The effects of hydrogen designs and electricity demand on the configurations of the North Sea hub and spoke energy system

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Executive summary

The North Sea plays a pivotal role in Europe's energy transition, offering vast potential for offshore wind energy expansion. One promising approach to harness this potential is the hub and spoke concept, in which offshore wind farms connect to energy hubs that distribute electricity to surrounding countries and other hubs. Despite the strategic importance of this approach, there remain significant uncertainties regarding the system's design, including decisions about installed capacity, hydrogen integration methods, and future electricity demand.

This study addresses these uncertainties by first identifying the offshore wind generation goals of the countries surrounding the North Sea. Next, it evaluates various methods for integrating hydrogen production into the energy system. Based on the findings, multiple scenarios were designed to represent a spectrum of future system arrangements.

A scenario-based energy flow model was created to simulate and compare the behavior of different network designs under varying assumptions about electricity demand and hydrogen inclusion. The analysis reveals that electricity demand has a major impact on system design. Higher demand reduces the availability of surplus electricity, thereby limiting both hydrogen production and the cable capacity needed to transport electricity across the network. The results also show that onshore hydrogen production requires approximately 11% more cable capacity than offshore hydrogen production, although it avoids additional offshore infrastructure costs.

This study concludes that the North Sea hub and spoke energy system could serve as a foundational element of a flexible, robust, and integrated European energy system. However, to support effective planning and implementation, several critical areas require further research. These include the development of a time-based optimization model that incorporates real weather data and demand profiles to reveal seasonal and daily performance patterns. Moreover, there is an urgent need for more accurate projections of future electricity and hydrogen demand, as these will heavily influence infrastructure decisions. Lastly, detailed economic assessments must be conducted to better understand the investment requirements, market dynamics, and potential policy interventions needed to make this vision feasible.

By clarifying key design choices and highlighting critical next steps, this research contributes to a more informed and coordinated development of the North Sea energy system, advancing Europe's transition toward a sustainable, carbon-neutral future.

1. Introduction

The North Sea is a key area in Europe's energy transition, playing a critical role in the region's efforts to decarbonize its energy systems and meet ambitious climate targets. Countries bordering the North Sea, such as the Netherlands, Germany, Denmark, and the United Kingdom, are all striving to increase their offshore wind capacity as part of their national energy strategies. This shared ambition presents a unique window of opportunity for better coordination and integration of energy grids, allowing for higher system efficiency and improved energy security in a world of ever more intermittent energy production. However, to fully use this potential, a common solution must be agreed upon.

One promising concept is the "hub and spoke" energy system, developed by the North Sea Wind Power Hub, an international consortium of energy companies and grid operators (Tennet, 2020). The idea envisions a centralized offshore hub network that connects multiple surrounding countries via a network of cables, enabling the exchange of electricity generated by vast wind parks in the North Sea. This approach could dramatically increase the flexibility, reliability, and capacity of Europe's energy system. Furthermore, this can lead to a large decrease in CO2 emissions (Jansen et al., 2022).

Despite the significant benefits and opportunities this concept offers, several key challenges must be addressed to ensure the project's success. Firstly, there are challenges regarding jurisdiction and cooperation, such as coordinating national energy policies, regulatory frameworks, allocation of investment costs and benefits, and how the electricity price will be determined in this concept(Alavirad et al., 2021). Secondly, the building of the hub and spoke concept will lead to challenges regarding the impact on the environment, marine life and on various industries that are dependent on the North Sea, such as fishing and shipping (North Sea Wind Power Hub, 2018). And finally, there are technical challenges such as transmissions losses, cross border connections, congestion, energy storage and hydrogen production (Gea-Bermúdez et al., 2023). Additionally, large inclusion of renewable energy in electricity markets can have far going effects (Brouwer et al., 2014). Furthermore, a major vulnerability of the hub and spoke model could be is its susceptibility to hub or spoke failures, which could result from technical malfunctions, extreme weather events, or deliberate sabotage. Since the system relies on a network of interconnected hubs, the failure of a single hub or spoke could disrupt electricity transmission, potentially leading to leading to grid instability, blackouts, or energy shortages in connected countries. Integrating these risks into the design phase is essential to avoid cascading failures that could lead to widespread system outages (Zama et al., 2022).

Nonetheless, if successfully implemented, the hub and spoke concept could serve as a cornerstone of Europe's green energy transition and a model for international renewable energy collaboration (North Sea Wind Power Hub, 2024b). This study aims to clarify and examine the various configurations of a future North Sea hub and spoke energy system, focusing on hydrogen integration methods both onshore and offshore, total installed offshore wind capacity in each nation, and variations in electricity demand. Through this analysis, we will uncover the mechanisms and complexities involved in developing the North Sea energy system.

The previously mentioned problems regarding the North Sea Wind Power Hub are highly relevant to the MSc Complex Systems Engineering and Management (CoSEM) program. Gaining more insights about the hub and spoke concept and what is needed for its implementation perfectly aligns with CoSEM's emphasis on designing and managing intricate socio-technical systems. Furthermore, it is closely aligned with the energy track I have chosen, which focuses on integrating renewable energy sources and the various issues regarding energy transition. Doing research into this hub and spoke concept addresses both the technical challenges associated with large-scale offshore wind projects and the complex governance frameworks necessary for their successful implementation.

This research has been divided into several chapters: Chapter 1 Introduction, Chapter 2 literature review, Chapter 3 Research design, Chapter 4 Wind generation and hydrogen inclusion, Chapter 5 Scenario creation, Chapter 6 Model inputs and development, Chapter 7 Results, Chapter 8 Discussion, and finally chapter 9 Conclusion.

2. Literature Review

2.1. Search Strategy

To gain a better insight into the different challenges of creating the North Sea hub, we have executed a literature review. We expected there to be a verry limited amounts of scientific literature, firstly because of the novelty of this subject and secondly because this subject is mainly being research by governmental organizations, such as the North Sea Wind Power Hub organization. This is the reason why we will review both scientific literature and grey literature (governmental reports). The scientific articles were acquired by using the Prisma search principle (Page et al., 2021). Because of accessibility of databases, we chose to focus exclusively on the Scopus database. Scopus is a peer-reviewed literature database including scientific journals, conference proceedings and books (Elsevier, n.d.). By using Scopus, we gained a comprehensive overview of the challenges of the North Sea power hub.

Table 1: literature review Prisma search inputs

Date of search:	April 17, 2025
Key words used:	“Wind power “ “Offshore Wind Farms”
Language of focus:	English
Field of interest:	Energy
Search strings used:	“North Sea” AND “Power Hub”
Boolean operators used:	AND

The Scopus search was done on 17th of april 2025. Firstly, to ensure output of only articles related to the North Sea power hub the key words “Wind power“ and “Offshore Wind farms” were used. Secondly, because of linguistic reasons, only articles in English were considered in the search. Thirdly, to make comparing the different articles possible it was necessary to only look at articles in the same field. The choice was made for the subject area of Energy, because this field fits best with the subject that we wish to research. Finally, the search was done using the search strings and Boolean operators, which gave the following search: “North Sea” AND “Power Hub”. We chose not to include the search term 'hydrogen,' even though hydrogen plays a key role in the hub and spoke concept. The reason for this is that this subject is still very new. We believe that including hydrogen in the search term would further reduce the number of sources found. When the search has been completed, articles which are irrelevant or inaccessible will be removed. If the results consist of 20 articles or less, snowballing will be used to get the remainder scientific articles. The governmental reports were mostly acquired by examining the databases of governmental organizations and by additional desk research. In figure 1 the search process for the different types of literature is visualized. An overview of the literature used in this review can be found in appendix A.

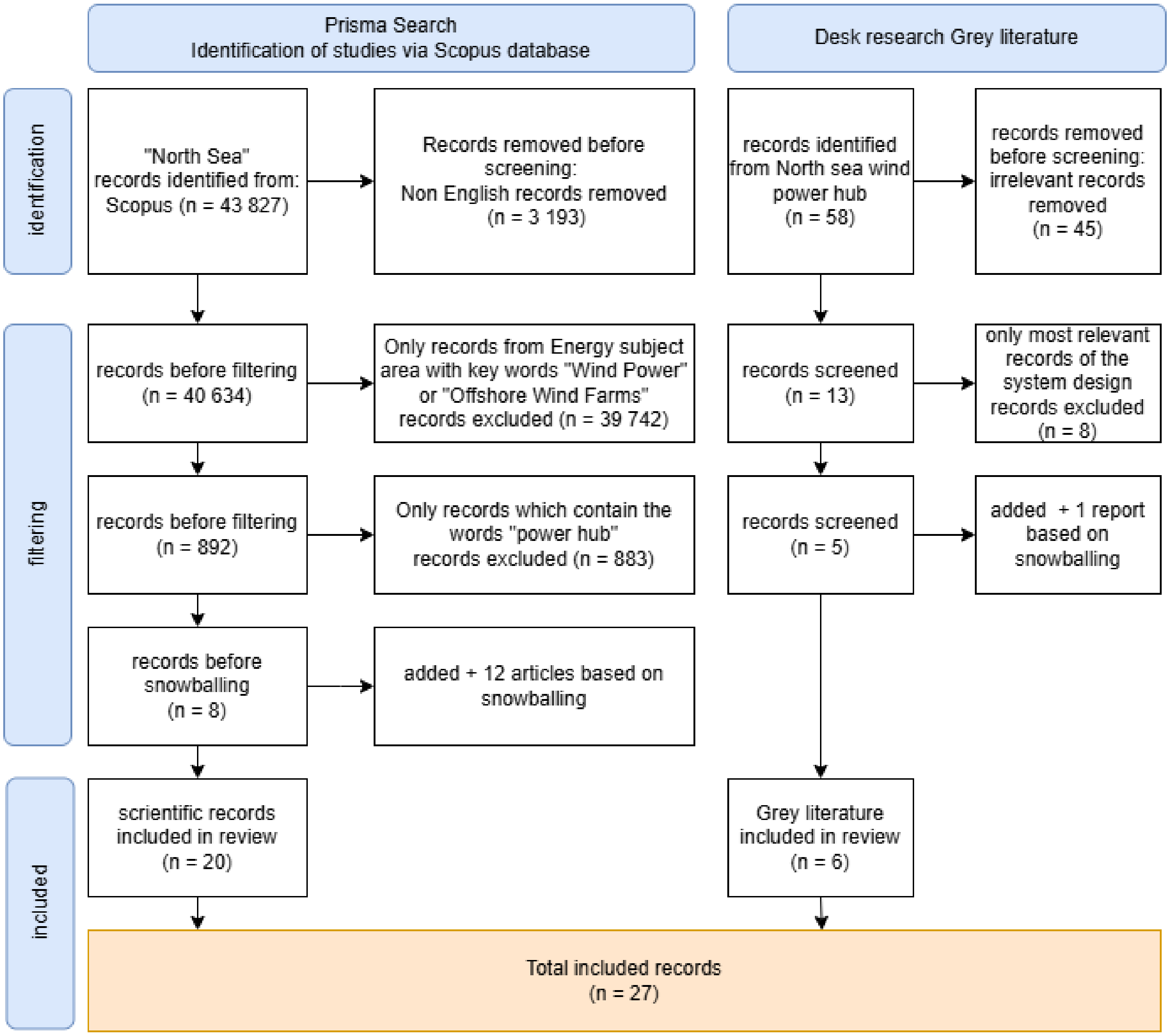

Figure 1: selection of the articles through Prisma and desk research

2.2. Hydrogen generation in the North Sea

To meet the climate goals of the countries surrounding the North Sea, a significant increase in green hydrogen production is required (Ibrahim et al., 2022). Green hydrogen is produced through electrolysis using electricity, sourced from renewable energy. In this context, hydrogen would be generated using excess electricity from large offshore wind farms during periods when supply exceeds demand (Dute et al., 2024). Several ways exist to integrate hydrogen production into the North Sea hub and spoke energy system: it can be produced onshore, offshore, or through a combination of both approaches (Ibrahim et al., 2022). If hydrogen is generated at offshore locations, it must be transported to the mainland by pipelines. Once onshore, hydrogen can be used for electricity generation to balance daily or seasonal fluctuations, or as a chemical fuel for industrial applications (Abdin et al., 2019). However, integrating hydrogen into the energy system will require significant additional investments in pipeline infrastructure and storage facilities, while reducing the need for cable capacity (Kim et al., 2023). Additionally, storage capacity is essential for addressing the mismatch between renewable energy generation and electricity consumption on both a daily and seasonal basis (Gea-Bermúdez et al., 2023).

According to the North Sea Wind Power Hub (2022), development of green hydrogen production must follow a phased approach. This begins with the addition of new wind generation capacity to the energy system, followed by the gradual integration of electrolysis capacity. As the system expands, excess renewable electricity can be used for hydrogen production. In this context, hydrogen production can also serve as a form of flexible demand, contributing to system balancing and improving overall efficiency (North Sea Wind Power Hub, 2022).

