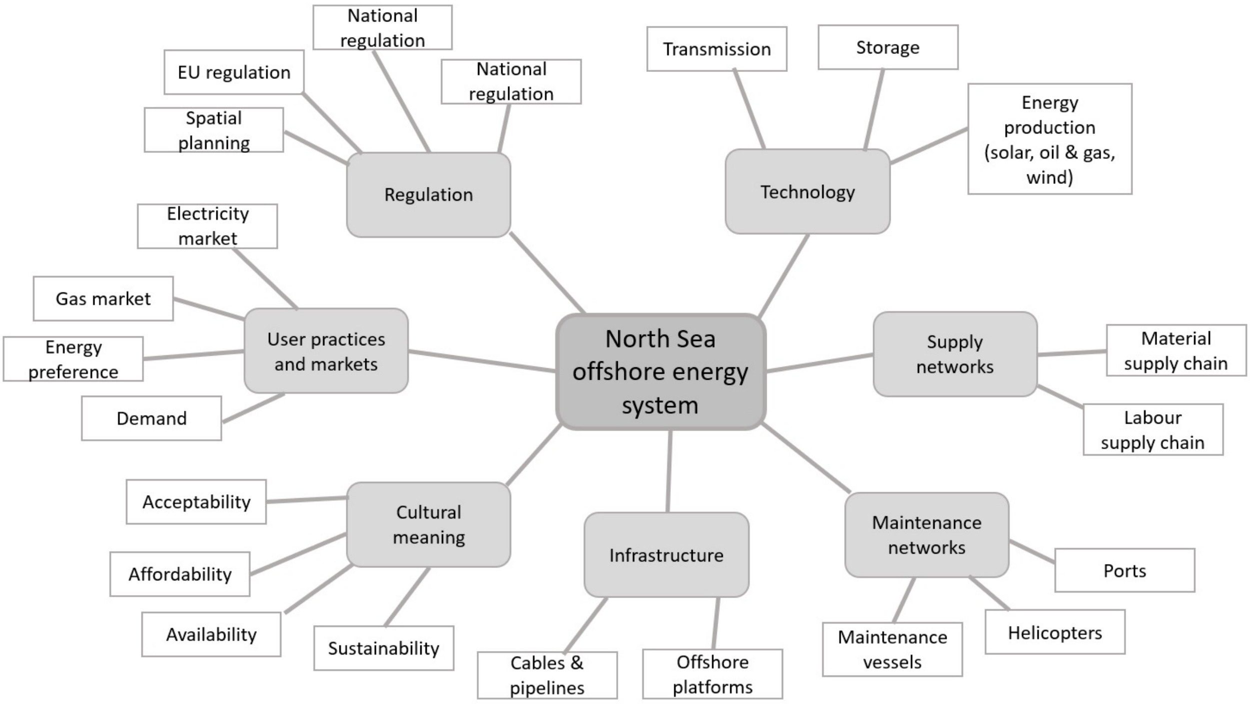


Figure 12: *Socio-technical system for North Sea offshore energy. Source: own elaboration based on Hafner and Tagliapietra, 2020; Scholten and Künneke, 2016; TenneT, 2023; Quirk et al., 2021; Schupp et al., 2021; Flynn, 2016; Gusatu et al., 2020*

4.2 Technological map of the North Sea

The main technological components of the current offshore system can be seen in Figure 13. Renewable energy is produced by offshore wind farm and floating solar farms. Via subsea cables, the produced electricity is transmitted to the offshore converter platforms, from where on it is sent via transmission cables onshore. Energy hubs in various concepts are currently constructed and will combine renewable offshore energy production, storage and transmission on a condensed area offshore (Lüth, 2022). The renewable energy sector is linked to the oil and gas sector by the requirements for helicopters for transport and special-purpose vehicles for offshore operations and maintenance tasks. Examples of such vehicles are Jack-up barges for the installation of assets and maintenance work (uit het Broek et al., 2019). Furthermore, the oil and gas sector operates on offshore platforms, from where the drilling with mining equipment is coordinated and the yield either sent to shore via pipelines or stored temporarily in so-called floating storage and offloading vessels for further transport by pipeline or tankers (Riddick et al., 2019).

The shipping industry is not only supplying tankers for the oil and gas sector but has large fleets of passenger ships such as ferries in the North Sea, next to a multitude of cargo ships that enter the port of Rotterdam as one of Europe's main gateways to the world freight traffic. Fishing vessels such as bottom trawlers are another technological component of this system (Rijnsdorp et al., 2020). Moreover, sensors, buoys and weather stations are part of the meteorological and oceanographic systems that monitor the North Sea and provide valuable insights into weather phenomenons and water developments (Momber et al., 2022).

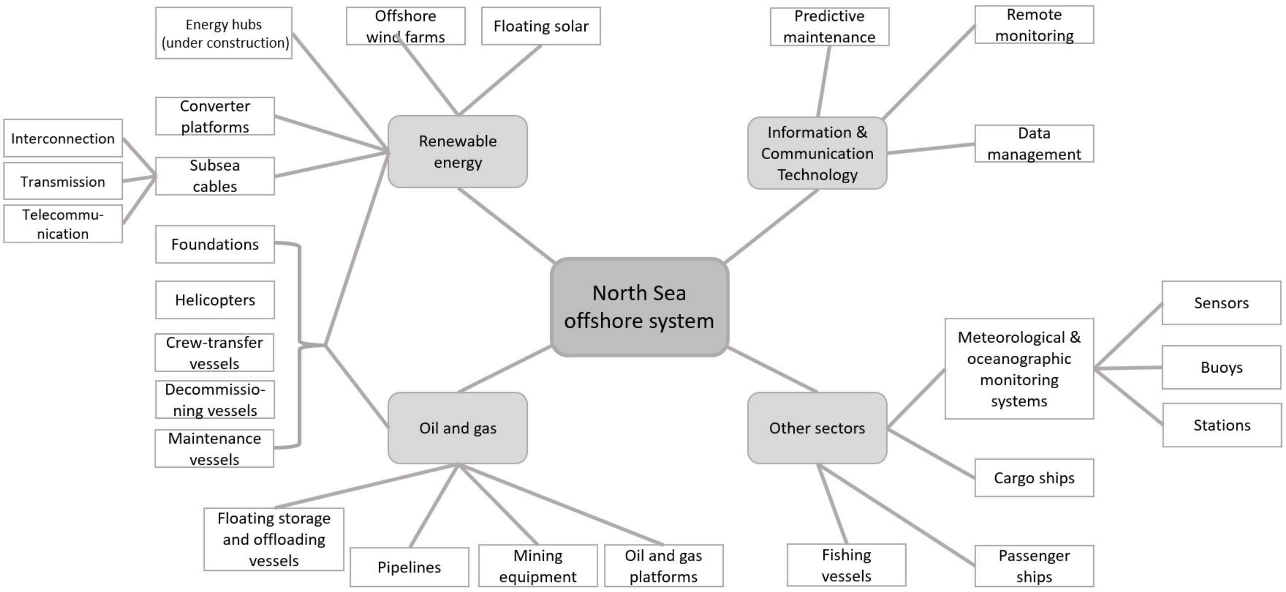


Figure 13: *Technological map of the North Sea offshore system. Source: own elaboration based on uit het Broek et al., 2019; Riddick et al., 2019; Schupp et al., 2021; Liyanage and Bjerkebaek, 2006; Buck and Langan, 2017; Mathew et al., 2006; Li et al., 2022; Golroodbari et al., 2021; Spro et al., 2015; Martínez-Gordón et al., 2022; Goetz and Shenoi, 2007; Jaatun et al., 2020*

4.3 Actor analysis

In Figure 14, the interconnectors between the different European TSOs with offshore business can be seen. From this image it becomes clear, that interconnection plays a significant role when analysing the offshore system. The majority of the interconnectors is operating on high-voltage direct current (HVDC) , which is the more economic solution for larger distances. The size of the TSO nodes is correlating with connectivity. Thus, the British (National Grid) and the Danish (Energinet) TSOs are strongly connected and, hence, are less dependent on national energy resources.

This interconnector map also shows that there is already a strong connection between the different TSOs with offshore business. The physical aspect of this connection is depicted in Figure 14. There is, however, a social aspect of the connection, significantly affecting the regime and niche level, which is hidden in this graph. The social connections will be illluminated in more detail in subsubsection 4.3.2. But first, an understanding of the relevant actors in the North Sea offshore energy system beyond the TSOs, their values, resources, power and interest is indispensable to reach a holistic understanding of the system. The process of identifying these actors is described in detail in subsection A.1.

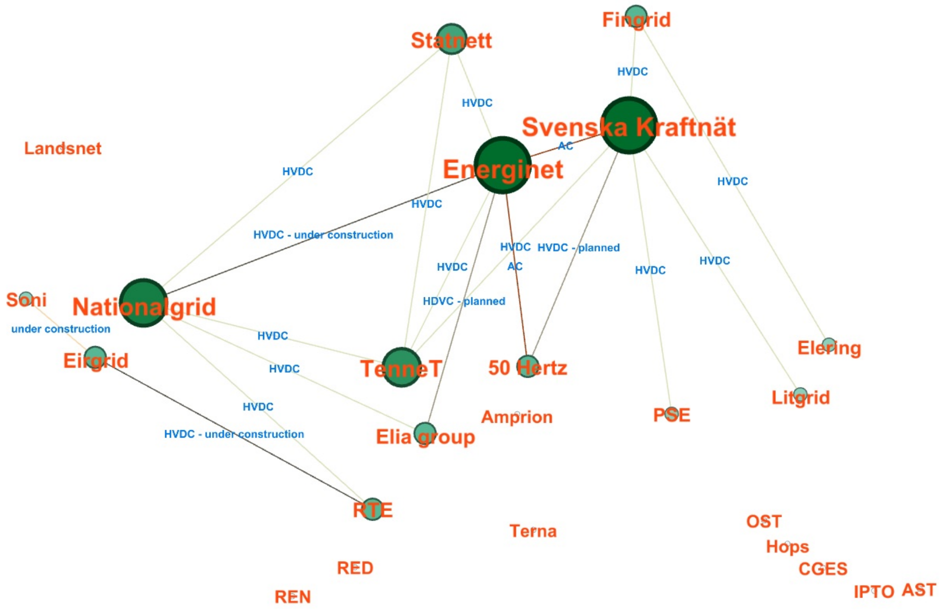


Figure 14: *Interconnector map of European offshore TSOs. Source: own elaboration using Gephi*

4.3.1 Value and Resource Analysis

To better understand the influence and role of the different actors in the system, the values (Table 2) and resources (Table 3) of the actors were analysed.
It becomes clear that the residents and fishers, together with the environmental NGOs have more informal power. It should be noted that especially lobbying can be highly effective. A good example are the successful lobbying efforts by oil and gas. Nevertheless, the NGOs, residents and fishers, together with WindEurope can be considered the least resourceful actors and are therefore considered the least powerful. For citizens the North Sea offshore energy system is also not on top of their mind if they do not live close to a substation at the shore, therefore the interest can be considered as rather low.

All TSOs have the mandate from their respective government to operate the transmission grid, which per se gives them significant power and interest. Moreover, they clearly possess technical expertise but what they are lacking is skilled workers, which research institutes can provide, next to knowledge and expertise. An interesting case is the military, which has a growing interest in the North Sea for military practice in the wake of the Russian war on Ukraine and they possess the legal power to play a significant role in the system. So far, they are not yet considered key players because the North Sea is not their main focus and for example the German military might prioritise the Baltic Sea due to the proximity to Russia but the military should be on the radar for a strong future presence.

Table 2: *Actor screening based on values*

Actor	Interests	Desired situation/ objectives	Level of interest
TenneT	Reach Dutch & German government capacity targets, provide security of energy supply	Leading offshore TSO in Europe	High
Orsted	Acceleration of permitting, priorisation of wind farms in marine spatial planning	Global leader in offshore wind development	Medium
Energinet	Reach Danish government capacity targets, provide security of energy supply	Sector coupling between offshore wind and hydrogen, power-2-X	High
Statnett	Reach Norwegian government capacity targets, provide security of energy supply	Become a relevant player in offshore wind, including floating wind	High
Svenska Kraftnät	Reach Swedish government capacity targets, provide security of energy supply	Become a relevant player in offshore wind	High
Military	Protection of North Sea, space for strategic positions of vessels and submarines	Military practice areas and space for naval vessels, security of offshore assets	Medium-high
Amprion	Grid expansion, adding offshore to reach German government capacity targets, provide security of energy supply	Meshed offshore grid, technology standards based on Eurobar initiative	High
Elia	Reach Belgium government capacity targets, provide security of energy supply	Build first energy island in North Sea and connect it with Denmark, integrated European grid	High
National grid	Reach UK's governmental capacity targets, provide security of energy supply	Key player offshore, integrated and centralised connections of offshore wind to onshore grid	High
EU regulators	Ensure security of energy supply, provide regulatory framework facilitating cross-border cooperation and accounting for interests of other sectors to drive energy transition	Successful transition towards renewable energy without compromising the interests of society, fishing industry, oil and gas, shipping and environmental conservation according to EU legislation	Medium
Oil & gas companies	Profit maximisation from oil and gas exploration of North Sea	Continue drilling as long as possible, strong role of in carbon capture & storage and hydrogen	High
Windpark operators	Priorisation of areas in auctions, speeding up of permitting, clear regulation that enables instead of constrains	300 GW of offshore wind in the North Sea	High
Environmental NGOs	Biodiversity and environmental protection areas	Nature-inclusive design of offshore energy infrastructure, designated space areas for nature protection areas	High
Shipping industry	Priority areas designated to shipping, uninterrupted operations, port accesibility	Acessible and cost-efficient shipping routes, involvement in offshore logistics	High
WindEurope	Promoting and representing wind industry in Europe	Establish offshore wind as main priority for marine spatial planning and permitting	High
National governments	Security of energy supply, economic feasibility	North Sea becomes Europe's 'Green Power Plant'	Medium
Residents	Security of affordable energy supply without disruption of their daily routines	Cheap and abundant energy from the North Sea without exacerbating climate change's impact on daily lifes	Medium-low
Research Institutes	Promote energy transition, minimise societal and environmental impacts	Successful energy transition meeting science-based targets providing lessons for similar systems	Medium-high
Fishing industry	Sufficient space for trawlers and nets, no disturbance of fish stocks by offshore constructions	Large share of space with designated areas reserved for fishing, allowing bottom trawling	High
Investors	Profit maximisation from risk-reduced investments into offshore energy	North Sea becomes Europe's 'Green Power Plant', long-term planning & investment security	Medium

Investors are another critical player for the energy transition. Due to the less established nature of renewable energy in comparison to oil and gas, funding is critical for its development. Renewable energy in the North Sea is an even more recent development, necessitating investments that go beyond financial support by national governments. Apart from the TSOs, with a mandate from the government, most actors are private market players. Therefore, attracting funding from investors is highly relevant for renewable energy developments in the North Sea. A mismatch exists between the risk aversion of investors, requiring long-term investment security and the dynamic nature of the North Sea offshore energy system. In case of amounting unpredictability, investors are likely to look elsewhere for funding opportunities. Hence, they have a strong position in the network.

Table 3: *Actor screening based on resources*

Actor	**Resources**	**Dependency: Critical actor?**
TenneT	Capital and physical infrastructure, government mandate, technical expertise	Yes
Orsted	Capital, global network, technical expertise	Yes
Energinet	Government mandate, technical expertise, capital	Yes
Statnett	Government mandate, capital, technical expertise	Yes
Svenska Kraftnät	Government mandate, capital, technical expertise	Yes
Military	Legal power, capital	No
Amprion	Government mandate, capital	Yes
Elia	Government mandate, technical expertise, capital	Yes
National grid	Government mandate, technical expertise, capital	Yes
EU regulators	Regulatory power	Yes
Oil & gas companies	Lobbying, offshore expertise, strong connection to governments, natural resources	Yes
Windpark operators	Technical expertise, lobbying, public support	No
Environmental NGOs	Public support, lobbying, media platforms	Yes
Shipping industry	Strong connection to government, informal power due to critical goods, capital	Yes
WindEurope	Lobbying, expertise in offshore wind	No
National governments	Legal power, capital, regulatory power	Yes
Residents	Voting, lobbying, resistance	No
Research Institutes	Knowledge and expertise, human resources, public support	No
Fishing industry	Public opinon, informal power due to influence in communities, respected by public, connection with government	No
Investors	Capital	Yes

It can also be seen that the wind park operators are of significant importance for the offshore energy system to develop into the direction desired by policy, however, their resources are rather limited. This can be explained by the fact that they are fully dependent on the tendering processes for spatial areas for their wind parks by the government.

The result of the actor analysis (subsection A.1) in terms of influence in the system, or power, and interest in the North Sea offshore energy system can bee seen in Figure 15.

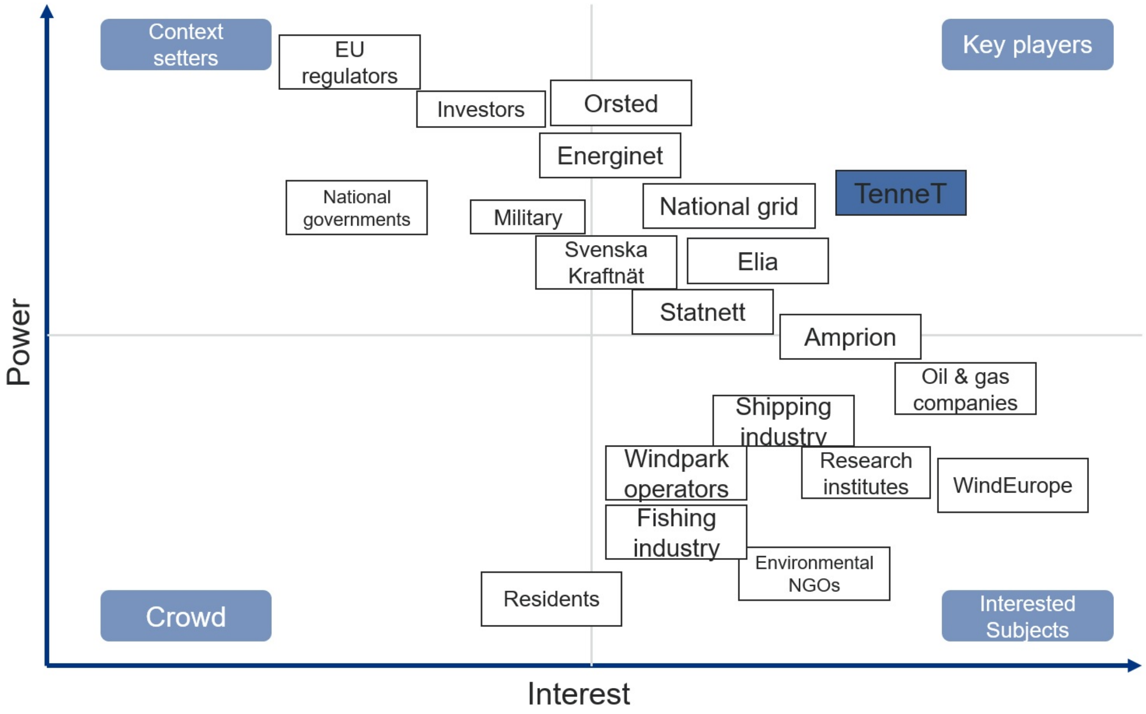


Figure 15: *Power-Interest matrix. Source: own elaboration*

4.3.2 Social Network Analysis

Following the process documented in subsection B.1, based on the actor analysis and the resulting Power-Interest matrix in Figure 15, the following Social Network Analysis is conducted for the key players within the North Sea offshore energy system.

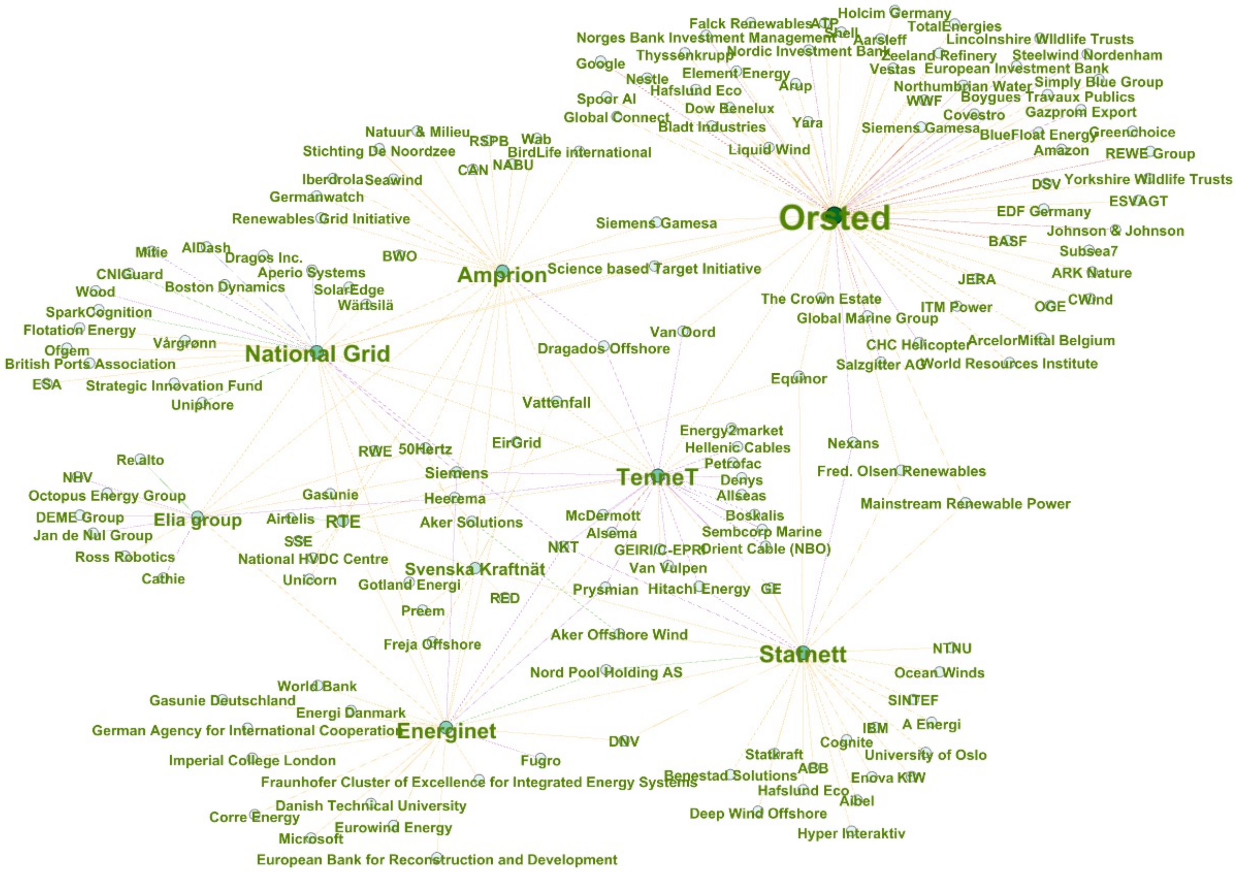


Figure 16: *Social Network Graph based on connections of the key players in the North Sea offshore energy system. Source: own elaboration using Gephi and the Yifan Hu algorithm*

The network density is the ratio of actual connections to potential. Potential connections are the maximum possible number of connections without connecting to nodes multiple times or self-connections (Newman, 2018). Hence, the density is always between 0 and 1. The analysed network has a density of 0.014. This relatively sparse network indicates that many actors rely on others to convey information. A look at the network in Figure 16 confirms this, there are a few well connected actors and many actors with just one connection. Thus, the next step is to identify these well-connected and, therefore, strongly positioned actors.

Analysing the centrality of actors in the system contributes to an overall understanding of the network and the position of specific actors within the network. The simplest measure of actor connectivity is degree centrality. It counts the number of ties connected to to each node (Newman, 2018). The average degree centrality in the network is 2.4. In Figure 17 it can be seen, that all TSOs and Orsted are high above that average, indicating their relevance in the network. Moreover, Orsted has a degree centrality that is more than twice as high as the next highest actor, Statnett.

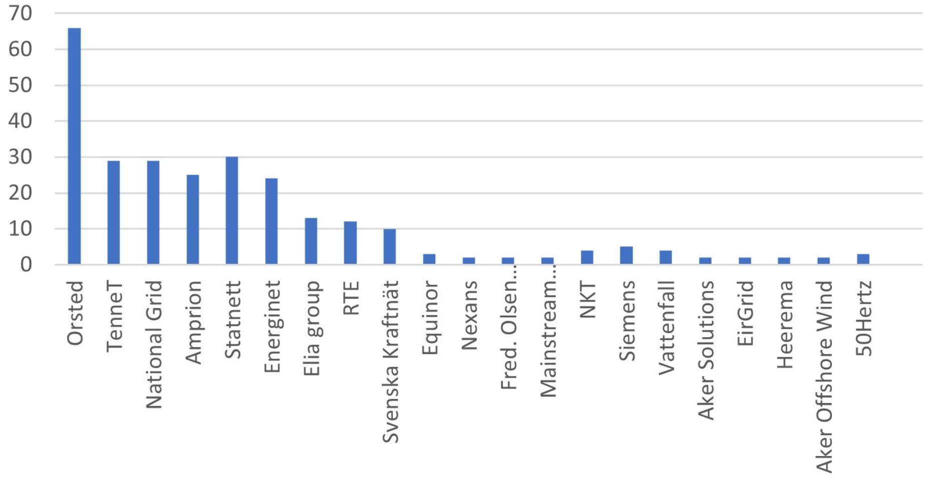


Figure 17: *Degree Centrality SNA. Source: own elaboration*

Two other relevant measurements for centrality need to be differentiated. Betwenness centrality measures the number of shortest paths between actors in the entire network in relation to the number of shortest paths that pass through one specific actor (Newman, 2018). In a nutshell, this implies the importance of an actor in the network. An actor with a high betweenness centrality can act as a mediator or broker (Hermans & Cunningham, 2018).

Closeness centrality gives an indication of the access of one actor in the system to all other actors. A high closeness centrality means an actor is able to quickly spread information in the network (Newman, 2018). For the actor network in Figure 16, a higher closeness centrality implies being more agile in case of regulatory changes. Orsted, for example, is therefore able to quickly convey information about new regulations to its project partners and contractors, giving it a competitive advantage due to its high closeness centrality Figure 20.

However, when comparing the closeness and betweeness centrality for the network of actors in the North Sea offshore energy system, it can be seen that betweenness centrality is of more relevance (see Figure 19 and Figure 20). The normalised closeness centrality of the most relevant actors is very similar, hence all actors are able to spread information relatively quickly. Conversely, when considering the betweenness centrality, the differences between the actors become clear. Orsted has by far the highest betweenness centrality, indicating its relevant position as a mediator between different actors. Therefore, Orsted is in the best position to control the flow of information, impact negotiations and has a strategic position to be well informed about potential niche developments or innovative partnerships. As one of the largest developer and operator of wind farms, Orsted can potentially make use of this strong position and start offering transmission tasks to the industry and in the future even customers, given a government mandate. This would further solidify its crucial role in the system and has the potential to disrupt the transmission aspects of the North Sea offshore energy system

It can be seen from the actor network in Figure 16 that Orsted is the best-connected actor in the system. Not only within the North Sea offshore energy system, but also globally, with connections to Google, Nestle, the World Resources Institute or TotalEnergies. One of the reasons is that Orsted is not only developing wind farms but also providing energy to global customers such as Google via Power Purchasing Agreements. This leads to a strong position in the network, with the possibility to leverage these connections. One potential use case is the threat to focus more on their growing market in the US, if European regulations are not favourable, which provides Orsted as one of Europe's leading renewable energy developer with significant leverage in negotiations.

Niche developments that Orsted is working on are floating offshore wind and hydrogen, as well as energy islands (see Figure 18). Moreover, Orsted is testing cargo drones for offshore wind farm operation and maintenance, for instance to deliver spare parts on demand to the offshore technicians. This potential innovation can reduce the need for humans to go offshore with helicopters, reducing costs and also safety risks.

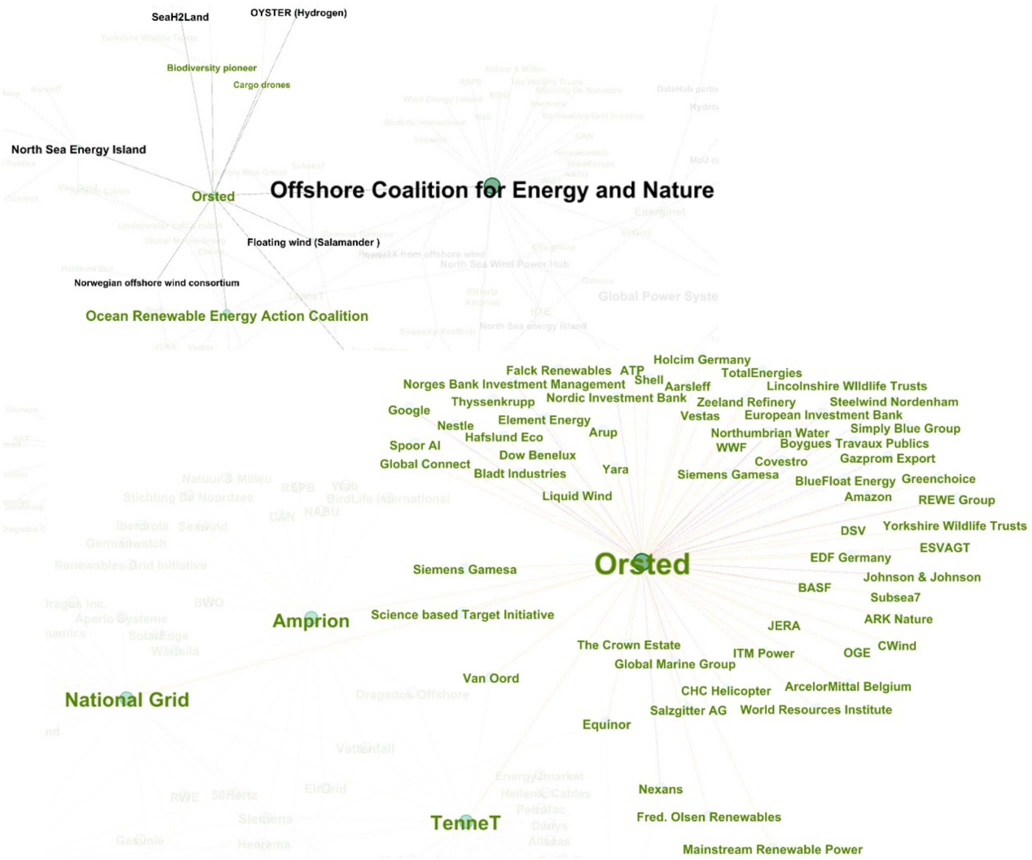


Figure 18: *Actor network of Orsted. Source: own elaboration using Gephi and the Yifan Hu algorithm*

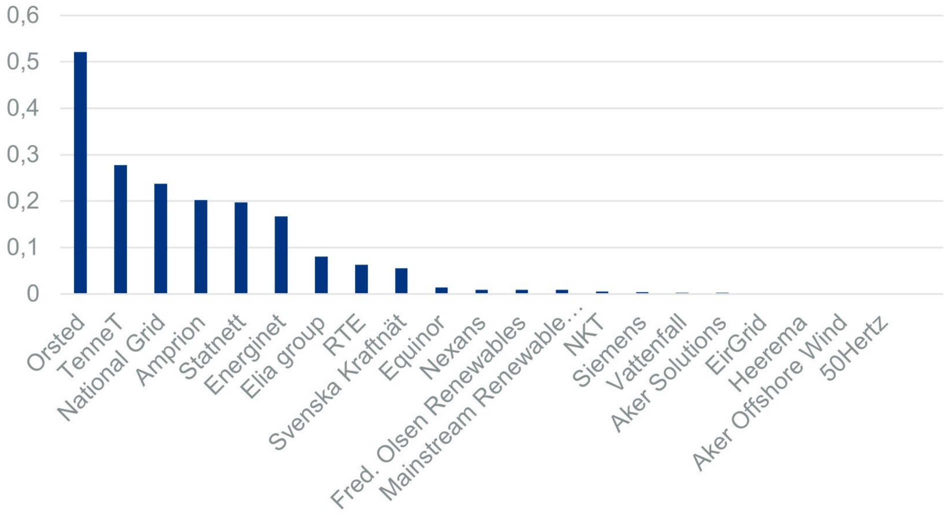


Figure 19: *Betweenness Centrality SNA. Source: own elaboration*

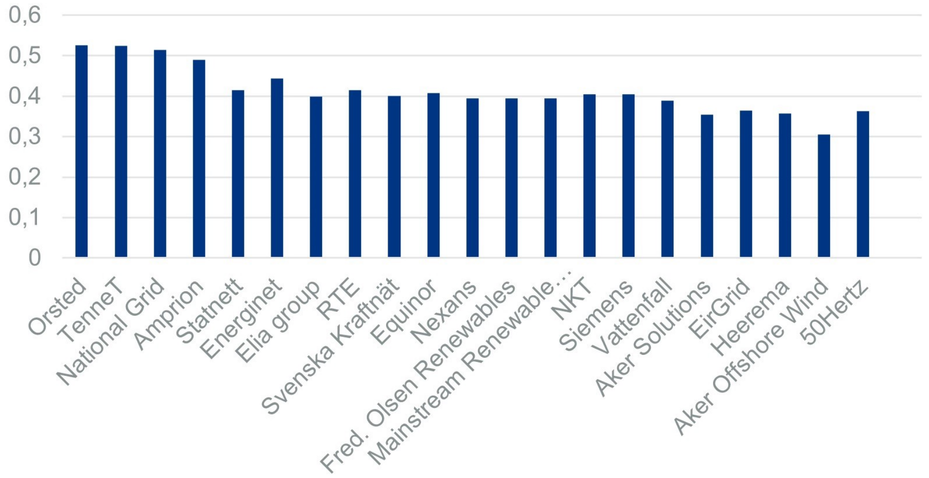


Figure 20: *Closeness Centrality. Source: own elaboration*

National Grid has the third highest betweenness centrality, underlining its relevance in the network. It focuses on the niches floating offshore wind and robotics, where a cooperation with Boston Dynamics, the world leader in robotics, is testing maintenance robot dogs for inside of interconnector halls, potentially reducing labour demand, optimising operations and reducing the danger to human life (Figure 26).

Energinet, the Danish TSO, is well connected with European research institutes, but also has highly valuable global connections via projects with the World Bank or Microsoft (see Figure 25). Relevant niche developments driven by Energinet are energy islands and hydrogen. Especially interesting is the cooperation with Gasunie Deutschland, the German gas network operator, on a cross-border hydrogen network. This bears the potential to become an onshore backbone to potential offshore hydrogen developments. Energinet's betweenness centrality is the fifth highest.

Statnett, the Norwegian TSO, appears to have a strong focus on software solutions and AI developments Figure 30. Not only are they experimenting with a potential niche innovation in gaming technology for health and safety training, they are also part of a project that uses AI for asset management. Moreover, they established a professorship collaboration with the Norwegian University of Technology on blockchain, AI and big data, investing in young talents and simultaneously participating in niche learnings on AI and digitalisation. From a network perspective, it can be seen in Figure 16 that they have a specific Nordic focus in their connections. Additionally, they are exploring projects on floating offshore wind, a niche development that has seems promising especially for deeper waters, such as the Norwegian part of the North Sea. Statnett's betweenness centrality is behind that of Amprion, National Grid and Tennet, which might be correlated with its more remote position and relatively new focus on offshore wind. However, in terms of absolute connections, it is only behind Orsted, enabling it to possibly leverage its many connections to close the gap relatively fast.

Energinet and National Grid are part of the Global Power System Transformation Consortium, which is bringing together global stakeholders to share learnings on a clean energy transition. The stakeholders include the World Bank, Imperial College London or Fraunhofer Cluster. this is an incubation room for ideas, knowledge sharing on technology adoption, workforce developments or open data tools, bearing significant potential for niche learning processes. Furthermore, it gives National Grid and Energinet direct access to potentially disruptive business idea and technological innovations, also from other parts of the world, before they reach the niche level.

Amprion is relatively new to offshore operations, as can be clearly seen from its network (Figure 27). The connections mainly result from two large coalitions it is part of, Eurobar and the Offshore Coalition for Energy and Nature. However, due to these two coalitions, its betweenness centrality is higher than Energinet's, which is operating offshore a lot longer and appears to be well connected. Also Amprion's closeness centrality is relatively high. This places Amprion in a position, where it can spread information quickly and can receive information about new developments quickly, potentially enabling a fast growth. One niche topic that Amprion experimenting with is a grid stabilisation pilot.

Elia Group is also part of the Offshore Coalition for Energy and Nature (Figure 28). Moreover, it is driving the developments of a Belgian energy island, that should eventually function as an interconnector between Belgium and Denmark. Other niche topics Elia Group is testing in projects are maintenance robots and AI for demand flexibility. It has a relatively low betwenness centrality compared to the other TSOs.

Among the TSOs, TenneT has the highest betweenness centrality, establishing its strong position in the network. Interestingly, TenneT's public network consists of many suppliers, most of them from the 2GW program. This is a niche attempt to standardise the offshore connections towards a meshed offshore grid with an open source approach, facilitating cooperation with suppliers Figure 29. Apart from that, TenneT is working on an energy hub and experimenting with underwater cable robots to automate operations.