Cost analyses reveal little difference between producing hydrogen offshore at energy hubs and producing it onshore (North Sea Wind Power Hub, 2024a). This suggests that multiple configurations may be explored. Offshore hydrogen production could be realized through platform-based electrolysis, island-based electrolysis, or a combination of both. A study by the North Sea Wind Power Hub (2024a) outlines two typical configurations: platform-based electrolysis is paired with 4 gigawatts (GW) of wind capacity and 2 GW of electrolysis capacity, while island-based systems support larger scales, with 10 GW of wind capacity and 6 GW of electrolysis. Each design presents specific advantages and trade-offs. Platform-based systems have a smaller environmental footprint, whereas island-based systems offer greater potential for future expansion (North Sea Wind Power Hub, 2024a). Understanding how these different hydrogen integration methods affect overall system design and performance is essential for the successful development of the hub and spoke energy system.

Hydrogen production is most cost effective when it follows solar PV generation patterns, with hydrogen storage playing a vital role in balancing supply and demand (Gea-Bermúdez et al., 2023). Contrary to the findings by the North Sea Wind Power Hub (2024a), some research indicates that producing hydrogen onshore is more advantageous due to lower costs and electricity prices, as offshore electrolysis is about ten percent more expensive and requires higher electricity prices (Gea-Bermúdez et al., 2023; Bødal et al., 2024). However, other studies highlight the economic benefits of locating hydrogen production offshore, especially when countries prioritize expanding offshore wind capacity to support green hydrogen production (Glaum et al., 2024). Despite these advantages, electrolyzers generally operate at less than fifty percent of their designed capacity on average, with offshore units usually having lower capacity factors than onshore units. These capacity factors are closely linked to the availability of renewable energy resources (Lüth et al., 2024). Regardless of the location of hydrogen generation, incorporating electrolysis into the energy system helps reduce curtailment of offshore wind farms (Farahmand et al., 2024).

2.3. North Sea system design standardizations

A lot of uncertainty exist about the exact layout of the hub and spoke energy system. Various configurations of the model cover the maritime territory of Germany, Denmark, Norway, The Netherlands and the United Kingdom. Each of these countries has different standards and procedures, and because of the international nature of the hub and spoke system. A common approach between participating countries is essential. For example, about the use of alternating current (AC) or direct current (DC inside the system (Ismail et al., 2022). Furthermore, there needs to be an agreement about the locations of the possible hubs and the connected offshore wind parks. The decision between AC and DC has a significant impact on initial and operational costs (Shinoda et al., 2022). Additionally, there is a great need for Real-Time monitoring, fast detection systems, relays, fuses and surge protectors (Zama et al., 2022). On top of these physical safety features the system needs to be designed in such a way as to prevent cascading failures, a situation in which a fault in one part of the system causes other parts of the system to also malfunction (Zama et al., 2022).

Optimizing transmission infrastructure in the North Sea is essential for supporting renewable energy integration, with a focus on minimizing costs while evaluating the benefits and trade-offs of different grid configurations for future scenarios (Chen et al., 2018). Strategic planning is crucial in developing a cost-effective offshore network, which must also address the intermittency challenge associated with renewable sources through effective energy storage solutions (Spro et al., 2015). Regulatory and standardization barriers pose significant challenges that must be navigated to facilitate seamless integration of these solutions. Additionally, the integration of energy transfer technologies is vital for enhancing regional cooperation and improving grid performance, allowing for more efficient power transmission across long distances (Dedecca et al., 2017). The combination of these factors show us the complexity of creating this international North Sea's offshore grid development, and also emphasizing the interplay between cost optimization, energy storage and innovative technologies.

The integration of ever more renewable generation in the Northern European electricity system raises concerns regarding frequency stability, as it leads to greater frequency fluctuations after disturbances (Obradovic et al., 2022). Current fluctuation strategies may be insufficient to maintain stability following significant outages, highlighting the necessity for enhanced grid management strategies.

2.4. North Sea system design variations

The development of energy hubs in the North Sea region supports the expansion of future offshore wind capacity (Durakovic et al., 2022). Additionally, incorporating green hydrogen production into the future energy system can significantly reduce curtailment of offshore wind farms (Durakovic et al., 2022). The North Sea hub and spoke system may include both current fixed-bottom turbines in shallow areas and floating turbines, which can be deployed in deeper offshore waters (Santhakumar et al., 2024). Santhakumar et al. (2024) found that by 2050, the offshore wind energy system in the North Sea could account for up to 51% of total electricity generation. Their study also concluded that, regardless of future planning decisions or technological developments, all suitable fixed-bottom offshore wind areas will be fully developed. The extent of floating wind deployment, however, will largely depend on technological progress and the location of green hydrogen production. If hydrogen is primarily produced onshore, floating wind capacity will be significantly lower, whereas offshore hydrogen production would support a greater expansion of floating wind (Santhakumar et al., 2024).

On 12 September 2022 the member countries of the North Sea Energy Cooperation signed a joint statement outlining their Renewable Energy generation ambitions. The Countries agreed to create a total offshore wind generation capacity of at least 76 gigawatt (GW) by 2030, 193 GW by 2040 and 260 GW by 2050 (North Sea Energy Cooperations, 2022). The North Sea Energy Cooperation is an organization of the European Union, therefore the planned offshore wind generation capacity of the United Kingdom is not included in the 260 GW target by 2050.

Large parts of the North Sea are currently designated as Natura 2000 sites. The Dogger Bank is a part in the middle of the North Sea which is relatively shallow. This area is situated at the intersection of the territorial waters of the Netherlands, Germany, Denmark and the United Kingdom. This area is ideal for creating large wind parks and artificial islands because of the shallow depth. However, most of this area is part of the Natura 2000 system and plays a crucial role in the marine ecosystem (North Sea Wind Power Hub, 2018). This leads to a dilemma on how you can best protect nature, while also using the strategic and economic position of the Dogger bank for the energy transition of the surrounding countries.

In a study done by the North Sea Wind Power Hub (2019) it was found that avoiding nature areas results in a lower offshore wind park capacity. When this study was conducted the 2050 generation capacity targets for the North Sea were significantly lower. They found that only 77 GW instead of the planned 110 GW could be constructed if Natura 2000 sites were not included in future construction plans. To reach the 180 GW target in this study by 2050, additional locations must be considered. Now that the current plans are significantly higher than the ones in this study, we can conclude that there needs to be careful planning to balance energy needs with environmental protection. The hub and spoke system plays a crucial role in optimizing wind energy integration while minimizing ecological disruption.

As stated by the North Sea Wind Power Hub (2024b), out of the 300 GW offshore wind capacity target set by the European Commission, 240 GW is planned to be installed in the North Sea, spanning the maritime territories of the Netherlands, Denmark, Belgium, Germany, Norway, and the United Kingdom. Around 70% of this 240 GW will be connected through hub and spoke configurations. Furthermore, when built the hub-to-hub and hub-to-shore connections will account for 33% of all new transmission capacity by 2050. With this larger amount of interconnection capacity grid stability and energy distribution will be enhanced (North Sea Wind Power Hub, 2024b). Additionally, system-wide grid capacity will expand by 60% between 2030 and 2050, reflecting the increasing electricity demand driven by the energy transition in North Sea countries. Given the restrictions posed by Natura 2000 sites, strategic planning is necessary to locate offshore wind farms in locations that maximize energy output while preserving biodiversity. The Dogger Bank, with its shallow waters and strategic location, presents a unique opportunity for large-scale offshore wind development. However, as a protected Natura 2000 site, it plays a vital role in the marine ecosystem, requiring innovative solutions to balance conservation efforts with the urgent need for renewable energy expansion.

2.5. Legal and economic effects

Because the hub and spoke energy system will span various countries surrounding the North Sea, there will be legal and economic challenges. One of these legal and economic challenges is the question of pricing. Will the electricity prices follow the current national boundaries? Will there be one electricity price be for the entire offshore energy system? Or will the electricity price be decided for each hub? The pricing and the connection capacity between the hubs will influence the market prices and economic efficiency of the model. In the case of large amounts of connection capacity among surrounding countries, electricity prices will stabilize, and energy security will increase (Alavirad et al., 2021). Additionally the development of the hub and spoke system will increase electricity prices in the summer and lower them in the winter, such that average yearly electricity price remains the same (Durakovic et al., 2022). Furthermore, the question of authority and ownership will need to be addressed. To overcome these challenges, it is essential to foster regional cooperation and align regulatory frameworks across countries. One of the options is the establishment of a supra-national Transmission System Operator to streamline cross-border projects and ensure compliance with EU energy policy objectives (Sunila et al., 2019).

2.6. Model assumptions in scientific literature

In this part of the literature review, we examine the assumptions that are used by some of the scientific studies to build their models. In the model by Durakovic et al. (2022), offshore wind generation capacity is distributed across 14 locations, with individual capacities ranging from 6.007 GW to 45.930 GW. Additionally, only three of these locations are identified as potential energy hubs. In the previous section, we discussed the hub sizes and hydrogen integration methods proposed by the North Sea Wind Power Hub (NSWPH) organization, which is actively involved in developing the North Sea energy system. NSWPH anticipates that energy hubs will be connected with between 4 GW and 12 GW of offshore wind capacity and will include 2 to 6 GW of electrolysis capacity (North Sea Wind Power Hub, 2024a). This shows that there is a significant discrepancy between the assumptions in Durakovic et al. (2022) and those of the NSWPH, particularly in terms of the number of offshore energy hubs and the amount of wind power connected to each hub. Furthermore, the model by Durakovic et al. (2022) applies strict maximum cable capacity limits for transmission: 1 GW between wind farms, 5 GW between a wind farm and its home country, 10 GW between a wind farm and an energy hub, and 20 GW between an energy hub and countries. These constraints, combined with the high offshore wind capacities at each hub, could force the model to prioritize hydrogen infrastructure, as the assumptions do not permit the full transfer of electricity through the network.

The research by Glaum et al. (2024) estimates that the installed offshore wind capacity in the North Sea could range between 330 GW and 420 GW, which is significantly higher than the 240 GW currently planned and expected by the surrounding countries (North Sea Wind Power Hub, 2024b). Notably, the study takes a broad, European perspective, including most of Europe in its modelling. For example, it examines how electricity and hydrogen produced in the North Sea region interacts with the energy system in countries as far away as Greece.

The following studies have each used models with a limited number of energy hubs to represent the North Sea energy system. The model developed by Bødal et al. (2024), which is based on the one developed by Durakovic et al. (2022), includes only a single energy hub and a small number of generation nodes, each with a high offshore generation capacity. Similarly, the study by Farahmand et al. (2024) also uses just one node to represent the energy system. In the study by Lüth et al. (2024), three energy islands are included in the model, with a combined wind capacity of 24 GW and an electrolysis capacity of 22 GW. Which is significantly less than the planned 240GW of offshore wind capacity by the North Sea Wind Power Hub organization (North Sea Wind Power Hub, 2024b).

2.7. Knowledge gaps

From the literature above we can identify several areas which require additional research. Firstly we identified in part 2.2 that there is currently no consensus on the locations where green hydrogen will be produced, onshore or offshore. In the literature review we found sources that preferred either location, while the organization currently designing the system states that when looking at costs there is no preference for a location (North Sea Wind Power Hub, 2024b).

Secondly, as discussed in Section 2.4, the 2050 generation capacity targets of the countries bordering the North Sea are highly ambitious and have evolved significantly in recent years. Moreover, the intention to use the hub and spoke system not only for electricity generation but also for cross-border energy transfer is expected to account for 33% of all new transmission capacity by 2050 (North Sea Wind Power Hub, 2024b). The combination of these evolving generation goals with the dual-purpose role of the hub and spoke system has not yet been thoroughly explored in the scientific literature, particularly regarding its impact on overall system design.

Finally we identified in part 2.6 that there is also no consensus on the model inputs and the exact layout of the North Sea energy system. In some studies only a single or a limited number of generation nodes are used to represent the entire system. The generation capacity of wind and green hydrogen varies drastically between the scientific articles. For example: the article of Lüth et al. (2024) has 24 GW of offshore wind generation capacity dispersed over 3 nodes, while Glaum et al. (2024) has a total system offshore wind generation capacity 420 GW.

With this research, we aim to address the above mentioned knowledge gaps. We will compare different methods of integrating hydrogen production, using an accurate representation of current offshore wind generation targets and the precise locations of planned wind farms. We will explore how these wind farms can be connected to form an effective and realistic hub and spoke energy system in the North Sea. In the following chapter 3, we will present the research questions designed to address the identified knowledge gaps. We will also address the corresponding methods and theoretical frameworks for each question.

3. Research design

In this chapter we will address the structural approach of the research. We will start with the research questions, which will fill in the previously identified knowledge gaps. Hereafter we will go into the methods used to answer each research question.

3.1. Research questions

As discussed in Section 2.7, the following research question addresses the key knowledge gaps related to hydrogen integration methods, offshore wind generation targets, and the spatial layout of planned wind farms. It also explores how these farms can be connected to form a realistic hub and spoke energy system in the North Sea.

What are the possible structural configurations of the hub and spoke energy system in the North Sea, and how are they influenced by changes in capacity goals, electricity demand and hydrogen inclusion methods?

We have created 5 different sub research questions that will help us answer the main research question. The first 3 sub questions will give us the possible design space and allow us to create the scenarios, and the final 2 questions will help us analyze the model results and gain the insights necessary to answer the main research questions.

1. What are the current goals and plans of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom regarding offshore wind power generation in the North Sea?
2. In which ways can hydrogen production be included into the North Sea hub and spoke energy system?
3. What are the different implementation scenarios of the hub and spoke energy system?
4. What is the effect of the hydrogen production methods, cable layouts and varying electricity demand on the total network length, total network cable capacity, Network diameter and hydrogen generation capacity?
5. How vulnerable is the network in the case of cable failure?

3.2. Methodology

This section outlines the approach taken to address each research question and the specific knowledge gaps they are intended to fill.

3.2.1. Hub and Hydrogen specifications

The first research question is: *What are the current targets and plans of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom for offshore wind power generation in the North Sea?* This question seeks to identify and analyze the national offshore wind development strategies of the North Sea countries. Addressing this question will help resolve the inconsistency observed in reported offshore wind capacity across scientific and grey literature, as noted in Section 2.7. The resulting synthesis will enable a more accurate representation of regional ambitions and provide a grounded basis for evaluating their implications on the structural configuration of the hub and spoke system.

The second research question is: *In which ways can hydrogen production be included into the North Sea hub and spoke energy system?* This question aims to explore and classify the possible configurations for incorporating green hydrogen production into the system, including onshore, and offshore production approaches. Hydrogen can play a vital role in Europe's energy transition, particularly when produced using excess renewable energy (Dute et al., 2024). This green hydrogen can then be used to generate electricity during periods of low renewable output, thereby supporting a fossil fuel–free energy system (Dute et al., 2024). However, as outlined in Section 2.7, current literature and policy documents offer no clear consensus on the future locations for green hydrogen production. Investigating these alternatives allows for the development of scenario-based models that reflect this uncertainty and enable a comparative assessment of their implications for system design, infrastructure requirements, and operational performance.

Both of these research questions will be addressed through desk research (Caudle, 2004), as the required information is expected to be primarily found in governmental reports and official documents. This was also evident from the literature review, which revealed that the majority of relevant studies have been published in recent years. Consequently, consulting the most up-to-date governmental sources is likely to yield the most accurate and relevant data. In addition, as discussed in section 2.4 of the literature review, national energy targets are evolving rapidly, further justifying the use of desk research as an appropriate method. The primary sources for this analysis will include the database of the North Sea Wind Power Hub (North Sea Wind Power Hub, 2025) and publications from the European Union (North Sea Energy Cooperation, 2022).

3.2.2. Scenario creation

The third research question is: What are the different implementation scenarios of the hub and spoke energy system? By addressing this question, we aim to define the design space of the future hub and spoke energy system. In addition, the analysis will consider projections for future electricity demand. Through desk research (Caudle, 2004), we will gather data from both scientific and grey literature to capture a comprehensive view of these variables. Based on this information, we will construct a set of implementation scenarios that reflect plausible configurations of the hub and spoke energy system. These scenarios will help to explore and eventually compare different design pathways, offering insights into how the systems structural configurations are impacted by changes in electricity demand, hydrogen inclusion methods and offshore wind generation capacity

3.2.3. Graph theory and model creation

The main research question, along with the final two sub-questions, will be addressed through a modeling approach. The model will be built upon the scenarios outlined in the third sub-question, which in turn are informed by the insights gained from the first two research questions. Employing a modeling approach enables a systematic comparison of the various effects and interdependencies among the input variables (Epstein, 2008). Furthermore, it allows us to explore the trade-offs between different design configurations and scenario outcomes (Epstein, 2008), helping to address the remaining uncertainties identified in Section 2.7.

The modeling method employed in this research is based on graph theory. This mathematical approach provides a structured framework for visualizing and analyzing the relationships between various hubs and their associated connection capacities. By applying graph theory, it becomes possible to quantify interactions within the network and evaluate their combined impact on overall system performance (Foulds, 1992). This method not only helps clarify the complexity of the energy system but also supports the exploration of different design configurations and scenarios. It enables analysis of how changes in capacity goals, electricity demand, and hydrogen integration strategies affect the network's structure and technical functionality.

Furthermore, the use of graph theory facilitates flow analysis across the network. This allows for the calculation of cable capacities, ensuring that the design meets a key requirement: the ability to transmit large volumes of electricity throughout the system(North Sea Wind Power Hub, 2024b). In this way, the network functions not only as a generation platform but also as a large-scale transmission system (North Sea Wind Power Hub, 2024b). Through this approach, the research addresses a key gap identified in Section 2.7: that previous studies have not yet combined current national offshore wind capacity goals, specific offshore wind farm locations, and the requirement for integrated high-capacity electricity transmission within a single model. The following section will provide a more detailed examination of how the various generation hubs are connected within the model and how flow analysis is applied. Both the flow analysis and the graph will be made in python using NetworkX. (n.d.) package.

3.2.3.1. Edge design

As previously mentioned, the goal is to develop a model that accurately represents the future North Sea energy system. This includes offshore wind park locations, their generation capacities, and potential hydrogen production methods. The estimated cost for the Dutch section alone is approximately 88 billion euros (Koster, 2025), suggesting that the full transnational network will likely be much more expensive. This emphasizes the need to find a balance between creating a highly connected network, which increases electricity transfer capacity as described by the North Sea Wind Power Hub (2024b), and keeping overall system costs manageable. The graph model used in this research consists of nodes, which represent generation and consumption locations, and edges, which represent the electricity cables that connect the nodes (Foulds, 1992). In the following section, we will examine three possible methods for connecting the nodes: Complete Graph, Delaunay Triangulation, and Minimum Spanning Tree.

A complete graph is a network in which every node is connected to every other node (Attenborough, 2003). While this structure ensures maximum connectivity, it does not realistically represent the future North Sea energy system. It introduces an excessive number of edges, far exceeding what is technically and economically feasible. This approach therefore fails to give an accurate representation of the future hub and spoke energy system. And thus fails to address the knowledge gap identified in Section 2.7.

Delaunay triangulation uses geometric principles to determine whether a pair of neighboring triangles forms an optimal set of connections between nodes (Lucas, n.d.). This results in a more efficient layout than a complete graph, producing a network that is relatively lean while still maintaining good connectivity. However, the total number of edges generated through Delaunay triangulation remains too high to realistically represent a cost-effective future electricity transmission network. To better reflect practical infrastructure limitations and reduce system costs, it is necessary to decrease the number of connections in this design. Doing so also helps address the knowledge gap identified in Section 2.7 by producing a more accurate and feasible network structure.

The Minimum Spanning Tree (MST) approach connects all nodes using the fewest possible edges and the shortest total distance, resulting in a highly lean and cost-efficient network (Sedgewick & Wayne, 2011). However, given the requirement to transport large volumes of electricity across the system, as highlighted by the North Sea Wind Power Hub (2024b), a network based solely on MST lacks the redundancy and robustness expected of large-scale transmission infrastructure. While an MST may not be suitable for the entire transnational system, it can be effectively applied within national boundaries. By first constructing national MSTs and then interconnecting them, a more meshed and robust network can be formed that better meets the operational demands of a future North Sea transmission system (North Sea Wind Power Hub, 2024b).

This research will examine two distinct cable layout strategies for the future North Sea energy network. The first is a reduced Delaunay triangulation, and the second is a network based on national Minimum Spanning Trees (MSTs) that are subsequently interconnected. The methodology for modifying both configurations will be presented in Section 6.2, “Model Edge Design and Capacities.” Because the MST inherently produces a minimal network, the Delaunay model is expected to result in a greater number of edges and a longer total cable length. By comparing these two layouts, the research aims to evaluate the impact of additional connections on system performance, thereby addressing the knowledge gap concerning the future layout of the North Sea energy system.

3.2.3.2. Flow analysis

According to Ohm’s Law, electricity flows through a network based on the resistance of its components (allaboutcircuits, n.d.). In power systems, cable resistance depends on design factors such as material, diameter, and length, which are influenced by transmission requirements. Estimating the resistance of future cables is challenging because high-capacity connections may use multiple smaller cables in parallel instead of a single large one, affecting overall resistance and flow dynamics.

The future North Sea hub and spoke energy system aims to transmit electricity to specific locations through a strategically coordinated network (North Sea Wind Power Hub, 2024b). While Ohm’s Law ultimately governs electricity flow, the design phase focuses on intended flow directions based on system needs rather than detailed physical modeling. Due to uncertainties in cable specifications and configurations, accurately applying Ohm’s Law at this stage is not feasible. Therefore, this research concentrates on directional flows, supporting the primary goal of reliable and efficient energy transmission across the North Sea region (North Sea Wind Power Hub, 2024b).

The flows in the network will be determined using the Network Simplex Algorithm, a method for solving the minimum-cost flow problem on a graph (Brunovsky, 2023). This algorithm works by iteratively adjusting flows along a spanning tree structure in the network to minimize total cost, while satisfying supply, demand, and capacity constraints (Brunovsky, 2023). Each edge in the graph has an associated cost per unit of flow, and the goal is to find the most efficient distribution of electricity that meets all node demands at the lowest total cost. The algorithm maintains feasibility by adjusting flows along cycles in the residual network and updates the spanning tree structure when it identifies a more cost-effective configuration. By using this algorithm we will be able to create a network with the lowest system costs for each scenario.

By applying this method using different weather scenarios, we can model the expected energy flows that the network must accommodate under varying conditions (North Sea Wind Power Hub, 2024b). For each edge, the highest flow value encountered across all scenarios will be stored as the required cable capacity. This approach yields a final network design that reflects peak operational demands. Once cable capacities are determined, we can systematically compare the outputs across the different model configurations created for each design scenario, providing insights into the performance, efficiency, and robustness of alternative network layouts.

3.2.4. Model analysis

Main research question: *What are the possible structural configurations of the hub and spoke energy system in the North Sea, and how are they influenced by changes in capacity goals, electricity demand and hydrogen inclusion methods?*

Sub question 4: What is the effect of the hydrogen production methods and varying electricity demand on the total network length, total network cable capacity, Network diameter and hydrogen generation?

Sub question 5: What are the physical vulnerabilities of the hub and spoke network?

These final research questions will be addressed by the previously mentioned scenario-based graph model, which will be made for this research. The fourth sub research question investigates the impact of different hydrogen production methods and varying electricity demand levels on key network characteristics, including total network length, total cable capacity, network diameter, and overall hydrogen generation. Furthermore, these metrics allow us to compare the previously mentioned Delaunay and MST cable configurations of the model. By simulating the various scenarios that combine different hydrogen implementation strategies and electricity demand levels, the analysis enables a direct comparison of their physical and functional implications. The resulting metrics provide a robust basis for evaluating trade-offs between system efficiency, complexity, and robustness across alternative design choices.

The final sub research question focuses on evaluating the physical vulnerability of the hub and spoke model, which is crucial for understanding its resilience to potential failures, whether caused by technical malfunctions, cyberattacks, or external disruptions. A single cable failure could result in significant energy transmission losses, grid instability, or even widespread blackouts. We will therefore look at the robustness of each design. To assess this, an N - 1 analysis will be conducted, where each cable is systematically removed from the model to determine whether the system remains operational under such conditions. By observing the system's performance in each case, it becomes possible to identify critical vulnerabilities within the network. This approach also enables a comparison of how different hydrogen integration strategies and variations in electricity demand affect the overall robustness of the system. It also provides insights into whether the MST or the Delaunay design is more effective in handling cable failures.

By addressing these 5 sub research questions, we can gain a comprehensive understanding of technical requirements and the dynamics at play within the future North Sea energy system. The scenarios developed by sub question 3 will play a central role in shaping the model. In particular, information on current offshore wind power plans and future capacity targets, along with various strategies for integrating hydrogen production, will provide a solid foundation for analyzing and comparing different network design configurations. And thus answering the main research question and filling in the identified knowledge gaps.

4. Wind generation capacity and hydrogen inclusion

In this chapter we will first discuss the current wind generation plans and goals of all nations surrounding the North Sea. After this we will take a look at the various ways hydrogen can be included in the future energy system of the North Sea area. By doing this we will answer the first two research questions:

What are the current goals and plans of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom regarding offshore wind power generation in the North Sea?

In which ways can hydrogen production be included into the North Sea hub and spoke energy system?

4.1. Offshore wind generation goals and plans

The current ambitions of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom reflect a strong collective commitment to expanding offshore wind power generation in the North Sea. This commitment has led to various goals and targets which are frequently updated and expanded upon. On September 12, 2022, the member countries of the North Sea Energy Cooperation, which include Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, and Norway, agreed on a collective offshore wind generation target of 260 GW (North Sea Energy Cooperations, 2022). While not all of these countries have direct access to the North Sea, the agreement represents a coordinated strategy to scale up renewable energy across the region. This commitment was further reinforced on April 24, 2023, when the climate ministers of these countries, together with the United Kingdom, signed the Ostend Declaration (Ministerie van Algemene Zaken, 2024). In this declaration, the signatories formally anchored their national and joint renewable energy targets, underlining their intention to transform the North Sea into a key region for sustainable energy production. According to the North Sea Wind Power Hub (2024b), approximately 240 GW of offshore wind capacity is planned for development within the North Sea region by Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom. Of this total capacity, around 70 percent is expected to rely on hub and spoke connections.

This context leads us to the following sub research question: *What are the current goals and plans of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom regarding offshore wind power generation in the North Sea?* Understanding the objectives and plans of these countries is essential for analyzing the future landscape of offshore wind development in the North Sea. When these goals are combined we will be able to accurately estimate the size, locations and generation capacity of a future hub and spoke energy system in the North Sea.