The Offshore Coalition for Energy and Nature is providing a discussion forum for European NGOs, members of the wind industry and TSOs to come together and combine nature inclusion measures into the renewable offshore energy development in the North Sea. This provides network building opportunities for relevant actors, niche learning and can be seen as a first step towards integrated solutions, combining the interests of multiple stakeholders to prevent conflicts after decisions are made. Key players in this coalition are TenneT, Elia group, Amprion, and Orsted.

Another niche development that deserves particular attention is the application of AI and the learnings by actors that take place in experimenting in different projects on how to most succesfully integrate it into offshore operations. Statnett for instance conducted a pilot project with GE and IBM, among others on how to use AI for predictive maintenance on its assets, potentially reducing labour needs and optimising operations. National Grid is using AI not only for real time monitoring of sensors that give live data and analysis of operations but also has a project together with the ESA, which is called 'Eye in the Sky Intitiative'. The aim of this project is to use satellite imagery and image recognition software for remote monitoring of the grid and predict and prevent spark disruptions or fires on voltage lines or assets. Especially in the rough conditions of offshore operations, with high operation costs, this has disruptive potential.

Table 4: *Niches identified by the SNA*

Niche development	**Category**
Demand flexibility	AI
Predictive maintenance	AI
Real-time asset monitoring	AI
Gaming technology for Health, Safety and Environment (HSE) training	AI
Satellite imagery for grid monitoring	AI
Grid stabilisation	AI
Birdlife data	AI
Cargo drones	Automation
Maintenance robots	Automation
Virtual power plant	Automation
Energy islands	Infrastructure
Floating offshore wind	Technology
Hydrogen	Technology
E-fuels for vessels	Technology

4.3.3 GFO-O as problem owner

Based on the SNA resource analysis, it can be seen that TenneT is one of the most powerful and important actors in the North Sea offshore energy system.

TenneT has operations as an electricity TSO in Germany and the Netherlands. Within these two countries, TenneT operates more than 25,000km of high voltage connections. With these, TenneT provides elcectricity on a yearly basis to roughly 45 million households. Its core tasks are are the transmission of electricity, market facilitation and providing system balancing services. The transmission business extends across the Netherlands and Germany onshore and offshore into these two countries' exclusive economic zones in the North Sea.

As a vision, TenneT aims to 'Connect everyone with a brighter energy future'. This should be achieved by securing energy supply now and in the future. Another important pillar to achieve this is to safeguard the financial health. Lastly, ensuring a secure, reliable and zero-carbon energy system should contribute to TenneT's vision.

Within TenneT, the cross-border department GFO-O is responsible for operation and maintenance of the transmission grid in the North Sea in the German as well as the Dutch part. GFO-O's vision is to be the leading offshore grid operator in Europe. For the operation and maintenance of the converter platforms, technicians need to be sent offshore to ensure the functionality of the platform. The technicians also check the equipment to detect early signals of ageing or material failure and corrosion due to the harsh environmental conditions in the North Sea. The mode of transport for the technicians are helicopters, which can be limited due to storms, requiring a system that is able to operate autonomously most of the time. Ideally, the number of days that technicians need to be physically present on the platform should be reduced to an absolute minimum, as it entails high costs and there is always a safety risk for human life.

Therefore, it is important for to understand the factors that impact the North Sea offshore energy system for GFO-O as a critical actor to successfully operate and maintain the transmission grid.

4.4 PESTLE analysis

The literature search was started by testing keyword combinations such as 'offshore', 'offshore wind', 'pestle', 'renewable', 'scenario', 'analysis', 'energy', 'North Sea' in various combinations. The constant terms where 'offshore' or 'North Sea' and 'energy'. The scenario component was integrated as it was assumed that literature on scenarios is building upon factors that are impacting the system for the foreseeable future. Furthermore, it was hoped to gain insights for this thesis's scenarios. The starting database was Google Scholar but due to the mixed results, Web of Science and Scorpus were were incorporated as well. Based on trial and error (either too many or too few search results), the following prompts proved to be the most fruitful initial keyword combinations. 'PESTLE AND renewable AND energy OR scenario AND analysis', 'External factor AND offshore energy AND offshore wind'. The latter was either combined with 'AND North Sea' or the search results were scanned on whether they had a connection to the North Sea offshore system. In case factors were found that had relevance in other offshore systems, for example in Irelands or Korea, the factors were searched in combination with 'North Sea' and 'energy' to ensure the applicability to this research. Because of the multidisciplinary nature of a PESTLE analysis, utilising all three databases made sense. Resulting was a combination of specialised scientific journals (Scopus and Web of Science) as well as broader literature including reports from Google Scholar. The most effective method however was to snowball based on the literature found in those three databases. Starting with a few insightful papers, the references were used to find new literature. Moreover, backward and forward citation was successfully applied. Due to scoping reasons, for forward citation it was only looked at the first 15 citations for each paper as they are deemed the most relevant in Google Scholar.

The following factors impacting the North Sea offshore energy system resulted from an extensive literature search, structured based on the PESTLE dimensions (Political, economic, social, technical, legal, environmental), see Figure 21 as an overview:

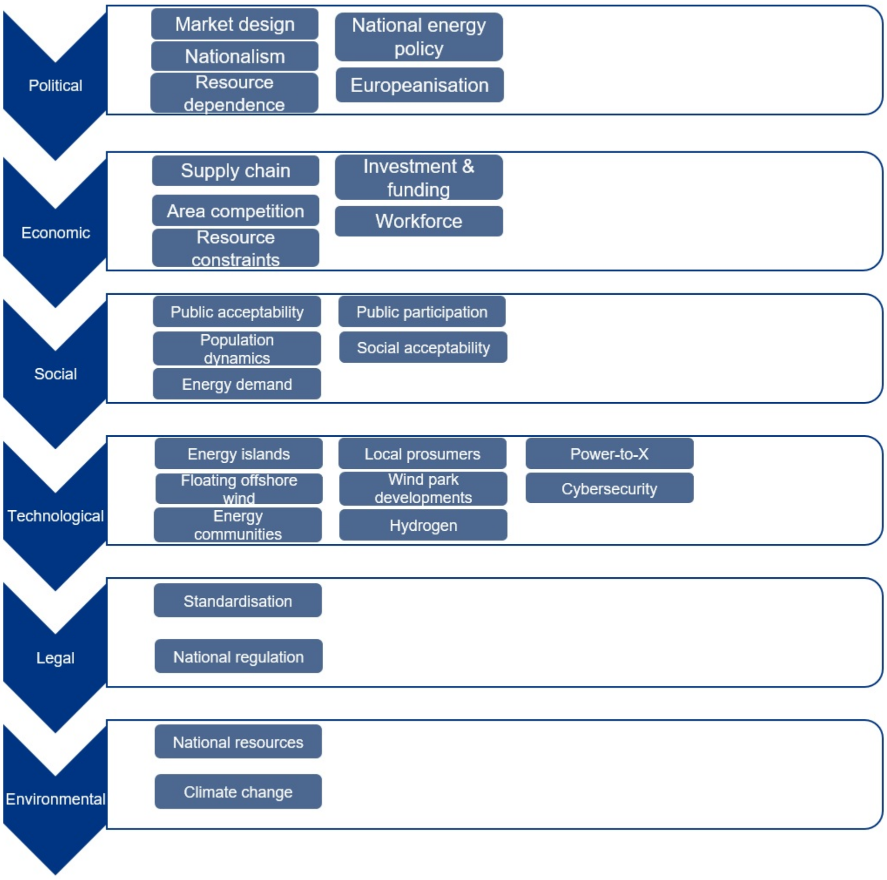


Figure 21: *External factors resulting from literature review. Source: own elaboration*

4.4.1 Political

Market design:
The role of the factor market design the energy transition is discussed extensively in the literature (Lindberg, 2022; Jehling et al., 2019; Scholten and Künneke, 2016). Even though there is an overarching tendency on how to structure electricity markets that applies to all European countries due to regulation, the individual electricity markets vary strongly in design by country. Different degrees of liberalisation result in different roles of TSO's and more or less private actors. Another distinction can be made between state-driven or market-driven design, the degree of interconnections to neighbouring countries and, hence, the possible dependence on other countries. In a state-driven design, there exist strong 'national champions' in some European countries, which are state-backed and dominant players in the electricity market. The pricing can vary between one pricing zone, meaning all consumers pay the same electricity price, as is the case in Germany, or different pricing zones with different electricity prices in one country, dependent on geographical location of demand and supply. The configuration of these pricing zones can be seen in Figure 22.

Figure 22: *Pricing zones in Europe. Source: modified after Nouicer and Meeus, 2019*

With a focus on offshore energy in the North Sea, the discussions regarding zonal or nodal pricing are of particular relevance for this thesis. The prevailing model in Europe is zonal pricing, where the electricity price is the same within one zone. Some countries are consisting of one pricing zone, such as Germany, while other countries comprise of multiple zones (Sweden) with different electricity prices for each zone (Eicke & Schittekatte, 2022). Within each zone, the costs for balancing supply and demand are paid by all consumers in the zone

(Borowski, 2020). Nodal pricing can be considered as local pricing reflecting the actual costs of electricity production at that specific node (Borowski, 2020; Eicke and Schittekatte, 2022). Also called ’locational marginal pricing’, nodal pricing gives accurate market signals in case of congestion or demand and supply mismatch due to its granularity (Hardy et al., 2023; Eicke and Schittekatte, 2022).

Considering the rapid growth of offshore electricity production with potential addition of energy islands, two different concepts for the offshore system can be considered. Home bidding zones connect the offshore electricity production to the country of its owner (Eicke and Schittekatte, 2022; Lüth, 2022). The onshore zone and, hence, the electricity price in this zone would extend to the offshore assets. This might be sufficiently reflective of the costs for the electricity produced offshore (Lüth, 2022). Another option is the offshore bidding zone, contradictory to the name, more in the direction of a nodal design (Eicke & Schittekatte, 2022). With several different nodes offshore, local pricing can reflect actual costs, lead to lower prices and give valuable market signals (Eicke and Schittekatte, 2022; Hardy et al., 2023; Lüth, 2022). It should be noted, that critics stress the complexity and computational expenses of nodal pricing compared to zonal pricing (Weibelzahl, 2017).

Market design is considered a key factor for the North Sea offshore energy system by 10 experts. Decisions on the design of offshore bidding zones need to be taken.

Nationalism:
A presence of nationalism in terms of energy means a focus on national interests and national energy security for the country. A rise of nationalistic tendencies could be observed in the wake of the war on Ukraine and the resulting energy blackmailing of Europe by Russia (Żuk & Żuk, 2022). And example of the result of such protectionist tendencies can be the focus on storage solutions within the country to avoid dependence on other countries (Antenucci et al., 2019). In times of a crisis, as recently witnessed, the priority of politicians is to keep energy in their own country and potentially store excess energy for its own citizens instead of distributing it to neighbouring countries in need (Żuk & Żuk, 2022). Here exists a relevant overlap with the factor market design, as can result in the preference of more domestic control of energy supply by the state (Antenucci et al., 2019; Żuk and Żuk, 2022). Especially for renewable energy sources and the current lack of storage capacities, nationalism poses a significant challenge for a European energy transition.

6 interviewees see the risk of rising nationalistic tendencies from a political perspective, leading to the prioritisation of national security of energy supply. One interviewee points out the potential development of a national demand to move back from wind energy to less fluctuating energy sources such as nuclear energy in the interest of national energy security. This is fuelled by the Russian war

on Ukraine and current nationalistic movements in multiple European countries.

Europeanisation:
The factor Europeanisation, mentioned among others by Kern and Smith (2008), is closely tied to market design and nationalism. It describes a European market with strong interconnections between countries, enabling energy flows from supply to demand across Europe. A trans-national market design, with grids expanding over national borders would have implications for the offshore grid in the North Sea, as discussed under the factor market design (Hancher et al., 2022). Europeanisation encompasses politicians and energy companies working together to find Europe-wide solutions to questions such as hydrogen, natural gas or storage and source funding to find the best solutions for Europe as a whole (Hancher et al., 2022). In times of crises, political leaders think 'Europe-first' by smartly distributing energy where it is needed the most in Europe. National voices matter, but only to a certain degree and if a country produces excess electricity, this is distributed to other countries instead of being stored for a potential crisis.

The rise of nationalistic tendencies stands in direct contrast to the increasing interconnection between energy markets and trend toward a more European approach, observed by 11 interview partners. They stress the need for interconnection across borders and a European approach in terms of policy and regulation for a successful transition.

National energy policy:
Policy options from a national perspective are feed-in tariffs or feed-in premiums. Subsidies in general, such as Contracts for Difference (CfD) or a preference towards a particular energy source, such as it is the case for wind in Denmark. This can result in a potential technological lock-in (or lock-out as was the case with solar in Germany). Carbon taxation is another example of national energy policy affecting the energy system in a country. Another dimension of national energy policy are the ambitions set by governments in cooperation with the industry. The most recent example is the North Sea Summit declaration, jointly published by all head of states neighbouring the North Sea (De Croo et al., 2023). Considering the North Sea as Europe's 'Green Power Plant', the aim stated in this declaration is to achieve 120 GW offshore wind capacity by 2030 (De Croo et al., 2023). These ambitions set high targets for the industry in terms of timeline and capacity produced to ensure a successful energy transition towards a carbon-neutral Europe. Moreover, an increased Europeanisation of the supply chain as well as cooperation with the NATO and EU to protect critical energy infrastructure in the North was emphasised. Notably, hydrogen scale-up as well as hydrogen interconnectors were part of the declaration. Additionally, the relevance of considering the environment was reiterated and the need to speed up the permitting process stated (De Croo et al., 2023).

In the Dutch 'Offshore Wind Energy Roadmap 2030', the multi-use of the North Sea and prioritisation among different interest groups was mentioned as a challenge, with the importance of prioritisation (Wiebes, 2020). The role of this prioritisation lies with the Dutch government, as discussed below with the factor area competition. The ambitious goals for renewable energy capacity form the North Sea were considered in the light of electricity currently accounting for 20% of the Dutch energy mix (Wiebes, 2020). Thus, the ambitious targets were deemed to be only realistic if not only electricity generation by offshore wind farms but also generation of renewable fuels or energy carriers for heating through hydrogen or ammonia was considered. Nevertheless, the essential role of the North Sea for the renewable energy supply of the Netherlands was emphasised (Wiebes, 2020).

9 interviewees see governmental policies and ambitions as a key driver of developments in the North Sea offshore energy system. Particularly governmental road maps are considered to play a significant role in providing clear directions, benefiting investment and facilitating area competition. In the Netherlands, a prioritisation by the government for offshore wind is perceived. However, experts criticise political deal-making that is not benefiting the energy transition, for instance with decisions benefiting the oil and gas sector or the Groningen area due to past issues, instead of long-term visions as negative aspect of governmental policies. Further not helping long-term development is the division of responsibility for the North Sea in many different ministries, which one expert mentioned as a problem in the Netherlands.

Resource dependence:
Due to the geographical location of resources, critical raw materials and critical metals are not abundant in Europe (Scholten, 2018). Europe imports most of the required critical metals and is therefore dependent on countries such as China for a reliable supply and stable prices (Hafner and Tagliapietra, 2020; Rabe et al., 2017). These critical metals are essential for the electronics industry as well as wind turbines, components of the European energy transition (Hafner & Tagliapietra, 2020). Moreover, there are few suitable substitutes, exacerbating the dependence on China (Hafner & Tagliapietra, 2020). China has a near monopoly on critical rare earths that are essential for wind turbines. The supply in the hand of a few countries, mostly China, contrasting the demand by the entire energy industry in Europe is creating the potential for geopolitical tensions, as China can leverage its resources strategically. Hence, there exists a European resource dependence on materials to enable the energy transition that cannot be solved only domestically.

Conflict between government and municipalities:
One expert mentions the conflict between government and municipalities as a factor. Energy infrastructure is constructed at municipalities but decisions are driven by the government, leading to interest conflicts.

One interviewee views the example of Finland as a learning opportunity on how to integrate municipalities in the energy transition. Different incentives ranging beyond electricity connections but rather touch upon social topics such as roads or services are viewed to potentially enable leapfrogging prolonged permitting and legal processes by bringing municipalities on board of the energy transition. This can be backed by literature (European Commission, 2020). However, it was also observed that the applicability of these incentives varies based on countries as they might be viewed to border on corruption based on national law.

Permitting:
Governmental permits for areas in which wind farms can be operated, are considered significant by 4 experts as barriers. Policies changed to almost double the length of permits, which goes in hand with more complicated and prolonged applications as more factors need to be taken into account by the wind farm operators. Circularity and ecology are the main themes that need to be considered, in addition to system integration. This is seen to increase pressure on the supply chain. In contrast to the more complicated permits for offshore wind farms, the relatively simple process of acquiring permits for oil and gas fields, given the right technical specifications, compromises the speed of the energy transition.

The requirement for faster permitting procedures is also voiced by De Croo et al. (2023). One interviewee brought up the issue of consequences of current policy decisions that can have a system-level impact in the long-term with a current lack of system-oriented planning. At least in the Netherlands, the Offshore Wind Energy Road Map aims to mitigate this issue, on the German side the ’Netzentwicklungsplan’ is tasked with a system perspective (Wiebes, 2020; Übertragungsnetzbetreiber, 2023)

4.4.2 Economic

Investment and funding:
Energy infrastructure requires long-term investment to build and maintain the assets (Hafner & Tagliapietra, 2020). Investment and funds can come from different sources, such as the government, private investors or corporate bonds (Hafner & Tagliapietra, 2020). Investment inherently bears risk due to the uncertainty of the future (Edomah et al., 2017). This risk can either only be perceived by investors or it can be an actual risk. However, energy infrastructure depends on funding and, hence, the willingness to take risks by investors (Jehling et al., 2019; Hafner and Tagliapietra, 2020). A lack of funding can significantly impact ambitions due to the long-term horizon and high up-front costs of energy infrastructure (Edomah et al., 2017). Thus, short-term unwillingness to invest due to external events will have long-term consequences for the European energy transition.

Economics of offshore energy:
3 experts point to the economics of bringing more energy production offshore, which they relate to higher costs compared to onshore production due to distance. Thereby, operation and maintenance becomes more challenging.

Area competition:
The North Sea is a system constrained by natural boundaries and therefore limited in size. This lead to competition among different actors within the energy sector but also between different sectors such as the shipping industry, fishing industry or the military (Nilsson et al., 2018; Kafas et al., 2018). All of these actors require space for their operations in the North Sea, which leads to potential conflicts (Gusatu et al., 2020). Within the energy sector, wind park operators, oil and gas companies, TSOs with offshore business and converter platforms are each making term claim for space which needs to be considered and coordinated (Kafas et al., 2018; Wiebes, 2020). This planning is done by national governments by so-called marine spatial planning, which is based on the exclusive economic zones of respective countries (García et al., 2021). Another level of difficulty is not only whom to designate space but also which actor to prioritise for which ares, bearing the potential for interest conflicts and political games due to the high stakes.

From a Dutch perspective, the main stakeholders on the North Sea encompass the fishing industry, shipping industry,nature conversation, environmental organisations, oil and gas companies, wind energy, coastal municipalities and the recreational sector (Wiebes, 2020). Their varying interests are taken into account in the permitting process for new wind farm zones. The Dutch Ministry of Economic Affairs and Climate Policy proposed a combined use of wind farms with the fishing industry by utilising stationary fishing gear instead of trawlers close to wind farms and developing aquaculture farms in the same areas of wind farms (Wiebes, 2020). Similarly, a combined use between nature conservation and wind farms can take the shape of fish hotels, pawning areas for fish protected by the energy infrastructure (Degraer et al., 2020; Wiebes, 2020). As a safe distance to shipping lanes is already integrated in the permitting process before an area is designated for a wind farm, the biggest conflicts are currently observed with the fishing industry and nature conservation (Wiebes, 2020).

Area competition is viewed by 8 interviewees as a potential source of conflict moving forward. Cooperation instead of competition is deemed to be key for achieving the ambitious capacity targets.6 interviewees mention spatial challenges of offshore energy infrastructure with the shipping industry, however, this is viewed as rather solvable in contrast to spatial competition with the fishing industry or nature. Mostly, the issue is more of regulatory nature, with national polices being tasked to provide the right prioritisation in an inclusive way that incorporates all stakeholders.

A proposed solution for the increasing area competition is multi-use of spaces. Conflict with shipping lanes is seen as somewhat less of an issue, as they are accounted for in offshore wind farm permits. In contrast, the fishing industry, ecology and the military are main sources of conflict for the offshore energy sector. One expert points out potential benefits of offshore energy such as offshore loading of ships, which would result in win for fishers as well as offshore wind industry. Multiple interviewees expect multi-use especially between military and offshore wind to be a possibility, even though there currently persist conflicting interests. Especially given the observed increasing presence of the military in the North Sea as a result of Russia's war on Ukraine, a need to integrate the military in spatial plans is emphasised. This bears also an opportunity to tackle security, another problem, that is increasing in relevance for energy infrastructure in the North Sea.

Multi-use has been proposed for example in the Dutch Offshore Wind Energy Roadmap 2030 as a solution to area competition (Wiebes, 2020). Schupp et al. (2021) propose the idea of charging fishing vessels from offshore wind electricity. However, one point that goes beyond what was found in the literature for the PESTLE analysis, is the relevance of multi-use, particularly between the military and offshore wind. With the recent tensions with Russia, this is highly relevant due to an increasing presence of military in the North Sea. A very recent line of research by the submariner network, the Multi-Frame project, conducted case studies in multiple areas world-wide on multi-use of ocean space (Lukic et al., 2023). An applicable example for this thesis is primarily the Dutch case study, but the entire topic should be integrated into further studies on offshore energy systems to apply lessons learned on how to effectively apply multi-use.

Resource constraints:
A slight overlap exists between resource constraints and resource dependence. However, this factor focuses less on the geopolitical tension between different world regions based on supply and demand of critical raw materials. Resource constraints adresses the concept of multiple actors competing for a limited pool of resources (Ploeg et al., 2021). Applied to the North Sea offshore system, this entails the competition for materials, oil and gas rigs, converter platforms, subsea cables and wind parks. Unless the pool of resources significantly expands, this factor has a significant impact on supply chains and long-term ambitions of several actors within the offshore energy system. Ploeg et al. (2021) argues, that resource constrains can stimulate more efficient use of resources, improve business practices as a result and can even be considered a driver for innovation.

Supply chain:
Next to resource constraints, actors in the system face a dependence on suppliers to not only deliver projects but also intermediate goods (Scholten, 2012). Weak suppliers or supplier monopolies have significant impacts on the prices, quality and delivery of intermediate goods and thereby also on the final products (Hafner and Tagliapietra, 2020; Gamarra et al., 2023; Kurbel, 2013). The global supply chain dependencies and recent supply chain struggles make companies within the offshore energy system facing the choice between outsourcing production steps and thereby continuing to rely on the supply chain or to manufacture more in-house. This is associated with higher resource requirements (primarily financial resources and labour, which affects the factor workforce) (Kurbel, 2013). The vulnerability of global supply chains is an issue that leads

to delays of energy projects (Rippel et al., 2019). Furthermore, global linkages are also affected by EU policy, regulating parts of the supply chains and requiring more European production which comes with challenges of its own (Rabe et al., 2017). The ambitions of moving towards a more Europe-focused supply chain were reiterated by the North Sea nations in their North Sea Summit declaration (De Croo et al., 2023). One example of the challenges for more European parts in the supply chain are higher wages, resulting in higher costs for the manufacturers (Rabe et al., 2017).

8 experts stress the critical role of the supply chain for the North Sea offshore energy system. The supply of skilled workers is currently lacking behind the demand, the available workforce is not sufficient. One interviewee pointed out that training existing workers should be preferred to acquiring and teaching new people as a result of the special demand of offshore work. On the materials side, the supply of special vessels such as jack-up barges for the offshore installations of wind farms and converter platforms is not up to the demand. A potential solution, presented by one expert, is more cooperation and sharing of such vessels instead of the perceived outdated tendering process that does not reflect the current situation with a strong need from multiple parties. Not enough material is available for wind turbine manufacturing, but also the supply chain for cables and steel needs improvement. The onshore supply chain is seen as part of the issue, due to the fact that it is almost impossible to keep it within one country, thereby introducing dependencies and uncertainties. Production facilities and ports are viewed as another aspect that require upgrades to improve the supply chain situation.

International supply chains are overly viewed by experts as vulnerable, not up to the demand and potential sources of conflict in the light of China-US tensions. With China's dominant position in raw materials and microchips, one interviewee views the supply chain as a potential make-or break point for the European energy transition. The EU's Critical Materials Act is viewed as a step in the right direction. Furthermore, one expert brought up the possibility of bringing mining activities for raw material to Europe in order to reduce supply chain vulnerability and dependence on China. To a certain extend that can certainly be done (Pavolová et al., 2022). However, public resistance is a major barrier and should be expected to be intense (Kivinen et al., 2020). Therefore, this should rather not be seen as a short-term solution to supply chain issues and is rather unlikely to happen in Europe, barring enormous geopolitical changes. 3 experts are optimistic about the development of the supply chain to meet demands for the rapid scaling of offshore energy technology. One interviewee also sees the need for a reliable international supply chain for a successful integration of hydrogen in the European energy system.

Workforce:
The energy transition in Europe is leading to a significant creation of jobs, with the Wind sector alone estimated to create roughly 400.000 jobs by 2025 (with the starting year of 2020) (Ram et al., 2020). However, there scarcity of skilled

workers that are able to work on the energy transition and, hence, create a gap in job demand and supply of skilled workers (Arcelay et al., 2021; Blanco and Rodrigues, 2009). Particular demand exists for the wind energy and offshore sector in the Nort Sea (Czako, 2020). Even though some of the skills from the oil and gas sector can be transferred, there exists a significant skill gap (Ibrion and Nejad, 2023; Brannstrom et al., 2022). This leads to a war for talent by the actors in the North Sea. Strategies to acquire skilled talent can range from campus recruiting to extensive external and internal training and education of existing workers. Nevertheless, there is a significant shortage of skilled workers already which is only expected to grow in the future (Ram et al., 2020). Moreover, new professions require new education and there might be positions where the skills are not even present yet.

6 experts mentioned the current lack of skilled workers as a relevant factor potentially constraining the energy transition. The gap between the pace of technological development and the available, sufficiently skilled people is viewed critical.

4.4.3 Social

Public acceptability:
The impact of narratives, primarily shaped by the media can lead to a public perspective that differs from reality. An example is the perception of solar energy as clean, fair and desirable energy (Demski et al., 2015; Palomo-Vélez et al., 2021). Consequently, the mining of raw materials in disputed regions under inhumane conditions appears to not be prevalent in the public perception of solar energy (Hafner & Tagliapietra, 2020). These narratives can be tapped into to shape public opinion and create a shift in public values that benefit the interests of certain groups. Another example is the split public opinion on nuclear energy based on different framings either as a clean and reliable source of ’clean’, cabon-neutral energy or as a risky technology that endangers entire populations and should be banned entirely (Demski et al., 2015; Kiser and Otero, 2023). The power of public narratives and thereby public acceptability of energy sources can have an impact on the choice of national energy sources.

5 interview partners mention public acceptance as an important factor for driving the energy transition. So far, renewable energy is perceived as desireable. However, this is deemed to change quickly, if the citizens are affected by higher prices or losing money because of energy infrastructure lowering their real estate values.

Demand for sustainability:
Another interviewee sees a development towards a sustainability-focused society, reflected in the standards of living. Thereby, a demand for sustainable energy solution is created, stimulating the renewable energy developments in the North Sea while demanding sustainability along the value chain to reach the climate targets. This aligns partly with the findings on public acceptance,

which is relatively high for renewable energy (Demski et al., 2015). However, the point goes beyond mere demand for renewable energy but focuses on a sustainable value chain, which at this point is not achieved due the environmental impact of raw material mining (Hafner & Tagliapietra, 2020).

Social acceptability:
Different types of energy production have varying degrees of impact on the environment. This impact on the environment, combined for instance with an impact on the livelihoods of residents affects the social acceptability, which is based on societal values (Künneke et al., 2015). Examples are protests against wind farms on land with, or high-voltage power lines that can be summarised by the 'not in my backyard'-mentality (Cohen et al., 2014; Künneke et al., 2015). These protests can constrain the energy system of the future from a societal level if not engaged with.

Energy demand:
Historic trajectories of energy demand are showing an increase in energy demand, stimulated by an electrification of the heating and transport sector (Díaz and Guedes Soares, 2020; Fahy et al., 2019; Swain and Karimu, 2020). Energy demand is a main driver for offshore wind developments (Díaz & Guedes Soares, 2020). The question is, whether energy demand will continue to rise or whether calls for de-growth are substantial and lead to a decrease in energy demand, facilitated by increasing energy efficiency (Hickel, 2019; Fahy et al., 2019). However, Fahy et al. (2019) note, that increased energy efficiency is mostly rendered ineffective as consumption increases as a result. Currently, there is not much flexibility in demand, energy consumption happens when required and is not determined or largely affected by energy supply (Gea-Bermúdez et al., 2021). The on-demand society considers energy as a basic necessity such as water, which is available at all times in the same quantities. Particularly with an increasing electrification and an increasing share of variable renewable energy sources such as solar and wind, demand flexibility would reduce the burden on storage solutions (Fahy et al., 2019). In times of high production of electricity, informed consumers could be incentivised to increase their demand, meaning to turn on the washing machine when there is a lot of wind energy available instead of at times, dictated by habits. One incentive for such demand side response are capacity subscriptions (Hennig et al., 2020). Public awareness of the energy footprint is slowly increasing and can also lead to a change in energy demand (Fahy et al., 2019).

On a European level, the development of energy demand is seen as a critical factor that determines the future of the North Sea offshore energy system by 6 experts. The location of the demand is highly relevant, especially the onshore location of industry that depends on electricity or will depend on hydrogen in the future to operate.5 experts mention high industry demand for energy as a critical factor that is driving offshore developments. Two experts see uncertainty in the demand development. It is considered to be dependent on the location within a country. Whether high demand is located close to the coast or further inland is perceived to have a huge impact on the energy transport and therefore the offshore energy system design.

Moreover, the varying demand between countries, especially in regards to time of the day was considered an uncertain development. In case of a disconnect between supply and industry demand, one expert voices concerns about industries moving out of Europe towards more reliable locations of energy production. The energy transition in sectors like heating, moving away from gas-based heating towards more electrified systems, is viewed to increase the demand for electricity production in the North Sea. This development can be found in the literature as well (Fahy et al., 2019). Onshore demand developments create a significant pressure on the offshore system to deliver the required amounts of energy, as Díaz and Guedes Soares (2020) point out.

Public participation:
The involvement of the public in decision processes within the energy transition directly correlates with a higher public acceptability (Cohen et al., 2014; Nielsen et al., 2019). If left out of the decision-making process, public acceptability can take a hit and lead to active resistance, mostly on a local level, against energy transition measures (Cohen et al., 2014).

Population dynamics:
The population in Europe is ageing (Balachandran et al., 2020). An ageing population across Europe could result in resistance against change of the energy system as can be perceived to endanger the affluence of people that benefited from the oil and gas age (Edomah et al., 2017; Biresselioglu et al., 2020). Moreover, the lack of young people in Europe reduces the pool of skilled workers available to drive the energy transition (Cristea et al., 2020). Another dynamic is migration, which can increase the pool of skilled workers but can also require extensive training (Marois et al., 2020). Population dynamics further add pressure on the workforce, necessitating migration policies to increase the supply of skilled workers for the North Sea offshore energy system.

4.4.4 Technological

Energy islands:
Artificial islands offshore that produce electricity from wind energy are so-called energy islands (Lüth, 2022). Multiple countries published concepts which are in varying levels of development (Lüth, 2022). Plans envision energy islands to function as interconnectors between different countries, with excess energy being sent to where it is demanded (Jansen et al., 2022). Thus, a European energy distribution and a more closer alignments of European markets can be reached. Another possibility is to have storage capabilities directly on the islands and potentially also conduct the conversion from electricity to gas or liquid on the island (Koelewijn et al., 2020; Kristiansen et al., 2018; Lüth, 2022). This stored energy could then be transported to shore via ship or pipeline (Quirk et al.,

2021).

5 experts note that a meshed DC offshore grid poses technological challenges, creating uncertainty. One such challeng is the maintenance of the large amount of subsea cables, that are needed to be laid for such a grid. Technological standards also play a huge role in such a grid. Additionally, one interviewee raised questions about the impact of electricity lines on gas pipelines that are placed close together at the seabed.

Floating offshore wind:
Water levels deeper than 60 meters are reaching the physical limitations of conventional bottom-fixed wind turbines (Bilgili and Alphan, 2022; Martinez and Iglesias, 2022). A potential solution is floating wind turbines, that are mounted onto a floating structured and attached to the seabed by use of cables (Piscopo & Scamardella, 2021). Thus, floating offshore wind enables installations in deeper water with more distance to shore, where wind speed are higher in general (Bilgili et al., 2011). These areas are currently also less crowded, promising mitigation to the area competition challenge in the North Sea (Gusatu et al., 2020). Pilot projects have been successful but the technology yet has to prove its scalability and maturity, especially with the supply chain lacking behind due to the novelty of this technology (Dahl et al., 2022). Moreover, costs for deployment and maintenance are increasing with distance from shore (Dahl et al., 2022).

Grid congestion:
The connection between the onshore grid and offshore production is another necessary element with various potential outcomes in the near future. If the current congestion in the onshore grid, observed in the Netherlands, Belgium, and Germany, continues in the medium-term future, this is forecasted to lead to increasing redispatch, in the worst case stopping the offshore development. Grid congestion is a factor, that adds to the findings of the PESTLE analysis and can be confirmed by various authors (Staudt et al., 2019; Corona et al., 2022; Attar et al., 2022).

2 experts mentioned the creation of energy corridors encompassing large direct current (DC) connections over long distances to facilitate the tying-in off the offshore grid. This was also proposed in the German grid development plan (Übertragungsnetzbetreiber, 2023). However, these corridors are anticipated to potentially be severely impacted by delays in permitting and changing regulations, especially when they stretch across country borders.

Energy communities:
On a local scale, neighbourhoods are increasingly becoming self-sustaining in terms of energy by collectively signing power purchasing agreements with nearby wind or solar projects (Reis et al., 2021). By combining multiple households to a community, a higher purchasing power is achieved and knowledge on smart energy solutions can be shared (Lowitzsch, 2019). In case of complete

energy autonomy, these energy communities won't need a grid connection anymore, and might even develop so-called microgrids (Edomah et al., 2017; Reis et al., 2021). This development is supported by EU policy, with the 'Clean Energy for All Europeans' package empowering consumers and providing incentives for consumer investment (European Commission, 2019). For the North Sea offshore energy system, this could result in less capacity required to be transmitted form offshore to shore. It could have potential impacts on the offshore electricity production targets in the long term.

Wind park developments:
Recent developments in wind parks show a trend towards higher turbine sizes, deeper waters and therefore larger distances to shore due to higher and more constant wind speeds at these areas (Díaz & Guedes Soares, 2020). Furthermore, the capacity produced per turbine is scaling up (Fernández-Guillamón et al., 2019). These trends imply challenges in the connection from the wind parks to the shore via converter platforms. For example, longer subsea cables will be required. Longer distances from shore to the wind parks and converter platforms also pose challenges adn higher costs for maintenance (Fernández-Guillamón et al., 2019). Additionally, there exists an oligopoly in wind turbine manufacturing, with over 70% of offshore wind turbines globally manufactured by seven European companies (Díaz & Guedes Soares, 2020). This concentrates significant power in the hands of a few and also opens up potential supply chain vulnerabilities. Moreover, China is pushing into the European wind turbine manufacturing market as well, even though currently European manufacturers are still dominating, especially in offshore wind turbines with its higher complexities (Lacal-Arántegui, 2019; Zhang et al., 2020; Fernández-Guillamón et al., 2019).

Hydrogen:
Hydrogen produced by electrolysis either offshore or onshore can have a significant impact on the offshore energy system (Singlitico et al., 2021). As a carrier of energy that can be stored for longer periods of time, it can contribute to solve the storage problem of the current European energy system (Kovač et al., 2021). Especially for hard-to-abate sectors such as heavy industry, long distance road transport or shipping, hydrogen seems to be a more efficient solution than electrification (Singlitico et al., 2021; Osman et al., 2022). Furthermore, there are discussions about connecting the existing gas network for example in the Netherlands and Germany with the electricity grid (Gils et al., 2021; Koirala et al., 2021). This could change the core transmission business of TSOs and expand their role of previously electricity-focused transmission towards a sector-coupled, system perspective including gas (hydrogen) transmission. A matter of debate is where hydrogen is optimally produced, either directly offshore at the sources of electricity production or whether it should be produced after the electricity is transported onshore (Singlitico et al., 2021; Calado and Castro, 2021). In case of offshore production, a potential business model changing the core business of TSO's would be electrolysers on converter platforms, resulting in dual use. However, this would pose additional requirements to the workforce,

with the need for additional skills. It should be noted at this point in time that hydrogen is not a mature technology yet and its share in the energy mix is around 2% (European Commission, 2023b). Thus, it needs to be seen whether it can hold its promises of being a significant factor in the energy transition.