Before we can answer this research question we will need to decide the geographical scope of the model. One way of choosing the scope of the model is by looking at the Levelized Cost of Energy (LCOE) (Sørensen et al., 2021). This metric shows the costs of creating electricity for a given system and location. From the research of Sørensen et al. (2021) we can see that the LCOE of offshore wind generation is strongly related to the depth of the water. This relation can also be seen when comparing figure 2 of the water depth and figure 3 of the LCOE.

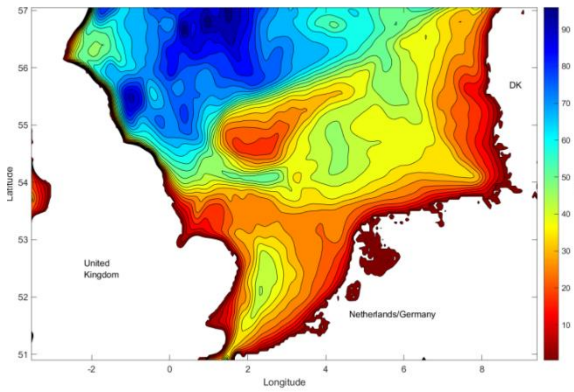

Figure 2: North Sea water depth (Sørensen et al., 2021)

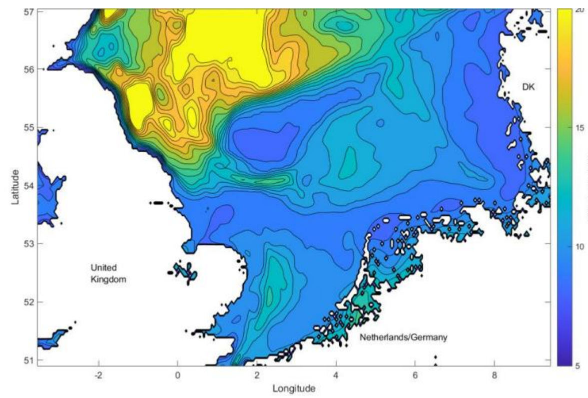

Figure 3: LCOE in the North Sea (Sørensen et al., 2021)

The southern and eastern parts of the North Sea are the most suitable areas for implementing the hub and spoke energy system, primarily due to the lower LCOE in these regions. These zones cover the Exclusive Economic Zones (EEZs) of Belgium, the Netherlands, Germany, and Denmark, along with a significant portion of the United Kingdom's EEZ. In contrast, only the southern tip of Norway's EEZ falls within this economically favorable zone for offshore wind development.

Despite the limited area within Norway's EEZ that is suitable for low-cost offshore wind generation, Norway could still play an important role in the future North Sea energy system. While the extent of Norway's future offshore wind capacity in the southern North Sea remains to be seen, its inclusion brings notable system-wide benefits. Norway's extensive hydroelectric resources position it as a highly flexible producer of green energy (International Energy Agency & Birol, 2022). This could allow Norway to start functioning as a large-scale hydroelectric battery. By using wind power to lower baseload hydroelectric consumption, and when offshore wind production is low, producing more hydroelectric power for export. In this way, integrating Norway into the network not only adds generation capacity but also enhances the functionality of the system as a whole. The hub and spoke energy system, in this context, serves not just as a means of distributing offshore wind power, but also as additional interconnection capacity that strengthens cross-border energy security and system reliability.

In the following section, we will examine the offshore wind power generation capacity targets set by Belgium, Denmark, Germany, the Netherlands, the United Kingdom, and Norway. We will also look at their currently installed offshore wind capacities, assess the additional capacity needed to meet their goals, and identify areas suitable for new offshore wind developments.

4.1.1. Belgium

Belgium has set a long-term goal of reaching 8 GW of offshore wind capacity by 2050, as part of its contribution to the North Sea's renewable energy transition (North Sea Energy Cooperation, 2022). As of now, the country has 2.091 GW of installed capacity, with an additional 3.5 GW already planned (Global Energy Monitor, n.d.). This generation capacity will be located in proximity to the Exclusive Economic Zones (EEZ) of both the Netherlands and the United Kingdom. This brings the total expected capacity to 5.591 GW. To meet the 2050 target of 8 GW, Belgium will need to add 2.409 GW on top of what is already installed and planned. Due to the limited size of Belgium's EEZ in the North Sea, the additional capacity of 2.409 GW will most likely be situated near existing or planned offshore wind farms, enabling smoother integration into a hub and spoke system by minimizing geographical distances. With a peak demand of 13.206 GW recorded in 2024 (ENTSO-E, 2024), Belgium's target of 8 GW in offshore wind capacity falls short of covering its total electricity needs, indicating it will likely rely on imports and act mainly as a consumer in the hub and spoke network.

4.1.2. Denmark

Denmark has set ambitious targets for offshore wind development, aiming to reach 12.9 GW by 2030, 22.65 GW by 2040, and 35 GW by 2050 (North Sea Energy Cooperation, 2022). However, these goals include capacity planned in both the North Sea and the Baltic Sea, as Denmark has a significant Exclusive Economic Zone (EEZ) in both regions. Therefore, only part of the national target applies to projects that can be integrated into the North Sea hub and spoke energy system.

Currently, Denmark has 0.821 GW of installed offshore wind capacity in the North Sea (Global Energy Monitor, n.d.). Plans are in place for an additional 6 GW to 17.5 GW, though there is some uncertainty due to legal issues surrounding state aid for certain developments (TGS, 2024). This range results in a projected capacity gap of between 28.179 GW and 16.679 GW needed to meet the 2050 goal, depending on the outcome of these legal hurdles. Assuming these issues are resolved and the 17.5 GW of planned capacity proceeds as expected, Denmark would need to add approximately 16.679 GW more to achieve its national target. However, when considering that a portion of the 35 GW goal will be fulfilled in the Baltic Sea, the capacity goal in the North Sea region decreases. When looking at the distribution of Denmark's EEZ between the North Sea and the Baltic Sea. We estimate that 25GW will be installed in the North Sea, and 10 GW in the Baltic Sea. In this case, Denmark would require an additional 6.679 GW beyond the current and planned capacity (25 GW – 17.5 GW – 0.821 GW) to meet its North Sea contribution. This remaining capacity could be achieved either by expanding the size of existing planned wind parks or by developing a new site within Denmark's North Sea EEZ.

Given the country's 2024 peak electricity demand of 9.070 GW (ENTSO-E, 2024), Denmark's long-term offshore wind target far exceeds its domestic consumption. As a result, Denmark is expected to act primarily as an electricity exporter within the hub and spoke energy system, helping to stabilize and supply energy to its regional partners across the North Sea.

4.1.3. Germany

Germany has outlined a very ambitious trajectory for offshore wind energy development, with national targets set at 30 GW by 2030, 40 GW by 2035, and 70 GW by 2050 (North Sea Energy Cooperation, 2022). However, since Germany's Exclusive Economic Zone (EEZ) includes territory in both the North Sea and the Baltic Sea, only part of this overall capacity will be installed in the North Sea, where it can contribute to the hub and spoke network. As of now, Germany has 6.861 GW of offshore wind capacity installed in the North Sea (Global Energy Monitor, n.d.), with an additional 21.633 GW planned (WAB, 2021). This brings the total to 28.494 GW, leaving a gap of 41.506 GW to reach the full 70 GW national target by 2050. Just as in the case of Denmark, not all of Germany's offshore wind capacity will be built in the North Sea. When we look at the distribution of Germany's EEZ we estimate that of the total 70GW goal 45 GW will be located in the North Sea. This would mean that Germany would still need to develop an additional 16.506 GW beyond what is already installed and planned.

Although Germany's EEZ in the North Sea is smaller than Denmark's, the expected 45 GW of capacity far exceeds Denmark's planned 25 GW. This shows Germany's ambitions and commitment to future offshore wind generation as a major source of electricity. Most existing offshore wind farms in Germany's EEZ are situated relatively close to shore, future expansions will need to push farther out into the German North Sea EEZ to reach their goals. Germany's offshore wind ambitions are also significant in the context of their own national electricity consumption. The country's peak demand in 2024 was 77.508 GW (ENTSO-E, 2024). In the case that 70 GW offshore goal is fully realized by 2050, and all offshore wind parks operate at full capacity, offshore wind alone would still fall short of covering peak demand. This underscores the fact that while offshore wind will play a critical role in Germany's energy mix, it must be complemented by other renewable sources, energy imports, and storage solutions. In the context of the hub and spoke model, Germany will mostly act as a consumer because of the high national electricity demand.

4.1.4. Netherlands

Compared to the previously discussed countries, the Netherlands has set indicative, rather than fixed, targets for offshore wind generation: 16–21 GW by 2030, 30–50 GW by 2040, and 40–70 GW by 2050 (North Sea Energy Cooperation, 2022). These broad ranges reflect the Dutch government's view that future electricity demand may not necessarily justify the higher end of these targets. As a result, the design of the Dutch system will range from a low-demand situation with 40 GW by 2050, to a high-demand situation requiring the full 70 GW, or an outcome somewhere in between. As of now, the Netherlands has an installed offshore wind capacity of 4.7 GW (Noordzeeloket, 2024), with an additional 18.8 GW already planned or under construction. Depending on the range of the previously mentioned goals, the additional capacity needed to meet the 2050 targets ranges from 16.5 GW to 46.5 GW.

To accommodate this potential expansion, new wind farms are expected to be constructed further into the northern and eastern parts of the Dutch North Sea EEZ, with particular interest in the Dogger Bank area. This region is attractive due to its relatively shallow water, which helps keep construction costs low (Sørensen et al., 2021). With a peak electricity demand of 19.477 GW in 2024 (ENTSO-E, 2024), even the lower bound of the Netherlands' 2050 offshore wind target would exceed current domestic demand. In fact, even if the country's demand were to double by 2050, the offshore wind capacity would still surpass it. This makes it clear that the Netherlands is positioning itself to act primarily as a producer and exporter of electricity within the North Sea hub and spoke system.

4.1.5. Norway

Norway has set a goal to reach 3 GW of offshore wind capacity by 2030, with plans to allocate space for 30 GW by 2040, maintaining the same target for 2050 (North Sea Energy Cooperations, 2022). However, Norway currently has no offshore wind generation capacity placed within the suitable area of the North Sea that could fall under the hub and spoke model. Like the United Kingdom, Norway faces geographical limitations, as not all of its North Sea territory is suitable for fixed-bottom offshore wind installations, because of the water depth. Within the area relevant to the hub and spoke system, Norway has plans to develop 3.6 GW of offshore wind power (Global Energy Monitor, n.d.). The feasibility of expanding offshore wind generation in Norway's North Sea region is closely tied to water depth, as there is a strong correlation between lower water depths and reduced construction costs (Sørensen et al., 2021). As shown in Figure 4, the shallowest waters are found in the southern tip of Norway's Exclusive Economic Zone in the North Sea (Engebretsen et al., 2016). This southern area is therefore the most suitable for offshore wind development and future integration into the hub and spoke system, offering the best conditions for cost-effective expansion.

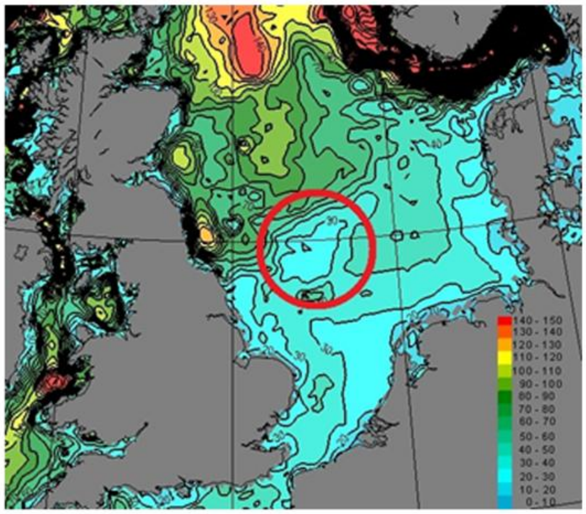

Figure 4: North Sea water depth and the Dogger bank (Engebretsen et al., 2016)

In 2020, 98% of Norway's electricity production came from renewable sources, with 92% generated specifically through hydroelectric power (International Energy Agency & Birol, 2022). This high share of renewable energy is primarily due to Norway's abundant hydroelectric resources, which have already made the country's electricity system largely carbon neutral. As a result, Norway's offshore wind goals are framed with flexibility. Rather than committing to a fixed build-out, Norway's objective is to make space for 30 GW of offshore wind by 2040 and 2050, but only build according to future needs. This approach is comparable to the Netherlands' strategy, where 40 GW of offshore wind will be built if demand stays moderate, and up to 70 GW if demand increases significantly.

Based on current plans and the available, most economical locations for offshore wind development in the North Sea, we estimate that Norway will create around 15 GW of total offshore wind capacity in a low-demand scenario. Of this, approximately 10 GW would be installed in their North Sea area, where construction costs are lowest, and 5 GW elsewhere in Norway's Exclusive Economic Zone. In this situation, 6.4 GW of additional capacity needs to be planned in their part of the Hub and spoke system. In a high-demand scenario, Norway could install up to 15 GW in both the North Sea and other areas, reaching the full 30 GW target. In this situation, 11.4 GW of additional capacity needs to be planned in their part of the hub and spoke system.