9 experts expect hydrogen to be a significant factor in the future energy system of the North Sea. Offshore hydrogen production is viewed as a likely technology, that however still needs to prove itself economically. In countries like Sweden, the role of hydrogen for industries such as steel manufacturing is essential for the energy transition. Furthermore, hydrogen is anticipated to mitigate storage issues and buffer the impact of times with low wind and solar energy. One expert sees blue hydrogen as a intermediate solution on the way to green hydrogen. Other experts point out that more hydrogen-based industry will lead to increased electricity demand.

Power-to-X:
Additional to conversion of electricity into hydrogen, other potential business models can incorporate the conversion of power to gas or to liquid (Singlitico et al., 2021; Crivellari and Cozzani, 2020). This so-called power-to-X, with X standing as a variable for different gases, such as ammonia or for liquid fuels (Singlitico et al., 2021). A potential production offshore could also add to the core business of TSO's, depending on whether it can be produced on converter platforms, energy islands or close to the wind turbines at additional infrastructure.

Cybersecurity:
With the current Russian invasion of Ukraine, Europe has experienced the use of energy as a weapon. Threats of blackouts are used for blackmailing, the reduced flow from gas pipelines or the complete shutdown can have significant impacts on the energy security of entire countries (Liuhto, 2021; Knodt and Kemmerzell, 2022). With potential aggressor lurking in the geopolitical sphere and current trends towards a smart grid with many digitally connected devices Diahovchenko et al. (2020), cybersecurity is a factor that dramatically increased in relevance (Dighe et al., 2022). Due to their distributed nature and many devices, smart grids are vulnerable to cyber attacks (Barichella, 2018; Hawk and Kaushiva, 2014). Similarly, the North Sea offshore system is highly dependent on continuous digitalisation and software solutions for optimisation of critical infrastructure (Dighe et al., 2022). This increases the potential fallout in case of targeted cyberattacks on vulnerable parts of the infrastructure. In the midst of a transition and scrambling to meet ever more ambitious targets by national governments, TSOs often still operate in old-fashioned ways before rapid digitalisation. Therefore, as TSOs are not software companies yet, they are vulnerable with potential implications for the security of energy supply of entire regions.

With growing amounts of critical energy infrastructure in the North Sea, threats of physical attacks or cyber-attacks were mentioned as a major concern in the medium-term future by 3 experts.

Small nuclear reactors:
3 interviewees expect nuclear to be at least part of the discussion for alternative energy sources, with small nuclear reactors being a promising technology that could develop in the right circumstances. The mentioned benefits of such technology are flexible energy generation that can be used for heating or hydrogen production as well as its carbon neutrality. However, public acceptance remains a main issue. This can be confirmed by literature (Office of Nuclear Energy, 2023). Moreover, the European Commission is supporting the research on small nuclear reactors (European Commission, 2023a).

Local prosumers:
Related to energy communities, local prosumers describes local, small-scale production of energy by consumers with the desire to feed excess energy into the grid and get a compensation in return (Lowitzsch, 2019; Campos and Marín-González, 2020). This can lead to grid overload due to already existing congestion issues (Piao et al., 2021). This might result in discontent, when excess energy from these local prosumers is not accepted by the respective TSO.

4.4.5 Legal

National Regulation:
6 experts are of the opinion that current regulation is holding back developments, mentioned topics are grid feed-in, lacking connection codes or restricting regulations regarding ecology. There exists an mismatch between European and national law, observed by 2 experts, particularly for ecology, where the Dutch law is perceived as too strict. Moreover, another expert added that there are currently temporary ecosystems developed in the North Sea with nature inclusive measurements at wind parks, resulting in temporarily increased wildlife at these areas, which will be destroyed once the wind park has to be removed. Regulations to prevent this are perceived to not be up to date.

Standardisation:
Standards for grid connections, such as high-voltage direct current can be a result of top-down policies (Parol et al., 2015). It can also originate in consortiums such as Eurobar and make its way up to the regime and eventual landscape level, resulting in pressure on the current regime to follow suit (Amprion GmbH, 2021). One such standard was set by the 2-GW program under the lead of TenneT, with the concept of open source technology, multi-terminal and multi-vendor readiness, providing a clear framework to work with for suppliers and project partners (TenneT TSO GmbH, 2023).

4.4.6 Environmental

Climate change:
The implications of climate change are manifold. For instance, extreme weather events can have pose structural damage to offshore materials and platform, as evidenced by recorded impacts on oil and gas platforms (Kaiser, 2009; Dong et al., 2022). Additionally, extreme wind gusts can restrict maintenance flights of helicopters (Kettle, 2016). Moreover, climate migration is having and will have a significant impact on the workforce (Vasić et al., 2022; Byravan and Rajan, 2017). Further implications can affect the supply chain, for instance if the Northern Sea Route becomes navigable by cargo ships all year round due to ice-freedom, this will reduce transfer times for intermediate goods (Keupp, 2015). On the other hand, local extreme weather events might endanger the transport or manufacturing of these intermediate goods.

National resources:
The presence of national resources affecting the energy transition vary from country to country. Norway for example is blessed by its abundance of hydropower, while the Netherlands possess a network of gas caverns which could play a role in hydrogen storage (Egging and Tomasgard, 2018; van Renssen, 2020).

Based on the actor analysis, the empirical PESTLE analysis and the results of the expert interviews regarding factors, the relevant factors are listed in Table 5 and categorised using MLP.

Table 5: *External factors categorised using MLP framework. Source: own elaboration*[1]

Landscape	**Regime**	**Niche**
Market design	National energy policy	Energy islands
Nationalism	National Resources	Floating offshore wind
Europeanisation	Permitting	Energy communities
Investment & funding	Area competition	Hydrogen
Economics of offshore energy	Resource constraints	Power-to-X
Supply chain	Public acceptability	Cybersecurity
Workforce	Social acceptability	Small nuclear reactors
Demand for sustainability	Public participation	Local prosumers
Energy demand	Grid congestion	Standardisation
Population dynamics	National regulation	Demand flexibility
Resource dependence	Wind park developments	Automation
AI developments		Robotics
Climate change		

---

[1] These identified factors are the basis for constructing the scenarios and used in Table 6, combined with the results of the procedure outlined in subsection B.3.

4.5 Interim Summary

The North Sea offshore energy system can be divided into seven socio-technical subsystems. These are 'Regulation', 'Technology', 'User practices and markets', 'Cultural meaning', 'Infrastructure', 'Maintenance networks', and 'Supply networks'. All TSOs with offshore business in the North Sea and Orsted result as key players from the actor analysis. Relevant context setters are investors, national governments, EU regulators, and the military. The SNA shows that Orsted has the strongest position in the network and can control the flow of information, while TenneT has the strongest position among TSOs. Among the landscape factors are market design, nationalism, Europeanisation, supply chain, workforce and AI developments. On the regime level, national energy policy, grid congestion, wind park developments and area competition are critical factors. On the niche level, technological innovations encompass hydrogen, energy island and small nuclear reactors, while standardisation, automation and demand flexibility play a relevant role as well.

5 Scenario Analysis and Discussion

In this chapter we will use the outcomes of the expert interviews to build and explore future scenarios for the North Sea offshore energy system. Within the scenarios, the implications for GFO-O are discussed. Furthermore, implications for the North Sea offshore system are drawn. Sub-question 4 is addressed by creating socio-technical scenarios. Sub-question 5 is addressed by assessing the impact of each scenario on GFO-O and discussing the results and their implications for GFO-O.

5.1 MLP Analysis of Future System

In the following section, the results of the expert interviews regarding the future offshore energy system are presented. This presentation is structured into MLP, using the codebook (Figure 11) to ensure that developments in all three MLP levels are part of the scenario building. Resulting are socio-technical scenarios grounded in MLP, making the development more natural and informed by theory, without losing out on expert insights going beyond what is currently available in the literature.

5.1.1 Landscape

The landscape is split into two different time horizons. The long-term developments, encompassing everything beyond the next 15 years and medium-term developments over the next 5 - 15 years. Moreover, these developments reach across borders and go beyond a national focus, which is where the regime and niche levels are located.

Long-term developments
2 interviewees were pointing out the time pressure due to long-term climate neutrality targets and ambitious capacity targets for 2050 at a European level, resulting in strong pressure on the regime level. Adding to the pressure from capacity targets, leading to wind farm constructions, is the increasingly crowded North Sea, reducing space for ecology, according to one interview partner. This is seen to possibly compromise the European climate targets.

Regulations and policy at the European level are deemed to change only slowly, not keeping up with the rapid developments in the North Sea offshore energy system. Hence, there is the perceived potential for slowing down necessary developments or not reacting fast enough to recent developments, where European steering would be required. This is already visible with permitting issues for wind parks or policy misalignment between the national and European level concerning ecology.

Medium-term developments

Undisputed by the interviewees is the need for the energy transition in order to mitigate the effects of climate change. One expert brought up changing weather due to climate change as a factor that can have a severe impact on offshore energy assets but requires further studies. Another impact of climate change is migration, which can increase the talent pool available for training to improve the skilled workforce. One expert pointed out the dilemma when it comes to sustainability. On the one hand, the energy transition is needed to achieve a sustainable world but on the other hand, in the wake of wind park developments, biodiversity is considered secondary. However, this has been different in the past and could change again, if there is a societal movement to protect for example rare bird species that are breeding in areas where energy infrastructure is supposed to be developed. Moreover, circularity is another factor that is viewed by one expert as a critical driver of future developments. Circularity not only for the design of wind turbine rotor blades but also in respect to area competition. Current legislation states that wind parks need to be fully decommissioned after the end of their life-time, for which one expert raised the question, what happens with these then deserted areas.

Interconnection of national energy systems is viewed by 12 experts as a development that will shape the future and is necessary for the North Sea offshore energy system. Interconnectors between countries to deal with the variability of wind energy and meshed DC-systems are developments that are foreseen. This means moving away from the current point-to-point connections of offshore wind farms to the onshore grid. It is mentioned that the offshore energy infrastructure needs to be inter-operable, allowing efficient construction, operation and maintenance by multiple suppliers and manufacturers. Adding to that is the expected standardisation of turbines emphasised by 2 experts, enabling faster growth and more efficient operations and maintenance. Furthermore, HVDC networks to bridge longer distances from sea to shore and enable energy corridors are viewed as key for a future European energy system.

8 interviewees expect an increasing build-out of offshore wind in the North Sea. This is driven by ambitious governmental policies on a national but also EU-level. This political push for offshore wind is predicted to continue even though two experts have warned against political shifts, which can potentially compromise these ambitions. Energy system thinking was mentioned by one expert as a prerequisite for a successful integration of different renewable energy sources and carriers such as hydrogen into the European energy system. With a significant increase of wind farms in the North Sea, the wake effect from one wind farm can have detrimental effects on other wind farms in a strongly crowded North Sea, as one expert points out. Moreover, 2 experts raise the question of commercial viability of these ambitious targets, stating that political ambitions can only drive the transition to a certain extend, from where an economic business model needs to step in and further drive the developments, which is at least questionable moving forward.

5.1.2 Regime

Incumbent actors
9 experts assign a relevant role to the oil and gas industry in the North Sea. Next to their spatial impact due to existing offshore mining platforms, they also play a role in driving or slowing down the energy transition. Particularly their interest in extending the lifespan of their platform as as long as possible is conflicting with the proposed policies to accelerate the energy transition to renewable energy sources. On the other hand, it was stressed by the experts that especially gas is needed in the transition to buffer the variability of wind and solar energy. Moreover, to extend their business model and remain relevant in the North Sea, the oil and gas sector is actively pushing the hydrogen agenda as it could mean a prolonged usage of their infrastructure. One experts sees a role for oil and gas in floating offshore wind and accelerating offshore wind developments in the North Sea by means of reinvesting parts of their enormous profits in renewable energy. Furthermore, the relationship being oil and gas and the renewable energy sector are viewed to have improved due to all stakeholder sitting on one table for years. This is seen as a positive note, able to facilitate future cooperation.

Policy regime
A question that is left for policies to answer is the governance of a future offshore grid, which is a big uncertainty as of now. The developments of offshore hubs and increased volumes of electricity production offshore require a new vision on how these are integrated in the current market design. National regulations and policies are not yet in place to enable cross-country agreements, instance between the UK and Northern Europe, that govern cooperation beyond the national exclusive economic zones.

Science regime
One expert pointed to an ongoing investigation about ecological impacts in the Netherlands. The studies' subject is the impact of wind turbines on birds. If the results confirm recent assumptions that birds are avoiding the wind turbines, this is seen to have implications on the role ecological factors play in the North Sea.

Socio-cultural regime
The experts currently perceive a backing from society for renewable offshore energy from the North Sea. This can be deceptive if unrealistic political targets lead to high costs and delays in the build out of energy infrastructure in the North Sea. Moreover, policy measures such as potential emission restrictions are viewed to contribute in a switch of public acceptance. Nature protection is also mentioned by 2 experts as relevant for public acceptance.

User and market regime
One expert points out the danger of a short-term decrease in demand, which could hold investments into the offshore system and therefore have drastic

consequences in the long run. A match between supply and demand is therefore seen as desirable, with relatively more demand to function as a driver for investment.

One expert voiced concern about the prioritisation of offshore bidding zones when they stretch beyond one country. Part of the concern is the allocation of electricity if multiple countries have similar demand and the supply of electricity is not enough to meet all the demands. The current national focus of market design is not able to solve this problem. The distribution of energy in times of less production from baseload technologies with a lot of input from offshore wind needs to be decided on in a fair way. Moreover, for back-up capacity, the prices are highly variable depending on the amount of electricity generation from renewable energy sources. High renewable generation means low prices and low renewable generation implies high prices. Adding to that, it needs to be determined, when energy will be imported in such cases and in what volumes.

Current market design doesn't incentivise energy autarky developments of countries, this is economically not efficient even though there is a perceived development toward national autarky, as seen in the landscape pressure towards national security of supply. The flexibility market is another aspect that is essential for a North Sea offshore energy system with a lot of capacity from renewable energy sources.

Use of power

4 interviewees see the use of lobbying power of the oil and gas industry as a serious threat to the energy transition efforts. Due to their position as incumbent actors, they are actively lobbying to continue their operations and influence governmental road maps in their favour, thereby prolonging the energy transition and taking away space needed for renewable energy infrastructure. Additionally, they launch PR campaigns that depict them as drivers of the energy transition, which is acknowledged by one expert as they invest part of their profits in renewable energy. However, another expert criticises the negligible sum of investment in renewables in comparison to the profits made of fossil fuels from oil and gas companies, holding back the energy transition.

3 experts criticise the use of power by the government. On the one hand, governments are seen to raise unrealistic national capacity targets for the North Sea that are increased frequently and deemed overly ambitious. Another perceived issue is a potential political shift, for example towards nuclear power, in the light of required long-term planning horizons of national TSOs. If the government decides to change the direction in such a way, this would pose significant issues for long-term infrastructure developments such as grids. In the worst case, this is perceived to lose the industry and public backing of such targets. Moreover, to achieve these ambitious targets, the national government for example in Sweden is feared to potentially overwrite municipality interests, which could endanger the democratic foundation of the energy transition.

5.1.3 Niche

Expectations
2 experts expect carbon capture and storage to play a central future role in the North Sea, driven mainly by the oil and gas industry.

Energy islands or energy hubs are expected by 5 experts. They are part of a foreseen system integration, with hub-based power-to-X generation in an integrated offshore system. A landscape driver for these developments is increasing interconnection. The connection with the onshore grid is a main concern, where one expert anticipates offshore ports in combination with decentralised infrastructure as an alternative to the central offshore-onshore grid connection.

4 interviewees expect floating offshore solar to be part of the future energy mix in the North Sea, with one expert pointing out the recent tender of Hollandse Kust West, where solar was part of RWE's bid. Other sources of energy such as tidal or wave energy are seen by 2 experts as potentially having a moderate impact on the system. In the northern part of the North Sea, one expert expects floating offshore wind to develop.

Learning
6 experts view hydrogen as a technology, where a lot of niche learning is still required. Examples are the economically efficient mode of transport, whether by ship or pipeline, decisions about import or local production, offshore pilots and the size of hydrogen infrastructure, small-scale in a decentralised way or large-scale. Furthermore, the international supply chain for hydrogen is viewed by one expert as rather uncertain.

Furthermore, 2 experts emphasise the comparable novelty of renewable energy infrastructure, which leaves a lot of room for learning. Such learnings are predicted to take place in niches. Examples are, when to move energy infrastructure offshore, how to economically operate it and where digitalisation is most useful for the system to reduce costs and optimise operations. An example of a potential learning stated by one expert is the use of sensors for predictive maintenance to reduce the need to go offshore with people too frequently, which is associated with high costs and safety risks.

International connections of energy infrastructure in the North Sea is another field, where niche learnings are anticipated to be key by 2 experts. Pilot projects are considered to be the 2 GW programme by Tennet, with multi-vendor capacity and connection standards between platforms.

How to integrate nature in an inclusive way into the North Sea offshore energy system is a learning process, as 5 experts state. Potential niche-learnings mentioned by the experts are bird protection measures by wind farms, more accurate and real time data about environmental impacts, or the impact of magnetic fields on different species.

One expert expresses the hope of learning from past crises such as the Russian war on Ukraine and applying these to the energy transition in the North Sea. The given example was the rapid construction of a floating liquid gas terminal, which could serve as a blueprint to accelerate the build-out of required infrastructure. Another type of infrastructure where learnings can be made in niches are ports. 2 experts see the potential for a port being turned into an assembly location for offshore wind turbines that could be the signal for more such developments, with particular relevance for floating offshore wind.

One expert views small scale nuclear reactors, using nuclear waste as a possible alternative energy source in the future. For as successful integration in the energy system, public acceptance needs to be considered. By learnings from pilot projects in countries, where the implementation was conducted in an inclusive way, the usage could be expanded to other countries with stronger resistance to the notion of nuclear energy.

Another expert sees the demand shift from consumers towards flexibility as a potential learning. More flexibility in the peak demand hours, incentivised by price reductions could potentially shift the energy demand away from one that is based on a fossil-fuel reliant energy system towards one based on production patterns with high volumes of variable offshore wind energy.

Network building
In the Netherlands, there is a North Sea meeting (The North Sea Consultation, see Noordzeeloket (2021)), bringing together all the relevant stakeholders in the system, as one expert mentioned. NGOs, government and industry are sitting at one table and share lessons learned and updating each other on developments.

5.2 Scenario Analysis

5.2.1 Scenario building

From the expert interviews and PESTLE analysis (Table 5) the following ranking of factors result (see Table 6). The process of evaluating them based on impact and uncertainty is outlined in subsection B.3.

Table 6: *Factor ranking based on impact and uncertainty*[2]

Factor	Uncertainty	Impact
Government policies	5	12
Energy demand	4	11
Supply chain	4	10
Spatial planning	2	2
Market Design	2	4
Ecological impact	3	8

The most impactful and most uncertain factor is government policies. Next, energy demand and supply chain are considered similar in terms of uncertainty, but energy demand is viewed by the experts to have a greater impact on the North Sea offshore energy system. Thus, it is decided to use government polices and energy demand as the two driving forces for the scenario building (see Table 6).

At this point, the factor energy demand needs to be discussed. The feedback from experts for the scenarios mainly entailed the relevance to distinguish energy demand and electricity demand for the North Sea offshore energy system. While energy demand can certainly be of value, also on the literature this distinction is emphasised as relevant (Ahmad and Zhang, 2020; Ritchie et al., 2022). Electricity demand is only a percentage of energy demand, roughly 20%, varying based on country, the rest is based on fuels (Ritchie et al., 2022). This means that if energy demand goes up, this can be a result of more demand for fuels or electricity or both. As a result, the factor energy demand only does not give an identification, whether the demand for renewable energy from the North Sea, which at the moment is solely electricity, mainly produced by offshore wind, goes up or down. As we are considering this particular system, it was decided to use electricity demand as a driving force for the scenarios instead of energy demand to prevent ambiguous interpretations. With the driving forces government policies and electricity demand, the following scenario cross results (Figure 23).

---

[2] In the expert interviews, it was ask to provide a ranking of the factors based on impact on the North Sea offshore energy system. For the first factor, three points were given, for the second factor, two points and so on. The numbers for the impact of each factor are calculated accordingly, the procedure is elaborated on in subsection B.3. For uncertainty, each mention of a factor as an uncertainty was given one point, as it was asked for a ranking. Thus, the factor government policies was mentioned five times as uncertain by the experts, and so on. The data can also be found in subsection B.3.

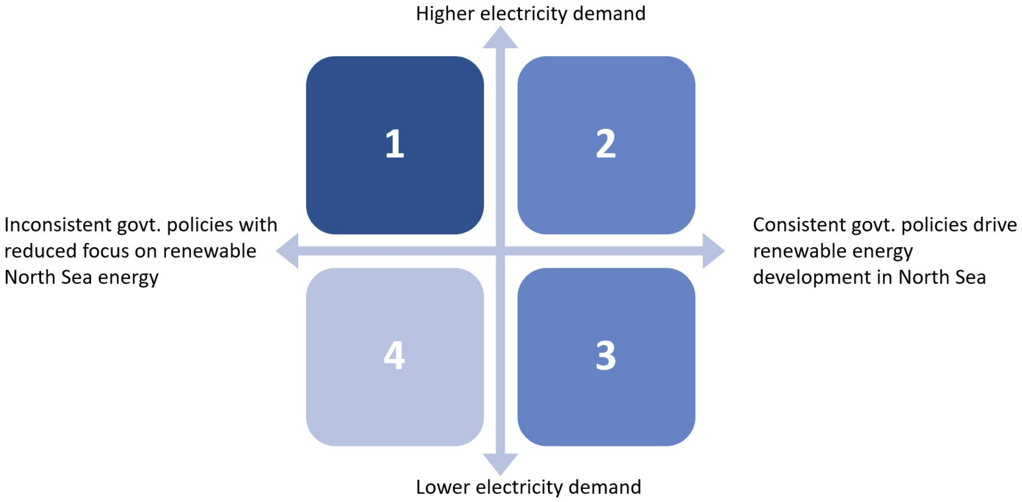


Figure 23: *Scenario cross. Source: own elaboration*

Following the method of socio-technical scenarios, outlined in the method section, the scenarios are started with a shared pre-future, projecting current trends and developments into the future.

Pre-future:
The Russian war on Ukraine, in combination with a rise of right-wing political parties in multiple European countries, has led to an increased relevance of national energy security. The rapid development of AI sped up digitalisation of the energy sector in general and fuelled trends towards more consumer awareness of electricity use and created a movement of companies that provided tools to enable a more flexible energy demand on a household level, corresponding to an increasing share of renewables in the energy mix. Supported is this development by the continuous cost reduction of solar panels. A downside of the AI developments is the increased energy demand due to the required data centers. Moreover, the consequences of climate change have reached Europe in form of unprecedented extreme weather, record temperatures on land and in the oceans. The necessity of the energy transition towards renewable energy sources became accepted by the overwhelming majority. In the midst of these development is the North Sea offshore energy system, with capacity targets of 120 GW renewable energy, mostly from offshore wind, in 2030 and 300 GW by 2050, agreed on by all neighbouring states. TSOs and offshore wind developer alike are scrambling to produce enough electricity and transmit it to the onshore grid to meet these ambitious targets.

Due to the young renewable energy regime in the North Sea, cracks and tension started to appear, with supply chain challenges for materials and special purposes vessels as well as an increasing gap of skilled workers. Multiple countries plan energy hubs, develop interconnectors and offshore wind turbine sizes as well as distances to shore increase. Hydrogen production is touted as the solution to all variability issues of offshore wind, where exactly this hydrogen is produced and by whom is, however, the topic of heated discussions at conferences and congresses.

Another unresolved question is the role of ecology, how much wildlife is impacted by the strong increase in offshore infrastructure and how fishers can continue to earn a living amid increasingly limited space. The market design of a potentially interconnected offshore grid is another challenge that creates uncertainty for the regime. Even though government policies stated clear capacity targets for the moment, these have almost doubled each year, creating pressure for the industry to deliver, and leaving uncertainty, whether they will be consistent in the future. Or whether there could be a future switch towards less focus on the North Sea energy system as the green factory for Europe, more towards onshore developments.

Additionally, the current demand flexibility developments are creating uncertainty as well. Debate still goes on, whether this will require an increased electricity demand, also driven by electrification of industry or whether demand will actually decrease, as a result of increased energy efficiency and local grid solutions. Thus, government policies and electricity demand are the two main driving forces, that determine the development and future of the North Sea offshore energy system.

5.2.2 Scenario 1

Higher electricity demand & inconsistent government policies with reduced focus on renewable North Sea energy

5 years:

Electrification of industry continued, combined with the heating transition in Europe toward heat pumps and away from gas-based heating, speeding up. This led to an increasing demand for electrification. Part of this development was due to the reduced role of Carbon Capture and Storage, which could not move beyond the niche innovation, as it was mainly driven by the oil and gas sector and could not develop into a viable business model because expected technological leaps did not happen. The import of blue hydrogen from Norway took on a large role in the transition of the heavy industry toward hydrogen, due to its abundant supply.

Europe-wide progress in the development of AI stimulated a rise in cyber-attacks on critical infrastructure. With AI tools widely available and regulations strongly lacking behind, access to more impactful technology shifted power into the hands of highly skilled individuals. Specialised hacker groups formed that offered their services to the highest bidder.

Moreover, the availability of AI tools sparked a rush for companies to provide smart solutions for demand flexibility on an aggregated neighborhood level. Helped by increasing numbers of prosumers and energy communities, these companies provided energy management services, controlling the electricity usage of heat pumps, EVs, solar panels, and smart home systems by aligning demand with the fluctuating supply from renewable energy sources. Thus, electricity became cheaper for consumers, and a trend toward more decentralized grid solutions started.

Meanwhile, small nuclear reactors, fueled by nuclear waste, developed from a niche innovation into a mature technology. They enabled reliable electricity supply on a local scale. The higher focus on national energy security led to multiple governments across Europe supporting this development. Especially governments with no access to the North Sea offshore energy system funded the development to become independent from Russian gas and electricity imports. The increased awareness of the public for the relevance of national energy security and the cheap and reliable electricity supply, combined with the perceived safety of these reactors due to their small size and hence, assumed lower risk, led to growing public acceptance in multiple countries.

International supply chains were affected by geopolitical tensions between the US and China. Attempts to bring raw material mining, required for the energy transition, to Europe failed due to enormous public resistance. Therefore, mining sites were developed in Australia and South America, but the transition of the supply chains for raw materials to these areas slowed down the offshore build-out in the North Sea, as critical magnets for the wind turbines became rare.

Local protests against the offshore-onshore connections on municipality ground became more severe in the Netherlands and Germany. Citizens started to protest the top-down approach, building electricity infrastructure in their backyards without benefits for the communities. These protests gained support from environmental NGOs who voiced their opposition against electricity cables crossing the Wadden Sea. The public acceptance started to decrease, as also farmers joined the protests, not understanding why they had to adhere to strict nitrogen regulations if the offshore energy industry was allowed to cross the protected Wadden Sea. As a result, government policies diverted their focus away from the unconditional support of offshore wind build-out as new governments started backing funding the development of small nuclear reactors and prioritised the import of Norwegian blue hydrogen to meet industry demand. This was cheaper than green hydrogen imports from Spain, Portugal and Northern Africa.

10 years:

The Eurobar initiative and the 2GW-program by TenneT in the North Sea developed into two competing concepts on how to design a standardized, interconnected offshore grid. Radial offshore connections became obsolete, and a meshed grid became the new standard. This standardization enabled more long-term planning for suppliers as well as TSOs and reduced pressure on the supply chain, as the variety of required materials and special vessels was reduced. However, it also increased the vulnerability to cyber-attacks due to the open-source design and standardized digital components. Successful cyber-attacks on the interconnected infrastructure further raised public concerns about the viability of the North Sea as the Green Powerplant of Europe. Cybersecurity developments by TSOs were too slow to keep pace with the rapidly increasing capacities of specialised hacker groups.

The transition of the heavy industry toward blue hydrogen stimulated investment in green hydrogen, as many investors realised its potential and the business model for green hydrogen. Successful experiments with onshore production of green hydrogen, combined with the available funding, sped up its development. Storage in old gas fields and salt caverns especially in the Netherlands fueled this development. An important role was played by the maturation and spread of small nuclear reactors, able to produce hydrogen onsite, also in the industrial areas in the Hinterland, therefore reducing the need to transport it over long distances and reducing the required investments into pipeline infrastructure. This, in turn, further fueled investments into small nuclear reactors, increasing their role in the European energy mix significantly.

As a consequence of these onshore developments, the need for electricity from the North Sea was reduced. The combination of small nuclear reactors, enabling more decentralized solutions for the industry, blue and green hydrogen, and increased storage capacities, made onshore energy developments more attractive. Additionally, the decentralization of onshore energy infrastructure gained public support and acceptance due to the not-in-my-backyard mentality of coastal municipalities that were opposing onshore-offshore connections, given the availability of microgrids. Energy efficiency became an afterthought, as consumers mostly covered their own demand, and industry could rely on the abundant energy production from small nuclear reactions and the availability of hydrogen.

The uncertainty regarding offshore energy due to reduced backing by government policies disincentivized offshore investment and further slowed down the build-out of offshore wind. Consumers organized themselves in groups, with increasing mistrust of the government, becoming prosumers, and microgrids were spawning like mushrooms all over Europe. Small-scale nuclear reactors supported this development. Storage was invested in by government and industry alike as the distributed North Sea offshore system was seen as too vulnerable to cyber-attacks. Countries like Spain and Portugal specialized in the training of refugees as technicians for small-scale renewable energy solutions. This benefited local prosumers, as these technicians were demanded in Europe to build and install local solar panels and construct microgrids. Training for offshore qualifications was considered too time-consuming and complex to be attractive for these upskilling programs due to the rough conditions and many safety requirements offshore.

15 years:

The supply chain in Australia and South America had matured, and offshore wind production was slowly picking up speed again, but not as fast as 15 years ago. Offshore renewable energy played less of a critical role for the European energy transition as initially expected. An interconnected grid was available, but TSOs were still struggling with cybersecurity, and times of unavailability did not contribute to investment and government backing. The capacity targets for 2050 had been reduced to 180 GW. Some offshore energy developers left Europe for the United States as government policies and financial incentives were more advantageous there.

Risks and opportunities for GFO-O:
In this scenario, GFO-O is operating and maintaining a meshed, interconnected grid. Hydrogen plays no role in its business and the reduced development speed of offshore wind energy enabled it to bridge the skilled worker gap by upskilling existing workers at a moderate pace. Initial workforce struggles were eventually mitigated. Ongoing problems are cybersecurity and occasional outages as a result.

5.2.3 Scenario 2

Higher electricity demand & consistent government policies drive renewable energy development in the North Sea

5 years:

Europe came closer together to tackle climate change. Alarming trends such as the unprecedented ocean temperatures increased the willingness to cooperate. Despite the cooperation, national governments drove investments in their exclusive economic zones, supporting floating solar, wave, and tidal energy in a race to be the most attractive country for developers to invest in. This profited the European energy transition and particularly the North Sea offshore energy system. The onshore grid, however, lagged behind the increasing supply, resulting in times of high grid congestion.

More interconnectors were constructed in the North Sea, and the first energy hubs were successfully operated as part of the meshed North Sea offshore energy grid. Rapid offshore developments resulted in pressure on the supply chain to deliver materials and vessels. So far, the supply chain was able to deliver, but only because the suppliers cut corners in terms of quality. Furthermore, the gap of skilled workers qualified for offshore work widened, increasing the pressure on the offshore energy system.

Ongoing communications in forums such as the North Sea agreement in the Netherlands brought all stakeholders in the North Sea together at a table and enabled the multi-use of multiple areas in the North Sea, with ecology, fishers, and offshore wind farms benefiting from each other. Fishers could fuel their boats offshore close to wind farms and were allowed to fish in more areas, while there was increased nature protection in other locations, with the combined use of wind farms as spawning grounds for fish and artificial reefs. These forums provided direct lines of communication and enabled cooperation due to constant conversations.

The oil and gas sector was the odd one out in the beginning, with public backlashes and protests against Shell and BP erupting in multiple countries. PR campaigns were publicly dismissed as greenwashing. The public opposition to oil and gas, combined with the rediscovered urgency of climate targets, led to governments forcing oil and gas companies to decommission faster. Many lawsuits and attempted settlement agreements resulted.

A high level of public acceptance could be reached by applying the lessons learned from Finland in integrating municipalities into the energy transition. Incentives for cooperation such as energy discounts or provision of public services were increasingly seen in municipalities all over Europe. The development of small nuclear reactors was strongly opposed due to the public acceptance of offshore wind developments and anti-nuclear sentiments, connected to the already worsening impacts of climate change on the planet.

10 years:

Communication efforts by the governments on multiple levels, combined with the urgency of increasingly felt climate change impacts due to extreme weather events and longer droughts, also in Northern Europe, resulted in high public acceptance and support for offshore renewable energy, particularly offshore wind.

The result of high public acceptance and integration of municipalities in solutions were leapfrogging on permitting issues, preventing previous delays due to long permitting processes. The public acceptance, combined with long-term investment security due to government policies which, together with microgrids in certain areas due to increased focus on providing energy security to energy communities, contributed to overcoming initial grid congestion issues due to a strongly accelerating offshore capacity build-out. Overall, a system perspective was gained due to communication between governments, industry, municipalities, and environmental NGOs constantly meeting in different discussion platforms, sharing learnings, and updating each other on their different perspectives for future developments.

The capacity targets from 2023 of 120 GW in the North Sea were even exceeded with 150 GW capacity produced from renewable energy in 2030. Hence, the targets for 2050 were increased to 310 GW to keep up with the developments. These targets provided investment signals to the industry and reduced investment risks, further stimulating investment and driving the build-out of offshore energy in the North Sea.

Supply chain quality issues led to aging of materials and platforms, exacerbated by the impact of extreme weather events. Therefore, material failure started to become an issue. The growing labor shortage became a major constraint for offshore developments until the oil and gas sector established its new business idea of shared offshore workers. This project, first tested among oil and gas companies, grew into a platform where skilled workers with offshore qualifications could be shared among companies working in the North Sea, depending on demand.

Facing pressure from the public and government regulations, the oil and gas sector exponentially increased its investment in renewable energy, particularly floating offshore wind near Norway or in the North of the UK. This process was accelerated by stronger carbon regulations of the industry from the EU. Experimentations with extending onshore bidding zones to the offshore grid as home bidding zones proved unsuccessful because of the lacking representation of local production prices. Thus, the market design was switched to more nodal, offshore bidding zones. A development that was enabled by landscape progress in AI, enabling Europe-level real-time electricity market simulations.

15 years:

The once-promising development of hydrogen was mainly driven by the interests of oil and gas, as well as demand flexibility issues. Due to public awareness campaigns by national governments and the role of prosumers in educating other consumers in their communities, combined with public awareness of the necessity to reach the climate targets, demand flexibility on a consumer level was achieved faster than expected.

Supply chain issues, especially on the quality side due to the ongoing acceleration of the offshore energy build-out, slowed down the development of storage capabilities in Europe, but reshoring some parts of the supply chain as well as the demand flexibility on a consumer level, reduced the amount of funding for hydrogen.

Moreover, without large-scale government funding in the early development stages, hydrogen proved to be not economically feasible for large-scale applications and remained a niche technology. Storing issues due to disputes about whether old gas field should be used for storage or not contributed to this. In the short term, the supply chain issues posed a problem for the offshore energy sector, but political backing by governments and public acceptance for reshoring to Europe (A result of grassroots organisations and government programs that helped the public understand the consequences of keeping large parts of the supply chain out of Europe) prevented a significant dip in investment and offshore production. Nevertheless, some critical industries left Europe for the Middle East and other regions with fewer regulations or more hydrogen production.

Implications for GFO-O:
In this scenario, communication is key for GFO-O. The tole of communication

forums with other stakeholders improves its operations. Even though it might mean sharing some insights with competitors, the benefits for the North Sea offshore energy system and finally for GFO-O outweigh the potential downsides in the long-run. A fitting term would be ’competitive cooperation’, which benefits everyone. Additionally, the education and communication with the public has a high relevance and needs to be integrated into GFOs tasks, a prerequisite for this is more public visibility.

Real-time electricity market simulations provide insights into consumption and demand patterns. This enables GFO-O to adopt the transmission of electricity accordingly. However, it requires more real-time operations, thereby reducing the room for errors, which can be costly in the harsh offshore conditions. Efficient, digitalised operations require a transition towards a more software focused approach, necessitating more software skills in the workforce. Drawing on the already present electricity market generations, digital twins of the converter platforms can improve offshore operations and maintenance while reducing the risks to human life.

The development of shared offshore workers can alleviate part of the workforce pressures GFO-O is facing. Although this new approach to safety and security, moving these skills from in-house to external, requires a mindset switch required. GFO-O is not alone anymore in taking care of its critical infrastructure, cooperation is key to ensure safety and security standards despite reduced control over the workers and their training.

The supply chain issues are particularly impactful on GFO-O, as specific spare parts are needed for maintenance work. If that is missing, either high prices or interrupted operations can be the consequence. Moreover, the increased material failure and weather impacts exert more pressure on GFO-O’s operations and its ability to quickly adapt. It raises the question how to optimally maintain the platforms, what to repair and when to replace parts already in advance. No hydrogen operations are required, therefore gas-related skills are not needed within GFO-O.

Following the build-out of other renewable offshore energy sources, new players mean new connections need to be made for GFO-O. As a consequence, this can potentially impact operations in the beginning until a certain standardisation of connections is reached.
Increased multi-use of space implies more inclusion of nature in GFO-O’s operation and maintenance plans and being more environmentally conscious to not lose public backing.

Rapidly developing production capacity in the North Sea is applying pressure on the workforce to operate the business. A meshed grid means new standards where knowledge needs to be transferred within the organisation or acquired externally. Moreover, energy hubs pose another technological challenge, where learnings will be required.

5.2.4 Scenario 3

Lower electricity demand & consistent government policies drive renewable energy development in North Sea

5 years:

The discovery of a European identity had led governments of different political orientations to work closely together in the face of climate change. National governments doubled down on sustainability, leading to stricter regulation regarding carbon emissions for the industry in all of Europe. The North Sea was seen as the green power hub of Europe, and the interconnection of the national grids received widespread support. First energy hubs became operational, and TenneT's 2GW program was being adopted by multiple countries as the standard for open-source interconnection for a meshed offshore grid.

Environmental NGOs increased their support for renewable offshore energy from the North Sea as they saw the benefit of Europe being a primary driver of the energy transition, being able to export solutions worldwide to mitigate the impact of climate change. For them, the benefits outweighed concerns about ecology, partly as a result of ongoing cooperation and communication in discussion forums. Part of these discussions also involved the shipping industry, fishers, the oil and gas sector, the offshore wind industry, as well as TSOs.

Demand flexibility, supported by the wide availability of AI tools, gained a hold in the onshore energy system in multiple countries. Energy communities and neighborhood initiatives profited from the improvements in smart systems, cheap solar panels, and an energy efficiency focus, driven by EU regulation. Overall electricity demand by consumers decreased. This led to demand being more closely aligned with supply, as multiple companies, including big DSOs, realised the business model behind smart energy management systems for entire areas.

Available computing power through AI led to a change towards a more nodal market design, better reflecting costs of production. The developments of small nuclear reactors and storage technology provided alleviation of energy issues in winter. AI developments enabled efficient offshore operations. Niche breakthroughs in robotics and predictive maintenance reduced the need to send people offshore, lowered the need for skilled workers, and accelerated the development of the North Sea as Europe's wind energy hub. Furthermore, fewer humans in the offshore system led to a decrease in the safety zones around wind farms and oil and gas rigs. AI helped the national governments to optimally assign space to the different stakeholders, including the military presence and integrated fishing areas into an offshore system heavily reliant on the multi-use of space. The ability to go further offshore more cost-effectively due to automation benefited the business model of floating offshore wind, heavily invested in by the oil and gas sector.

Stricter regulations from the national governments and the EU created investment incentives into Carbon Capture and Storage for oil and gas companies. First pilots on platforms, originally planned to be decommissioned, looked promising. Security of funding helped overcome initial technological challenges and economic inefficiency in the beginning. Seeing their old business model becoming obsolete due to strict regulations, the oil and gas sector heavily focused on CCS and offshore hydrogen development.

Different pilots for onshore hydrogen raised questions about which country should produce it and therefore mainly benefit from it. The focus of the oil and gas sector on offshore hydrogen resulted in more pressure for this niche development, combined with storage debates. Moreover, Spain, Portugal and Northern Africa were able to provide cheap green hydrogen.

Cyber-attacks on the increasingly interconnected and standardized offshore infrastructure became an issue that led to outages in multiple areas bordering the North Sea. Surprising for many TSOs, the public did not erupt in protests. Due to demand flexibility and increased storage capacities, these outages almost went unnoticed in the beginning.

10 years:

Within the North Sea, a meshed offshore grid was operational, with multiple energy hubs providing electricity to all neighboring countries of the North Sea. The pressure on the onshore hydrogen niche was too large, and it couldn't keep up with the funding of oil and gas companies for offshore hydrogen. Therefore, hydrogen production on energy hubs in the North Sea became the norm. More demand flexibility and the maturation of carbon capture and storage, combined with some industries being driven out of Europe by strict regulations, reduced the onshore demand for North Sea electricity. Moreover, an initial experiment by one TSO with rolling outages for planned maintenance and grid repair work proved so successful that outages of 2 hours during the night took root all over Europe, further reducing electricity demand. As a consequence, the European offshore stakeholders came together, strongly supported by national government policies with a focus on the North Sea offshore energy system and joined forces to develop Europe into the world-leading offshore hydrogen producer and exporter. The experience of the oil and gas sector, the shipping industry, combined with knowledge from TSOs and the production from the offshore wind industry, taking into account environmental interests from NGOs, led to a push directly for green hydrogen, thereby leapfrogging the blue hydrogen technology in use in other areas around the world. This leapfrogging was facilitated by the import of green hydrogen from Spain, Portugal and Northern Africa.

A result of this strong cooperation was not only shared space but also data sharing among all North Sea offshore stakeholders. Springing up from a successful pilot project between Orsted and Equinor, the creation of a North Sea data sharing platform optimized operations and led to further automation of the offshore system, reducing the risks to humans, the environment, and increasing profitability. It also laid the groundwork for founding the offshore cybersecurity alliance, a platform to share lessons learned about cybersecurity, decreasing the frequency and impact of cyber-attacks. The green hydrogen development further fueled offshore wind developments and incentivized some ports to become assembly yards for offshore wind turbines, speeding up the build-out of floating offshore wind. It also limited small nuclear reactors to a niche technology in the European energy mix, as the ’not in my backyard’ mentality of consumers and anti-nuclear sentiments by NGOs favoured green offshore hydrogen over any nuclear energy sources closer to their homes.

The impact of supply chain issues due to original equipment manufacturers experiencing challenges with the quality of their parts led to some cases of material failure. However, the impact was rather small as CCS and demand flexibility, combined with rolling outages, left enough room for repair works. Especially the rapid production of hydrogen, providing storage capacities, made these impacts less significant for the overall system.

15 years:
Europe had become the world leader in offshore energy production and its leading exporter.

The public tolerated offshore energy as less affecting than onshore wind energy, resulting from microgrid developments and a ’not-in-my-backyard mentality’. The role of the transmission grid was consequently reduced mainly to the energy corridors, and TSOs were shifting their operations to knowledge sharing and sending technicians to help build microgrids and integrate green hydrogen into the European energy mix.

Implications for GFO-O:
Just as in Scenario 2, the 2 GW program and development of energy hubs requires additional skills in the workforce due to the technological novelty of these niche evolutions. Hence, training of existing workers or acquisition of new workers is required.

Increasing demand flexibility in this scenario can help GFO-O to receive more data about consumption and electricity demand from the aggragated smart energy management systems, facilitating its transmission operations. Potential data sharing from GFO-O’s side can help in mitigating grid congestion issues.

The public acceptance of rolling outages gives GFO-O more time to do maintenance and repair works. It can lead to a reconsideration of the requirement to deliver electricity 24/7. Does the reliable supply of energy mean energy provision at all times? Rolling outages also alleviate pressure on the workforce and, hence, GFO-O can keep up with offshore energy production developments.

Resulting from the combination of automation with AI developments and robotics reduces the need to send people offshore in this scenario. Therefore, less pressure applies on the workforce and more innovative solutions become possible. For example digital twins of converter platforms, similar to virtual power plants. Remote monitoring becomes possible, reducing the risk for humans the need for offshore training efforts. This can result in cost reductions for GFO-O.

With the interconnected grid, data privacy and security are a challenge for GFO-O. More digital skills are needed. When sharing the data with other offshore companies, decisions need to be made on what data needs to stay within GFO-O and what can be shared. The upside of the data sharing is more efficient operations and enhanced cybersecurity.

The maturation of offshore hydrogen raises the question, whether green hydrogen can be produced on GFO-O's converter platforms. Another possibility would be a joint pipeline operation in a partnership with a gas TSO. These two potential results from the available offshore hydrogen technology can potentially disrupt GFO-O's business model of electricity transmission.
Optimised multi-use of space implies a closer cooperation with the military, which can provide more physical security to GFO-O's offshore assets.

5.2.5 Scenario 4

Lower electricity demand & inconsistent government policies with reduced focus on renewable North Sea energy
5 years:
Government policies were increasingly divided by differing interests. Some countries focused more on national energy security than others. As a result, countries like Germany attempted to reshore their material supply chain and reduce their industry's linkage with and dependence on China. This created short-term construction delays for offshore infrastructure in these countries and slowed down the build-out of the transmission grid. Meanwhile, Denmark, the UK, and the Netherlands worked closely together to increase interconnection in the North Sea. They developed a standard for an offshore grid based on TenneT's 2 GW program, with strongly managed cybersecurity capabilities. These three countries also made heavy investments in floating solar, which started to take off on small energy hubs.

Refocusing on national energy security, Norway approved new gas fields in the North Sea, which it produced to provide abundant and cheap blue hydrogen. The EU became its main customer, and blue hydrogen flooded the market. Green hydrogen imports from Spain, Portugal and Northern Africa were not able to compete with the price of blue hydrogen. This development also reduced investment in other storage technologies.

The initially high-capacity targets for the North Sea faced an enormous challenge with severe supply chain issues, particularly the shortage of permanent magnets for wind turbines, on which China had a near monopoly. Despite the high costs associated with variable renewable supply and the insufficient supply of battery storage, governments chose to stick to the high-capacity targets, accepting higher electricity production costs. Floating solar development in the North Sea matured faster than expected but could not solve the variability issues.

Additionally, the scaling up of green hydrogen was disincentivized and delayed, with only sporadic funding from some governments, due to the availability of cheap Norwegian blue hydrogen. This resulted in periods of 'Dunkelflaute' (low wind and solar generation) leading to high electricity prices, much to the discontent of consumers. Opposition against wind energy began to develop and put pressure on governments to take action. Given the global interconnected nature of the supply chain issues, they were deemed unsolvable in the foreseeable future. As a result, European governments shifted their focus toward more gas imports and sought short-term solutions.

This process diverted attention away from the North Sea, with governments operating in crisis mode, focusing resources on supply chain challenges, and calming public opinion. In negotiation forums, the German industry and government lacked a clear direction as they dealt with other urgent matters. Consequently, the overall direction for the North Sea offshore energy system and the unity of stakeholders began to develop cracks and tensions. Opposition between different actors, particularly between NGOs and the offshore wind sector, started to emerge, causing the sector to lose some of its policy backing.

Moreover, some countries completed successful experiments with small nuclear reactors that used nuclear waste as fuel. However, in other countries, this technology remained banned due to public opposition. The oil and gas industry strongly invested in carbon capture and storage as part of their lobbying efforts for increased operations, showing promising initial results.

10 years:

Continuous lobbying efforts by the oil and gas sector paid off, and multiple other countries adopted Norway's example. This allowed oil and gas companies to extend their operations in the North Sea to bridge the supply gap. New platforms were built, compromising the climate targets and delaying the energy transition in favor of short-term reliable energy supply. Carbon capture and storage continued to mature, albeit not fast enough to offset the rapid increase in carbon emissions from the North Sea offshore energy system. Governments recognized the risk of losing public support by solely supporting oil and gas, leading to a significant increase in government investments in CCS. Some unused converter platforms, resulting from continuous supply chain struggles, were repurposed to produce blue offshore hydrogen and expand CCS further. Advancements in AI and digitalization improved mining rigs' capabilities to operate autonomously, reducing energy costs. The opposition became divided, with some groups protesting against the oil and gas companies and demanding more ambitious climate targets. However, many low-income households were satisfied with the cheap energy prices following the Russian war and high inflation. The combination of even cheaper energy prices and government-promoted investments in CCS reduced public concerns about climate targets and increased acceptance of the new (old) energy system.

The availability of cheap hydrogen and mature small nuclear reactors led to the development of more decentralized onshore electricity grids, which were less dependent on offshore electricity. The onshore gas network was expanded to meet the rising demand for cheap energy.

15 years:

The ongoing operations of the oil and gas sector further delayed the transition to heat due to the abundant gas supply. As a result, less electricity was required, partly due to the widespread adoption of blue hydrogen by hard-to-abate industries. Offshore renewable energy, struggling with variable supply and supply chain issues, lost support from politicians and the public. Investment eventually stalled, and developers started seeking opportunities elsewhere. The United States became an attractive destination due to tax benefits resulting from legislation building upon the Inflation Reduction Act, primarily designed to attract foreign industries. Many European initiatives that were not reliant on oil and gas followed the developers to the US, further reducing energy demand in Europe. Additionally, some industries relocated to North Africa and the Middle East to benefit from abundant and cheap solar energy. This led to rapid developments in ammonia production as it was easier to ship to Europe to meet the rising energy demand.

Implications for GFO-O:

The 2 GW program, small energy hubs and solar developments necessitate a fast frowth for GFO-O's workforce. Especially due to the cybersecurity developments, more digitalised operations and digital skills are required. For these digitally skilled workers, GFO-O would be competing with the oil and gas sector, which has stronger financial power. This results from the offshore energy system in the North Sea losing the government backing in this scenario. Thus, an unclear direction leads to investment insecurity. GFO-O is facing the decision whether to over-invest and gamble on a future revival of renewable energy in the North Sea or to under-invest and therefore risk transmitting less electricity than demand requires. This would have severe implications for households and could lead to a significant public backlash.

Supply chain issues result in delayed repair work due to lack of material. The transmission capability of GFO-O is further diminished.

The onshore grid developments in this scenario, combined with industry moving away from Europe requires less transmission of electricity from GFO-O. A consequence are either times without transmission or a shift of the core business focus. A potential cooperation with oil and gas companies to install carbon capture and storage on GFO-O's converter platform could be such a shift in the business model.

5.2.6 Scenario Results

For a quantitative analysis of the scenarios, the currently planned capacity from offshore wind of the North Sea countries was considered in Table 7. Based on the sum of 119.59 - 126.99 GW, taken from the countries' individual targets and the 120 GW from a joint statement at the North Sea Summit (De Croo et al., 2023), 1̃20 GW were considered the optimistic best-case scenario for 2030. Given the significant uncertainty and political ambition behind these numbers, the total amount of 300 GW by 2050 was considered rather unrealistic. Assuming that this can be considered more of a direction and investment signal, a slightly less optimistic outlook was adopted. After consultation with an expert, the numbers in Table 8 were considered as realistic enough to be a starting point for discussions and further quantitative research. It needs to be stressed at this point that caution should be exercised when considering political targets, due to the political games and reasons going beyond scientific knowledge being involved in stating public numbers.

Table 7: *Planned capacity from offshore wind in North Sea by country*[3]

	Netherlands	**Germany**	**Belgium**	**Sweden**	**Norway**	**UK**	**Denmark**	**Sum**	**Ostend Declaration**
2030	21.58 GW	28.61 GW	5.4 - 5.8 GW	5 GW*	?**	46 GW	3 - 10 GW	119.59 - 126.99 GW	120 GW
2040					30 GW				
2050									300 GW

Table 8: *Comparison of capacity produced by offshore wind in the scenarios*[4]

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2045	125 - 150 GW	175 - 225 GW	125 - 175 GW	100 - 125 GW

---

[3] *The official number for Sweden is 15 GW for North Sea and Baltic Sea combined, more specific numbers for Sweden's part of the North Sea could not be found. Because of the small size of Sweden's North Sea part, 5 GW were assumed to be realistic.**For Norway, only a capacity target for 2040 could be found and due to its current lack of offshore wind, capacity estimates for 2030 are challenging. Sources: Ministry of General Affairs, 2020; FPS Economy, 2023; Danish Energy Agency, 2020; Department for Energy Security and Net Zero and Department for Business and Trade, 2023; Deutsche WindGuard, 2022; WindEurope, 2022b; WindEurope, 2022c;Swedish Agency for Marine and Water Management, 2022; De Croo et al., 2023

[4] For Scenario 1 and Scenario 4, a conservative estimate based on the planned capacity was taken, with Scenario 1 slightly above the countries' capacity targets stated above and Scenario 4 slightly below these targets. Due to the negative outlook for offshore wind production in these scenarios, a smaller range was given than in the other two scenarios. After consultation with an expert, Scenario 2 and 3 were

If a strong offshore system is producing more electricity or offshore hydrogen for the onshore system, the niche development of small nuclear reactors is limited. Only in case of a strong focus on national security, it becomes an alternative to support decentralised grids in a local context. Thus, they should not seen as a niche innovation that would inhibit the growth of the North Sea offshore energy system.

Carbon Capture and Storage is mainly driven by more energy demand due to increased operations of oil and gas companies. The only scenario were it develops past the niche status and emerges into the regime level given higher electricity demand is that of strong regulations for carbon emissions and societal pressure on oil and gas companies to transition towards a more sustainable business model.

AI developments play a significant role in all scenarios. It is a driver for automation of the offshore system, resulting in cost reductions and safer operations for all actors, including oil and gas. Moreover, AI developments stimulates demand flexibility, another development with an impact on the North Sea offshore energy system across the scenarios. For the offshore system, demand flexibility is seen to reduce the pressure on the transmission operators and also mitigate supply chain issues to a certain degree.

In the scenarios with less demand flexibility, storage becomes more important, with hydrogen one potential alternative if storage technology is not increasing fast enough due to insufficient investment.

The role of hydrogen for the offshore system is observed across the scenarios as critical, if the technology develops past the niche level. It can also be seen that it is possible for the offshore energy system to flourish without hydrogen, if government policies and public support align to drive forward offshore growth. Blue hydrogen was able to create a technological lock-in in one scenario to prevent the development of green hydrogen out of its niche, due to its abundance and cheap supply. However, in another scenario, blue hydrogen supply was able to stimulate an industry transition towards hydrogen, thereby driving demand, from which green hydrogen profited. Storage of hydrogen are an area of concern, whether this happens in salt caverns or old gas fields depends also on public acceptance. Moreover, green hydrogen imports from Spain, Portugal and Northern Africa can prove to become a viable alternative to hydrogen production in or around the North Sea.

Cybersecurity and standardisation are factors that were shown to be critical for the offshore energy system. Especially if unsolved, both can result in a slowdown of the offshore developments. Another crucial factor for the North Sea offshore energy system was supply chain, with a large role in all scenarios.

---

deemed to be of higher uncertainty regarding the range. The target of 300 GW stated in the Ostend Declaration was considered barely in reach for Scenario 2 due to its highly ambitious nature. Source: based on expert input and Ministry of General Affairs, 2020; FPS Economy, 2023; Danish Energy Agency, 2020; Department for Energy Security and Net Zero and Department for Business and Trade, 2023; Deutsche WindGuard, 2022; WindEurope, 2022b; WindEurope, 2022c; Swedish Agency for Marine and Water Management, 2022; De Croo et al., 2023

Disruptions or reshoring attempts of parts of the supply chain, proved to be costly for the long-term development of the offshore system.

One scenario demonstrated the possibility of planned outages, that can result in beneficial outcomes for the transmission system operators and the demand side alike. In that scenario, it gives TSOs the time for repair work while not disrupting electricity needs by industry and consumers, at the same time alleviating grid congestion issues. Proving to be advantageous for both the offshore and onshore system in the long-run.

5.3 Discussion

A finding that has emerged is that the offshore system is strongly influenced by the developments in the onshore system. The factors supply chain, grid congestion and demand flexibility are located mainly onshore. The global nature of the supply chain reduces the level of control that individual actors in the North Sea offshore energy system possess over it. However, all actors are affected if the supply of jack-up barges, maintenance vessels, steel for the construction of infrastructure or magnets and raw materials is for offshore wind is lacking behind demand. An alternative that can prove relevant for GFO-O is to initiate a cooperation with other actors for sharing vessels. This can reduce the competition and create win-win situations in the face of scarcity of these highly-demanded special-purpose vessels.

The scenarios show that the supply chain remains a crucial factor also for potential future states of the system and can become a make-or-break point for renewable energy in the North Sea. Any attempts to reshore parts of the supply chain will take years to alleviate the pressure. Moving parts of the supply chain away from countries like China comes at high costs. It requires significant amounts of time as well, particularly due to their quasi-monopoly on the magnets for wind turbines, for example. Given the rapid developments in the North Sea, this time might prove too long. It can disincentivise investment, therefore causing long-term damage to the build-out of offshore wind due to the long-term planning horizon and required investment stability of offshore infrastructure. For GFO-O, this implies strategic investments into critical materials but also entails a dependence on other actors that is hard to break away from, even if anticipating developments correctly.

Grid congestion and demand flexibility are also essential for the North Sea offshore energy system. Grid congestion can be another breaking point for developing renewable energy in the North Sea, as too much congestion will lead to government policies focusing more on the onshore system. This will remove the current investment security due to strong support by government policies and can draw long-term investment away from the North Sea. Increased demand flexibility can be considered a buffer not only for congestion issues in the transmission grid but also for a slow down in offshore wind build-out or supply chain issues. A certain degree of independence of the onshore system will allow more flexibility for the offshore system to deal with bumps on the road towards the current capacity targets without immediately losing government support or public acceptance. The development of demand flexibility can benefit GFO-O in the long-run as it reduces the pressure on the operation and maintenance activities. Thereby, not only anticipation but also possibly stimulation of demand flexibility could prove profitable in the longer term.

AI developments are a driver for multiple factors, including demand flexibility and digitalisation. Most critical is its role as an enabler for niche innovations such as automation, robotics, and virtual power plants, which can accumulate and result, for example, in digital twins of converter platforms or wind turbines, enabling real-time monitoring and significantly enhancing the efficiency of operations and maintenance, reducing the need to go offshore and, therefore, also drive down costs. Another niche amplified by AI developments is predictive maintenance. These aspects have the potential to emerge from the niche level and disrupt the regime, enforcing a change of how the system is currently operated. With all the hype surrounding AI developments, its energy requirements due to data centres should not be overlooked. As one of the most dynamics developments with impacts on the offshore as well as the onshore system, AI developments will be critical for GFO-O's operations moving forward. Therefore, building capacities in-house and staying updated is essential to not be left behind.

Based on the scenarios, small nuclear reactors seem less influential for the overall development of the North Sea offshore energy system than initially assumed after the discussions with experts, the current development of the technology and based on the backing of the European Union. The impact on GFO-O can be considered negligible at this point unless there are major breakthrough in the near future.

Offshore developments focus mainly on technological innovations such as energy hubs, standardisation, market design, and wind park developments. Wind parks are moving further offshore, increasing in size and number, requiring longer subsea cables resulting in more critical infrastructure in the North Sea. On the one hand, this increases the potential damage from hypothetical physical attacks; on the other hand, moving further offshore makes operations more expensive. Especially for transmission system operators, either longer subsea cables must be laid to wind farms, potentially even floating ones, complicating the connection, or platforms need to move further offshore, implying longer transport routes for helicopters. This increases vulnerability in the face of extreme weather events such as strong storms. The vulnerability of the offshore system can be predicted to increase with a certain level of confidence. Thus, the impact of these developments on GFO-O will most likely be felt in the workforce, with additional skills requirements and higher cost implications.

Energy hubs and standardisation are two niche developments that have yet to prove themselves. There exists strong confidence that energy hubs are the future of the North Sea offshore energy system and the scenarios point in that direction as well, however, there still exists technical challenges as well as the question of market design. Drawing on the insights from literature and scenarios, a separate nodal market design seems to be more likely for the future, also considering the developments of AI as an enabler, however, such a design would disrupt the current regime and implications especially for electricity pricing, also for TSOs, are unclear. With the 2GW-program by TenneT being a realistic candidate to become the standard for interconnection, GFO-O is well positioned to benefit from in-house knowledge and can start planning for the workforce required to operate and maintain these platforms.

Moreover, national energy security can either be a driver of offshore developments, as seen in some scenarios, or an inhibitor by reducing interconnection and cooperation. GFO-O can have some lobbying influence on political decision makers to maintain the focus on the offshore system, but more realistically, this is up to other departments within TenneT and the outcomes are uncertain.

Hydrogen is still surrounded by uncertainty, irrespective of its supposed need for the future energy system in the North Sea. Will it mature in time? Where will it be produced, onshore or offshore, and who can produce it most effectively? Can it become economically viable? Is investment in green or blue hydrogen preferred in the short-term to reach green hydrogen in the long-term? These questions need to be answered before it can be successfully integrated into the energy mix, and it is far from certain that it will eventually play a significant role. Planning for a possible hydrogen future, also on platforms, can position GFO-O well in case that this technology manages to make the leap from the niche level.

Cybersecurity is currently a niche topic, not much talked about in the literature, but its significance for the future offshore system is undeniable from the scenario analysis. One reason why it is not on top of mind might be that there has been no large cybersecurity breach so far, creating media attention and raising awareness for the topic. It can be said, that it requires particular attention given the increasing interconnection of the offshore system and its increasing digitalisation. Given the nature of the impact of cyber attacks and the possible ripple effects, increasing cybersecurity measures and placing the emphasis on preventing them to the extend possible seems to be a worthwile investment for GFO-O. Especially bearing in mind that it operates cricital infrastructure with high relevance for society.

Multi-use of space can be seen as the future of the North Sea offshore energy system. Given that many different actors have diverse interests at stake, the most promising solution is to bring all stakeholders together and find amicable results. The inclusion of ecology is as important as adding the military with its increased presence into such considerations. Discussion forums are an effective way not only to stay informed about recent developments but also to continue a stakeholder dialogue and prevent conflict proactively for GFO-O.

It became clear that to successfully grow the North Sea offshore energy system and link it to the onshore grid; there is no way around integrating municipalities in the process. The top-down approach of governments, deciding where the onshore-offshore connections are built, is likely to spark public resistance against offshore development. One strong advantage of the offshore system, particularly offshore wind over onshore wind, is less opposition from the public as it is 'not in their backyard'. This advantage would be undermined by antagonising municipalities and, therefore, reducing public acceptance by leaving out municipalities in the decision process. Positive examples of inclusive approaches can be seen, for example, in Finland. Communication between all stakeholders and including the public in decision-making is key for the energy transition to succeed. The implications for GFO-O of this insight are rather small as other departments within TenneT are more likely to deal with this.

5.4 Interim Summary

Offshore developments are intricately linked to onshore system progress. Factors like supply chain, grid congestion, and demand flexibility play a critical role in the growth of the offshore system. AI advancements are transformative, driving automation and niche innovations, such as predictive maintenance. These developments have the potential to disrupt the current regime. The role of hydrogen in the future energy mix remains uncertain. While its importance is acknowledged, questions about its maturity, production methods, and economic viability remain. Preparing for a possible hydrogen future is crucial for the offshore sector. Cybersecurity emerges as a critical concern with the increasing interconnection and digitalisation of the offshore system. Proactive investment in cybersecurity measures is essential to safeguard critical infrastructure. Embracing multi-use of space and fostering stakeholder dialogue, including ecological considerations, can pave the way for the development of the offshore system. The involvement of municipalities in decision-making processes is crucial for public acceptance and the success of the energy transition. Inclusive approaches can mitigate public resistance and enhance cooperation.

6 Conclusion and recommendations

In conclusion, the current regime in the North Sea offshore energy system is under pressure by both landscape factors and niche development. Cracks and tensions develop that open up the regime and make it more susceptible to changes. These changes can emerge from niche developments such as hydrogen, demand flexibility, or standardisation. Another origin of these changes can come from the landscape level, with factors such as national energy security, climate change or global supply chains altering the set of rules that govern the regime. Multi-use of space will increase in the future and determine the interactions between the different actors in the system. Incumbent actors such as the oil and gas sector are clinging to power and using lobbying tactics to continue operations within the current regime.

Orsted has the strongest position in the actor network and the potential to influence the direction of change by leveraging its network. Moreover, TenneT's GFO-O has a critical role in the network as the TSO that has the most control over the flow of information, shaping, for example, the standardisation niche developments in its favour. Suppose GFO-O is able to become adaptive in the face of the uncertain developments of the North Sea offshore energy system. In that case, it can play a strong role in providing security of energy supply to the onshore system by fulfilling its transmission tasks. This will contribute to solving the current transmission bottleneck between offshore production and onshore electricity consumption and, thereby, facilitate the European energy transition.

Based on the niche development, the future energy system in the North Sea could potentially look like the one displayed in Figure 24.

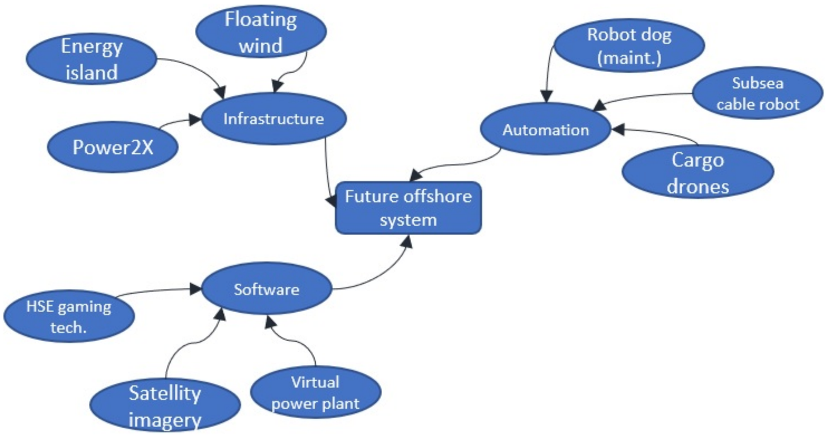


Figure 24: *Future North Sea energy system. Source: own elaboration*

6.1 Answering the research questions

Main research question

How does the application of an Extended Multi-Level Perspective (E-MLP) framework enhance the understanding of the complex socio-technical and uncertain dynamic nature of the North Sea offshore energy system, thereby informing GFO-O´s strategy to facilitate the energy transition?

To answer the main research questions, the four sub-questions will be answered sequentially.

Sub-question 1

What is an Extended Multi-Level Perspective framework?

The E-MLP framework is used to analyse socio-technical system in the light of transitions. it combines MLP with a PESTLE analysis, an actor analysis, and SNA to disect the system into landscape, regime and niche level and analyse each level in more detail than the application of only MLP would provide. Thereby, a holistic understanding of a static socio-technical system can be achieved. However, E-MLP goes further by combining exploratory scenario planning and socio-technical scenarios to draw different futures for the system and depict it in the light of uncertainty to examine its dynamic nature. Having analysed a socio-technical system holistically in a static and dynamic manner with E-MLP, this can provide valuable input for policy recommendations.

Sub-question 2

What are the main characteristics of the North Sea offshore energy system captured by the use of the extended multi-level perspective framework?

On a landscape level, the main factors are national energy security, electricity demand, ecological impact, interconnection, climate change and the supply chain.

Within the regime level, conflicts exist between the incumbent actors in regard to spatial planning. An outdated market design within the user and market regime is not keeping up with the current developments in energy hubs and cross-national interconnection. The market design also fails to incorporate the increasing share of renewable energy production from the North Sea. Current training of the available workforce is lacking behind the requirements, especially in regards to digital skills. The use of power, especially successful lobbying by the oil and gas sector, threatens the European energy transition, leading to disadvantageous government policies. Moreover, governments are using their power in a way that is creating too ambitious North Sea capacity targets, threatening industry and public support. Technological challenges address the uncertainty of proposed future system components such as meshed offshore grids. Public acceptance of offshore renewable energy is critical to the socio-cultural regime. The science regime encompasses ongoing studies on the ecological impacts of offshore energy infrastructure in the North Sea. Within the policy regime, government policies and ambitions are a key driver for developments in the North Sea. Moreover, current regulations and long permitting procedures limit offshore wind build-out.

The most relevant niches are carbon capture and storage, cybersecurity, small nuclear reactors, hydrogen, standardisation, demand flexibility, and storage. One important niche learning concerns the uncertainties surrounding hydrogen, where and in what form to use it best. Discussion forums such as the North Sea Consultation bring together all stakeholders to share learning and update each other on relevant developments. Niche expectations encompass the high expectations for hydrogen to become a relevant factor in the future energy system; the same applies to energy hubs.

Sub-question 3

Why is GFO-O a key player in the context of the North Sea offshore energy system?

The transmission aspect, GFO-O's core task, is critically relevant for linking the North Sea offshore energy system to the onshore and onshore grid. The actor analysis shows that GFO-O has significant resources and a strong interest in the North Sea offshore energy system. From the SNA, it can be seen that among all TSOs, TenneT has the highest betweenness centrality and a comparatively high closeness centrality, enabling it to share information in the network quickly while controlling the flow of information.

Sub-question 4

What are plausible socio-technical scenarios capturing the evolution of the North Sea offshore energy system in the next 15 years?

Four different scenarios depict possible futures of the system. A strong dependence on the onshore system is common for all of them. Depending on the consistency and focus of government policies on the North Sea offshore energy system and the evolution of electricity demand, a strongly interconnected renewable energy system being the main source of electricity for the offshore system is as plausible as an offshore system dominated by oil and gas production. Drivers for the latter scenario are supply chain issues for offshore renewable energy and inconsistent government policies, focused on the national security of energy supply and the public preferring cheap fossil fuel energy and blue hydrogen over variable and, therefore, expensive renewable offshore energy. Another plausible socio-technical scenario shows strong collaboration between the oil and gas sector and offshore renewable energy, driven by strict carbon regulations that leads to Europe becoming the world leader in exporting green hydrogen from offshore production. Additionally, one scenario depicts a struggling offshore energy system due to inconsistent policies, public resistance against top-down approaches, supply chain issues and the maturation of small nuclear reactors and onshore hydrogen supporting decentralised onshore grids, less dependent on offshore electricity.

Possible capacity ranges for offshore wind produced in the four scenarios by 2045 are:

- Scenario 1: 125 - 150 GW
- Scenario 2: 175 - 225 GW
- Scenario 3: 125 - 175 GW
- Scenario 4: 100 - 125 GW

Sub-question 5

Taking into account the static and dynamic characteristics of the North Sea offshore energy system, how can GFO-O adapt its strategy in the face of uncertainty to perform its core tasks and facilitate the energy transition?

GFO-O can leverage its network to influence standardisation processes by other actors and drive its 2 GW program as the standard for offshore grid connections in the North Sea. Furthermore, investing in automation, digitalisation, and a skilled workforce will help GFO-O deal with future challenges resulting from the current landscape and niche developments. Monitoring AI developments and growing in-house capacities are of critical importance. Additionally, reshoring parts of the material supply chain, such as vessel production or even pursuing vessel-sharing concepts with other actors to reduce the uncertainty of material supply should be a priority for GFO-O. Moreover,investigating the integration of hydrogen into its business model and reconsidering the necessity of electricity supply 100% of the time, when the introduction of rolling outages could prove beneficial for GFO-O and society, will help GFO-O to adapt its strategy and facilitate the energy transition.

6.2 Academic contribution

This thesis introduces a new research framework, E-MLP and applies it to the case study of GFO-O, the operations and maintenance department of a transmission system operator in the North Sea offshore energy system. This new framework enhances MLP by adding a detailed analysis of the factors affecting the system, adding the case study with a detailed analysis of the landscape to the body of MLP studies, as demanded by Andrews-Speed. E-MLP and this thesis also contribute to the literature on design for energy infrastructure, presented by Scholten and Künneke (2016) by analysing the energy infrastructure across multiple dimensions.

By adding an actor analysis and SNA, the regime and niche level of the socio-technical system are more extensively studied than MLP allows. Going beyond the analysis of rules and institutions governing the regime level (Geels, 2004b), E-MLP thereby allows the study of interactions between the actors, furthering the understanding of the socio-technical system. The actor analysis also adds to institutional theory by identifying values shared among the actors in the system, defined by Scholten and Künneke (2016) as informal institutions.

Introducing a tweak to SNA as it was presented by Hermans and Cunningham (2018), enables the actor analysis to handle the regime level and the niche level. This is achieved by creating a second network graph in which specific topics such as AI, floating wind, or projects, and consortia are considered as a node and therefore displayed in the graph. As a result, a visual analysis of the niche developments arising from the SNA is made possible. The actor analysis analyses the regime level, while the SNA provides information about interactions on the regime level as well as innovations from the niche level.

Furthermore, this thesis offered a novel approach to scenario analysis by combining the framework of exploratory scenario planning presented by Enserink et al. with the concept of socio-technical scenarios, described in Elzen et al. (2004a). Using the factors identified by PESTLE, SNA and expert interviews as driving forces to create four distinct scenarios, which are then developed using the benefits of socio-technical scenarios can add significant value to the body of literature on scenarios.

Moreover, the North Sea offshore energy system has not been studied in a holistic way as a socio-technical system. Thereby, this thesis contributed to create a a first understanding of this critical system for the European energy transition. This can and should be expanded on by future studies. Furthermore, it provides policy makers with theory-informed insights that can be leveraged to design inclusive policies benefiting society.

6.3 Recommendations for GFO-O

Based on the findings above, the following policy recommendations for GFO-O are drawn:

To mitigate supply chain challenges and material supply uncertainties, reshoring the parts of the supply chain, wherever possible, should be planned already. An example is evaluating whether special purpose vessels can be manufactured in Europe, for example Rotterdam instead of in Singapore. Thereby, material dependence on uncertain global supply chains, vulnerable to shocks, can be mitigated and operations and maintenance tasks improved due to availability of critical materials. Additionally, the possibility of cooperating with other actors to share special-purpose vessels should be explored to mitigate the uncertainties of future supply chain developments, depicted in the scenarios.

To account for digitalisation, more skilled workers are needed. Digital skills will be in high demand, as the scenarios and factors show, and the prerequisite for GFO-O's future tasks. Moreover, other actors are already ahead in the development of their digital capacities, such as Statnett or National Grid, as was seen in the SNA. Thus, an emphasis must be on finding and bringing these talented people into GFO-O. For this, partnerships and a shared professorship with Dutch Technological Universities should be pursued to create a pipeline of bright, digitally skilled talent, following the example of Statnett. Moreover, training programs should be started to up-skill existing workers and transition the focus towards a software-first approach. This will enable GFO-O to deal effectively with cybersecurity, create digital twins and achieve real-time operations, reducing costs, increasing efficiency, and improving its operations.