Norway's peak electricity demand was 24.930 GW in 2024 (Entsoe, 2024), meaning that even in the low-demand scenario, the planned wind capacity would cover a substantial portion of its domestic needs. Considering that the majority of Norway's current energy already comes from carbon-neutral hydroelectric power, the country is well positioned to act as a major exporter and generator in the hub and spoke system. Furthermore, the addition of large-scale offshore wind capacity would allow Norway to use its hydroelectric resources more flexibly. By reducing constant hydroelectric output and instead using it to balance fluctuations in wind generation, Norway could play a critical stabilizing role in the hub and spoke network, ensuring reliable power supply during periods of low wind production.

4.1.6. United Kingdom

The United Kingdom is expected to reach around 100 GW of offshore wind capacity by 2046, according to the Electricity System Operator (ESO, 2024). Of this total, approximately two thirds, or about 66 GW, is anticipated to come from fixed-bottom installations, which are better suited to shallower waters compared to floating wind farms (UK Floating Offshore Wind (FLOW) Task Force 2024). Many of the most suitable locations for fixed-bottom offshore wind development lie within the UK's North Sea Exclusive Economic Zone, particularly in areas that align with the envisioned hub and spoke energy system, as can be seen in figure 5. Based on the goal of 66GW and geographical suitability, we estimated that around 45 GW of this capacity will be located in the hub and spoke area of the North Sea.

Figure 5: Fixed mount offshore wind farm locations (UK Floating Offshore Wind (FLOW) Task Force, 2024)

Currently, the United Kingdom has 8.913 GW of offshore wind capacity installed in the North Sea (Global Energy Monitor n.d.), with an additional 24.911 GW already planned. This brings the total to 33.824 GW (4C Offshore, n.d.). To reach the estimated 45 GW in the North Sea area, the United Kingdom still needs to plan or construct about 11.176 GW. The additional offshore wind parks needed to reach the United Kingdom's 45 GW contribution to the North Sea hub and spoke system will most likely be developed further out on the Dogger Bank and near the Exclusive Economic Zones (EEZs) of neighboring countries. These areas offer suitable conditions for fixed-bottom wind installations and are strategically positioned for inclusion into the Hub and Spoke system.

The UK's electricity demand, with a recorded peak of 51.442 GW in 2019 according to Open Power System Data (2020), offers an important reference point for evaluating its future energy role. If the UK reaches its projected 100 GW of offshore wind capacity by 2050, of which 45 GW would be located in the hub and spoke region, the country's function in the system will vary depending on weather conditions. In a situation where only the North Sea hub and spoke wind farms are generating electricity, the UK could act as a net consumer within the network. However, if strong wind conditions allow the entire 100 GW network to operate near full capacity, the UK would not only be able to meet its domestic demand but also have the potential to export electricity to other countries.

4.1.7. Conclusion

The nations surrounding the North Sea have established ambitious targets for the expansion of offshore wind energy generation. However, current development plans remain insufficient to fully achieve these objectives, necessitating further initiatives to bridge the gap between existing capacities and future goals. Belgium requires only a modest increase in capacity, whereas Germany and the Netherlands will need to undertake substantial additional planning and development, as indicated in Table 2. It is noteworthy that the Netherlands has adopted a flexible target, with its ultimate capacity depending on future electricity demand. A comparable situation exists in Norway, where 98% of domestic electricity production is already derived from renewable sources, predominantly hydroelectric power (International Energy Agency & Birol, 2022). Consequently, Norway's expansion plans are more moderate and contingent on future demand scenarios.

From a spatial and economic perspective, the Dogger Bank emerges as a prime location for further offshore wind developments due to its relatively shallow water depths, which contribute to lower construction costs. Nevertheless, the Dogger Bank forms part of the Natura 2000 network of protected natural areas, potentially complicating the approval and development process. As emphasized by the North Sea Wind Power Hub (2019), achieving large-scale offshore wind expansion without some degree of impact on protected areas may be unavoidable.

Table 2: overview of capacity and goals of the hub and spoke nations, (North Sea Energy Cooperations, 2022), (Global Energy Monitor, n.d.), (Entsoe, 2024), (Open Power System Data, 2020)

country	Current installed Offshore capacity North Sea (GW)	Peak Demand 2024 (GW)	Already planned additional capacity (GW)	Planned capacity North Sea 2050 (GW)	Additional capacity needed for 2050 goal (GW)
Belgium	2.091	13.206	3.500	8	2.409
Denmark	0.821	9.070	7.200 - 18.010	25	6.679
Germany	6.861	77.508	5.483	45	16.506
Netherlands	4.7	19.477	18.8	40 - 70	16.5 – 46.5
Norway	0	24.930	3.6	10 - 15	6.4 – 11.4
United Kingdom	8.913	51.442	24.911	45	11.176

Furthermore, Table 2 illustrates that several countries planned offshore wind capacities exceed their current peak electricity demands. This trend highlights a strategic intent to generate electricity not only for domestic consumption but also for export within the integrated North Sea hub and spoke network. The Netherlands and Denmark, in particular, are expected to assume prominent roles as net exporters. Norway presents a unique case; with an electricity sector already predominantly carbon neutral, the additional offshore wind capacity will primarily serve to support exports and enhance system flexibility. By reducing the base load on its hydroelectric resources, Norway will be able to deploy its hydroelectric generation capacity in a more dynamic manner, contributing to an increase in energy security across the broader North Sea region.

This chapter began by posing the research question: *What are the current goals and plans of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom regarding offshore wind power generation?* Through a detailed overview of each nation's offshore wind generation goals and current development plans, we have established a comprehensive understanding of the goals and plans of future offshore wind capacity in the North Sea region. This foundational analysis will serve as a crucial input for the modeling efforts presented in subsequent chapters, where the possible design variations and scenarios of the hub and spoke system will be further explored.

4.2. Hydrogen inclusion in the hub and spoke energy system

In addition to large-scale offshore wind power generation, there are also plans to integrate hydrogen production capacity into the energy system. This integration is particularly important, as the previous section demonstrated that, under full production conditions, total electricity generation would significantly exceed the peak demand of each individual country. The intention is to use this surplus electricity to produce green hydrogen. During periods of low renewable energy generation, this hydrogen can then be converted back into electricity, supporting a carbon-neutral energy system. Currently, the European Union has set a target of at least 40 GW of green hydrogen production capacity by 2030 (European Commission, 2020). These EU goals, combined with the potential for large-scale excess electricity from offshore wind, give rise to the following research question: In which ways can hydrogen production be included into the North Sea hub and spoke energy system?

The Nations which would be part of the hub and spoke system each have their own hydrogen frameworks and goals. Belgium is aiming to establish a minimum of 150 MW of hydrogen production capacity by 2026 (Green Hydrogen Organisation Belgium, n.d.). While the production goal itself is relatively modest, Belgium's broader focus lies in the development of hydrogen transport infrastructure. The country plans to significantly expand its hydrogen network to meet domestic demand by 2050 and to facilitate cross-border hydrogen exports to the Netherlands, Germany, and France. Furthermore, Belgium intends to play a key role in European energy security by enabling strategic hydrogen storage within its territory. Denmark has committed to developing between 4 and 6 GW of hydrogen production capacity by 2030 and plans to construct long-term underground hydrogen storage in large salt caverns (Green Hydrogen Organisation Denmark, n.d.). This infrastructure will not only serve domestic energy needs but also enable Denmark to act as a regional energy buffer by exporting hydrogen during periods of low renewable generation elsewhere. Germany's hydrogen strategy sets a goal of 10 GW of production capacity by 2030. However, this figure is expected to fall short of national demand, leading to a projected reliance on imports for 50 to 70 percent of hydrogen consumption (Green Hydrogen Organisation Germany, n.d.). The Netherlands has announced a hydrogen production target of 4 GW by 2030 (Green Hydrogen Organisation Netherlands, n.d.). In parallel, it is developing regulatory and infrastructural frameworks aimed at furthering the transition to hydrogen as a major energy carrier.

Norway's approach differs due to its unique energy profile. With 98 percent of its electricity already coming from renewable resources, such as hydroelectric power (International Energy Agency & Birol, 2022). Therefore, large-scale hydrogen production is not seen as essential for domestic use. Instead, Norway is prioritizing the creation of flexible regulatory frameworks that enable integration and future deployment of hydrogen, while avoiding firm production targets (Green Hydrogen Organisation Norway, n.d.). The United Kingdom has set a target of 5 GW of hydrogen production capacity by 2030 (Green Hydrogen Organisation United Kingdom, n.d.). Similar to the Netherlands, the UK is focusing on establishing policy frameworks to support future scaling of hydrogen production, aligning with the broader transition of its energy system.

Table 3: countries 2030 hydrogen and 2050 offshore wind goals

Country	2030 green hydrogen generation goals		Planned offshore wind capacity North Sea 2050
Belgium	At least	0.15 GW	8 GW
Denmark	Between	4 – 6 GW	25 GW
Germany		10 GW	45 GW
The Netherlands		4 GW	40 – 70 GW
Norway	to be determined		10 – 15 GW
United Kingdom		5 GW	45 GW

These national hydrogen strategies remain primarily oriented toward short-term objectives, with most targets concentrated around the year 2030. In contrast, the envisioned development of a North Sea hub and spoke energy system is structured around a long-term timeline extending to 2050. As evidenced by the disparity shown in Table 3, a significant gap exists between the near-term hydrogen production targets and the longer-term offshore wind capacity goals. This misalignment can be attributed to persistent uncertainties regarding the future role and scalability of hydrogen within the future energy system (Le et al., 2024). As a result, many countries are hesitant to make full, long-term commitments to a hydrogen-based infrastructure, opting instead to prioritize flexible frameworks and incremental development until the strategic importance of hydrogen becomes clearer.

There are multiple pathways through which hydrogen production could be integrated into the future hub and spoke energy system in the North Sea. A central decision in this integration concerns the location of electrolysis: whether hydrogen will be produced onshore or offshore. Each of these approaches presents distinct advantages and limitations, leading to different possible designs for hydrogen inclusion (North Sea Wind Power Hub, 2022).

Producing hydrogen Onshore involves transporting the electricity generated by offshore wind farms via high-capacity subsea cables to coastal facilities, where it is then used to produce hydrogen. While this requires more extensive electrical transmission infrastructure, particularly high-capacity cables, it offers cost advantages in terms of construction and maintenance, as electrolysis facilities are cheaper to build and easier to operate on land(North Sea Wind Power Hub, 2022).

In contrast, offshore electrolysis entails producing hydrogen directly at sea, near the wind generation sites. This approach reduces the need for large-capacity electricity transmission cables, as the electricity is immediately converted to hydrogen offshore. However, it necessitates the development of new hydrogen pipeline infrastructure to transport the gas to shore. These offshore pipelines, if connected to each other, could function as a secondary hub structure in the system, allowing for transportation of hydrogen throughout the system. A more detailed examination of offshore hydrogen production reveals further distinctions, particularly regarding the structural design of the generation hubs. One key consideration is whether the electrolysis facilities are constructed on artificial islands or offshore platforms (North Sea Wind Power Hub, 2024a). Artificial islands offer the advantage of accommodating larger electrolysis capacities and allows for more connected wind power. However, their construction is more capital-intensive and can have a greater environmental footprint. In contrast, offshore hydrogen production platforms present a more modular and less intrusive option.

The variations discussed above, along with the relatively short-term orientation of national hydrogen generation goals, align with the findings presented in the literature review in Chapter 2. Consequently, we will examine three possible configurations for integrating hydrogen production into the hub and spoke energy system. These configurations are based on designs currently being developed by the North Sea Wind Power Hub (2024a; 2024b), and include: **Onshore electrolysis**, **Offshore electrolysis using modular platforms** and **offshore electrolysis on artificial islands**. Each configuration presents distinct trade-offs in terms of cost, scalability, environmental impact, and infrastructure requirements. In the following sections, we will explore these three hydrogen production approaches in greater detail, outlining their operational characteristics, advantages, and associated challenges within the broader context of the future North Sea energy network.

4.2.1. Onshore generation

In this onshore hydrogen variation of the system, electricity is produced by offshore wind farms and is then transmitted to the mainland via high-capacity submarine cables, where it is converted into hydrogen through electrolysis at land-based facilities. This approach is both flexible and adaptive, particularly in the context of uncertain future hydrogen demand. By situating electrolysis onshore, nations can more easily scale production in response to evolving market needs(Gea-Bermúdez et al., 2023; Bødal et al., 2024). If hydrogen demand grows, additional electrolysis capacity can be added incrementally. Conversely, if demand does not materialize as expected, significant investments in offshore infrastructure will not have been wasted.

Another advantage of this model is its relative simplicity in offshore infrastructure: only electrical transmission cables are needed at sea, eliminating the requirement for undersea hydrogen pipelines. This reduces the complexity of the marine network and shifts most technological and safety challenges to land, where they are generally easier to manage (North Sea Wind Power Hub, 2018). However, the growing influx of electricity from offshore wind farms can place additional pressure on national power grids on land, which are already experiencing congestion-related challenges (De Boer, 2025). Offshore hydrogen production methods that generate hydrogen directly at sea can absorb some of the electricity demand at the source, resulting in less electricity being transmitted to the mainland and potentially easing the strain on onshore grid infrastructure.