If the 2 GW program is to rise from the niche level to become the new standard for an interconnected offshore grid, this would further solidify TenneT's strong position, as TenneT can spread information in its extensive network and acquire new partners and suppliers. For this, leveraging the network and increasing it is crucial by joining other standardisation discussion forums such as Eurobar. This would prevent having to deal with different connection types depending on who the current project partner is. Following the scenario analysis and SNA, GFO-O is well informed to already invest in the workforce required to operate the 2GW platforms as it seems to become the standard in the North Sea offshore energy system.

Investment in maintenance robots and cargo drones should be conducted to reduce the need to go offshore as much as possible. By increasing the automation of offshore operations, the safety of human life is increased, and operations become more efficient. This should be combined with the investment in in-house AI capabilities and potentially a monitoring system to prevent being left behind by the rapid pace of AI developments, which are also a driving force for demand flexibility. Early investment in AI therefore seems to be profitable in the long-term.

Based on the scenario with rolled outages, an investigation should be started about the necessity for a 24/7 electricity supply by a TSO. Given the right circumstances, research should be conducted on whether the reliability of energy supply for 80-90% of the time is also sufficient to meet demand. Particularly when introducing rolling outages during two hours in the night, a cost-benefit analysis should be performed to assess if the decrease in grid congestion, reduced investment requirements and maintenance benefits outweigh the costs and whether this could be socially accepted. Provided that demand flexibility is increasing, there might be a case to be made that rethinking the current operations and not only increasing transmission capacity but refocusing on quality, also to alleviate pressure on the workforce, can be better for GFO-O's operations and society.

A study should be initiated to investigate the potential of producing green hydrogen on GFO-O's converter platforms, given the maturation of hydrogen. Alternatively, a potential partnership with the Dutch and German gas TSO, Gasunie, should be explored to see whether GFO-O can play a role in hydrogen transmission, changing its core business of electricity transmission.

Orsted's development should be closely monitored due to its strong actor network position and global connectivity. In case of changing regulations that enable Orsted to take over transmission tasks, this could impact GFO-O's tasks.

6.4 Recommendations for Policymakers

Driving the multi-use of space should be a priority for policy makers. For this, the studies from the multi-frame project can prove valuable insights (Lukic et al., 2023). This line of research should be closely followed and pilot studies initiated that apply lessons learned from this research on how to effectively apply multi-use of space.

The military is bound to become a more relevant actor in the future in the North Sea, due to the recent geopolitical developments. Establishing a dialogue what the implications are and creating awareness about phyisal and cyber threats to North Sea offshore energy infrastructure can be beneficial for all actors involved.

Incentivising demand flexibility on a consumer level can reduce the burden on the offshore system and further support renewable energy production in the North Sea. Therefore, awareness campaigns and possible market incentives can prove vital in the long-term.

6.5 Limitations

It should be stated at this point that there are potential limitations to the selected approach, as stated below:

The complex nature of the problem at hand required the usage of multiple analysis tools, ranging from SNA, PESTLE, the multi-level framework and socio-technical scenarios. Due to time constraints, going into detail for one or each of these tools proved to be not feasible. Therefore, valuable insights might have been missed that for example a study only focused on the actor network in the North Sea with an in-depth application of only SNA might have provided.

Overall, only publicly available data has been used to prevent issues resulting from confidentiality clauses. This limited the pool of information to draw from. On the other hand, it enabled better study repeatability, which would have been impossible if integrating highly confidential data from TenneT, for instance.

The interviews were semi-structured, based on the experts' views on external factors and future states of the system, without including the findings of this thesis' PESTLE analysis to prevent bias in the results. This has limited the answers to what was on top of the experts' minds. A discussion based on the literature findings could have been more thought-provoking and insightful. However, for this thesis, validation of the literature finding was considered more relevant than extensive discussions with experts.

The scenarios were created based on theory and the expert's findings, combined with some degree of creativity by the author. However, a certain path dependence is unavoidable, which might have led to a stronger extrapolation of current trends into the future than intended. As the future is inherently uncertain, an outlook until 2050, with a complete freedom to explore possibilities that might sound completely impossible today, could also provide interesting insights into the system, as we simply know what we don't know.

The PESTLE analysis is limited by time constraints and the keywords that were used initially. Other initial keywords might have provided other papers from which to snowball. Furthermore, only a very limited amount of the actual knowledge and literature could be examined in the given time, meaning that the PESTLE findings are everything but conclusive, as there is so much more knowledge available, especially considering that only literature in English, German and to a certain degree Dutch could be analysed by the author. Adding other languages to the research might change the outcome significantly.

The choice of experts for the thesis was mainly from the Netherlands and Germany, even though some were from other countries bordering the North Sea. This can limit the perspective slightly; a larger number of experts, also from the UK and Norway would enhance the results.

In the SNA, the links are undirected. When considering shareholder relationships, for example, this is a limitation as it is not immediately clear from the network graph which of the two actors holds shares of the other. Furthermore, ties and nodes are unweighted, thereby additional information is missed out on. Another limitation of the SNA is the focus on the key players only. As a result, many relevant actors are not analysed in more detail, which could have provided additional information for example about niche developments.

The capacity numbers are based on a lot of assumptions and serve more as a rough direction than a precise calculation. Due to the strong uncertainty and lack of data for the time in between now and 2045, it was only focused on numbers for 2045 instead of following the capacity development over time, which could provide more insights into the developments. With the focus on the North Sea offshore energy increasing and potentially more studies being conducted, hopefully more data becomes available. This data can then be leveraged to create more accurate calculations.
In the newest draft of the German grid development plan, 50Hertz, previously only tasked with transmission business in the Baltic Sea, has been assigned a role to develop converter platforms in the North Sea as well (Übertragungsnetzbetreiber, 2023). Including 50Hertz in the analysis was beyond the scope of this thesis but provides the material for future studies, especially because it is part of the Elia (the Belgian TSO). Thus, interesting dynamics in terms of cooperations might result in the future.

6.6 Extensions and future work

When considering the SNA, adding weights (monetary or political) to the nodes will change the outcome of the social network analysis. The weight in betweenness centrality is in the nominator; thus, an attached weight will have a bigger impact on betweenness centrality than on closeness centrality where the weight is in the denominator. Weights can be for example based on the market capitalisation of an actor, or on the number of political connections.

The subject of future studies can be to study the oil and gas sector more closely. For this thesis, a certain level of homogeneity was assumed. However, future research could consider the oil and gas sector in a heterogeneous way, analysing Equinor, Shell, and BP separately in the actor analysis and the SNA. Especially when it comes to technological development and automation, there are many insights to be gained due to their extensive experience in offshore operations and significant R&D budgets. Including more actors in the SNA will increase its meaningfulness and the information gained about niche developments. For this, the SNA data from this thesis can be used as a starting point and expanded on.

Another addition can be to take one factor, for example, supply chain, and analyse this particular factor in the context of the North Sea offshore energy system. Conducting an actor analysis of the most relevant actors in the offshore supply chain, performing an SNA and PESTLE analysis of what factors impact the supply chain. Complementing this by the chosen scenario analysis framework from this study can function as a test case on how much detail E-MLP can provide.

In this thesis, E-MLP was developed and applied to the North Sea offshore energy system. To test its applicability, the study of another system with similar features, such as the Baltic Sea offshore energy system should be conducted. This can provide meaningful insights into possible areas of improvement, also regarding the use of SNA and actor analysis within E-MLP. In such a study, the feasibility of performing a PESTLE analysis within each level of MLP can be tested, to assess wheter this could improve E-MLP.

Another topic of future studies can be applying E-MLP to other regimes in the energy transition, such as the heating or mobility sector. Thereby, the method can be tested and enriched.

The scenario capacity numbers are a starting point for quantitative scenario modelling and can serve as a ballpark number to start more precise calculations for statistical modelling providing more reliable numbers. Especially the development over time would be an interesting topic for statistical modelling or to apply decision-making under deep uncertainty.

Bibliography

Achinas, S., Horjus, J., Achinas, V., & Euverink, G. J. W. (2019). A pestle analysis of biofuels energy industry in europe. *Sustainability*, *11*(21), 5981. https://doi.org/10.3390/su11215981

Acosta, C., Ortega, M., Bunsen, T., Koirala, B., & Ghorbani, A. (2018). Facilitating energy transition through energy commons: An application of socio-ecological systems framework for integrated community energy systems. *Sustainability*, *10*(2), 366. https://doi.org/10.3390/su10020366

Agency, E. E. (2018). *Perspectives on transitions to sustainability* (Vol. No 25/2017). https://doi.org/10.2800/332443

Ahmad, T., & Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Reports*, *6*, 1973–1991. https://doi.org/10.1016/j.egyr.2020.07.020

Amprion GmbH. (2021). European tsos launch eurobar initiative for standardised offshore grids. https://www.amprion.net/Press/Press-Detail-Page_31552.html

Andrews-Speed, P. (2016). Applying institutional theory to the low-carbon energy transition. *Energy Research & Social Science*, *13*, 216–225. https://doi.org/10.1016/j.erss.2015.12.011

Antenucci, A., Del Crespo Granado, P., Gjorgiev, B., & Sansavini, G. (2019). Can models for long-term decarbonization policies guarantee security of power supply? a perspective from gas and power sector coupling. *Energy Strategy Reviews*, *26*, 100410. https://doi.org/10.1016/j.esr.2019.100410

Arcelay, I., Goti, A., Oyarbide-Zubillaga, A., Akyazi, T., Alberdi, E., & Garcia-Bringas, P. (2021). Definition of the future skills needs of job profiles in the renewable energy sector. *Energies*, *14*(9), 2609. https://doi.org/10.3390/en14092609

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°c global warming could trigger multiple climate tipping points. *Science (New York, N.Y.)*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Attar, M., Repo, S., & Mann, P. (2022). Congestion management market design- approach for the nordics and central europe. *Applied Energy*, *313*, 118905. https://doi.org/10.1016/j.apenergy.2022.118905

Balachandran, A., de Beer, J., James, K. S., van Wissen, L., & Janssen, F. (2020). Comparison of population aging in europe and asia using a time-consistent and comparative aging measure. *Journal of aging and health*, *32*(5-6), 340–351. https://doi.org/10.1177/0898264318824180

Barichella, A. (2018). Cybersecurity in the energy sector: A comparative analysis between europe and the united states. https://www.ifri.org/sites/default/files/atoms/files/barichella_cybersecurity_energy_sector_2018.pdf

Bilgili, M., & Alphan, H. (2022). Global growth in offshore wind turbine technology. *Clean Technologies and Environmental Policy*, *24*(7), 2215–2227. https://doi.org/10.1007/s10098-022-02314-0

Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, *15*(2), 905–915. https://doi.org/10.1016/j.rser.2010.11.006

Biresselioglu, M. E., Demir, M. H., Demirbag Kaplan, M., & Solak, B. (2020). Individuals, collectives, and energy transition: Analysing the motivators and barriers of european decarbonisation. *Energy Research & Social Science*, *66*, 101493. https://doi.org/10.1016/j.erss.2020.101493

Blanco, M. I., & Rodrigues, G. (2009). Direct employment in the wind energy sector: An eu study. *Energy Policy*, *37*(8), 2847–2857. https://doi.org/10.1016/j.enpol.2009.02.049

Borges Posterari, J., & Waseda, T. (2022). Wave energy in the pacific island countries: A new integrative conceptual framework for potential challenges in harnessing wave energy. *Energies*, *15*(7), 2606. https://doi.org/10.3390/en15072606

Borowski, P. F. (2020). Zonal and nodal models of energy market in european union. *Energies*, *13*(16), 4182. https://doi.org/10.3390/en13164182

Brannstrom, C., Ewers, M., & Schwarz, P. (2022). Will peak talent arrive before peak oil or peak demand?: Exploring whether career choices of highly skilled workers will accelerate the transition to renewable energy. *Energy Research & Social Science*, *93*, 102834. https://doi.org/10.1016/j.erss.2022.102834

Buck, B. H., & Langan, R. (Eds.). (2017). *Aquaculture perspective of multi-use sites in the open ocean: The untapped potential for marine resources in the anthropocene*. Springer open. http://www.springer.com/

Buckendahl, C. W., Schraw, G. J., & McCrudden, M. T. (Eds.). (2015). *Use of visual displays in research and testing: Coding, interpreting, and reporting data*. Information Age Publishing.

Byravan, S., & Rajan, S. C. (2017). Taking lessons from refugees in europe to prepare for climate migrants and exiles. *Environmental Justice*, *10*(4), 108–111. https://doi.org/10.1089/env.2016.0026

Calado, G., & Castro, R. (2021). Hydrogen production from offshore wind parks: Current situation and future perspectives. *Applied Sciences*, *11*(12), 5561. https://doi.org/10.3390/app11125561

Campos, I., & Marín-González, E. (2020). People in transitions: Energy citizenship, prosumerism and social movements in europe. *Energy Research & Social Science*, *69*, 101718. https://doi.org/10.1016/j.erss.2020.101718

Cholewa, M., Mammadov, F., & Nowaczek, A. (2022). The obstacles and challenges of transition towards a renewable and sustainable energy system in azerbaijan and poland. *Mineral Economics*, *35*(1), 155–169. https://doi.org/10.1007/s13563-021-00288-x

Clemente, J. (2010). Energy as a foundation of modern life. *35*, 33–48. https://www.jstor.org/stable/24812713

Cohen, J. J., Reichl, J., & Schmidthaler, M. (2014). Re-focussing research efforts on the public acceptance of energy infrastructure: A critical review. *Energy*, *76*, 4–9. https://doi.org/10.1016/j.energy.2013.12.056

Corona, L., Mochon, A., & Saez, Y. (2022). Electricity market integration and impact of renewable energy sources in the central western europe region: Evolution since the implementation of the flow-based market coupling mechanism. *Energy Reports*, *8*, 1768–1788. https://doi.org/10.1016/j.egyr.2021.12.077

Correljé, A., & van der Linde, C. (2006). Energy supply security and geopolitics: A european perspective. *Energy Policy*, *34*(5), 532–543. https://doi.org/10.1016/j.enpol.2005.11.008

Cristea, M., Noja, G. G., Stefea, P., & Sala, A. L. (2020). The impact of population aging and public health support on eu labor markets. *International journal of environmental research and public health*, *17*(4). https://doi.org/10.3390/ijerph17041439

Crivellari, A., & Cozzani, V. (2020). Offshore renewable energy exploitation strategies in remote areas by power-to-gas and power-to-liquid conversion. *International Journal of Hydrogen Energy*, *45*(4), 2936–2953. https://doi.org/10.1016/j.ijhydene.2019.11.215

Czako, V. (2020). *Employment in the energy sector: Status report 2020*. Publications Office of the European Union. https://doi.org/10.2760/95180

Dahl, I. R., Tveiten, B. W., & Cowan, E. (2022). The case for policy in developing offshore wind: Lessons from norway. *Energies*, *15*(4), 1569. https://doi.org/10.3390/en15041569

DAndrea, M., Gonzalez, M. G., & McKenna, R. (2021). Synergies in offshore energy: A roadmap for the danish sector. https://doi.org/10.48550/arXiv.2102.13581

Danish Energy Agency. (2020). Offshore wind in denmark by 2030. https://www.et.aau.dk/digitalAssets/897/897100_offshore-wind-in-denmark-by-2030---dea---october-2020.pdf

De Croo, A., Frederiksen, M., Macron, E., Scholz, O., Varadkar, L., Bettel, X., Rutte, M., Gahr Støre, J., & Sunak, R. (2023). Ostend declaration on the north seas as europe's green power plant: Delivering cross-border projects and anchoring the renewable offshore industry in europe. https://windeurope.org/wp-content/uploads/files/policy/position-papers/20230424-Ostend-Declaration-Leaders.pdf de Andres, A., MacGillivray, A., Roberts, O., Guanche, R., & Jeffrey, H. (2017). Beyond lcoe: A study of ocean energy technology development and deployment attractiveness. *Sustainable Energy Technologies and Assessments*, *19*, 1–16. https://doi.org/10.1016/j.seta.2016.11.001

Dedecca, J. G., Hakvoort, R. A., & Ortt, J. R. (2016). Market strategies for offshore wind in europe: A development and diffusion perspective. *Renewable and Sustainable Energy Reviews*, *66*, 286–296. https://doi.org/10.1016/j.rser.2016.08.007

Degraer, S., Carey, D. A., Coolen, J. W., Hutchison, Z. L., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography*, *33*(4), 48–57.

de Maere d'Aertrycke, G., Smeers, Y., de Peufeilhoux, H., & Lucille, P.-L. (2020). The role of electrification in the decarbonization of central-western europe. *Energies*, *13*(18), 4919. https://doi.org/10.3390/en13184919

Demirtas, O., Derindag, O. F., Zarali, F., Ocal, O., & Aslan, A. (2021). Which renewable energy consumption is more efficient by fuzzy edas method based on pestle dimensions? *Environmental science and pollution research international*, *28*(27), 36274–36287. https://doi.org/10.1007/s11356-021-13310-0

Demski, C., Butler, C., Parkhill, K. A., Spence, A., & Pidgeon, N. F. (2015). Public values for energy system change. *Global Environmental Change*, *34*, 59–69. https://doi.org/10.1016/j.gloenvcha.2015.06.014

Department for Energy Security and Net Zero & Department for Business and Trade. (2023). Offshore wind net zero investment roadmap. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1167856/offshore-wind-investment-roadmap.pdf

Deutsche WindGuard. (2022). Status des offshore-windenergieausbaus in deutschland: Jahr 2022. https://www.wind-energie.de/fileadmin/redaktion/dokumente/publikationen-oeffentlich/themen/06-zahlen-und-fakten/20230116_Status_des_Offshore-Windenergieausbaus_Jahr_2022.pdf

Diahovchenko, I., Kolcun, M., Čonka, Z., Savkiv, V., & Mykhailyshyn, R. (2020). Progress and challenges in smart grids: Distributed generation, smart metering, energy storage and smart loads. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, *44*(4), 1319–1333. https://doi.org/10.1007/s40998-020-00322-8

Díaz, H., & Guedes Soares, C. (2020). Review of the current status, technology and future trends of offshore wind farms. *Ocean Engineering*, *209*, 107381. https://doi.org/10.1016/j.oceaneng.2020.107381

Dighe, V. V., Gomez, J. F., Dussi, S., Poort, J., & Omrani, P. S. (2022). Digitalization of north sea energy systems. https://publications.tno.nl/publication/34640253/riR05s/dighe-2022-digitalization.pdf

Dong, J., Asif, Z., Shi, Y., Zhu, Y., & Chen, Z. (2022). Climate change impacts on coastal and offshore petroleum infrastructure and the associated oil spill risk: A review. *Journal of Marine Science and Engineering*, *10*(7), 849. https://doi.org/10.3390/jmse10070849

Edomah, N., Foulds, C., & Jones, A. (2017). Influences on energy supply infrastructure: A comparison of different theoretical perspectives. *Renewable and Sustainable Energy Reviews*, *79*, 765–778. https://doi.org/10.1016/j.rser.2017.05.072

Egging, R., & Tomasgard, A. (2018). Norway's role in the european energy transition. *Energy Strategy Reviews*, *20*, 99–101. https://doi.org/10.1016/j.esr.2018.02.004

Eicke, A., & Schittekatte, T. (2022). Fighting the wrong battle? a critical assessment of arguments against nodal electricity prices in the european debate. *Energy Policy*, *170*, 113220. https://doi.org/10.1016/j.enpol.2022.113220

Elzen, B., Geels, F., Hofman, P., & Green, K. (2004a). Socio-technical scenarios as a tool for transition policy: An example from the traffic and transport domain. In B. Elzen, F. W. Geels, & K. Green (Eds.), *System innovation and the transition to sustainability*. Edward Elgar Publishing.

Elzen, B., Geels, F. W., & Green, K. (2004b). *System innovation and the transition to sustainability*. Edward Elgar Publishing. https://doi.org/10.4337/9781845423421

Enserink, B., Bots, P., van Daalen, E., Hermans, L., Koppenjan, J., Kortmann, R., Kwakkel, J., Slinger, J., Ruijgh van der Ploeg, T., & Thissen, W. (2022). Policy analysis of multi-actor systems. https://doi.org/10.5074/T.2022.004

European Commission. (2000). *Green paper: Towards a european strategy for the security of energy supply*. Office for Official Publications of the European Communities.

European Commission (Ed.). (2019). *Clean energy for all europeans*.

European Commission. (2020). Green transition becomes reality in ii municipality, oulu region, finland. https://s3platform.jrc.ec.europa.eu/en/w/green-transition-becomes-reality-in-ii-municipality-oulu-region-finland.

European Commission. (2023a). Declaration on eu smr 2030: The role of research, innovation, education and training in the safety of small modular reactors (smrs) in the european union. https://research-and-innovation.ec.europa.eu/system/files/2023-04/ec_rtd_eu-smr-declaration-2030.pdf

European Commission. (2023b). Hydrogen. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

Fahey, L. (Ed.). (1998). *Learning from the future: Competitive foresight scenarios*. Wiley.

Fahy, F., Goggins, G., & Jensen, C. (2019). *Energy demand challenges in europe*. Springer International Publishing. https://doi.org/10.1007/978-3-030-20339-9

Fernández-Guillamón, A., Das, K., Cutululis, N. A., & Molina-García, Á. (2019). Offshore wind power integration into future power systems: Overview and trends. *Journal of Marine Science and Engineering*, *7*(11), 399. https://doi.org/10.3390/jmse7110399

Flynn, B. (2016). Marine wind energy and the north sea offshore grid initiative: A multi-level perspective on a stalled technology transition? *Energy Research & Social Science*, *22*, 36–51. https://doi.org/10.1016/j.erss.2016.08.009

FPS Economy. (2023). Belgian offshore wind energy. https://economie.fgov.be/en/themes/energy/belgian-offshore-wind-energy

Fuenfschilling, L., & Truffer, B. (2014). The structuration of socio-technical regimes—conceptual foundations from institutional theory. *Research Policy*, *43*(4), 772–791. https://doi.org/10.1016/j.respol.2013.10.010

Gamarra, A. R., Banacloche, S., Lechon, Y., & Del Río, P. (2023). Assessing the sustainability impacts of concentrated solar power deployment in europe in the context of global value chains. *Renewable and Sustainable Energy Reviews*, *171*, 113004. https://doi.org/10.1016/j.rser.2022.113004

García, P. Q., García Sanabria, J., & Chica Ruiz, J. A. (2021). Marine renewable energy and maritime spatial planning in spain: Main challenges and recommendations. *Marine Policy*, *127*, 104444. https://doi.org/10.1016/J.MARPOL.2021.104444

Garg, A., Naswa, P., & Shukla, P. R. (2015). Energy infrastructure in india: Profile and risks under climate change. *Energy Policy*, *81*, 226–238. https://doi.org/10.1016/j.enpol.2014.12.007

Gea-Bermúdez, J., Jensen, I. G., Münster, M., Koivisto, M., Kirkerud, J. G., Chen, Y.-k., & Ravn, H. (2021). The role of sector coupling in the green transition: A least-cost energy system development in northern-central europe towards 2050. *Applied Energy*, *289*, 116685. https://doi.org/10.1016/j.apenergy.2021.116685

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, *31*(8-9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2004a). From sectoral systems of innovation to socio-technical systems. *Research Policy*, *33*(6-7), 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Geels, F. W. (2004b). Understanding system innovations: A critical literature review and a conceptual synthesis. In B. Elzen, F. W. Geels, & K. Green (Eds.), *System innovation and the transition to sustainability*. Edward Elgar Publishing.

Geels, F. W. (2005). *Technological transitions and system innovations: A co-evolutionary and socio-technical analysis*. Edward Elgar. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=227192

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, *36*(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Genus, A., & Coles, A.-M. (2008). Rethinking the multi-level perspective of technological transitions. *Research Policy*, *37*(9), 1436–1445. https://doi.org/10.1016/j.respol.2008.05.006

Gils, H. C., Gardian, H., & Schmugge, J. (2021). Interaction of hydrogen infrastructures with other sector coupling options towards a zero-emission energy system in germany. *Renewable Energy*, *180*, 140–156. https://doi.org/10.1016/j.renene.2021.08.016

Goetz, E., & Shenoi, S. (Eds.). (2007). *Critical infrastructure protection* (Vol. 253). Springer US. http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1605183

Golroodbari, S., Vaartjes, D. F., Meit, J., van Hoeken, A. P., Eberveld, M., Jonker, H., & van Sark, W. (2021). Pooling the cable: A techno-economic feasibility study of integrating offshore floating photovoltaic solar technology within an offshore wind park. *Solar Energy*, *219*, 65–74. https://doi.org/10.1016/j.solener.2020.12.062

Göransson, L., Lehtveer, M., Nyholm, E., Taljegard, M., & Walter, V. (2019). The benefit of collaboration in the north european electricity system transition—system and sector perspectives. *Energies*, *12*(24), 4648. https://doi.org/10.3390/en12244648

Gusatu, Yamu, Zuidema, & Faaij. (2020). A spatial analysis of the potentials for offshore wind farm locations in the north sea region: Challenges and opportunities. *ISPRS International Journal of Geo-Information*, *9*(2), 96. https://doi.org/10.3390/ijgi9020096

Hafner, M., & Tagliapietra, S. (Eds.). (2020). *The geopolitics of the global energy transition* (1st ed. 2020, Vol. 73). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-030-39066-2

Hancher, L., Meeus, L., Nouicer, A., Reif, V., Belmans, R., Conti, I., Ferrari, A., Galdi, G., Kneebone, J., Olczak, M., Piebalgs, A., Pototschnig, A., Stampatori, D., & Schittekatte, T. (2022). *The eu green deal* (2022 edition, Vol. issue 2022, 06). European University Institute (EUI). https://fsr.eui.eu/publications/?handle=1814/75156

Hardy, S., Themelis, A., Yamamoto, K., Ergun, H., & van Hertem, D. (2023). Optimal grid layouts for hybrid offshore assets in the north sea under different market designs. https://doi.org/10.48550/arXiv.2301.00931

Hawk, C., & Kaushiva, A. (2014). Cybersecurity and the smarter grid. *The Electricity Journal*, *27*(8), 84–95. https://doi.org/10.1016/j.tej.2014.08.008

Hennig, R., Jonker, M., Tindemans, S., & de Vries, L. (2020). Capacity subscription tariffs for electricity distribution networks: Design choices and congestion management. *2020 17th International Conference on the European Energy Market (EEM)*, 1–6. https://doi.org/10.1109/EEM49802.2020.9221994

Hermans, L. M., & Cunningham, S. W. (2018). *Actor and strategy models: Practical applications and step-wise approaches* (1. published.). John Wiley & Sons Inc.

Heubaum, H., & Biermann, F. (2015). Integrating global energy and climate governance: The changing role of the international energy agency. *Energy Policy*, *87*, 229–239. https://doi.org/10.1016/j.enpol.2015.09.009

Hickel, J. (2019). Degrowth: A theory of radical abundance. *Real-World Economics Review*, *87*, 54–68.

Höjer, M., Ahlroth, S., Dreborg, K.-H., Ekvall, T., Finnveden, G., Hjelm, O., Hochschorner, E., Nilsson, M., & Palm, V. (2008). Scenarios in selected tools for environmental systems analysis. *Journal of Cleaner Production*, *16*(18), 1958–1970. https://doi.org/10.1016/j.jclepro.2008.01.008

Hoogma, R. (2002). *Experimenting for sustainable transport*. Taylor & Francis. https://library.oapen.org/bitstream/id/70e19091-1983-422f-897e-b4485805af8f/1005879.pdf

Huber, M., Dimkova, D., & Hamacher, T. (2014). Integration of wind and solar power in europe: Assessment of flexibility requirements. *Energy*, *69*, 236–246. https://doi.org/10.1016/j.energy.2014.02.109

Huss, W. R. (1988). A move toward scenario analysis. *International Journal of Forecasting*, *4*(3), 377–388. https://doi.org/10.1016/0169-2070(88)90105-7

Ibrion, M., & Nejad, A. R. (2023). On a road map for technology qualification, innovation and cost reduction in floating offshore wind: Learning from hywind and norwegian approach. *Journal of Physics: Conference Series*, *2507*(1), 012008. https://doi.org/10.1088/1742-6596/2507/1/012008

IEA. (2020). Renewables 2020. https://www.iea.org/reports/renewables-2020

Intergovernmental Panel on Climate Change. (2022a). Climate change 2022 mitigation of climate change. summary for policymakers. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf

Intergovernmental Panel on Climate Change. (2022b). Climate change 2022: Impacts, adaptation and vulnerability. contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change. https://www.researchgate.net/profile/Sina-%20Ayanlade/publication/362431678_Climate_Change_2022_Impacts_Adaptation_and_Vulnerability_W%20orking_Group_II_Contribution_to_the_Sixth_Assessment_Report_of_the_Intergovernmental_Panel_%20on_Climate_Change/links/62ea52343c0ea87887793180/Climate-Change-2022-Impacts-Adaptation-%20and-Vulnerability-Working-Group-II-Contribution-to-the-Sixth-Assessment-Report-of-the-%20Intergovernmental-Panel-on-Climate-Change.pdf

Jaatun, M. G., Bodsberg, L., Grotan, T. O., & Elisabeth Gaup Moe, M. (2020). An empirical study of cert capacity in the north sea. *2020 International Conference on Cyber Security and Protection of Digital Services (Cyber Security)*, 1–8. https://doi.org/10.1109/CyberSecurity49315.2020.9138865

Jansen, M., Duffy, C., Green, T., & Staffell, I. (2022). Island in the sea: The prospects and impacts of an offshore wind power hub in the north sea. *Advances in Applied Energy*, *6*, 100090. https://doi.org/10.1016/j.adapen.2022.100090

Jehling, M., Hitzeroth, M., & Brueckner, M. (2019). Applying institutional theory to the analysis of energy transitions: From local agency to multi-scale configurations in australia and germany. *Energy Research & Social Science*, *53*, 110–120. https://doi.org/10.1016/j.erss.2019.01.018

Kafas, A., Ripken, M., Kirsty, W., Billet, M., Sangiuliano, S., Ooms, E., & Scheffler, U. (2018). Status quo report on offshore energy planning provisions in the north sea region. https://northsearegion.eu/media/11129/northsee-offshore-energy-status-quo-main-report-final-version-120418.pdf

Kaiser, M. J. (2009). The impact of weather on offshore energy losses. *Energy Sources, Part B: Economics, Planning, and Policy*, *4*(1), 59–67. https://doi.org/10.1080/15567240701421864

Kaiser, R. (2014). *Qualitative experteninterviews*. Springer Fachmedien Wiesbaden.

Kang, J., & Guedes Soares, C. (2020). An opportunistic maintenance policy for offshore wind farms. *Ocean Engineering*, *216*, 108075. https://doi.org/10.1016/j.oceaneng.2020.108075

Kern, F., & Smith, A. (2008). Restructuring energy systems for sustainability? energy transition policy in the netherlands. *Energy Policy*, *36*(11), 4093–4103. https://doi.org/10.1016/j.enpol.2008.06.018

Kettle, A. J. (2016). Assessing extreme events for energy meteorology: Media and scientific publications to track the events of a north sea storm. *Energy Procedia*, *97*, 116–123. https://doi.org/10.1016/j.egypro.2016.10.033

Keupp, M. M. (Ed.). (2015). *The northern sea route: A comprehensive analysis*. Springer Gabler. https://doi.org/10.1007/978-3-658-04081-9

Khan, I., Zakari, A., Ahmad, M., Irfan, M., & Hou, F. (2022). Linking energy transitions, energy consumption, and environmental sustainability in oecd countries. *Gondwana Research*, *103*, 445–457. https://doi.org/10.1016/j.gr.2021.10.026

Kiser, L., & Otero, L. D. (2023). Multi-criteria decision model for selection of nuclear power plant type. *Progress in Nuclear Energy*, *159*, 104647. https://doi.org/10.1016/j.pnucene.2023.104647

Kivinen, S., Kotilainen, J., & Kumpula, T. (2020). Mining conflicts in the european union: Environmental and political perspectives. *Fennia - International Journal of Geography*, *198*(1-2), 163–179. https://doi.org/10.11143/fennia.87223

Knodt, M., & Kemmerzell, J. (Eds.). (2022). *Handbook of energy governance in europe* (1st ed. 2022). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-030-43250-8

Koelewijn, R., van Dam, M., & Hulsbosch-Dam, C. (2020). North sea energy: Report on offshore structural integrity and safety performance of h2 production, processing, storage and transport. https://north-sea-energy.eu/static/84050b605af439a07d9806c763618802/10a.-FINAL-NSE3_D4.2-Report-on-offshore-structural-integrity-and-safety-performance-of-H2-production-processing-storage-and-transport.pdf

Koirala, B., Hers, S., Morales-España, G., Özdemir, Ö., Sijm, J., & Weeda, M. (2021). Integrated electricity, hydrogen and methane system modelling framework: Application to the dutch infrastructure outlook 2050. *Applied Energy*, *289*, 116713. https://doi.org/10.1016/j.apenergy.2021.116713

Koivisto, M., Gea–Bermúdez, J., & Sørensen, P. (2020). North sea offshore grid development: Combined optimisation of grid and generation investments towards 2050. *IET Renewable Power Generation*, *14*(8), 1259–1267. https://doi.org/10.1049/iet-rpg.2019.0693

Kovač, A., Paranos, M., & Marciuš, D. (2021). Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy*, *46*(16), 10016–10035. https://doi.org/10.1016/j.ijhydene.2020.11.256

Kristiansen, M., Korpås, M., & Farahmand, H. (2018). Towards a fully integrated north sea offshore grid: An engineering–economic assessment of a power link island. *WIREs Energy and Environment*, *7*(4). https://doi.org/10.1002/wene.296

Künneke, R., Mehos, D. C., Hillerbrand, R., & Hemmes, K. (2015). Understanding values embedded in offshore wind energy systems: Toward a purposeful institutional and technological design. *Environmental Science & Policy*, *53*, 118–129. https://doi.org/10.1016/j.envsci.2015.06.013

Kurbel, K. (2013). *Enterprise resource planning and supply chain management: Functions, business processes and software for manufacturing companies*. Springer. http://www.loc.gov/catdir/enhancements/fy1407/2013943475-d.html

Kuzemko, C., Blondeel, M., Dupont, C., & Brisbois, M. C. (2022). Russia's war on ukraine, european energy policy responses & implications for sustainable transformations. *Energy Research & Social Science*, *93*, 102842. https://doi.org/10.1016/j.erss.2022.102842

Lacal-Arántegui, R. (2019). Globalization in the wind energy industry: Contribution and economic impact of european companies. *Renewable Energy*, *134*, 612–628. https://doi.org/10.1016/j.renene.2018.10.087

Leal Filho, W., Azul, A. M., Brandli, L., Lange Salvia, A., & Wall, T. (2020). *Industry, innovation and infrastructure*. Springer International Publishing. https://doi.org/10.1007/978-3-319-71059-4

Li, M., Jiang, X., Carroll, J., & Negenborn, R. R. (2022). A multi-objective maintenance strategy optimization framework for offshore wind farms considering uncertainty. *Applied Energy*, *321*, 119284. https://doi.org/10.1016/j.apenergy.2022.119284

Lindberg, M. B. (2022). The power of power markets: Zonal market designs in advancing energy transitions. *Environmental Innovation and Societal Transitions*, *45*, 132–153. https://doi.org/10.1016/j.eist.2022.08.004

Liuhto, K. (2021). *The future of energy consumption, security and natural gas: Lng in the baltic sea region*. Springer International Publishing AG. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6711393

Liyanage, J. P., & Bjerkebaek, E. (2006). Use of advanced technologies and information solutions for north sea offshore assets: Ambitious changes and socio-technical dimensions. *Journal of International Technology and Information Management*, *15*(4). https://doi.org/10.58729/1941-6679.1177

Loorbach, D., Frantzeskaki, N., & Avelino, F. (2017). Sustainability transitions research: Transforming science and practice for societal change. *Annual Review of Environment and Resources*, *42*(1), 599–626. https://doi.org/10.1146/annurev-environ-102014-021340

Lowitzsch, J. (2019). Investing in a renewable future – renewable energy communities, consumer (co-)ownership and energy sharing in the clean energy package. *Renewable Energy Law and Policy Review*, *9*(2), 14–36.

Lukic, I., Kurzweil, K., Guyot Tephany, J., McCann, J., Hodson, C., Rebours, C., & Thomas, J.-B. (2023). Ocean multi-use blueprints collection. https://doi.org/10.5281/zenodo.7784785

Lüth, A. (2022). *Offshore energy hubs as an emerging concept: Sector integration at sea* (Doctoral dissertation No. 45.2022). Copenhagen Business School [Phd].

Luukkanen, J., Akgün, O., Kaivo-oja, J., Korkeakoski, M., Pasanen, T., Panula-Ontto, J., & Vehmas, J. (2015). Long-run energy scenarios for cambodia and laos: Building an integrated techno-economic and environmental modelling framework for scenario analyses. *Energy*, *91*, 866–881. https://doi.org/10.1016/j.energy.2015.08.091

MacKinnon, D., Karlsen, A., Dawley, S., Steen, M., Afewerki, S., & Kenzhegaliyeva, A. (2022). Legitimation, institutions and regional path creation: A cross-national study of offshore wind. *Regional Studies*, *56*(4), 644–655. https://doi.org/10.1080/00343404.2020.1861239

March, J. G., & Olsen, J. P. (1983). The new institutionalism: Organizational factors in political life. *American Political Science Review*, *78*(3), 734–749. https://doi.org/10.2307/1961840

Marois, G., Bélanger, A., & Lutz, W. (2020). Population aging, migration, and productivity in europe. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(14), 7690–7695. https://doi.org/10.1073/pnas.1918988117

Martinez, A., & Iglesias, G. (2022). Mapping of the levelised cost of energy for floating offshore wind in the european atlantic. *Renewable and Sustainable Energy Reviews*, *154*, 111889. https://doi.org/10.1016/j.rser.2021.111889

Martínez-Gordón, R., Sánchez-Diéguez, M., Fattahi, A., Morales-España, G., Sijm, J., & Faaij, A. (2022). Modelling a highly decarbonised north sea energy system in 2050: A multinational approach. *Advances in Applied Energy*, *5*, 100080. https://doi.org/10.1016/j.adapen.2021.100080

Mathew, J., Ma, L., Tan, A., & Anderson, D. (Eds.). (2006). *Engineering asset management: Proceedings of the first world congress on engineering asset management (wceam) 2006* (1st ed. 2006). Springer London; Imprint: Springer. https://permalink.obvsg.at/

Meeus, L. (2014). Offshore grids for renewables: Do we need a particular regulatory framework? *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2402777

Ministry of General Affairs. (2020). Offshore wind energy. https://www.government.nl/topics/renewable-energy/offshore-wind-energ

Momber, A. W., Wilms, M., & Brün, D. (2022). The use of meteorological and oceanographic sensor data in the german offshore territory for the corrosion monitoring of marine structures. *Ocean Engineering*, *257*, 110994. https://doi.org/10.1016/j.oceaneng.2022.110994

Mytilinou, V., Kolios, A. J., & Di Lorenzo, G. (2017). A comparative multi-disciplinary policy review in wind energy developments in europe. *International Journal of Sustainable Energy*, *36*(8), 754–774. https://doi.org/10.1080/14786451.2015.1100194

National Grid. (2023). What are electricity interconnectors? https://www.nationalgrid.com/stories/energy-explained/what-are-electricity-interconnectors

Newman, M. E. J. (2018). *Networks* (Second edition). Oxford University Press. https://doi.org/10.1093/oso/9780198805090.001.0001

Nielsen, H. N., Aaen, S. B., Lyhne, I., & Cashmore, M. (2019). Confronting institutional boundaries to public participation: A case of the danish energy sector. *European Planning Studies*, *27*(4), 722–738. https://doi.org/10.1080/09654313.2019.1569594

Nilsson, H., van Overloop, J., Ali Mehdi, R., & Pålsson, J. (2018). Transnational maritime spatial planning in the north sea: The shipping context. https://northsearegion.eu/media/4836/northsee_finalshippingreport.pdf

Noordzeeloket. (2021). North sea consultation. https://www.noordzeeloket.nl/en/network/north-sea-consultation-0/

Nouicer, A., & Meeus, L. (2019). *The eu clean energy package*. European University Institute.

Office of Nuclear Energy. (2023). Advanced small modular reactors: (smrs). https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Hydrogen production, storage, utilisation and environmental impacts: A review. *Environmental Chemistry Letters*, *20*(1), 153–188. https://doi.org/10.1007/s10311-021-01322-8

Palomo-Vélez, G., Perlaviciute, G., Contzen, N., & Steg, L. (2021). Promoting energy sources as environmentally friendly: Does it increase public acceptability? *Environmental Research Communications*, *3*(11), 115004. https://doi.org/10.1088/2515-7620/ac32a8

Parol, M., Robak, S., Rokicki, L., & Wasilewski, J. (2015). Selected issues of cable link designing in hvac and hvdc submarine power grids. *2015 Modern Electric Power Systems (MEPS)*, 1–8. https://doi.org/10.1109/MEPS.2015.7477202

Pavolová, H., Čulková, K., Šimková, Z., Seňová, A., & Kudelas, D. (2022). Contribution of mining industry in chosen eu countries to the sustainability issues. *Sustainability*, *14*(7), 4177. https://doi.org/10.3390/su14074177

Perera, R. (2020). *The pestle analysis*. Nerdynaut.

Perveen, R., Kishor, N., & Mohanty, S. R. (2014). Off-shore wind farm development: Present status and challenges. *Renewable and Sustainable Energy Reviews*, *29*, 780–792. https://doi.org/10.1016/J.RSER.2013.08.108

Piao, L., de Vries, L., de Weerdt, M., & Yorke-Smith, N. (2021). Electricity markets for dc distribution systems: Locational pricing trumps wholesale pricing. *Energy*, *214*, 118876. https://doi.org/10.1016/j.energy.2020.118876

Piscopo, V., & Scamardella, A. (2021). Comparative study among non-redundant and redundant stationkeeping systems for floating offshore wind turbines on intermediate water depth. *Ocean Engineering*, *241*, 110047. https://doi.org/10.1016/j.oceaneng.2021.110047

Ploeg, M., Knoben, J., Vermeulen, P., & van Beers, C. (2021). Rare gems or mundane practice? resource constraints as drivers of frugal innovation. *Innovation*, *23*(1), 93–126. https://doi.org/10.1080/14479338.2020.1825089

Purvins, A., Zubaryeva, A., Llorente, M., Tzimas, E., & Mercier, A. (2011). Challenges and options for a large wind power uptake by the european electricity system. *Applied Energy*, *88*(5), 1461–1469. https://doi.org/10.1016/J.APENERGY.2010.12.017

Quirk, D. G., Underhill, J. R., Gluyas, J. G., Wilson, H. A., Howe, M. J., & Anderson, S. (2021). The north sea through the energy transition. *First Break*, *39*(4), 31–43. https://doi.org/10.3997/1365-2397.fb2021026

Rabe, W., Kostka, G., & Smith Stegen, K. (2017). China's supply of critical raw materials: Risks for europe's solar and wind industries? *Energy Policy*, *101*, 692–699. https://doi.org/10.1016/j.enpol.2016.09.019

Ram, M., Aghahosseini, A., & Breyer, C. (2020). Job creation during the global energy transition towards 100% renewable power system by 2050. *Technological Forecasting and Social Change*, *151*, 119682. https://doi.org/10.1016/j.techfore.2019.06.008

Reis, I., Gonçalves, I., A.R. Lopes, M., & Henggeler Antunes, C. (2021). Business models for energy communities: A review of key issues and trends. *Renewable and Sustainable Energy Reviews*, *144*, 111013. https://doi.org/10.1016/j.rser.2021.111013

Rentier, G., Lelieveldt, H., & Kramer, G. J. (2023). Institutional constellations and policy instruments for offshore wind power around the north sea. *Energy Policy*, *173*, 113344. https://doi.org/10.1016/j.enpol.2022.113344

Riddell, G. A., van Delden, H., Maier, H. R., & Zecchin, A. C. (2019). Exploratory scenario analysis for disaster risk reduction: Considering alternative pathways in disaster risk assessment. *International Journal of Disaster Risk Reduction*, *39*, 101230. https://doi.org/10.1016/j.ijdrr.2019.101230

Riddick, S. N., Mauzerall, D. L., Celia, M., Harris, N. R. P., Allen, G., Pitt, J., Staunton-Sykes, J., Forster, G. L., Kang, M., Lowry, D., Nisbet, E. G., & Manning, A. J. (2019). Methane emissions from oil and gas platforms in the north sea. *Atmospheric Chemistry and Physics*, *19*(15), 9787–9796. https://doi.org/10.5194/acp-19-9787-2019

Rijnsdorp, A. D., Hiddink, J. G., van Denderen, P. D., Hintzen, N. T., Eigaard, O. R., Valanko, S., Bastardie, F., Bolam, S. G., Boulcott, P., Egekvist, J., Garcia, C., van Hoey, G., Jonsson, P., Laffargue, P., Nielsen, J. R., Piet, G. J., Sköld, M., & van Kooten, T. (2020). Different bottom trawl fisheries have a differential impact on the status of the north sea seafloor habitats. *ICES Journal of Marine Science*, *77*(5), 1772–1786. https://doi.org/10.1093/icesjms/fsaa050

Rippel, D., Jathe, N., Becker, M., Lütjen, M., Szczerbicka, H., & Freitag, M. (2019). A review on the planning problem for the installation of offshore wind farms. *IFAC-PapersOnLine*, *52*(13), 1337–1342. https://doi.org/10.1016/j.ifacol.2019.11.384

Ritchie, H., Roser, M., & Rosado, P. (2022). Energy [https://ourworldindata.org/energy]. *Our World in Data*.

Schmidt-Scheele, R. (2020). ‘plausible’ energy scenarios?! how users of scenarios assess uncertain futures. *Energy Strategy Reviews*, *32*, 100571. https://doi.org/10.1016/j.esr.2020.100571

Scholten, D. (2012). *Keeping an eye on reliability: The organizational requirements of future renewable energy systems*. Eburon.

Scholten, D. (2013). The reliability of energy infrastructures; the organizational requirements of technical operations. *Competition and Regulation in Network Industries*, *14*, 173–205.

Scholten, D. (Ed.). (2018). *The geopolitics of renewables* (Vol. 61). Springer. https://doi.org/10.1007/978-3-319-67855-9

Scholten, D., & Künneke, R. (2016). Towards the comprehensive design of energy infrastructures. *Sustainability*, *8*(12), 1291. https://doi.org/10.3390/su8121291

Schupp, M. F., Kafas, A., Buck, B. H., Krause, G., Onyango, V., Stelzenmüller, V., Davies, I., & Scott, B. E. (2021). Fishing within offshore wind farms in the north sea: Stakeholder perspectives for multi-use from scotland and germany. *Journal of environmental management*, *279*, 111762. https://doi.org/10.1016/j.jenvman.2020.111762

Sharmina, M., Abi Ghanem, D., Browne, A. L., Hall, S. M., Mylan, J., Petrova, S., & Wood, R. (2019). Envisioning surprises: How social sciences could help models represent ‘deep uncertainty’ in future energy and water demand. *Energy Research & Social Science*, *50*, 18–28. https://doi.org/10.1016/j.erss.2018.11.008

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? techno-economic overview of alternative integration designs for green hydrogen production into offshore wind power hubs. *Renewable and Sustainable Energy Transition*, *1*, 100005. https://doi.org/10.1016/j.rset.2021.100005

Soares, C. A., Shendrikova, D., Crevani, G., Silinto, B., & Colombo, E. (2023). Enabling factors for the development of mini-grid solutions in mozambique: A pestle-based analysis. *Energy Strategy Reviews*, *45*, 101040. https://doi.org/10.1016/j.esr.2022.101040

Söder, L., Tómasson, E., Estanqueiro, A., Flynn, D., Hodge, B.-M., Kiviluoma, J., Korpås, M., Neau, E., Couto, A., Pudjianto, D., Strbac, G., Burke, D., Gómez, T., Das, K., Cutululis, N. A., van Hertem, D., Höschle, H., Matevosyan, J., von Roon, S., … de Vries, L. (2020). Review of wind generation within adequacy calculations and capacity markets for different power systems. *Renewable and Sustainable Energy Reviews*, *119*, 109540. https://doi.org/10.1016/j.rser.2019.109540

Spro, O. C., Torres-Olguin, R. E., & Korpås, M. (2015). North sea offshore network and energy storage for large scale integration of renewables. *Sustainable Energy Technologies and Assessments*, *11*, 142–147. https://doi.org/10.1016/j.seta.2014.12.001

Staudt, P., Rausch, B., Garttner, J., & Weinhardt, C. (2019). Predicting transmission line congestion in energy systems with a high share of renewables. *2019 IEEE Milan PowerTech*, 1–6. https://doi.org/10.1109/PTC.2019.8810527

Storm, S. (2012). *Macroeconomics beyond the nairu*. Belknap Press of Harvard University Press. https://doi.org/10.4159/harvard.9780674063242

Swain, R. B., & Karimu, A. (2020). Renewable electricity and sustainable development goals in the eu. *World Development*, *125*, 104693. https://doi.org/10.1016/j.worlddev.2019.104693

Swedish Agency for Marine and Water Management. (2022). Marine spatial plans for the gulf of bothnia, the baltic sea and the skagerrak/kattegat: National planning in sweden's territorial waters and exclusive economic zone. https://www.havochvatten.se/download/18.798438e41885446677e564af/1686294691426/report-marine-spatial-plans-2022.pdf

Tenggren, S., Wangel, J., Nilsson, M., & Nykvist, B. (2016). Transmission transitions: Barriers, drivers, and institutional governance implications of nordic transmission grid development. *Energy Research & Social Science*, *19*, 148–157. https://doi.org/10.1016/j.erss.2016.06.004

TenneT. (2023). Tennet offshore. https://www.tennet.eu/offshore-overview

TenneT TSO GmbH. (2023). The 2 gw program. https://www.tennet.eu/about-tennet/innovations/2gw-program

Tosatto, A., Beseler, X. M., Østergaard, J., Pinson, P., & Chatzivasileiadis, S. (2022). North sea energy islands: Impact on national markets and grids. *Energy Policy*, *167*, 112907. https://doi.org/10.1016/j.enpol.2022.112907

Tsao, J. Y., Schubert, E. F., Fouquet, R., & Lave, M. (2018). The electrification of energy: Long-term trends and opportunities. *MRS Energy & Sustainability*, *5*(1). https://doi.org/10.1557/mre.2018.6

Übertragungsnetzbetreiber. (2023). Netzentwicklungsplan strom 2037 mit ausblick 2045, version 2023: Zweiter entwurf der übertragungsnetzbetreiber. https://www.netzentwicklungsplan.de/sites/default/files/2023-06/NEP_2037_2045_V2023_2_Entwurf_Teil1_2.pdf

uit het Broek, M. A., Veldman, J., Fazi, S., & Greijdanus, R. (2019). Evaluating resource sharing for offshore wind farm maintenance: The case of jack-up vessels. *Renewable and Sustainable Energy Reviews*, *109*, 619–632. https://doi.org/10.1016/j.rser.2019.03.055

United Nations. (2016). Paris agreement. https://unfccc.int/sites/default/files/resource/parisagreement_publication

van Hoof, L., Steins, N. A., Smith, S., & Kraan, M. (2020). Change as a permanent condition: A history of transition processes in dutch north sea fisheries. *Marine Policy*, *122*, 104245. https://doi.org/10.1016/j.marpol.2020.104245

van Renssen, S. (2020). The hydrogen solution? *Nature Climate Change*, *10*, 799–801.

Vasić, M., Duica, M., Berber, N., Enukidze, N., Vasić, S., & Weis, L. (2022). Migrant workers and workforce integration: Challenges for managers in european companies. *Strategic Management*, (00), 29. https://doi.org/10.5937/StraMan2200027V

Wade, W. (2012). *Scenario planning: A field guide to the future*. John Wiley & Sons.

Waldo, J. (2006). On system design. *ACM SIGPLAN Notices*, *41*(10), 467–480. https://doi.org/10.1145/1167515.1167513

Wang, H., & Redfern, M. (2010). The advantages and disadvantages of using hvdc to interconnect ac networks. *45th International Universities Power Engineering Conference UPEC2010*, 1–5.

Wei, M., McMillan, C. A., & de La Rue Can, S. (2019). Electrification of industry: Potential, challenges and outlook. *Current Sustainable/Renewable Energy Reports*, *6*(4), 140–148. https://doi.org/10.1007/s40518-019-00136-1

Weibelzahl, M. (2017). Nodal, zonal, or uniform electricity pricing: How to deal with network congestion. *Frontiers in Energy*, *11*(2), 210–232. https://doi.org/10.1007/s11708-017-0460-z

Weimer-Jehle, W., Buchgeister, J., Hauser, W., Kosow, H., Naegler, T., Poganietz, W.-R., Pregger, T., Prehofer, S., von Recklinghausen, A., Schippl, J., & Vögele, S. (2016). Context scenarios and their usage for the construction of socio-technical energy scenarios. *Energy*, *111*, 956–970. https://doi.org/10.1016/j.energy.2016.05.073

Wiebes, E. (2020). Letter to parliament offshore wind energy roadmap 2030. https://www.government.nl/topics/renewable-energy/documents/parliamentary-documents/2018/03/27/letter-to-parliament-offshore-wind-energy-roadmap-2030

WindEurope. (2022a). North sea offshore wind to help repower the eu. https://windeurope.org/newsroom/press-releases/north-sea-offshore-wind-to-help-repower-the-eu/

WindEurope. (2022b). Norway announces big new offshore wind targets. https://windeurope.org/newsroom/news/norway-announces-big-new-offshore-wind-targets/

WindEurope. (2022c). Sweden: Making up lost ground on offshore wind. https://windeurope.org/newsroom/news/sweden-making-up-lost-ground-on-offshore-wind/

Witt, T., Dumeier, M., & Geldermann, J. (2020). Combining scenario planning, energy system analysis, and multi-criteria analysis to develop and evaluate energy scenarios. *Journal of Cleaner Production*, *242*, 118414.

Yang, J., Zhang, W., Zhao, D., Zhao, C., & Yuan, J. (2022). What can china learn from the uk's transition to a low-carbon power sector? a multi-level perspective. *Resources, Conservation and Recycling*, *179*, 106127. https://doi.org/10.1016/j.resconrec.2021.106127

Zhang, S., Wei, J., Chen, X., & Zhao, Y. (2020). China in global wind power development: Role, status and impact. *Renewable and Sustainable Energy Reviews*, *127*, 109881. https://doi.org/10.1016/j.rser.2020.109881

Żuk, P., & Żuk, P. (2022). National energy security or acceleration of transition? energy policy after the war in ukraine. *Joule*, *6*(4), 709–712. https://doi.org/10.1016/j.joule.2022.03.009

Appendix

A Actor Analysis

A.1 Step by step guide: Actor Analysis

1. **Identify problem owner**
a. Data: List of European TSOs with offshore business.
b. Choice: Due to the scope of this thesis on the North Sea and TenneT being the only cross-border TSO with North Sea offshore business, the choice for TenneT was made. The cross-border aspect was considered important as the relevance for society is deemed high when a TSO has to supply many households and also operate cross-borders, increasing the potential bottleneck.

2. **Identify relevant actors**
a. Data: Public data of major stakeholders in North Sea (papers, government & company websites).
b. Choice: Considering all stakeholders in the North Sea, including all suppliers and every company that has some offshore business does not comply with the time constraints for the master thesis. Moreover, an organisational level was chosen to reduce the number of actors, therefore not different ministries for each country but national government was considered an actor. This was done to comply with the higher-level scope of the entire thesis and insights on organisational level were deemed sufficient to add value to the thesis. Oil and gas companies and wind park operators were grouped into an aggregated actor due to resource constraints and an assumed homogeneity in their actions. This might limit the insights as there are differing interests, but this limitation was considered acceptable to stay within the scope of the thesis.

Reasons for selecting actors were direct involvement in the offshore energy system, including all North Sea TSOs, wind park operators, and oil and gas companies. Orsted was chosen as a special case due to its status as a global player and being a wind park developer as well as operator. Other companies such as RWE could have been chosen for that, but the dominant position of Orsted in the market was the key reason to include it. WindEurope was chosen as the voice of the wind industry as the most relevant source of electricity in the North Sea at the moment and therefore executing opinion leadership. Actors such as national governments, EU regulators and investors were chosen due to their strong position in the North Sea system and the dependence of other actors on them. Research institutes were deemed relevant as they provide knowledge, and many actors rely on their research. The shipping industry and fishing industry were included as they are an integral part of the North Sea offshore system, highly relevant for society and they have a strong interest in how developments in the energy system are affecting them. For reasons of interest and being affected, residents and environmental NGOs were added as well.

3. **Actor screening**
a. Data: Public data that provides information about each of the identified actors. For practical reasons, these ranged from papers to company websites. As information about the interests and objectives was not always available from the actors themselves, newspaper articles were chosen as an additional data source, accepting the inherent bias and justifying it with the lack of information that was attainable in the time span of the thesis.
b. Choice: Values, resources and dependency of each actor were emphasised as critical for this thesis because they are deemed to be most relevant to arrive at a power-interest diagram. Given the lack of extensively available data sources, it was settled on these. The interest of each actor in general was considered, as well as the desired situation because the thesis also analysed future developments of the system by the use of scenarios. Assessing the level of interest was necessary for the power-interest diagram. Resources were important to examine in order to analyse each actors' power.

4. **Identify critical actors based on resources**
a. Data: Public data that provides information about each of the identified actors. For practical reasons, these ranged from papers to company websites. As information about the interests and objectives was not always available from the actors themselves, newspaper articles were chosen as an additional data source, accepting the inherent bias and justifying it with the lack of information that was attainable in the time span of the thesis.
b. Choice: The dependency was deemed relevant to understand the actors' situation in the network and assess whether they were critical to the system.

5. **Identify key players and context setters**
a. Data: Public data from above and the previous analysis steps.
b. Choice: Based on a power-interest diagram, the actors were classified into crowd, interested subjects, context setters and key players. The last two were deemed to most relevant ones as they possess the greatest power and highest interest.

A.2 Actor Analysis Data

Table 9: *Sources actor analysis*

Actor	**Sources**
Amprion	https://www.amprion.net/Netzjournal/Beitr%C3%A4ge-2020/Eurobar-Offshore-Vernetzung-ist-die-Zukunft.html https://offshore.amprion.net/
Elia	https://www.eliagroup.eu/en/windgrid https://www.elia.be/-/media/project/elia/elia-site/company/publication/studies-and-reports/investment-plans/federal-developement-plan/2023/20230508_federal_development_plan_of_the_belgian_transmission_system_2024-2034_executive_summary.pdf
National grid	https://www.nationalgrid.com/electricity-transmission/who-we-are/how-we-are-regulated https://www.nationalgrid.com/electricity-transmission/ https://www.nationalgrideso.com/document/262676/download
Shipping industry	https://northsearegion.eu/media/4836/northsee_finalshippingreport.pdf
WindEurope	https://windeurope.org/about-us/ https://windeurope.org/about-us/mission-values/
Orsted	https://orsted.com/en/who-we-are/our-purpose/our-vision-and-values
Energinet	https://en.energinet.dk/media/dulncpbw/energy-in-time-energinet-strategy-2022.pdf
Statnett	https://www.rivieramm.com/news-content-hub/news-content-hub/norway-planning-additional-areas-for-offshore-wind-statnett-to-be-offshore-tso-65881
TenneT	https://www.tennet.eu/about-tennet/about-us/our-strategy https://annualreport.tennet.eu/2022/annualreport
Military	https://www.noordzeeloket.nl/en/functions-and-use/militair-gebruik/ https://www.havochvatten.se/download/18.798438e41885446677e564af/1686294691426/report-marine-spatial-plans-2022.pdfhttps://english.defensie.nl/organisation/navy/tasks
EU regulators	https://northsearegion.eu/media/18749/north-sea-programme-2021-2027-priorities-and-specific-objectives.pdf https://www.noordzeeloket.nl/en/policy/beleid-regelgeving/europese-regelgeving/https://energy.ec.europa.eu/topics/infrastructure/high-level-groups/north-seas-energy-cooperation_en
Oil & gas companies	https://www.reuters.com/business/energy/shell-boost-dividend-cut-spending-new-ceo-plan-2023-06-14/ https://www.equinor.com/about-us/strategy
Windpark operators	https://orsted.com/en/who-we-are/our-purpose https://www.enbw.com/renewable-energy/wind-energy/our-offshore-wind-farms/https://www.government.nl/topics/renewable-energy/offshore-wind-energyhttps://english.rvo.nl/information/offshore-wind-energy
Fishing industry	https://tethys.pnnl.gov/publications/ongoing-conflict-between-offshore-wind-farms-fishing-industry-north-sea https://www.noordzeeloket.nl/en/functions-and-use/visserij/https://www.wur.nl/en/research-results/research-institutes/economic-research/show-wecr/the-dutch-fishery-sector-is-shrinking-and-this-does-not-just-affect-fishermen.htm
National governments	https://www.e3g.org/publications/offshore-wind-in-the-north-seas/ https://windeurope.org/wp-content/uploads/files/policy/position-papers/20230424-Ostend-Declaration-Leaders.pdf
Residents	https://www.jstor.org/stable/24324674
Research Institutes	https://www.wur.nl/en/Research-Results/Research-Institutes/marine-research/Themes/Offshore-wind-energy/Background-Offshore-wind-in-a-healthy-North-Sea-system.htm https://www.sintef.no/en/latest-news/2021/offshore-wind-new-ocean-grid-project-in-the-north-sea
Investors	https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Offshore-wind-energy-in-the-north-sea.pdf
Svenska Kraftnät	https://www.svk.se/en/ https://www.svk.se/siteassets/2.utveckling-av-kraftsystemet/transmissionsnatet/utbyggnad-av-transmissionsnat-till-havs/report—commission-regarding-preparatory-work-for-the-expansion-of-the-transmission-grid-into-swedish-territorial-waters.pdf

B Social Network Analysis

B.1 Step by step guide: Social Network Analysis

1. **Perform actor analysis to identify key players**
a. Data: Public data, as can bee seen in the actor analysis documentation.
b. Choice: For this thesis, the SNA was focused on the key players to ensure that the actors with the highest interest and power in the system were part of the network analysis. It was decided to build upon an actor analysis as it was the procedure taught in the EPA study program Hermans and Cunningham (2018) and thereby an in-depth understanding of the actors can be reached, that is valuable for reaching a holistic understanding of the system, the goal of this thesis.

2. **Population**
a. Data: Publicly available data. Due to few available analyses that provide insights into the network of each actor, this data had to be collected using multiple sources. Companies are mostly open about which projects they are pursuing and publish it in the news sections of their websites. Other sources were projects and connections are stated are annual reports and financial reports. Adding to this, data was acquired from technical journals, mainly 'Power Technology', which was deemed well-informed about offshore developments and projects between actors. Different actors that joined in a consortium were stated on the consortium's website and used for this thesis.
b. Choice: The key players from the actor analysis were considered as the starting point for the SNA. For practical reason, it was focused only on the key players as a starting point to stay within the limited time available for the study. Only the direct connections of key players were considered for the same reason.

3. **Desk research and content analysis**
a. Data: It was focused on publicly available data, as stated above, to ensure reproducibility. Additionally, data sources older than 5 years were considered outdated and not considered due to the fast-paced developments and changes in the system.
b. Choice: Ties are unweighted because it would be a highly subjective choice and as the North Sea offshore energy system is a fairly new system, few literature and sophisticated data is available to reduce the level of subjectivity of weighted ties. Furthermore, unweighted ties fit the goal of the SNA to get an understanding of the network and niche developments. Moreover, ties are undirected because the focus is on projects, collaborations and memberships of actors in discussion forums, which do not require directed ties.

For example, Orsted is working with DSV on a project for cargo drones. This was found on Orsted's website under news. The project topic is clearly 'cargo drones' and the connection type 'project'. Similarly, another connection type is ‘customer’, when Microsoft for example has signed a power purchase agreement with Orsted. In this case, a directed tie could have been helpful, but due to the focus of the key players, it is clear that Orsted is selling power to Shell and not the other way around. Other connection types are ‘supplier’, where the relationship is clear, ‘financial’ and ‘funding’. In theory, the latter two would require directed ties and could even be more meaningful by introducing weighted ties based on monetary weight. However, the connection type ‘project’ is by far the most prominent in the analysis and only a few financial and funding connections could be found. Therefore, the limitation of missing out on some insight was accepted, especially because the network graph is only a visualisation and if in doubt, the well-documented sources can be consolidated. The formatting of the tables were made on purpose to enable filtering by the project or actor name in excel, to access relevant information quicker. The connection types can be seen in Figure 31.

4. **Visualisation**
a. Data: Gephi, publicly available data, analysis up to this step.
b. Choice: Gephi was chosen due to the familiarity from Actor and Strategy Models and its intuitive interface with effective visualisations. The Yifan Hu algorithm was chosen to visualise the data as it is particularly useful for visualising clusters and based on the data structure, there are clusters around each actor. For the analysis, it was looked at density as a network metrics to get a first understanding of the network itself. As actor metrics, degree centrality, closeness centrality and betweenness centrality were picked as the most commonly used and insightful ones for this thesis. At this step, a second SNA was visualised based on the same data, which deviates from the SNA procedure introduced by Hermans and Cunningham (2018). By adding the project names directly as nodes in Gephi (Figure 34) and also introducing some broader themes such as ‘AI’ (Figure 33), the second SNA was tweaked in a way that enabled an easy visual identification of niche-level developments. Thereby, consortia, cooperations, niche innovations and business models could be made visible by just analysing the network (Figure 32). It reduced the need to go to the data table and tediously look for niche-level development in the projects.

5. **Presentation**
a. Data: Analysis up to this step.
b. Choice: The positions of the key players in the social network were identified and elaborated on. Furthermore, a list of niche developments resulted from the visualisation.

B.2 SNA Model

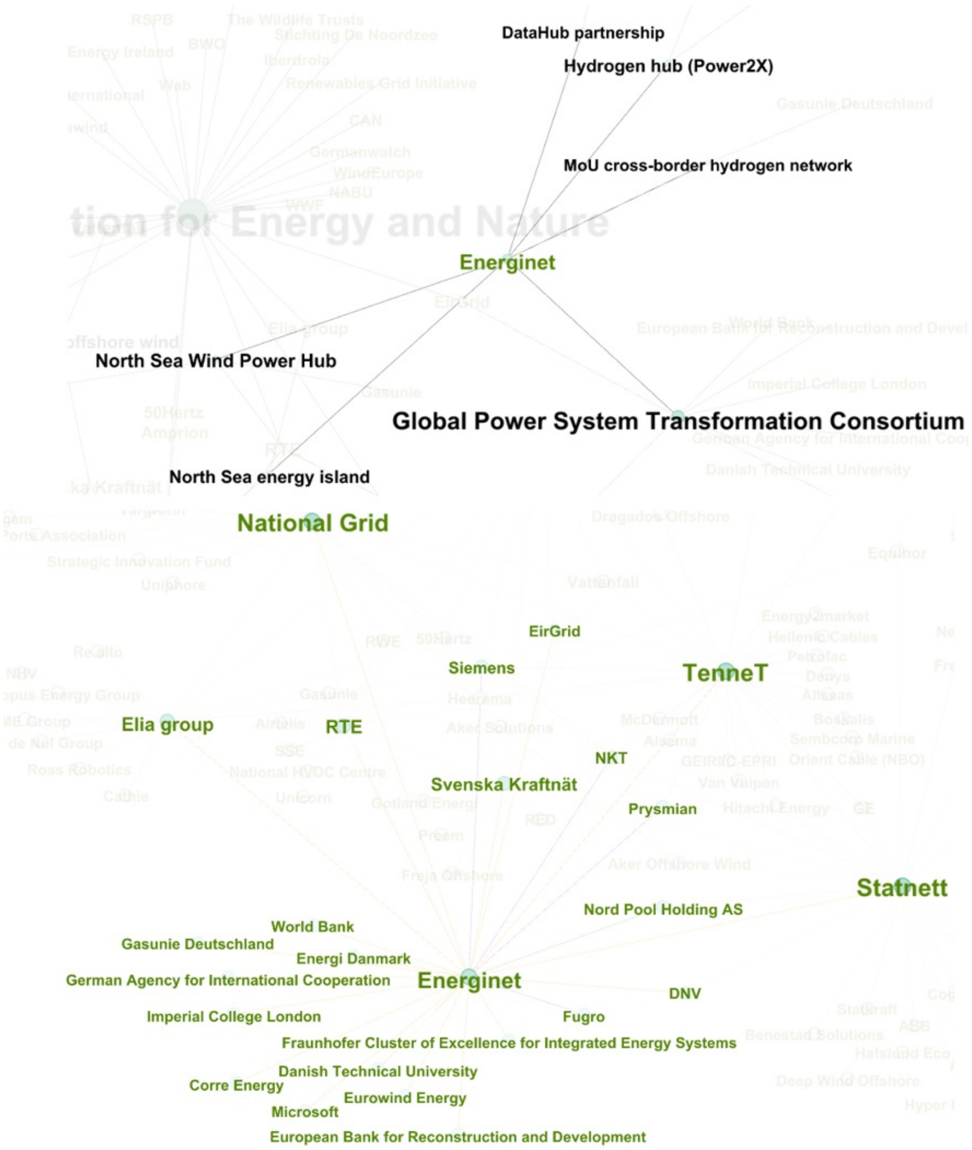


Figure 25: *Actor network Energinet. Source: own elaboration using Gephi and the Yifan Hu algorithm*

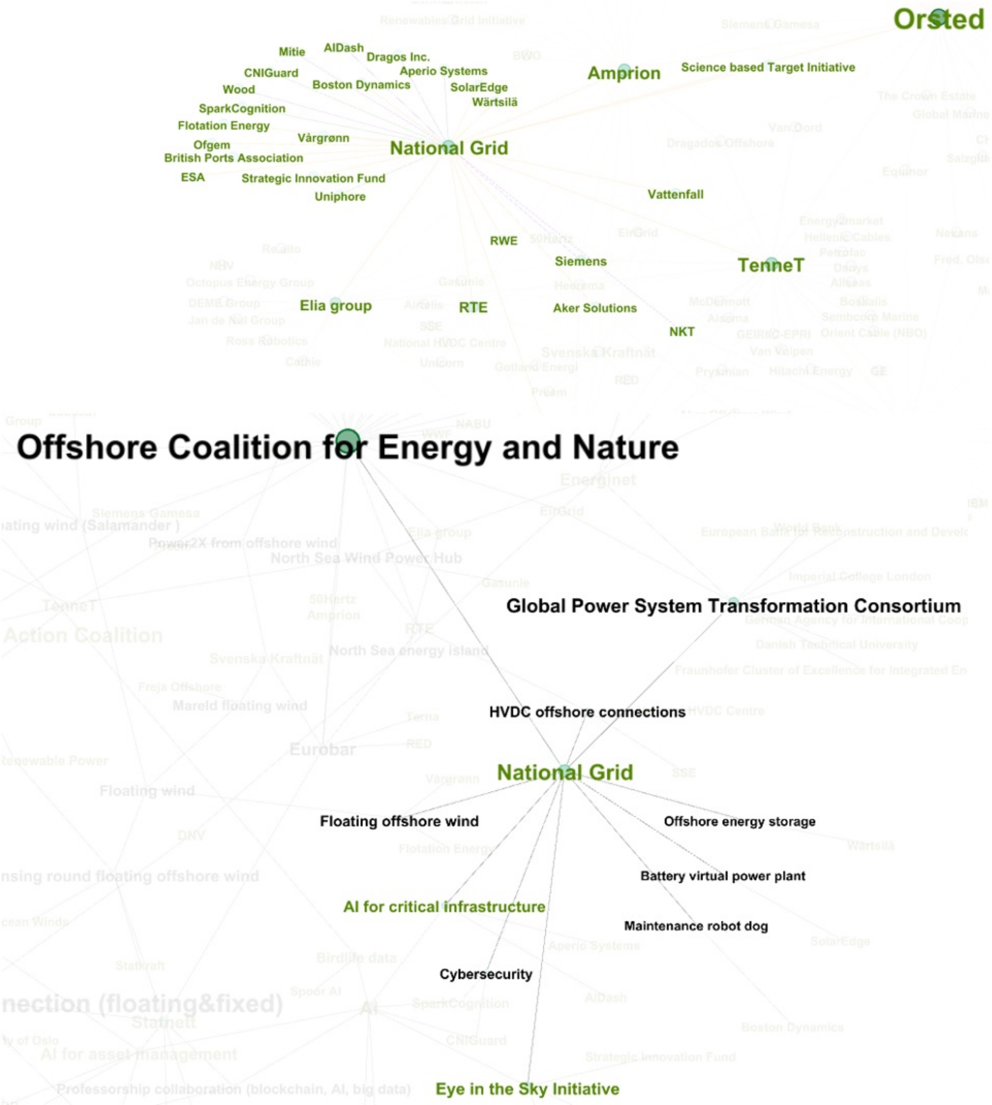


Figure 26: *Actor network National Grid. Source: own elaboration using Gephi and the Yifan Hu algorithm*