However, centralizing energy transmission through a limited number of large offshore cables introduces a critical point of vulnerability. A failure in one of these major transmission lines could disrupt large portions of the system, raising concerns about the overall vulnerability of the network (Dashti et al., 2021).

4.2.2. Artificial islands

The second approach for integrating hydrogen production into the hub and spoke energy system involves the construction of artificial islands dedicated to large-scale offshore energy conversion. One such conceptual design includes an island supporting 10 GW of connected offshore wind capacity and up to 6 GW of hydrogen production through electrolysis (North Sea Wind Power Hub, 2024a). This model offers several advantages. When created this island can more easily be expanded when demand increases or to facilitate future energy storage. Additionally fewer but larger hydrogen pipelines would be required to connect these islands to surrounding nations, simplifying the broader infrastructure network (when compared to smaller scale offshore hydrogen production). Additionally, artificial islands can be equipped with docking ports to facilitate maintenance, and the offshore location minimizes public safety risks, as any accidents involving hydrogen production would occur far from populated areas.

However, this design also presents significant challenges. The most suitable location for such an island is the Dogger Bank, due to its relatively shallow waters (Engebretsen et al., 2016), which reduces construction costs. Yet, this area is part of the Natura 2000 network, a European Union protected zone, raising serious environmental and legal concerns (North Sea Wind Power Hub, 2018). Furthermore, the substantial investment required to build artificial islands may not be justifiable if future hydrogen demand remains uncertain. Finally there are safety risks to this design (North Sea Wind Power Hub, 2024a). Compared to the modular system discussed in the next chapter, this island is expected to be continuously manned (North Sea Wind Power Hub, 2024a). Consequently, any failure on the island would have more significant consequences than those in the modular design. Additionally the carbon footprint for this design is expected to be double that of the modular design we will discuss in the following part (North Sea Wind Power Hub, 2024a).

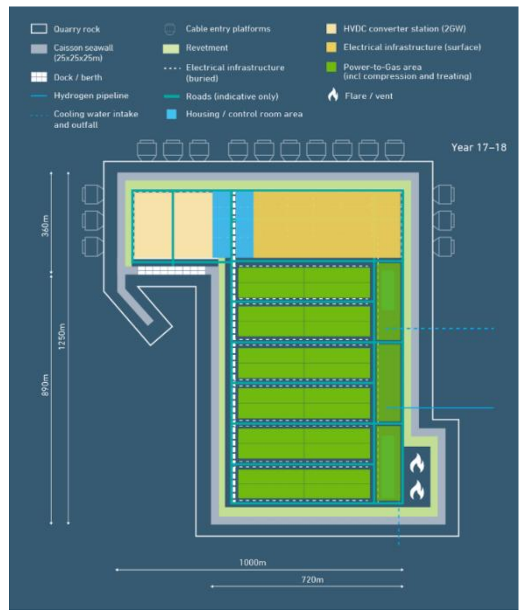

Figure 6: possible design of a 10GW artificial island (North Sea Wind Power Hub, 2024a)

4.2.3. Modular hydrogen hubs

The third approach for integrating hydrogen production within the hub and spoke energy system involves a modular network of smaller offshore hubs. Each hub would consist of approximately 4 GW of connected wind power and up to 2 GW of electrolysis capacity, implemented via platform-based structures (North Sea Wind Power Hub, 2024a). These modular units can be flexibly deployed and combined to meet local variations in hydrogen demand and offshore wind availability, allowing for a highly adaptable and scalable system.

One of the key benefits of this modular design is its flexibility. Additional platforms can be installed as demand grows, enabling gradual and cost-effective scaling of the system (North Sea Wind Power Hub, 2024a). This approach also has a comparatively lower environmental impact, as smaller platforms can be distributed across various offshore locations, avoiding sensitive areas like the Dogger Bank, which would be more heavily affected by large-scale construction projects such as artificial islands.

However, as we can see in figure 7 a decentralized modular network would require a greater number of smaller-scale hydrogen pipelines to transport hydrogen between hubs as compared to the island based approach. This increases the complexity and potential cost of the infrastructure compared to a more centralized island-based model. Despite this, the adaptability and reduced ecological footprint of smaller modular hubs make them a promising option for balanced offshore hydrogen integration (North Sea Wind Power Hub, 2024a).

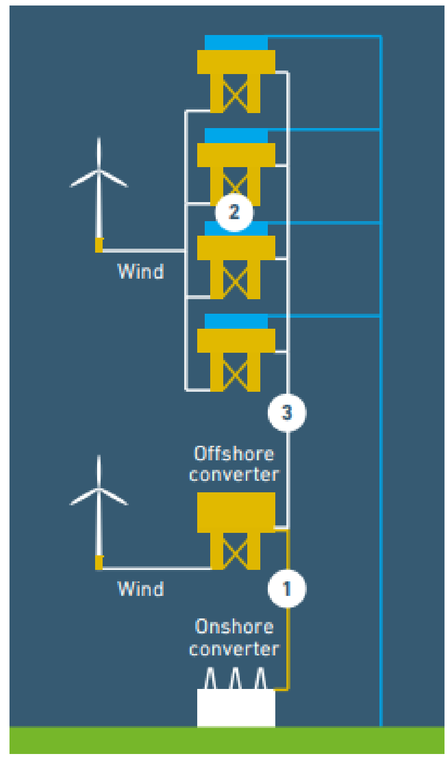

Figure 7: possible design of a 4GW modular hub (North Sea Wind Power Hub, 2024a)

4.2.4. Conclusion

Current national hydrogen strategies across North Sea countries are shaped by significant uncertainty regarding hydrogen's long-term role in the future energy system. While all participating nations have begun outlining hydrogen frameworks, their goals remain largely oriented toward 2030, revealing a cautious, incremental approach. These strategies contrast sharply with the significantly higher offshore wind capacity goals projected for 2050, highlighting a disconnect between the near-term caution surrounding hydrogen and the long-term vision for renewable generation. This discrepancy underscores how uncertainty about future hydrogen demand continues to limit large-scale infrastructure investment and full integration planning.

We started with the following research question: In which ways can hydrogen production be included into the North Sea hub and spoke energy system? After looking into the complexities and design variations we found three primary configurations, which offer potential pathways for integrating hydrogen production into the hub and spoke energy system. First, **onshore hydrogen production** involves transmitting electricity from offshore wind farms to land based hydrogen production facilities. This method offers flexibility, as hydrogen production capacity can be scaled in response to actual demand. It also avoids the need for offshore hydrogen pipelines. However, it raises public safety concerns due to the explosive nature of hydrogen and creates system vulnerability if reliant on a limited number of large transmission cables. Second, **large-scale offshore production on artificial islands** provides centralized hydrogen generation directly at sea, potentially handling 10 GW of wind power and 6 GW of hydrogen production. This design supports future scalability and reduces onshore safety risks, but it is capital-intensive and poses significant ecological challenges, particularly if located in sensitive areas like the Dogger Bank. Finally, a **modular platform-based approach** envisions smaller 4 GW hubs with 2 GW hydrogen capacity. These can be flexibly deployed across the North Sea, offering scalability and lower environmental impact. However, this decentralized model requires a more complex and extensive pipeline network to transport hydrogen to shore. Each of these configurations have distinct advantages and trade-offs, leading to a large design space for the future role of hydrogen inclusion in the hub and spoke system.

5. Scenario creation

In the previous chapter, we explored various uncertainties related to hydrogen production methods and the anticipated generation capacity of the hub and spoke system. In this chapter we will answer the following research question: What are the different implementation scenarios of the hub and spoke energy system? We will integrate these previously found uncertainties with projected variations in future electricity demand to develop distinct scenarios for use in the subsequent graph based flow model.

5.1. Electricity demand

The future demand for electricity will significantly influence the requirements and performance of the hub and spoke energy system. Key questions arise: will the model be able to generate sufficient electricity under varying weather conditions? Where will this electricity be directed, and how much surplus could be allocated for hydrogen production? To better understand these dynamics, this section examines multiple projections for European electricity demand in 2050.

According to Enerdata, electricity demand in Europe is expected to rise from 4,175 TWh in 2030 to 5,676 TWh in 2050, which is an increase of approximately 36% (Global 2050 Projections for Total Electricity Generation | Enerdata, n.d.). National projections further illustrate the variability in expected trends. In Germany, for example, average electricity demand in 2050 may decrease by 6% compared to 2010 levels, while peak demand is projected to rise by 15%. Conversely, in the United Kingdom, average electricity demand could increase by 25%, with peak demand potentially rising by up to 49% in the same period (Boßmann & Staffell, 2015). Electricity consumption in Europe has generally declined since 2008. Despite this, system operators anticipate future growth, with expectations of annual increases between 1% and 7% until 2030. This would correspond to a cumulative demand increase of 5% to 40% by 2030 relative to 2024. However, some sources caution that even these optimistic forecasts may not materialize (Weiss et al., 2024). Furthermore, societal and economic developments could further widen the range of possible outcomes. According to Brugger et al. (2021), total electricity demand may deviate from baseline scenarios by as much as +42% or -51%, depending on future trends such as electrification, industrial transformation, and energy efficiency.

Given this substantial uncertainty about future electricity demand, three distinct demand variations will be developed for the model and the scenarios. The first variation assumes stagnant electricity demand; this could be driven by technological innovations and the relocation of heavy industry away from Western Europe. The second scenario reflects a high-demand future, with a 60% increase in electricity needs. This could result from widespread electrification and the emergence of new sectors, such as data centers for artificial intelligence. The third, intermediate scenario models a 30% increase in demand, representing a moderate pathway in which electrification occurs but is less pronounced than in the high-demand case. By exploring these three variations, the model can account for a wide range of possible futures and assess how different levels of electricity demand might affect energy distribution, system design and the potential role of hydrogen in the North Sea energy system.

By combining the variations in electricity demand with the different offshore wind generation goals and hydrogen integration approaches, we arrive at Table 4, from which we can create possible design scenarios of the hub and spoke system.

Table 4: design variations hub and spoke system

Peak demand 2050	Installed capacity 2050	Hydrogen inclusion 2050
Remains stagnant	Full goal, in case of large demand	Onshore
Increases by 30%	Smaller goal in case of small demand	Island based
Increases by 60%		Modular based

5.2. Design scenarios

In this part we will discuss how scenarios will be created from table 4. If each design variation will be combined with each other we would get, 3 * 2 * 3 = 18 different scenarios. When creating the scenarios some combinations of variables are unrealistic. For instance, when we combine the high electricity demand growth with a low-capacity goal. When electricity demand increases the goals will be adjusted accordingly. So, in 2050 when the system is created, we won't see a system with large installed wind capacity and stagnant electricity demand growth. This reasoning is also true for a situation in which demand increases by 60%, in this situation a small generation goal will be illogical. So stagnant demand will be combined with a small capacity goal, and a 60% increase in demand will be combined with the full capacity goal. This reduces the total number of feasible scenarios to 4 per hydrogen inclusion method.

However, the total number of scenarios can be reduced further. As discussed in Section 4.2, the island-based electrolysis approach presents several disadvantages compared to the modular alternative, including concerns related to safety, construction emissions, build time, and scalability (North Sea Wind Power Hub, 2024a). Importantly, the modular approach can achieve the same electrolysis capacity as the island-based method (North Sea Wind Power Hub, 2024a). Since the model developed in this study focuses on the effects of installed electrolysis capacity rather than costs or environmental impacts, we expect only minimal differences between the island-based and modular configurations. Therefore, the number of island-based scenarios will be reduced to two. This still enables comparison with the other methods and allows us to validate this expectation.

Additionally, as discovered in Section 6.1 on offshore wind parks, the difference between the low and high capacity layouts is approximately 24 percent. This indicates that if capacity remains stagnant while demand increases, a mismatch of around 30 percent between generation and demand will occur. In a scenario where demand increases by 60 percent and high-capacity targets are implemented, the mismatch rises to approximately 36 percent. Since the model determines flows based on installed generation capacity and electricity demand, we expect that increasing demand while keeping capacity constant will produce similar system outcomes. For example, shifting from low capacity with stagnant demand to low capacity with medium demand, or from high capacity with medium demand to high capacity with high demand, is likely to yield comparable results.

As a result, the total number of scenarios used in this study is reduced to the 8 shown in Table 5. These scenarios are divided into three distinct groups based on the hydrogen integration method. The first group includes scenarios using the modular hydrogen approach, combined with different capacity goals and levels of electricity demand. The second group consists of scenarios based on the onshore hydrogen production method, again combined with varying capacity and demand. The final group includes the island-based hydrogen approach, paired with selected variations in demand and generation capacity.

Table 5: Design scenarios hub and spoke system

Scenario:	Demand	Capacity goal	Hydrogen inclusion
1 Medium build out **Base scenario**	30% increase	Full goal	Modular based
2 Small build out	0% increase	Small goal	Modular based
3 Large build out	60% increase	Full goal	Modular based
4 Small onshore	0% increase	Small goal	Onshore
5 medium onshore	30% increase	Small goal	Onshore
6 large onshore	60% increase	Full goal	Onshore
7 Few islands	0% increase	Small goal	Island based
8 Many islands	30% increase	Full goal	Island based

5.2.1. Build out

The **modular hydrogen** scenarios reflect a flexible, scalable approach to hydrogen integration in the hub and spoke energy system. The scenarios **Medium build out (1)**, **Small build out (2)**, and **Large build out (3)**, cover a broad range of possible electricity demand pathways, from stagnation to a 60% increase. The underlying rationale is that modular offshore hydrogen platforms are easier to add to the system and can be created in more different places. This modular approach allows for an easier build out and more flexibility to deal with uncertain future electricity demand. By varying demand given the modular hydrogen approach we will be able to compare these scenarios with each other, which gives us additional insights into the layout and the design of the model in the scenarios. The **Medium build out (1)** scenario has been selected as the base scenario for further analysis, as it offers a balanced representation of moderate demand growth and full generation capacity. This combination provides a flexible framework that accommodates the considerable uncertainties surrounding long-term electricity demand and the evolving role of hydrogen in the energy system.