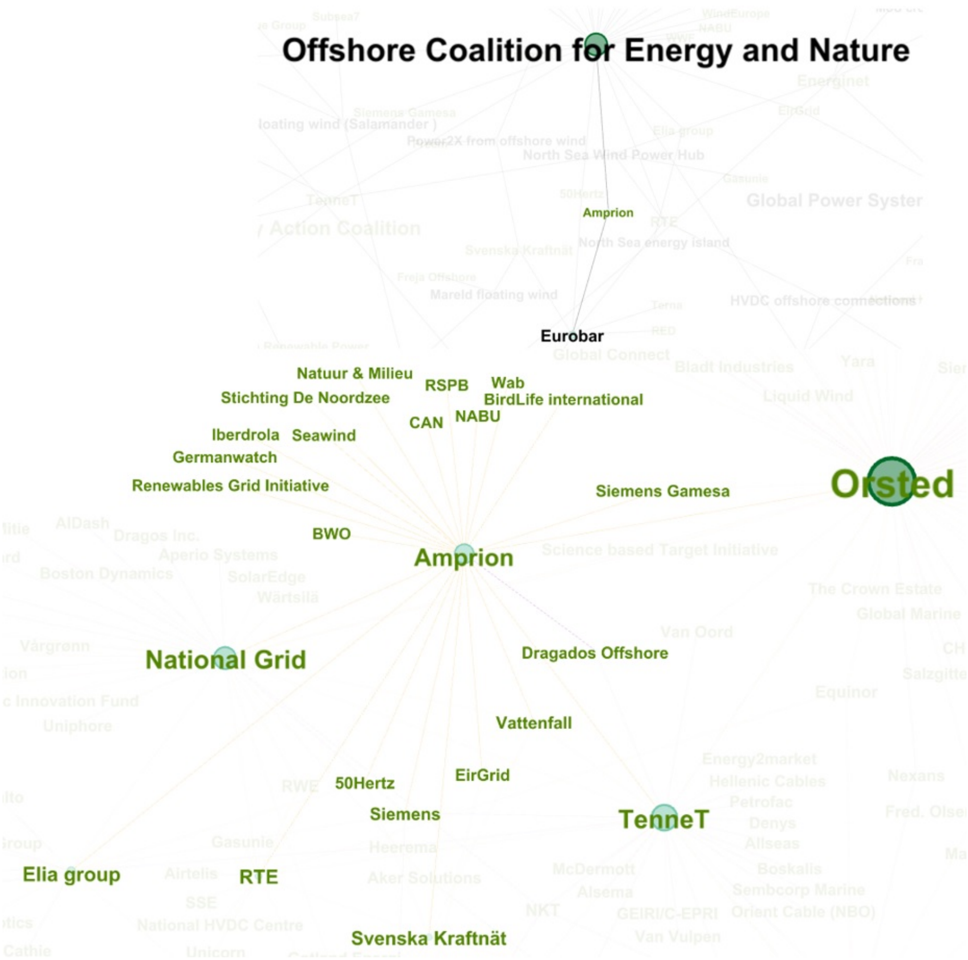


Figure 27: *Actor network Amprion. Source: own elaboration using Gephi and the Yifan Hu algorithm*

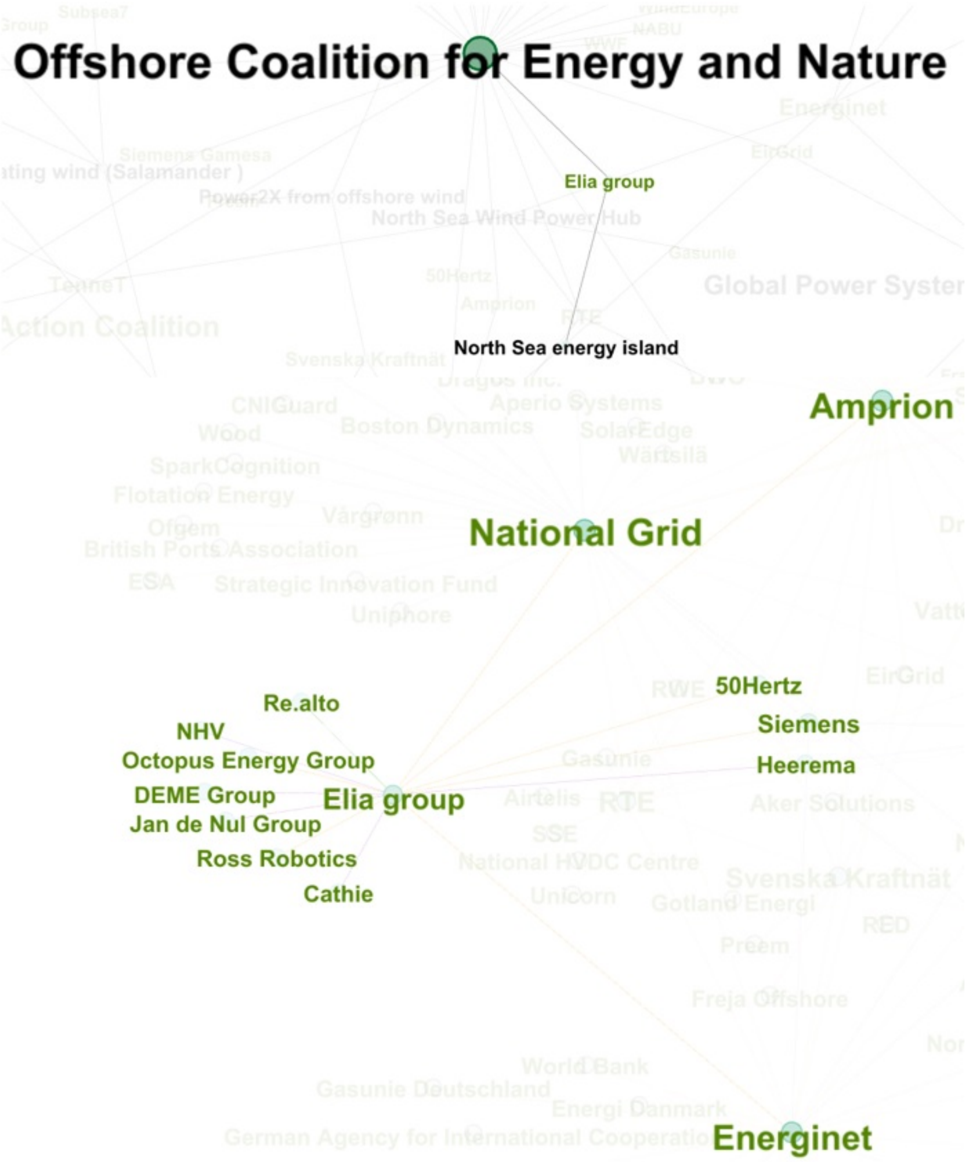


Figure 28: *Actor network Elia group. Source: own elaboration using Gephi and the Yifan Hu algorithm*

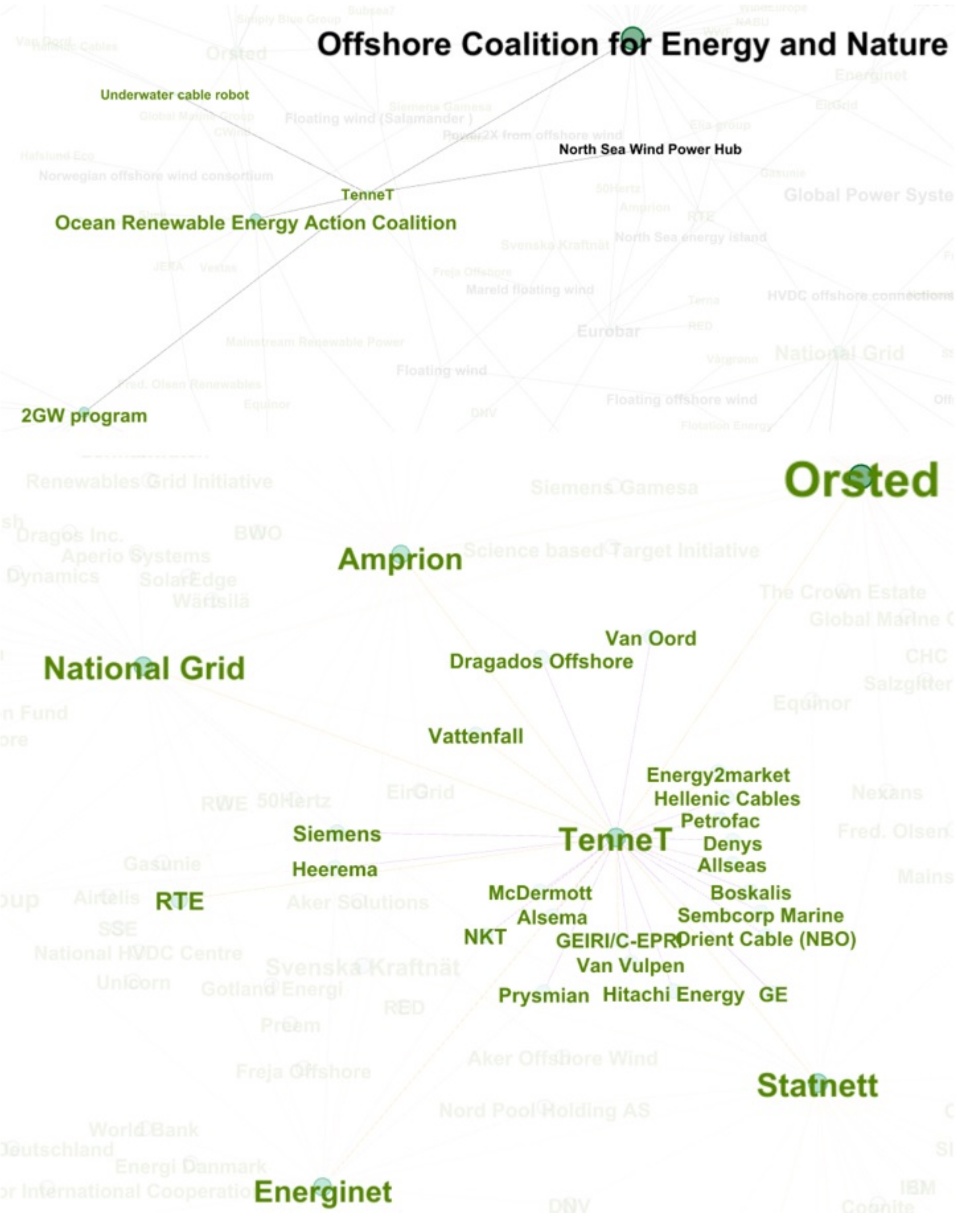


Figure 29: *Actor network TenneT. Source: own elaboration using Gephi and the Yifan Hu algorithm*

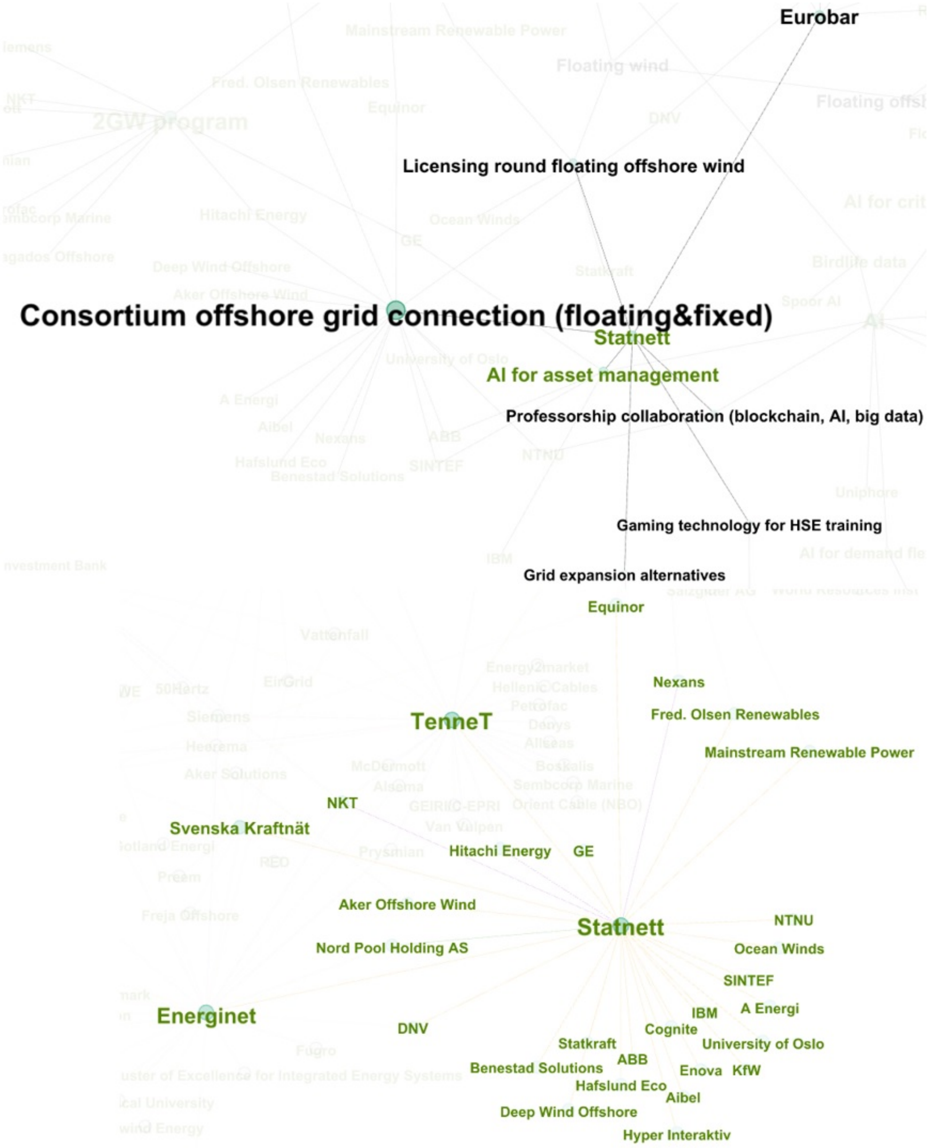


Figure 30: *Actor network Statnett. Source: own elaboration using Gephi and the Yifan Hu algorithm*

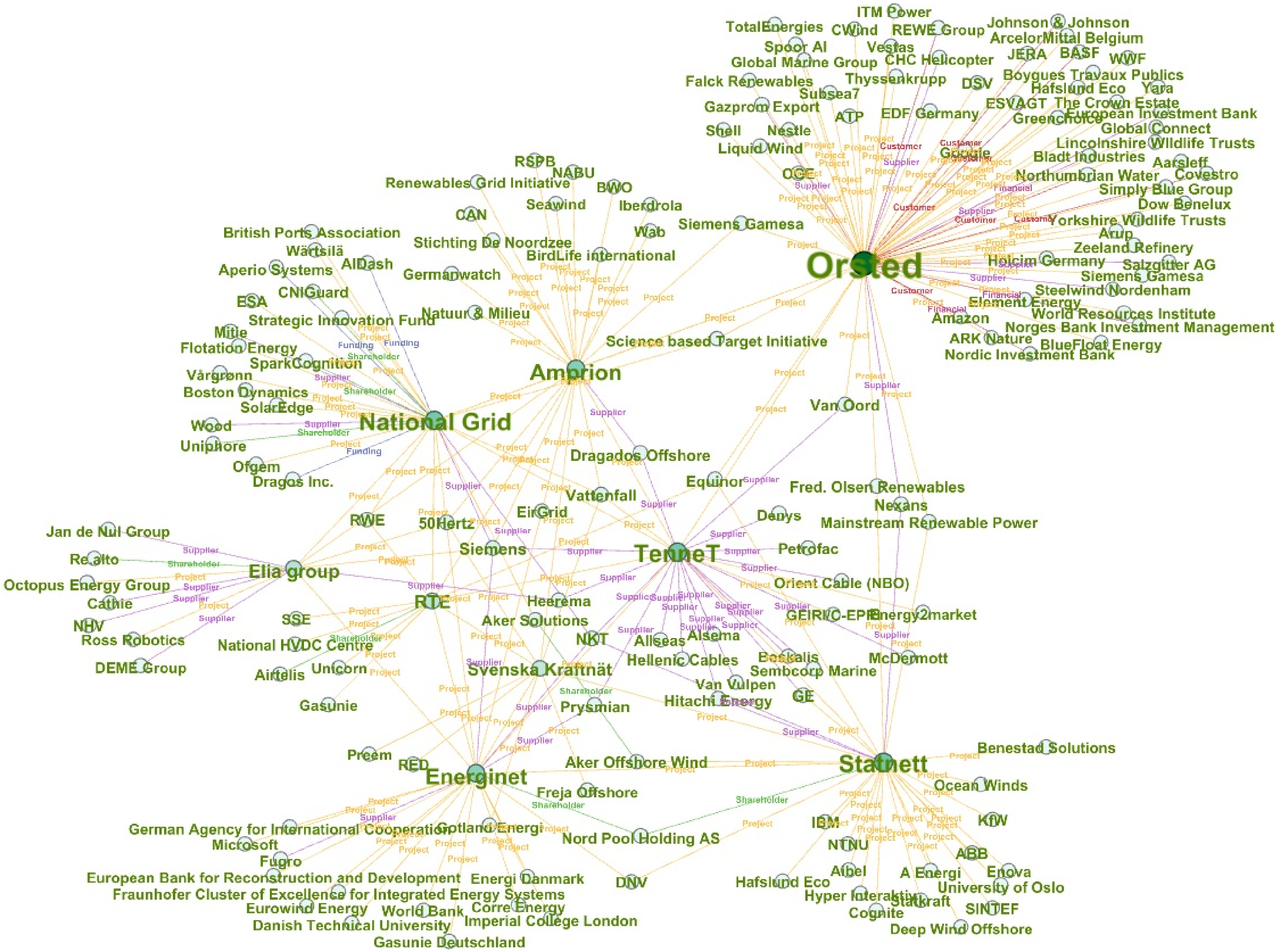


Figure 31: *Overview actor network including labels for ties. Source: own elaboration using Gephi and the Yifan Hu algorithm*

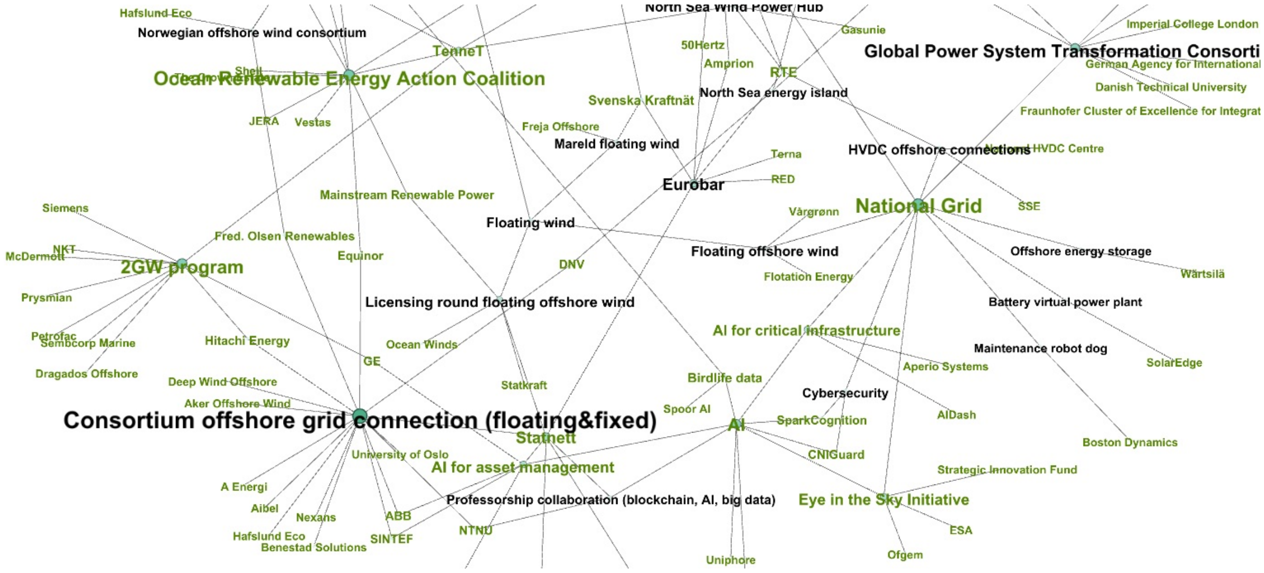


Figure 32: *SNA with visualisation of niche level developments. Source: own elaboration using Gephi and the Yifan Hu algorithm*

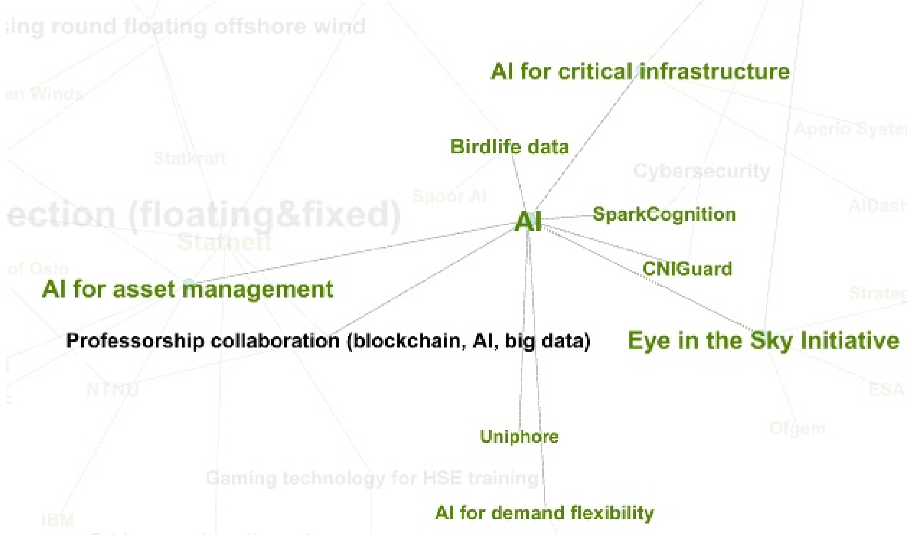


Figure 33: *AI as an example topic for the niche level SNA*

Table 10: *Centrality measures of most relevant nodes in SNA*

ID	Actor	Closeness Centrality	Betweenness Centrality	Degree Centrality
0	Orsted	0,5264798	0,5217451	66
52	TenneT	0,5248447	0,2780812	29
65	National Grid	0,5136778	0,2377215	29
67	Amprion	0,4898551	0,2028928	25
97	Statnett	0,4152334	0,1972357	30
99	Energinet	0,4435696	0,1671614	24
86	Elia group	0,3985849	0,0807206	13
75	RTE	0,4152334	0,0634041	12
92	Svenska Kraftnät	0,4004739	0,0555603	10
44	Equinor	0,4072289	0,0142977	3
17	Nexans	0,3948598	0,0089406	2
30	Fred. Olsen Renewables	0,3948598	0,0089406	2
49	Mainstream Renewable Power	0,3948598	0,0089406	2
101	NKT	0,4043062	0,0052417	4
68	Siemens	0,4052758	0,0034552	5
79	Vattenfall	0,3885057	0,0023873	4
133	Aker Solutions	0,3535565	0,0022998	2
91	EirGrid	0,3650108	0,0018482	2
129	Heerema	0,3572939	0,001607	2
153	Aker Offshore Wind	0,3056058	0,001434	2
70	50Hertz	0,3626609	0,0009	3

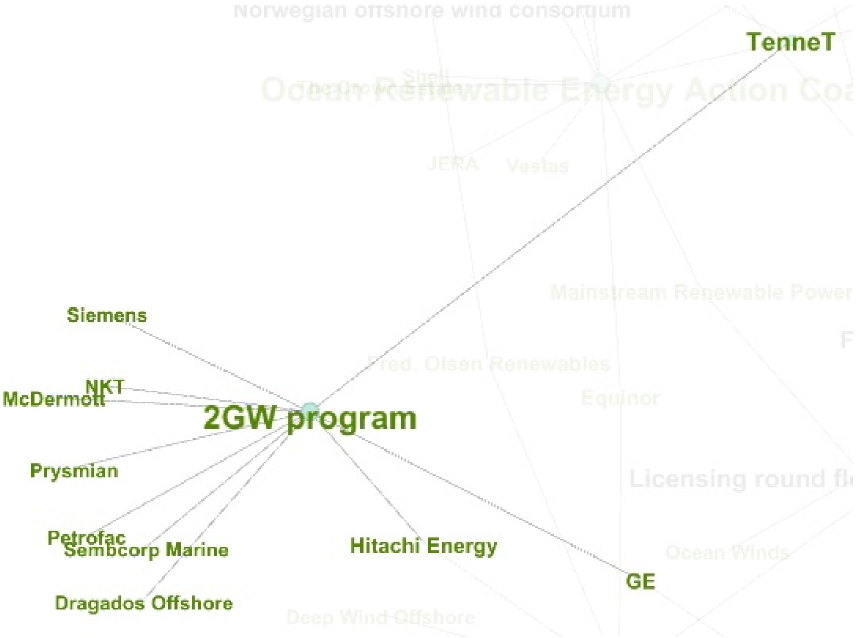


Figure 34: *2 GW program as an example project for niche level SNA*

Table 11: *Interconnectors between European offshore TSOs*

TSO 1	TSO 2	Interconnector name	Connection type	Source
Eirgrid	RTE	Celtic Interconnector	HVDC	https://www.nsenergybusiness.com/projects/celtic-interconnector/
Eirgrid	Soni	North South Interconnector	under construction	https://www.soni.ltd.uk/the-grid/projects/tyrone-cavan/the-project/
National Grid	Statnett	North Sea Link	HVDC	https://www.statnett.no/en/our-projects/interconnectors/north-sea-link/
National Grid	Energinet	Viking Link	HVDC	https://viking-link.com/
National Grid	TenneT	Britned	HVDC	https://www.britned.com/
National Grid	Elia group	Nemolink	HVDC	https://www.nemolink.co.uk/
Energinet	TenneT	Cobra Cable	HVDC	https://www.tennet.eu/projects/cobracable
Energinet	Svenska Kraftnät	Oresund 400kV	AC	https://www.offshore-energy.biz/nkt-boskalis-secure-oresund-400kv-interconnector-project/
Energinet	Statnett	Skagerrak Link	HVDC	https://www.offshore-technology.com/contractors/cables/nexans/pressreleases/pressskagerrak-40th-anniversary/
Energinet	Elia group	Triton Link	HVDC	https://www.offshore-energy.biz/energinet-and-elia-launch-tender-for-new-north-sea-interconnector/
Energinet	50Hertz	Kriegers Flak	HVDC	https://www.50hertz.com/Grid/Griddevelopement/Concludedprojects/CombinedGridSolution
Svenska Kraftnät	PSE	SwePol	HVDC	https://library.e.abb.com/public/0d242958cb0fb2a5c1256fda004aeab7/swepol.pdf
Svenska Kraftnät	TenneT	Balticcable	HVDC	https://balticcable.com/our-asset/
Svenska Kraftnät	50Hertz	Hansa PowerBridge	HVDC	https://www.50hertz.com/Grid/Griddevelopement/Offshoreprojects/HansaPowerBridge
Svenska Kraftnät	Litgrid	Nordbalt	HVDC	https://www.nkt.com/references/nordbalt-the-baltic-sea
Statnett	TenneT	NordLink	HVDC	https://www.statnett.no/en/our-projects/interconnectors/nordlink/
Fingrid	Svenska Kraftnät	Fenne-Skan	HVDC	https://www.fingrid.fi/en/news/news/2021/fenno-skan-1-lifetime-will-be-extended-until-2040/
Fingrid	Elering	EstLink	HVDC	https://www.elering.ee/en/cross-border-electricity-trade#tab2

Table 12: *Data for the SNA part 1 - key players, domain and connection type*

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
2	Orsted	DSV	Transport& logistics	Project
3	Orsted	Lincolnshire Wildlife Trusts	Biodiversity	Project
4	Orsted	Yorkshire Wildlife Trusts	Biodiversity	Project
5	Orsted	Spoor AI	AI	Project
6	Orsted	Gazprom Export	Gas	Supplier
7	Orsted	ARK Nature	Biodiversity	Project
8	Orsted	TotalEnergies	Energy	Project
9	Orsted	ESVAGT	Shipping	Project
10	Orsted	Simply Blue Group	Blue economy developer	Project
11	Orsted	Subsea7	Engineering	Project
12	Orsted	Salzgitter AG	Steel & technology	Supplier
13	Orsted	Falck Renewables	Renewable energy	Project
14	Orsted	BlueFloat Energy	Offshore wind	Project
15	Orsted	Amazon	Technology	Customer
16	Orsted	Liquid Wind	e-fuel	Project
17	Orsted	Siemens Gamesa	Wind energy	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
18	Orsted	Nexans	Cable manufacturer	Supplier
19	Orsted	CHC Helicopter	Helicopter operator	Supplier
20	Orsted	Covestro	Raw materials	Customer
21	Orsted	REWE Group	Trade & tourism	Customer
22	Orsted	BASF	Chemical producer	Customer
23	Orsted	Google	Technology	Customer
24	Orsted	Johnson & Johnson	Pharmaceuticals	Customer
25	Orsted	Nordic Investment Bank	Financial	Financial
26	Orsted	Science Based Targets initiative	Climate Change certification	Project
27	Orsted	European Investment Bank	Financial	Financial
28	Orsted	ITM Power	Hydrogen	Project
29	Orsted	Element Energy	Battery technology	Project
30	Orsted	Siemens Gamesa	Wind energy	Project
31	Orsted	Bladt Industries	Offshore manufacturer	Supplier
32	Orsted	Steelwind Nordenham	Steel manufacturer	Supplier
33	Orsted	Fred. Olsen Renewables	Renewable energy	Project
34	Orsted	Hafslund Eco	Renewable energy/infrastructure	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
35	Orsted	World Resources Institute	Global research	Project
36	Orsted	Norges Bank Investment Managament	Financial	Financial
37	Orsted	Yara	Ammonia producer	Project
38	Orsted	ArcelorMittal Belgium	Steel producer	Project
39	Orsted	Dow Benelux	Material science	Project
40	Orsted	Zeeland Refinery	Oil & gas	Project
41	Orsted	Greenchoice	Energy company	Project
42	Orsted	EDF Germany	Renewable energy	Project
43	Orsted	Holcim Germany	Sustainable consruction	Project
44	Orsted	OGE	Gas grid operator	Project
45	Orsted	Thyssenkrupp	Steel producer	Project
46	Orsted	Nestle	Food and beverage	Customer
47	Orsted	Equinor	Norwegian TSO	Project
48	Orsted	CWind	Offshore services	Project
49	Orsted	Global Marine Group	Offshore engineering	Project
50	Orsted	JERA	Energy trade	Project
51	Orsted	Vestas	Wind energy	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
52	Orsted	Mainstream Renewable Power	Renewable energy	Project
53	Orsted	Shell	Oil & gas, energy	Project
54	Orsted	Siemens Gamesa	Wind energy	Project
55	Orsted	TenneT	Dutch & German TSO	Project
56	Orsted	The Crown Estate	Commercial business	Project
57	Orsted	Northumbrian Water	Water & sewage services	Customer
58	Orsted	WWF	Biodiversity	Project
59	Orsted	ATP	Pension company	Project
60	Orsted	Aarsleff	Large-scale projects	Project
61	Orsted	Boygues Travaux Publics	Regeneration and sustainable infrastructure	Project
62	Orsted	Van Oord	International marine contractor	Project
63	Orsted	Arup	Sustainable development	Project
64	Orsted	Global Connect	Digital infrastructure	Project
65	Energinet	TenneT	TSO	Project
66	Energinet	Svenska Kraftnät	TSO (Sweden)	Project
67	Energinet	Statnett	TSO (Norway)	Project
68	Energinet	Prysmian	Cable manufacturer	Supplier

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
69	Energinet	NKT	Cable supplier	Supplier
70	Energinet	Siemens	Technology	Supplier
71	Energinet	National Grid	TSO	Project
72	Energinet	Nord Pool Holding AS	Power market operator	Shareholder
73	Energinet	National Grid	TSO	Project
74	Energinet	EirGrid	TSO (Ireland)	Project
75	Energinet	Imperial College London	University	Project
76	Energinet	Fraunhofer Cluster of Excellence for Integrated Energy Systems	Research Institute	Project
77	Energinet	Danish Technical University	University	Project
78	Energinet	World Bank	Financial	Project
79	Energinet	German Agency for International Cooperation	International enterprise	Project
80	Energinet	European Bank for Reconstruction and Development	Financial	Project
81	Energinet	Microsoft	Software	Project
82	Energinet	Eurowind Energy	Windpark owner	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
83	Energinet	Corre Energy	Long duration energy storage projects (NL)	Project
84	Energinet	Energi Danmark	Balance responsible party	Project
85	Energinet	Gasunie Deutschland	Gas network operator	Project
86	Energinet	Gasunie	Gas network operator	Project
87	Energinet	TenneT	TSO (NL)	Project
88	Energinet	DNV	Classification, maritime industry	Project
89	Energinet	Elia group	TSO (Belgium)	Project
90	Energinet	Fugro	Geodata	Supplier
91	Elia group	National Grid	TSO (UK)	Project
92	Elia group	Energinet	TSO (DK)	Project
93	Elia group	50 Hertz	TSO (GER)	Project
94	Elia group	Re.alto	Market place for energy data	Shareholder
95	Elia group	Octopus Energy Group	Financial services & energy	Project
96	Elia group	Siemens	Energy	Project
97	Elia group	Ross Robotics	Autonomous inspection & maintenance	Project
98	Elia group	Energinet	TSO (DK)	Project
99	Elia group	National grid	TSO (UK)	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
100	Elia group	DEME Group	Offshore infrastructure	Supplier
101	Elia group	Jan de Nul Group	Offshore infrastructure	Supplier
102	Elia group	NHV	Helicopter services	Supplier
103	Elia group	Cathie	Engineering consultancy	Supplier
104	Elia group	Heerema	Offshore energy structures	Supplier
105	National grid	Siemens	Energy	Supplier
106	National grid	TenneT	TSO	Project
107	National grid	NKT	Offshore equipment	Supplier
108	National grid	Orsted	Offshore wind	Project
109	National grid	Flotation Energy	Offshore wind	Project
110	National grid	Vårgrønn	Offshore wind	Project
111	National grid	Wärtsilä	Energy storage company	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
112	National grid	Siemens	Energy	Project
113	National grid	Aker Solutions	Oil and gas	Project
114	National grid	Vattenfall	Energy producer	Project
115	National grid	Mitie	Facilities management & services	Supplier
116	National grid	Wood	Engineering and consulting	Supplier
117	National grid	RWE	Energy	Project
118	National grid	SolarEdge	Energy, software, storage	Project
119	National grid	Boston Dynamics	Robotics	Project
120	National grid	Strategic Innovation Fund	Finance	Project
121	National grid	Ofgem	Independent national regulatory authority	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
122	National grid	ESA	Space agency	Project
123	National grid	Science Based Targets initiative	Climate Change certification	Project
124	National grid	Siemens	Energy	Project
125	National grid	British Ports Association	Ports	Project
126	National grid	Dragos Inc.	Cybersecurity leader for industrial controls systems /operational technology	Funding
127	National grid	Aperio Systems	AI for industrial sensor data	Funding
128	National grid	AIDash	AI and satellite imagery	Funding
129	National grid	CNIGuard	Internet of things-based asset protection and management	Shareholder
130	National grid	SparkCognition	AI for process optimization & cybersecurity	Shareholder

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
131	National grid	Uniphore	AI for conversation services	Shareholder
132	Svenska Kraftnät	Vattenfall	Energy operator	Project
133	Svenska Kraftnät	Gotland Energi	Grid owner	Project
134	Svenska Kraftnät	Freja Offshore	Offshore wind power	Project
135	Svenska Kraftnät	Vattenfall	Energy	Project
136	Svenska Kraftnät	Preem	Fuel producer	Project
137	Svenska Kraftnät	50Hertz	German TSO	Consortium
138	Svenska Kraftnät	Amprion	German TSO	Consortium
139	Svenska Kraftnät	RED	Spanish TSO	Consortium
140	Svenska Kraftnät	RTE	French TSO	Consortium