5.2.2. Onshore

The **onshore hydrogen** scenarios explore the feasibility of producing hydrogen at coastal facilities using electricity transmitted from offshore wind farms. These include **Small shore (4)**, **Medium shore (5)**, and **Large shore (6)**, each varying in demand and installed capacity. The onshore model offers economic and infrastructural simplicity, as it eliminates the need for offshore hydrogen pipelines. In **Small shore (4)**, stagnant demand is paired with a smaller generation goal, reflecting a conservative system design where onshore electrolysis can be scaled as needed. The scenario **Medium shore (5)** will combine a medium demand growth with a small capacity goal. This scenario will allow us to estimate the effect of increasing electricity in the case of a lower capacity goal. And finally, the scenario **Large shore (6)** applies this same logic to growing demand levels.

5.2.3. Artificial islands

The **island-based hydrogen** scenarios **Few islands (7)** and **Many island (8)** investigate centralized offshore hydrogen production using artificial energy islands. These islands offer large hydrogen production capacity and safety benefits by distancing hydrogen infrastructure from populated areas. **Few islands (7)** pairs stagnant demand with a limited capacity goal, representing a minimal but spatially distributed configuration. In contrast, **Many islands (8)** envisions a 30% increase in electricity demand alongside a full offshore wind build-out, allowing the artificial islands to serve as a central production and distribution hub. While this approach simplifies pipeline architecture, it raises concerns about environmental impact, particularly if the islands are created in ecologically sensitive regions such as the Dogger Bank.

5.3. Conclusion

We started this chapter with the research question:

> What are the different implementation scenarios of the hub and spoke energy system?

By developing eight distinct implementation scenarios, we capture a broad range of possible futures for the hub and spoke energy system. These scenarios integrate variations in electricity demand, installed offshore wind capacity, and hydrogen production strategies, offering a comprehensive basis for subsequent modeling efforts. The modular, onshore, and island-based hydrogen inclusion approaches each present unique benefits and trade-offs in terms of scalability, infrastructure complexity, and system robustness. By analyzing and comparing these scenarios, we can acquire insights into the tradeoffs and effects of designs.

6. Model inputs and development

In the first part of this chapter, we will analyze which offshore wind parks can be included in our hub and spoke model. We identify existing parks and, where necessary, propose additional ones to meet the previously defined national generation targets. In addition, electricity demand functions will be developed for each country's landing point(s). These functions account for offshore wind capacity located outside the modeled area, as well as existing onshore wind generation. We assume that onshore wind capacity will remain roughly at its current level, due to strong public opposition to new developments. With the continued expansion of offshore wind capacity, resistance to onshore wind is expected to increase, as the public shows a growing preference for generating wind power at sea rather than on land (energynews, 2024; Benn, 2025; De Looze & Cuppen, 2023). The demand functions are not adjusted for solar power, as the focus is on the system's design requirements. The system must be capable of meeting demand even during periods when solar generation is minimal or nonexistent, such as at night or during the fall and winter months, when sunlight is limited and energy demand is typically the highest. The exact model inputs and motivation can be found in appendix A, Hub Generation Capacity and Demand.

In the second part of the chapter, we will explain how connections between hubs and landing points are established within the model. This process is based on the country-specific Minimum Spanning Tree (MST) network and the network derived from Delaunay triangulation, as discussed in section 3.2.3.1 on edge design. Cable capacities are determined using the network simplex algorithm across various weather scenarios, ensuring the network can meet demand under all conditions. Only cables that are used in at least one scenario are retained in the final model. After creating these edges, we can determine the hydrogen production potential, a super generator and super consumer are added to the model to identify excess electricity, which indicates the capacity for hydrogen production. Nodes with surplus power can then be identified, and hydrogen capacity can be allocated to them based on the scenarios.

And finally, the key metrics are discussed. These metrics can be used to evaluate and compare network designs, including total edge length and capacity, model diameter, and the number and capacity of hydrogen nodes. These metrics help assess spatial efficiency, energy transport capacity, network robustness, and hydrogen generation capacity. Additionally, the percentage of essential edges measures the network's robustness under single-edge failures, providing insights into reliability across different scenarios and layouts.

6.1. Offshore wind parks

This section provides an overview of the offshore wind generation potential and peak electricity demand for each country involved in the North Sea energy system. It serves as a summary of the full process used to determine the wind generation capacity and corresponding national electricity demand. A detailed explanation of this process, including the underlying assumptions and data sources, can be found in Appendix A.

Table 6: Number of hubs and total generation capacity in the model

Country	Number of Hubs	Wind generation inside the model(GW)	Wind generation outside of the model (GW)	Peak Demand 2024 (GW)
Belgium	1	5.9	6.4	13.206
Denmark	4	24.2	15.4	9.070
Germany	6	33	100.5	77.508
Netherlands	8 (Low) / 11 (High)	34.1 (Low) / 64.1 (High)	12.8	19.477
Norway	4 (Low) / 6 (High)	10.6 (Low) / 15.6 (High)	9.5 (low) / 19.5 (high)	24.930
United Kingdom	12	39.5	41.86 (low) / 75.9 (high)	51.442

As shown in Table 6, Germany has a significant amount of wind generation capacity located outside the boundaries of the future North Sea energy system. This 100.5 GW of wind capacity, consists of 63.5 GW from onshore wind and 37 GW from offshore wind installations situated either in the Baltic Sea or in parts of the North Sea that are not suitable for connection to the planned hub and spoke network (Bundesverband WindEnergie (BWE), 2025). Similarly, the United Kingdom also has a substantial share of wind generation capacity located outside the model's scope. This includes offshore wind farms that fall outside the defined boundaries set in Section 4.1, as well as onshore wind generation (ESO, 2024). Furthermore, the United Kingdom's 100 GW offshore wind target is divided into 66.6 GW from fixed-bottom installations and 33.3 GW from floating wind projects (ESO, 2024). Given the substantial scale of the floating wind component, it is unlikely that the full target will be achieved if peak electricity demand in the United Kingdom remains unchanged (ESO, 2024). In addition, the offshore wind generation goals of the Netherlands and Norway are presented as ranges rather than fixed targets. These ranges reflect national planning uncertainties and are discussed in greater detail in Section 4.1. All these inputs form the basis for constructing geographically realistic hubs and landings in the model. Figure 8 on the following page provides a visual representation of all offshore wind parks and connection points for the countries in the North Sea hub and spoke system. Furthermore we can see in figure 8 that the total installed capacity in the low capacity scenario is 146.84 GW, while in the high capacity scenario it increases to 181.84 GW, which is an increase of 23.8%.

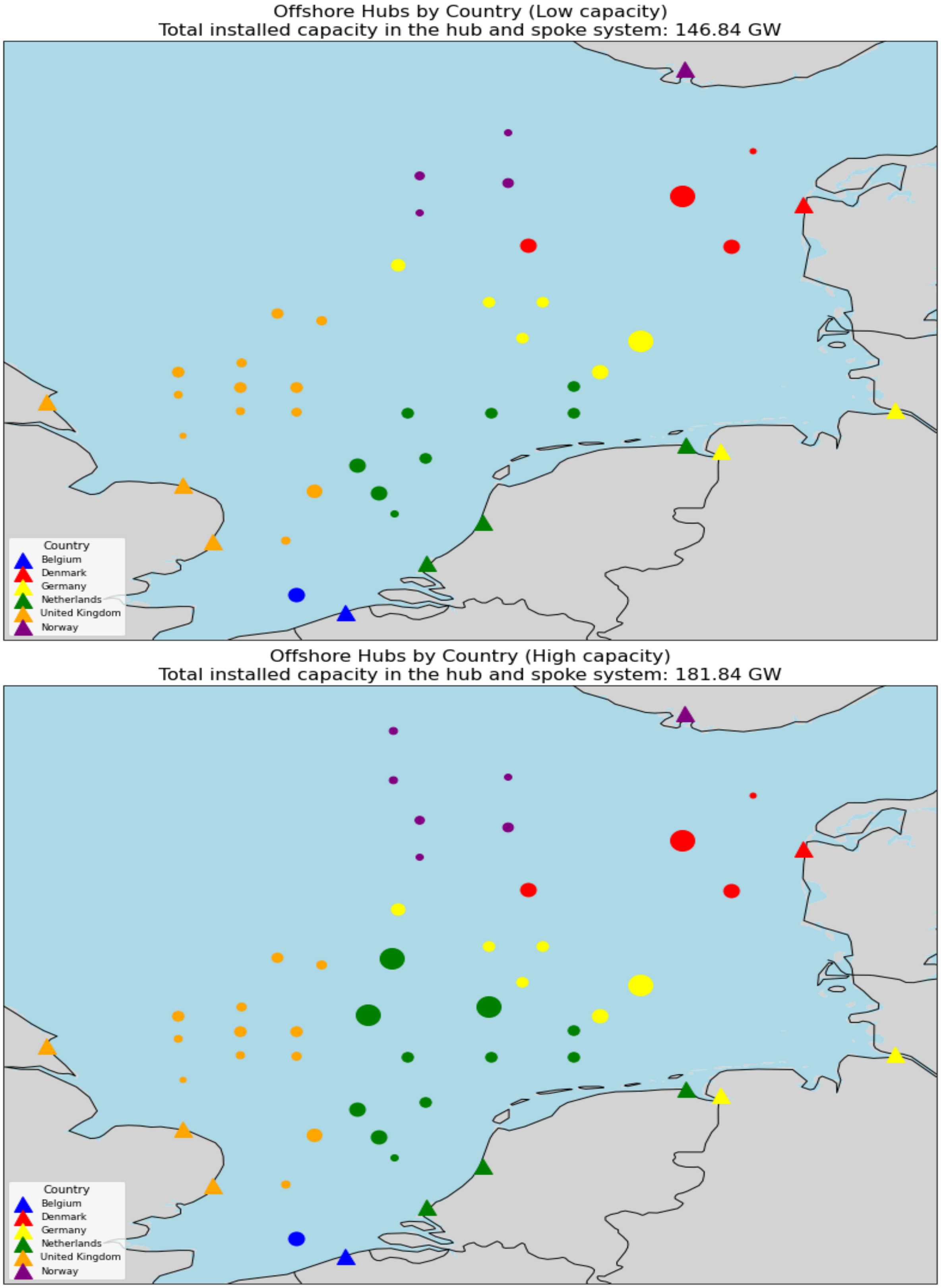

Figure 8: Generation hubs and landings in both system capacity layouts.

6.2. Model edge design and capacity determination

Now that an inventory of all hubs, landing points, and their associated generation capacities and electricity demand has been completed, the next step is to establish the connections between these elements. As discussed and justified in Section 3.2.3.1: Edge Design, the model will incorporate two variations for determining network edges. The first variation is based on national Minimum Spanning Trees (MST), which are subsequently interconnected to form a meshed network structure (Sedgewick & Wayne, 2011). The second variation uses Delaunay triangulation, with the total number of edges reduced to better reflect realistic infrastructure constraints (Lucas, n.d.). These two network configurations enable the simulation of large-scale electricity transfers between North Sea countries, a key objective of the future energy system (North Sea Wind Power Hub, 2024b). Moreover, by reducing the number of edges in the Delaunay network or by applying the MST approach, the model provides a more accurate representation of a realistic future transmission network. This directly addresses the knowledge gap identified in Section 2.7, where existing studies often overlook spatial and economic constraints. Leaner network designs are particularly important, given that the cost of future offshore electricity infrastructure is expected to reach several hundred billion euros (Koster, 2025).

In the remainder of this sub chapter, we will first discuss the creation of the MST edge design. Next, we will examine the Delaunay method for generating network edges. Third, we will explore how flow analysis is applied to determine the required cable capacities. Finally, we will consider the existing interconnection cables between the various North Sea countries and their role in the overall network design.

6.2.1. Minimum spanning tree approach

The Minimum Spanning Tree (MST) approach is the first of two methods used to establish offshore grid connections. In this approach, each country first optimizes its internal cable layout, forming individual minimum spanning trees (Sedgewick & Wayne, 2011). Cross-border connections are then created to link these national networks. Direct connections between landing points are not permitted. Firstly because there is already a large amount of network congestion in land based electricity infrastructure (De Boer, 2025). These land based systems are already under strain, which makes a future layout and their capacities difficult to predict. And secondly because the offshore hub and spoke energy network is intended to transport all electricity (North Sea Wind Power Hub, 2024b), modeling cables which are on land would therefore be outside the scope of the model. The only exception we will make to this rule is the connection between the landing points at Emden (Germany) and the one at Eemshaven (Netherlands). These sites are located very close to one another and are separated by water, allowing for a feasible subsea connection. Therefore, this connection will be manually added to the model.