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
141	Svenska Kraftnät	Statnett	Norwegian TSO	Consortium
142	Svenska Kraftnät	Terna	Italian TSO	Consortium
143	Svenska Kraftnät	Energinet	Danish TSO	Project
144	Svenska Kraftnät	Statnett	Norwegian TSO	Project
145	Statnett	Nexans	Cable manufacturer	Supplier
146	Statnett	TenneT	German TSO	Project
147	Statnett	Kf W	Financial	Project
148	Statnett	Hitachi Energy	Power supplier	Supplier
149	Statnett	Equinor	Oil and gas	Project
150	Statnett	Fred.Olsen Renewables	Renewable energy	Project
151	Statnett	Hafslund Eco	Hydropower	Project
152	Statnett	Hitachi Energy	Power supplier	Project
153	Statnett	ABB	Technology	Project
154	Statnett	A Energi	Energy products	Project
155	Statnett	Aker Offshore Wind	Offshore wind	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
156	Statnett	Benestad Solutions	Manufacturing for oil and gas, defense	Project
157	Statnett	Deep Wind Offshore	Offshore wind	Project
158	Statnett	Aibel	Critical energy infrastructure	Project
159	Statnett	Nexans	Cable manufacturer	Project
160	Statnett	DNV	Consultancy	Project
161	Statnett	SINTEF	Research institute	Project
162	Statnett	NTNU	University	Project
163	Statnett	University of Oslo	University	Project
164	Statnett	Enova	Project developer renewables	Project
165	Statnett	Svenska Kraftnät	Swedish TSO	Project
166	Statnett	NTNU	University	Project
167	Statnett	Hyper Interaktiv	Webdesign	Project
168	Statnett	NKT	Cable supplier	Supplier
169	Statnett	Nexans	Cable manufacturer	Supplier
170	Statnett	TenneT	German TSO	Project
171	Statnett	KfW	Finance	Project
172	Statnett	Cognite	Software	Project
173	Statnett	Sintef	Research Institute	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
174	Statnett	IBM	Software	Project
175	Statnett	ABB	Technology	Project
176	Statnett	GE	Energy	Project
177	Statnett	Nord Pool	Power exchange	Shareholder
178	Statnett	Mainstream Renewable Power	Renewable energy	Project
179	Statnett	Ocean Winds	Wind power developer	Project
180	Statnett	Statkraft	Renewable energy provider	Project
181	RTE	Energinet	Danish TSO	Project
182	RTE	Gasunie	Gas network operator	Project
183	RTE	TenneT	Dutch TSO	Project
184	RTE	RWE	Energy	Project
185	RTE	National Grid	UK TSO	Project
186	RTE	Airtelis	Helicopter operations	Shareholder
187	RTE	Unicorn	Information systems	Project
188	RTE	National Grid	UK TSO	Project
189	RTE	National HVDC Centre	HVDC research	Project
190	RTE	Scottish and Southern Energy (SSE)	Energy infrastructure & services	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
191	RTE	Equinor	Oil and gas	Project
192	TenneT	NKT	Cable supplier	Supplier
193	TenneT	Prysmian	Cable manufacturer	Supplier
194	TenneT	Hitachi	Power supplier	Supplier
195	TenneT	GE	Energy	Supplier
196	TenneT	McDermott	Engineering & construction	Supplier
197	TenneT	Siemens	Energy	Supplier
198	TenneT	Dragados Offshore	Offshore engineering	Supplier
199	TenneT	Sembcorp Marine	Marine engineering	Supplier
200	TenneT	Petrofac	Energy services	Supplier
201	TenneT	Van Oord	Offshore infrastructure	Supplier
202	TenneT	Hellenic Cables	Cable manufacturer	Supplier
203	TenneT	Allseas	Subsea construction	Supplier
204	TenneT	GEIRI/C-EPRI	Research Institute	Project
205	TenneT	Boskalis	Maritime services	Supplier
206	TenneT	Orient Cable (NBO)	Cable provider	Supplier
207	TenneT	Statnett	Norwegian TSO	Project
208	TenneT	Heerema	Offshore energy projects	Supplier
209	TenneT	Vattenfall	Energy producer	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
210	TenneT	BASF	Chemical company	Project
211	TenneT	Denys	Cable engineering	Supplier
212	TenneT	Alsema	Cable installation	Supplier
213	TenneT	Van Vulpen	Drilling	Supplier
214	TenneT	Orsted	Wind energy	Project
215	TenneT	Energy2market	Virtual power plant	Project
216	Amprion	TenneT	German TSO	Project
217	Amprion	Siemens	Technology	Project
218	Amprion	Siemens	Technology	Supplier
219	Amprion	Dragados Offshore	Offshore engineering	Supplier
220	Amprion	50Hertz	German TSO	Project
221	Amprion	BirdLife international	Nature conservation	Project
222	Amprion	BWO	Windpark operator association	Project
223	Amprion	National grid	TSO UK	Project
224	Amprion	Natuur & Milieu	Environmental protection	Project
225	Amprion	Orsted	Renewable energy	Project
226	Amprion	Renewables Grid Initiative	Renewable energy	Project
227	Amprion	RTE	French TSO	Project

1	**Company 1**	**Company 2**	**Domain**	**Connection type**
228	Amprion	RSPB	Biodiversity	Project
229	Amprion	Seawind	Wind energy assets	Project
230	Amprion	Siemens Gamesa	Wind energy assets	Project
231	Amprion	Stichting De Noordzee	Environmental protection	Project
232	Amprion	TenneT	Dutch TSO	Project
233	Amprion	Vattenfall	Energy producer	Project
234	Amprion	Wab	German Wind energy association	Project
235	Amprion	The Wildlife Trusts	Biodiversity	Project
236	Amprion	WindEurope	Wind energy	Project
237	Amprion	Wind Energy Ireland	Irish wind energy	Project
238	Amprion	WWF	Biodiversity & nature	Project
239	Amprion	Elia group	Belgian TSO	Project
240	Amprion	Germanwatch	Sustainable development	Project
241	Amprion	Iberdrola	Renewable energy	Project
242	Amprion	NABU	Environmental protection	Project
243	Amprion	CAN	Climate change	Project
244	Amprion	EirGrid	Irish TSO	Project

Table 13: *Data for the SNA part 2 - project topic and sources*

1	**Project topic**	**Source**
2	Cargo drones	https://orsted.com/en/media/newsroom/news/2022/06/13654538
3	Biodiversity pioneer	https://orsted.com/en/media/newsroom/news/2022/06/13653868
4	Biodiversity pioneer	https://orsted.com/en/media/newsroom/news/2022/06/13653868
5	Birdlife data	https://orsted.com/en/media/newsroom/news/2022/06/13652903
6	Gas supply	https://orsted.com/en/media/newsroom/news/2022/05/20220531530111
7	Project	https://orsted.com/en/media/newsroom/news/2022/05/13651322
8	Holland coast west (tender bid)	https://orsted.com/en/media/newsroom/news/2022/05/20220513524811
9	Green fuel vessel	https://orsted.com/en/media/newsroom/news/2022/04/13648631
10	Floating offshore wind (Salamander)	https://orsted.com/en/media/newsroom/news/2022/04/20220406509711

1	**Project topic**	**Source**
11	Floating offshore wind (Salamander)	https://orsted.com/en/media/newsroom/news/2022/04/20220406509711
12	Manufacturing	https://orsted.com/en/media/newsroom/news/2022/01/20220125471111
13	Floating offshore wind	https://orsted.com/en/media/newsroom/news/2022/01/20220117468011
14	Floating offshore wind	https://orsted.com/en/media/newsroom/news/2022/01/20220117468011
15	Corporate power purchase agreement (CPPA)	https://orsted.com/en/media/newsroom/news/2022/01/orsted-takes-final-investment-decision-on-ballykeel-onshore-wind-farm
16	e-methanol (FlagshipONE)	https://orsted.com/en/media/newsroom/news/2022/01/orsted-partners-with-liquid-wind-and-expands-presence-in-green-fuels-with
17	Hornsea 2 (wind park)	**https://orsted.com/en/media/newsroom/news/2021/12/20211220460511**
18	Hornsea 2 (windpark)	Hornsea Project Two: a 1.4GW windfarm being built in the North Sea (power-technology.com)
19	Hornsea 2 (windpark)	Hornsea Project Two: a 1.4GW windfarm being built in the North Sea (power-technology.com)

1	Project topic	Source
20	Borkum Riffgrund 3	https://orsted.com/en/media/newsroom/news/2021/12/20211201449611
21	Borkum Riffgrund 3	https://orsted.com/en/media/newsroom/news/2021/12/20211201449611
22	Borkum Riffgrund 3	https://orsted.com/en/media/newsroom/news/2021/12/20211201449611
23	Borkum Riffgrund 3	https://orsted.com/en/media/newsroom/news/2021/12/20211201449611
24	CPPA (Ireland)	https://orsted.com/en/media/newsroom/news/2021/11/13637536
25	Loan	https://orsted.com/en/media/newsroom/news/2021/11/20211112443011
26	Net-Zero Standard	https://orsted.com/en/media/newsroom/news/2021/10/13634593
27	Loan	https://orsted.com/en/media/newsroom/news/2021/09/13632201
28	OYSTER (hydrogen)	https://orsted.com/en/media/newsroom/news/2021/09/862313889301790
29	OYSTER (hydrogen)	https://orsted.com/en/media/newsroom/news/2021/09/862313889301790
30	OYSTER (hydrogen)	https://orsted.com/en/media/newsroom/news/2021/09/862313889301790

1	**Project topic**	**Source**
31	Monopile foundations	https://orsted.com/en/media/newsroom/news/2021/09/113355730339739
32	Monopile foundations	https://orsted.com/en/media/newsroom/news/2021/09/113355730339739
33	Norwegian offshore wind consortium	https://orsted.com/en/media/newsroom/news/2021/06/363524256672655
34	Norwegian offshore wind consortium	https://orsted.com/en/media/newsroom/news/2021/06/363524256672655
35	Working paper on renewable energy future	https://orsted.com/en/media/newsroom/news/2021/06/177261390139136
36	Partnership (Borssele 1 & 2)	https://orsted.com/en/media/newsroom/news/2021/05/419222030612334
37	SeaH2Land	https://orsted.com/en/media/newsroom/news/2021/03/451073134270788
38	SeaH2Land	https://orsted.com/en/media/newsroom/news/2021/03/451073134270788
39	SeaH2Land	https://orsted.com/en/media/newsroom/news/2021/03/451073134270788
40	SeaH2Land	https://orsted.com/en/media/newsroom/news/2021/03/451073134270788

1	**Project topic**	**Source**
41	Trade & balance power form onshore wind (NL)	https://orsted.com/en/media/newsroom/news/2020/12/182440405582545
42	Westküste100	https://orsted.com/en/media/newsroom/news/2020/08/855576841937376
43	Westküste100	https://orsted.com/en/media/newsroom/news/2020/08/855576841937376
44	Westküste100	https://orsted.com/en/media/newsroom/news/2020/08/855576841937376
45	Westküste100	https://orsted.com/en/media/newsroom/news/2020/08/855576841937376
46	PPA	https://orsted.com/en/media/newsroom/news/2020/04/876008283577483
47	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
48	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity

1	**Project topic**	**Source**
49	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
50	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
51	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
52	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
53	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
54	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity

1	**Project topic**	**Source**
55	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
56	Ocean Renewable Energy Action Coalition	https://orsted.com/en/media/newsroom/news/2020/01/ocean-renewable-energy-action-coalition-launches-to-accelerate-global-offshore-wind-capacity
57	Race Bank offshore wind park	https://orsted.com/en/media/newsroom/news/2019/02/orsted-and-northumbrian-water-group-sign-uk-s-first-offshore-wind-corporate-ppa
58	Partnership	https://orsted.com/en/media/newsroom/news/2022/10/13662962
59	North Sea Energy Island	https://northseaenergyisland.dk/en/partnere
60	North Sea Energy Island	https://northseaenergyisland.dk/en/partnere
61	North Sea Energy Island	https://northseaenergyisland.dk/en/partnere
62	North Sea Energy Island	https://northseaenergyisland.dk/en/partnere
63	North Sea Energy Island	https://northseaenergyisland.dk/en/partnere
64	North Sea Energy Island	https://northseaenergyisland.dk/en/partnere
65	COBRAcable	https://en.energinet.dk/about-our-news/news/2019/03/14/preparation-for-including-cobracable-in-the-market-coupling/

1	**Project topic**	**Source**
66	Shareholder of eSett Oy (Nordic imbalance settlement)	https://en.energinet.dk/about-our-news/news/2019/05/13/energinet-joins-the-nordic-imbalance-settlement-and-becomes-shareholder-in-esett-oy/
67	Shareholder of eSett Oy (Nordic imbalance settlement)	https://en.energinet.dk/about-our-news/news/2019/05/13/energinet-joins-the-nordic-imbalance-settlement-and-becomes-shareholder-in-esett-oy/
68	Viking Link (UK-DK)	https://en.energinet.dk/about-our-news/news/2019/07/23/prysmian-nkt-and-siemens-to-supply-cables-and-converters-for-viking-link/
69	Viking Link (UK-DK)	https://en.energinet.dk/about-our-news/news/2019/07/23/prysmian-nkt-and-siemens-to-supply-cables-and-converters-for-viking-link/
70	Viking Link (UK-DK)	https://en.energinet.dk/about-our-news/news/2019/07/23/prysmian-nkt-and-siemens-to-supply-cables-and-converters-for-viking-link/
71	Viking Link (UK-DK)	https://en.energinet.dk/about-our-news/news/2019/07/23/prysmian-nkt-and-siemens-to-supply-cables-and-converters-for-viking-link/
72	Energinet is minority shareholder	https://en.energinet.dk/about-our-news/news/2019/12/05/energinet-sells-most-shares-in-nord-pool/

1	**Project topic**	**Source**
73	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
74	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
75	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
76	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
77	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
78	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
79	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
80	Global Power System Transformation Consortium	https://globalpst.org/who-we-are/
81	DataHub partnership	https://en.energinet.dk/about-our-news/news/2020/11/11/new-generation-datahub-to-boost-green-transition/

1	**Project topic**	**Source**
82	Hydrogen hub (Power2X)	https://en.energinet.dk/about-our-news/news/2020/11/30/new-large-scale-hydrogen-hub-to-support-denmarks-green-transition/
83	Hydrogen hub (Power2X)	https://en.energinet.dk/about-our-news/news/2020/11/30/new-large-scale-hydrogen-hub-to-support-denmarks-green-transition/
84	Wind turbines in capacity market for manual reserves ->balancing grid	https://en.energinet.dk/about-our-news/news/2020/12/16/milestone-wind-turbines-can-balance-the-electricity-grid/
85	MoU - cross-border hydrogen network	https://en.energinet.dk/about-our-news/news/2022/09/01/mou-brint/
86	North Sea wind Power Hub	https://northseawindpowerhub.eu/vision
87	North Sea wind Power Hub	https://northseawindpowerhub.eu/vision
88	North Sea energy island	https://www.offshore-mag.com/renewable-energy/article/14279106/dnv-supporting-north-sea-energy-island-design
89	North Sea energy island (cooperation agreement –feasibility studies)	https://en.energinet.dk/about-our-news/news/2021/11/23/realization-of-interconnections-to-energy-islands-moves-a-big-step-closer/

1	**Project topic**	**Source**
90	Cable route surveys for North Sea Energy Island	https://www.power-technology.com/news/fugro-cable-route-contract/
91	Nautilus (Interconnector)	https://www.elia.be/en/infrastructure-and-projects/infrastructure-projects/nautilus
92	TritonLink (hybrid interconnector, connectsenergy islands and DK + BE)	https://www.elia.be/en/infrastructure-and-projects/infrastructure-projects/tritonlink
93	WindGrid (Build offshore infrastructure) international energy company (subsidiary)	https://www.50hertz.com/en/News/FullarticleNewsof50Hertz/12258/with-the-establishment-of-windgrid-elia-group-wants-to-make-a-fundamental-contribution-to-accelerating-the-energy-transition
94	Corporate start-up company (energy data exchange, bridges consumers and providers)	https://www.eliagroup.eu/en/news/press-releases/2020/10/20201013_realto
95	Use of KrakenFlex (ML & AI powered platform matching supply and demand for energy assets) – demand flexibility	https://www.eliagroup.eu/en/news/press-releases/2021/11/20211103_elia-group-and-octopus-energy-group-sign-agreement
96	Autonomous inspection robots for HVDC converter halls	https://www.eliagroup.eu/en/news/press-releases/2021/11/20211116_emc_robots
97	Autonomous inspection robots for HVDC converter halls	https://www.eliagroup.eu/en/news/press-releases/2021/11/20211116_emc_robots

1	**Project topic**	**Source**
98	Princess Elisabeth Island (energy hub connecting nemolink (UK) & TritonLink (DK))	https://www.eliagroup.eu/en/news/press-releases/2022/12/20221214_federal-government-endorses-belgian-energy-island-as-spearhead-project-for-rrf-fund
99	Princess Elisabeth Island (energy hub connecting nemolink (UK) & TritonLink (DK))	https://www.eliagroup.eu/en/news/press-releases/2022/12/20221214_federal-government-endorses-belgian-energy-island-as-spearhead-project-for-rrf-fund
100	Energy island	https://www.eliagroup.eu/en/news/press-releases/2023/02/20230228_epci-contract-energy-island-to-deme-and-jan-de-nul
101	Energy island	https://www.eliagroup.eu/en/news/press-releases/2023/02/20230228_epci-contract-energy-island-to-deme-and-jan-de-nul
102	Helicopter for platform transport	https://www.offshorewind.biz/2022/10/07/nhv-completes-first-sustainable-aviation-flight-in-offshore-wind-industry/
103	Marine consultancy services for offshore wind cables	https://www.offshorewind.biz/2020/10/06/cathie-to-work-on-future-belgian-and-german-offshore-grid-links/

1	**Project topic**	**Source**
104	Offshore Switchyard Platform	https://www.offshorewind.biz/2018/11/06/osy-platform-jacket-touching-down-in-belgian-north-sea/
105	Hornsea 2	Fussey Engineering Backs Hornsea 2 (oedigital.com)
106	Lion Link	National Grid and TenneT plan to create Anglo-Dutch electricity link (power-technology.com)
107	Hornsea 3 (Windpark)	NKT receives cabling contract for Hornsea 3 offshore wind farm (power-technology.com)
108	Hornsea 3 (Windpark)	NKT receives cabling contract for Hornsea 3 offshore wind farm (power-technology.com)
109	Floating offshore wind (Green Volt and Cenos)	Vårgrønn and Flotation Energy awarded exclusivity to develop up to 1.9 GW of floating offshore wind in Scotland (vargronn.com)
110	Floating offshore wind (Green Volt and Cenos)	Vårgrønn and Flotation Energy awarded exclusivity to develop up to 1.9 GW of floating offshore wind in Scotland (vargronn.com)
111	Offshore energy storage	Wärtsilä given contract for 200MW energy storage system in UK (power-technology.com)
112	Norfolk Boreas offshore wind project	Aker secures contract for Norfolk Boreas offshore wind farm (power-technology.com)

1	**Project topic**	**Source**
113	Norfolk Boreas offshore wind project	Aker secures contract for Norfolk Boreas offshore wind farm (power-technology.com)
114	Norfolk Boreas offshore wind project	Aker secures contract for Norfolk Boreas offshore wind farm (power-technology.com)
115	Service contract	Mitie wins two multimillion pound contracts with National Grid (cleaningmag.com)
116	Service contract	Wood expands utilities footprint with new National Grid framework contract | Wood (woodplc.com)
117	Sofia offshore wind farm project	RWE Greenlights GBP 3 Billion Sofia Offshore Wind Farm | Offshore Wind
118	Battery virtual power plant	1st Virtual Power Plant from SolarEdge Supporting UK Grid - CleanTechnica
119	Robot dog for routine asset maintenance and fault detection	Who let the dogs out? | National Grid Group
120	Eye in the Sky initiative – space technology to monitor infrastructure & improve grid reliability	Britain’s energy networks look to space to help boost climate change resilience | National Grid Group

1	**Project topic**	**Source**
121	Eye in the Sky initiative - space technology to monitor infrastructure & improve grid reliability	Britain’s energy networks look to space to help boost climate change resilience | National Grid Group
122	Eye in the Sky initiative - space technology to monitor infrastructure & improve grid reliability	Britain’s energy networks look to space to help boost climate change resilience | National Grid Group
123	Emission reduction targets	National Grid Electricity Transmission has emissions reduction targets approved by the Science Based Targets initiative | National Grid Group
124	Decarbonisation tool	National Grid and Siemens develop new tool to help UK ports transition to net zero | National Grid Group
125	Decarbonisation tool	National Grid and Siemens develop new tool to help UK ports transition to net zero | National Grid Group
126	Investment, National Grid has joined the Dragos board	Dragos Announces Record-Setting $110M Investment in Industrial Cybersecurity with Series C Funding | National Grid Group

1	**Project topic**	**Source**
127	AI for critical infrastructure, joined board	[29 Oct] National Grid Partners Invests in two Artificial Intelligence Startups to Protect Critical Infrastructure | National Grid Group
128	AI for critical infrastructure, joined board	[29 Oct] National Grid Partners Invests in two Artificial Intelligence Startups to Protect Critical Infrastructure | National Grid Group
129	Portfolio additions	National Grid Partners Closes Three More Deals | National Grid Group
130	Portfolio additions	National Grid Partners Closes Three More Deals | National Grid Group
131	Portfolio additions	National Grid Partners Closes Three More Deals | National Grid Group
132	Study of joint electricity supply with grid owner Vattenfall & Gotland Energi	Commission regarding preparatory work for the expansion of the transmission grid into Swedish territorial waters (svk.se)
133	Study of joint electricity supply with grid owner Vattenfall & Gotland Energi	Commission regarding preparatory work for the expansion of the transmission grid into Swedish territorial waters (svk.se)
134	Mareld Floating wind	Freja Offshore – Sustainable wind power, off shore

1	**Project topic**	**Source**
135	Power2X from offshore wind	Vattenfall and Preem to investigate large scale decarbonization using offshore wind and hydrogen - Vattenfall
136	Power2X from offshore wind	Vattenfall and Preem to investigate large scale decarbonization using offshore wind and hydrogen - Vattenfall
137	Eurobar	European TSOs launch Eurobar Initiative for Standardised Offshore Grids | Svenska kraftnät (svk.se)
138	Eurobar	European TSOs launch Eurobar Initiative for Standardised Offshore Grids | Svenska kraftnät (svk.se)
139	Eurobar	European TSOs launch Eurobar Initiative for Standardised Offshore Grids | Svenska kraftnät (svk.se)
140	Eurobar	European TSOs launch Eurobar Initiative for Standardised Offshore Grids | Svenska kraftnät (svk.se)

1	**Project topic**	**Source**
141	Eurobar	European TSOs launch Eurobar Initiative for Standardised Offshore Grids | Svenska kraftnät (svk.se)
142	Eurobar	European TSOs launch Eurobar Initiative for Standardised Offshore Grids | Svenska kraftnät (svk.se)
143	Cooperation for Nordic energy system	solutions-report-2022.pdf (svk.se)
144	Cooperation for Nordic energy system	solutions-report-2022.pdf (svk.se)
145	North Sea Link (UK-Nor interconnector)	Installation of the world's longest subsea interconnector | Statnett
146	Shared ownership of NordLink interconnector	Fault during testing of NordLink | Statnett
147	Shared ownership of NordLink interconnector	Fault during testing of NordLink | Statnett
148	Testing of North Sea Link	Successful testing of the North Sea Link installations in Suldal | Statnett
149	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF

1	**Project topic**	**Source**
150	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
151	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
152	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
153	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
154	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
155	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
156	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
157	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
158	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
159	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF

1	**Project topic**	**Source**
160	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
161	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
162	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
163	Consortium - Grid connection system, floating and fixed	Offshore wind: New Ocean Grid project in the North Sea - SINTEF
164	“Alternatives to expanding the power grid”	Better utilisation of the power grid can save society billions | Statnett
165	Joint venture “Fifty AS” – tools for power balancing	Svenska kraftnät and Statnett launch joint venture | Statnett
166	Collaboration on professorship – blockchain, big data, AI	NTNU and Statnett to collaborate on blockchain and machine learning professorship | Statnett
167	Gaming technology for Health, Safety and Environment (HSE) training	Using gaming technology for HSE training | Statnett
168	NordLink cable	Norwegian-German power cable being installed | Statnett

1	**Project topic**	**Source**
169	NordLink cable	Norwegian-German power cable being installed | Statnett
170	NordLink cable	Norwegian-German power cable being installed | Statnett
171	NordLink cable	Norwegian-German power cable being installed | Statnett
172	Research & development agreement for process digitalisation	Statnett speeds up the digital transformation | Statnett
173	AI for asset management (SAMBA)	Asset management with artificial intelligence | Statnett
174	AI for asset management (SAMBA)	Asset management with artificial intelligence | Statnett
175	AI for asset management (SAMBA)	Asset management with artificial intelligence | Statnett
176	AI for asset management (SAMBA)	Asset management with artificial intelligence | Statnett
177	Ownership in power exchange	Statnett reduces its ownership interest in power exchange Nord Pool | Statnett

1	**Project topic**	**Source**
178	Licensing round for development of floating offshore wind park (Utsira Nord)	The consortium - Utsira Offshore Wind
179	Licensing round for development of floating offshore wind park (Utsira Nord)	The consortium - Utsira Offshore Wind
180	Licensing round for development of floating offshore wind park (Utsira Nord)	The consortium - Utsira Offshore Wind
181	North Sea Wind Power Hub (RTE contributes to feasibility report)	North Sea Wind Power Hub offshore project relies on RTE international’s expertise on risk assessment of HVDC systems by Control and Protection replicas - RTE international (rte-international.com)
182	North Sea Wind Power Hub (RTE contributes to feasibility report)	North Sea Wind Power Hub offshore project relies on RTE international’s expertise on risk assessment of HVDC systems by Control and Protection replicas - RTE international (rte-international.com)

1	**Project topic**	**Source**
183	North Sea Wind Power Hub (RTE contributes to feasibility report)	North Sea Wind Power Hub offshore project relies on RTE international's expertise on risk assessment of HVDC systems by Control and Protection replicas - RTE international (rte-international.com)
184	Sophia offshore wind farm (RTE as technical consultant)	RTE international acts as HVDC technical consultant to Sofia Offshore Wind Farm - RTE international (rte-international.com)
185	Sophia offshore wind farm (RTE as technical consultant)	RTE international acts as HVDC technical consultant to Sofia Offshore Wind Farm - RTE international (rte-international.com)
186	Subsidiary company or RTE	Our partners - Airtelis
187	Coordination tool for renewable energy among European TSOs	RTE international and Unicorn have launched 3 coordination tools to continue the integration of renewable energy - RTE international (rte-international.com)
188	Expertise for HVDC offshore connections	RTE international provides a methodology and recommendations for offshore wind farm connection studies - RTE international (rte-international.com)

1	**Project topic**	**Source**
189	Expertise for HVDC offshore connections	RTE international provides a methodology and recommendations for offshore wind farm connection studies - RTE international (rte-international.com)
190	Expertise for HVDC offshore connections	RTE international provides a methodology and recommendations for offshore wind farm connection studies - RTE international (rte-international.com)
191	HVDC studies for oil platform connections	RTE international’s expertise to support Equinor’s offshore project - RTE international (rte-international.com)
192	2GW cable connections	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
193	2GW cable connections	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
194	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes

1	**Project topic**	**Source**
195	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
196	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
197	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
198	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
199	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes
200	2GW program	TenneT selects NKT and Prysmian for world’s largest offshore cable systems to connect increasing Dutch offshore wind volumes

1	**Project topic**	**Source**
201	Underwater robot for cable installation (Deep Dig-It)	Underwater robot laying cables successfully crossed the Rotterdam Maasmond to connect Hollandse Kust (zuid) (tennet.eu)
202	Underwater robot for cable installation (Deep Dig-It)	Underwater robot laying cables successfully crossed the Rotterdam Maasmond to connect Hollandse Kust (zuid) (tennet.eu)
203	Hollandse Kust (zuid)	Hollandse Kust (zuid) Alpha topside installed at the North Sea (tennet.eu)
204	BorWin6 (world wide HVDC developer)	McDermott - McDermott Awarded Its Largest Ever Renewable Energy Project by TenneT (mcdermott-investors.com)
205	Hollandse Kust Beta cable + interconnector cable to Alpha	TenneT awards Boskalis consortium Hollandse Kust West Beta export cabling contract
206	Hollandse Kust Beta cable + interconnector cable to Alpha	TenneT awards Boskalis consortium Hollandse Kust West Beta export cabling contract
207	NorNed (Interconnector)	NorNed back in operation with adjusted operational conditions (tennet.eu)
208	Jacket Hollandse Kust (zuid)	Beta jacket for offshore power socket Hollandse Kust (zuid) installed (tennet.eu)
209	Windpark Hollandse Kust (zuid)	Beta jacket for offshore power socket Hollandse Kust (zuid) installed (tennet.eu)

1	**Project topic**	**Source**
210	Windpark Hollandse Kust (zuid)	Beta jacket for offshore power socket Hollandse Kust (zuid) installed (tennet.eu)
211	Hollandse Kust West (Beta) – contractor combination NRG	TenneT awards NRG contract for onshore cable connection of Hollandse Kust (West Beta) project
212	Hollandse Kust West (Beta) – contractor combination NRG	TenneT awards NRG contract for onshore cable connection of Hollandse Kust (West Beta) project
213	Hollandse Kust West (Beta) – contractor combination NRG	TenneT awards NRG contract for onshore cable connection of Hollandse Kust (West Beta) project
214	Windpark Borkum Riffgrund 1 – virtual power plant	Ørsted offshore wind farm is the first to supply balancing capacity to German grid (tennet.eu)
215	Windpark Borkum Riffgrund 1 – virtual power plant	Ørsted offshore wind farm is the first to supply balancing capacity to German grid (tennet.eu)
216	Seetrassen 2030	https://offshore.amprion.net/Offshore-Projekte/Seetrassen-2030/

1	**Project topic**	**Source**
217	Grid management partnership	https://www.amprion.net/Press/Press-Detail-Page_30528.html
218	Construction convertert platforms DolWin4 and BorWin4	https://www.amprion.net/Press/Press-Detail-Page_44160.html
219	Construction convertert platforms DolWin4 and BorWin4	https://www.amprion.net/Press/Press-Detail-Page_44160.html
220	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
221	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
222	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
223	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
224	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
225	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
226	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
227	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
228	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
229	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
230	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
231	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
232	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
233	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below

1	**Project topic**	**Source**
234	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
235	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
236	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
237	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
238	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
239	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
240	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
241	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
242	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
243	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below
244	Offshore coalition for Energy and Nature	https://offshore-coalition.eu/#portlets-below

B.3 Scenario Analysis

When asking the experts about the factor ranking based on impact, the first interviewee provided five factors. Because this was deemed not feasible afterwards, the factors to be ranked were reduced to three. To make the ranking comparable, the fourth and fifth factor were also given only one point, as were the third factor for all other interviewees. The ranking can be found in Table 14.

When asking for a factor ranking based on uncertainty, no ranking was asked for as this was part of the conversation. Therefore, no ranking could have been provided for each actor and each mention of a factor was assigned one point. Some experts provided more than three factors in the flow of the conversation, which was deemed to be still relevant, as each factor was only assigned one point. The ranking can be found in Table 15. The combined ranking can be found in Figure 35.

Table 14: *Factor ranking based on impact*

Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**	**Expert 7**	**Expert 8**	**Expert 9**	**Expert 10**	**Expert 11**	**Expert 12**	**Expert 13**	**Ranking**	**Points assigned**
Government policies	Standardisation	Supply chain	Ecological impacts	Supply chain	Workforce	Public support	Market design	Energy demand	Government policies	Supply chain	Energy demand	Ecological impacts	1	3
Energy demand	Grid congestion	Regulations	Grid congestion	Regulations	Government policies	Regulations	Interconnection	Ecological impacts	Energy demand	Permitting	Energy autarky	Government policies	2	2
Oil and gas interests	Government policies	Market design	Spatial planning	Business case	Regulations	Risk perceptions	Grid congestion	Government policies	Grid congestion	Public acceptance	Supply chain	Energy demand	3	1
Spatial planning													4	1
Public support													5	1

Table 15: *Factor ranking based on uncertainty*

Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**	**Expert 7**	**Expert 8**	**Expert 9**	**Expert 10**	**Expert 11**	**Expert 12**	**Expert 13**	**Ranking**	**Points assigned**
Energy demand	Spatial planning	Market design	Ecological impacts	Economic development	Political instability/security	Regulations	Market design	Ecological impacts	Energy demand	Supply chain	Supply chain	Hydrogen	1	1
Technological development	Workforce	Technological development	Spatial planning	Government policies	Supply chain	Political instability/security	Energy demand	Supply chain	Onshore grid development	Geopolitical tensions	Cooperation	Government policies	1	1
Government policies	Government policies	Standardisation	Technological development	Workforce	Government policies				Supply chain	Small nuclear reactors	Technological development	Ecological impacts	1	1
		Offshore grid design							Demand flexibility & energy storage		Energy demand	Political instability/security	1	1
											Weather impact & wake effects		1	1

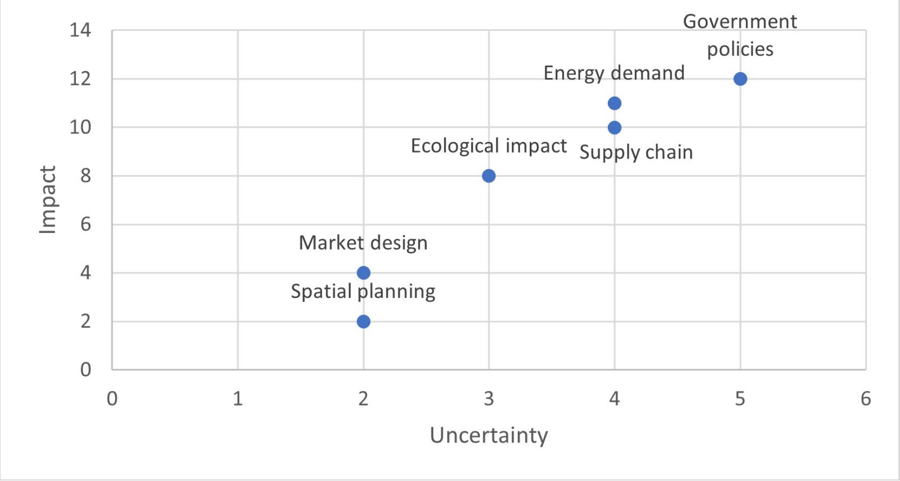


Figure 35: *Factor ranking based on uncertainty and impact*

Interview guideline

Semi-Structured expert interviews: External factors affecting the North Sea offshore energy system

1. Could you please introduce yourself and provide an overview of your expertise and experience related to the North Sea offshore energy system?

2. Based on your understanding and expertise, which external factors do you believe will have the most significant impact on the offshore energy system in the North Sea in the near future? Please provide a brief explanation for each factor.

3. Out of the factors you mentioned, could you rank the top five factors in terms of their potential impact on the North Sea offshore energy system? Please explain why you assigned each factor its respective rank.

4. Are there any specific factors that you believe are currently underestimated or overlooked but could significantly affect the North Sea offshore energy system in the near future? If that is the case, can you please elaborate.

   4.1 (If not mentioned) In the literature, there was little to be found on environmental factors affecting the North Sea offshore energy system. What role do you see environmental factors playing over the next 5 years?

5. Considering the factors you mentioned, how do you envision potential futures for the North Sea offshore energy system over the next five years? What are the key scenarios or pathways that you foresee?

6. Could you describe one or more specific scenarios that you believe could have a significant impact on the North Sea offshore energy system? What are the key drivers and events behind these scenarios?

7. Based on your professional experience, what are the necessary components or actions required to achieve the scenarios you mentioned?

8. Are there any potential risks or challenges associated with the scenarios you described? How could these challenges be addressed or mitigated effectively?

9. Where do you see potential for conflict of the offshore energy system with and other sectors, such as environmental conservation, shipping, or tourism? How might these interactions shape the future of the offshore energy system?

10. How do you anticipate the regulatory landscape evolving for the North Sea offshore energy system? Are there any specific policy changes or developments that you consider particularly relevant?

11. Based on your expertise, what are the key uncertainties regarding the scenarios that could disrupt the North Sea offshore energy system?

12. Is there any additional information or perspective that you believe would be valuable for understanding the factors and future scenarios impacting the North Sea offshore energy system? Please share any thoughts or insights you deem relevant.

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT TEMPLATES AND GUIDE
(English Version: January 2022)

You are being invited to participate in a research study titled *Contextual analysis of the North Sea offshore energy system - Using PESTLE and exploratory scenario analysis to assess the impacts of external factors on TenneT's GFO-O*. **This study is being done by Peter Schmidt from the TU Delft in cooperation with TenneT.**

The purpose of this research study is to study the offshore energy system in the North Sea. Therefore, the thesis focuses on the role of the Dutch and German transmission system operator TenneT as a case study. External factors impacting TenneT's department Grid Field Operations – Offshore (GFO-O) are identified and their impacts on its performance assessed. For this, PESTLE is used within the multi-level perspective framework and combined with an exploratory scenario analysis to account for uncertainties over the next five years and provide policy recommendation to the management to ensure reliable electricity supply.

The interview will take you approximately 30-45 minutes to complete. The data will be used for research purposes as part of a master's thesis investigating external factors in the North Sea offshore energy system. We will be asking you questions regarding the external factors that you regard as critically impacting the North Sea offshore energy system, ask you to provide a ranking of the factors, Moreover, we will ask you to provide about potential futures for this system, what pathways you see to get there and what necessary components will be.

In case of in-person interviews, the interviews will be audio-recorded or video-recorded in case of an online-interview. As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by deleting the records and transcripts of the interviews after they have been used for the research purposes. Even though transcripts will be generated from the interviews and temporarily securely stored within TU Delft, in the thesis only aggregated answers will be used and the transcript destroyed after publication of the corresponding master's thesis. In the appendix of the thesis, only the code book used for coding the interviews, the informed consent form template and the interview guideline will be added. No personal information from the interview partners will be published and no commercially or professionally sensitive questions will be asked.

Your participation in this study is entirely voluntary and you can withdraw at any time. In that case, all data collected up to that point will be deleted and destroyed. No financial compensation will be provided for participating in the study. You are free to omit any questions. The master's thesis is expected to be finished and published in August 2023.

In case you need to contact the research team for any reason, you can reach them through the following
contact details:

- Peter Schmidt (corresponding researcher): P.Schmidt-1@student.tudelft.nl
- Thomas Hoppe (responsible researcher): t.hoppe@tudelft.nl

By answering the questions below and signing the form, you are agreeing to this Opening Statement and providing informed consent to participate in the study.

PLEASE TICK THE APPROPRIATE BOXES	**Yes**	**No**
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
1. I understand that the (identifiable) personal data I provide will be destroyed after publishing the master's thesis.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
2. I understand that after the research study the de-identified information I provide will be used in aggregated form for policy recommendations and decision-making processes by TenneT.	☐	☐

Signatures

____________________________ ___________________________ _________
Name of participant [printed] Signature Date

[Add legal representative, and/or amend text for assent where participants cannot give consent as applicable]

I, as legal representative, have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

____________________________ _________________________ __________
Name of witness [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

__________________________ ____________________ _________
Researcher name [printed] Signature Date

Study contact details for further information: [*Name, phone number, email address*]