The only thing we will have to determine now is how the MSTs will be connected to each other. Each country will have a connection to each neighboring country, these connections will be determined based on distances between the nodes. Using this method we will create a more meshed network which will be better suited to the goal of transferring large scale electricity flows(North Sea Wind Power Hub, 2024b).

Figure 9 displays the Minimum Spanning Trees (MSTs) for each country under the high-capacity goal scenario. It also shows the additional connections added between countries based on the shortest distances between nodes. These connections are also listed in Table 7. As illustrated, each national MST has been connected to each neighboring country. Notably, the connection between the United Kingdom and Germany is established through edge 4, which already connects the United Kingdom to the Netherlands. By adding edge 5, the model creates an indirect link between the United Kingdom and Germany via the Netherlands. This reduces the system length, and increases system connectivity. Additionally, edge 9 represents the manually added connection between Eemshaven in the Netherlands and Emden in Germany. This link is particularly short and crosses a narrow stretch of sea, making it a logical and efficient connection between the two countries.

Table 7: Edges connecting the high capacity MSTs

Edge number in figure 9	From	To	Motivation
1	Netherlands	Belgium	Shortest connection
2	Germany	Norway	Shortest connection
3	Belgium	United Kingdom	Shortest connection
4	Netherlands	United kingdom	Shortest connection
5	United Kingdom	Netherlands/Germany	Shortest connection
6	Germany	Denmark	Shortest connection
7	Netherlands	Germany	Shortest connection
8	Denmark	Germany	Shortest connection
9	Netherlands	Germany	Manual connected edge Eemshaven, Emden

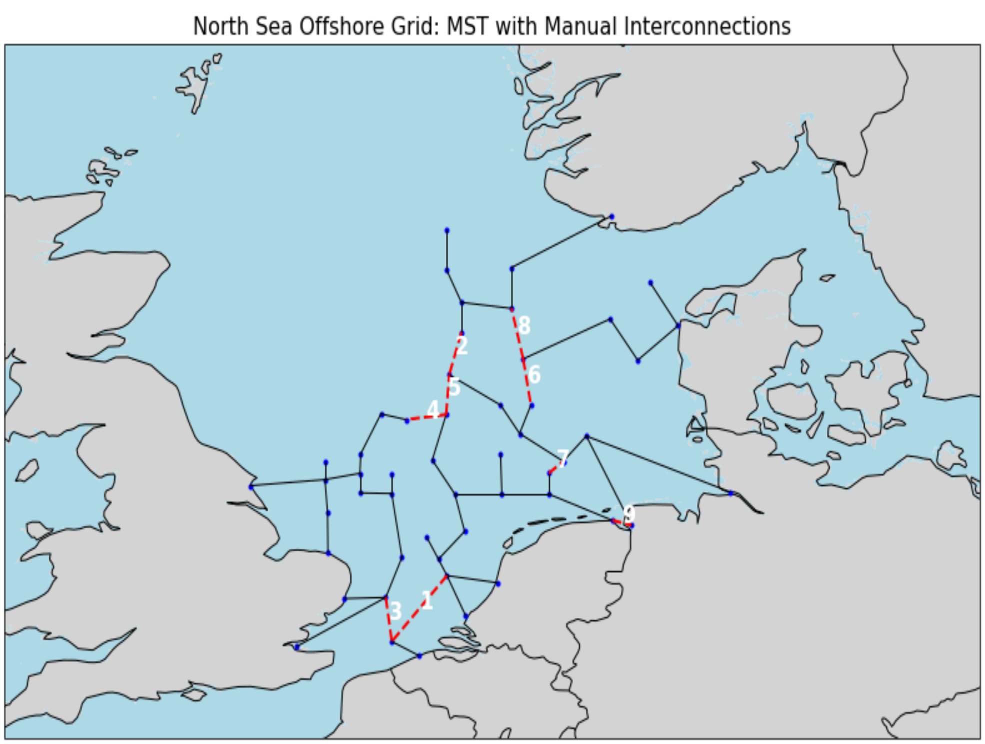

Figure 9: High-capacity model MSTs with connection cables

Figure 10 shows the Minimum Spanning Trees (MSTs) for each country under the low-capacity goal scenario. It also includes the additional cross-border connections, which were added based on the shortest distances between nodes. These connections are listed in Table 8. As shown, each national MST has been connected to its neighboring countries to ensure a fully interconnected network. A notable difference compared to the high-capacity layout is the connection between the United Kingdom and Germany (edge 7), which is now a direct link. In the high-capacity scenario, this connection passed through a node in the Netherlands, but since this intermediate node does not exist in the low-capacity scenario, a direct connection was created. As in the previous scenario, edge 9 connects Eemshaven in the Netherlands to Emden in Germany, representing a short and logical cross-border link.

Table 8: Edges connecting the low capacity MSTs

Edge number in figure 10	From	To	Motivation
1	Netherlands	Belgium	Shortest connection
2	Germany	Norway	Shortest connection
3	Netherlands	United Kingdom	Shortest connection
4	Belgium	United Kingdom	Shortest connection
5	Germany	Netherlands	Shortest connection
6	Germany	Denmark	Shortest connection
7	Germany	United Kingdom	Shortest connection
8	Denmark	Norway	Shortest connection
9	Netherlands	Germany	Manual connected edge Eemshaven, Emden

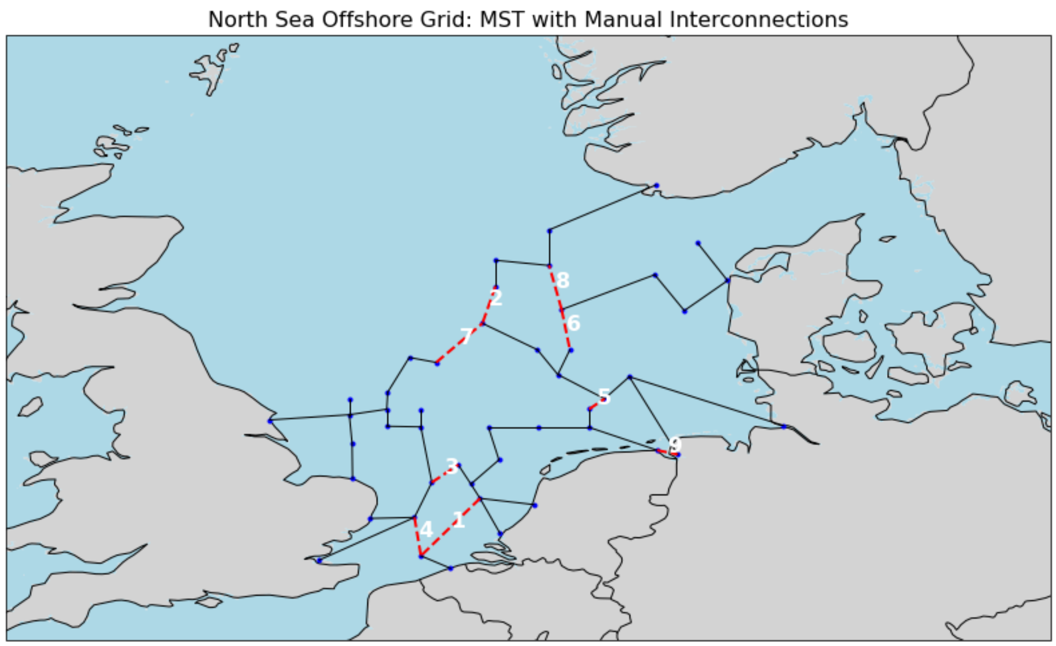

Figure 10: Low-capacity model MSTs with connection cables

6.2.2. Delaunay Triangulation

The second method used to create the edges in the model is Delaunay Triangulation. As explained in Section 3.2.3.1: Edge Design, this approach applies geometric principles to form triangles that represent an optimal set of connections between nodes (Lucas, n.d.). However, as previously discussed, applying the full Delaunay triangulation results in a high number of edges. Including all these connections would not align with the objective of this research, which is to address the knowledge gap related to the lack of realistic and cost-effective representations of a future offshore hub and spoke energy system. Since offshore infrastructure is expected to require investments of several hundred billion euros, overly dense networks do not reflect financially feasible system layouts (Koster, 2025). Direct connections between landing points are excluded, as previously discussed in 6.2.1, due to existing congestion in land-based infrastructure and because the offshore hub and spoke network is intended to handle all cross-border electricity transmission (De Boer, 2025;North Sea Wind Power Hub, 2024b). Again the only exception to this is the connection between Eemshaven (Netherlands) and Emden(Germany).

Figure 11: High and low-capacity Delaunay networks

Figure 11 displays the Delaunay networks for the high-capacity scenario on the left and the low-capacity scenario on the right. The red nodes 1 to 5 are the additional nodes that are added in the high capacity scenario. Similar to the MST configurations, several edges have been manually added. The first is the connection between Eemshaven and Emden (edge 2), included due to their close geographical proximity. The second is a connection from Büttel-Hamburg to the NEWGER2 wind park (edge 1), as this link is part of the German government's official plans (WAB, 2021). Excluding this connection would result in a situation where a key German landing point is not connected to its own offshore wind parks, which would be unrealistic from a planning and policy perspective (WAB, 2021).

Now that the complete Delaunay networks have been constructed, it is necessary to address the reduction of the total number of edges in order to meet the objectives of this research. As previously discussed, one of the key aims is to develop a realistic and cost-effective representation of a future offshore hub and spoke energy system. Running the weather scenarios on the full Delaunay network leads to a situation in which the model prefers direct connections, as these offer the shortest paths. However, this results in an overly extensive network composed of many long, low-capacity cables, which is neither practical nor economically viable.

To reduce the total network length while maintaining system performance, two different approaches were considered. The first approach involved iteratively removing the cable with the lowest capacity until the network reached a specified target length. The second approach introduced an optimization factor into the edge weights, which adjusts the edge weights, which leads to the model favoring shorter connections and encourages electricity to flow through intermediate nodes rather than relying solely on direct links. These two methods were selected because they reflect two distinct strategies for network simplification. The first is a post-processing technique that directly removes less critical cables based on simulated results, while the second integrates edge prioritization into the simulation process itself. After careful evaluation, the second method was chosen. The iterative removal approach presents significant drawbacks. Most notably, it requires re-running the full simulation after each cable is removed, since each removal affects flow patterns and the importance of remaining edges. This causes instability in the results, as the final network structure can vary greatly depending on the sequence of removals. In contrast, applying an exponential optimization factor to the edge weights influences routing behavior during the flow analysis itself(Lucas, n.d.). This allows for a consistent and scalable reduction in network length without the need for repeated simulation runs. It also ensures that shorter and more efficient cable routes are naturally prioritized (Lucas, n.d.), supporting the goal of developing a lean, cost-effective, and operationally sound network, which addresses the knowledge gap identified in part 2.7. The specific methodology for implementing this optimization is described in the following section.

The flows in the network are determined using the Network Simplex Algorithm, a method used to solve the minimum-cost flow problem on a graph (Brunovsky, 2023). Each edge in the graph is assigned a cost per unit of electricity flow, and the objective is to find the most efficient distribution of electricity that meets all node demands at the lowest total cost. In the initial setup, the cost or weight of each edge corresponds to its physical length. This leads the model to favor direct connections, as they are the shortest and therefore least costly. However, if the goal is to reduce the overall physical length of the network infrastructure, these edge weights must be modified. By raising the edge weights to the power of an optimization factor, the relative cost of longer connections increases more rapidly than that of shorter ones. This adjustment encourages the model to prefer shorter, potentially indirect connections, thereby guiding the system toward a more compact network design (Brunovsky, 2023).

$$Cable\ weight^{optimize\ factor}$$

When the optimization factor is set to an extremely high value, the algorithm will prioritize only the shortest possible connections, effectively producing the minimal total network length. Using an iterative process we will produce a Delaunay network with a total cable length approximately 1.5 times that of the shortest possible configuration, which can be obtained using a very high optimization factor. A scaling factor of 1.5 is chosen because it retains enough network complexity to preserve a meshed structure, while also ensuring a reasonable basis for comparison with the leaner national MST design. As discussed in Section 3.2.3.1, even after applying this reduction method, we expect the Delaunay-based network to remain longer than the previously introduced national MST based network due to its more meshed structure. Importantly, this difference in total network length is intentional. It allows us to examine how the size and density of a network affect its vulnerability and overall performance. For example, we can analyze how each network responds to the failure of a single cable and assess whether a more meshed design offers improved robustness compared to the MST configuration. This comparison provides valuable insight into the underlying dynamics of the network and supports the broader goal of evaluating trade-offs between redundancy, performance, and cost in the design of future offshore energy infrastructure.

6.2.3. Edge capacity determination

As motivated in part 3.2.3.2. The flows in the network will be calculated using the Network Simplex Algorithm, a method designed to solve the minimum-cost flow problem on a graph (Brunovsky, 2023). Each edge has an associated cost per unit of flow, and the algorithm seeks the most efficient distribution of electricity that meets all demands at the lowest total cost. It maintains feasibility by modifying flows along cycles in the residual network and updating the tree structure when more cost-effective configurations are found (Brunovsky, 2023). This algorithm is well suited for modeling large-scale energy networks, as it allows us to simulate how electricity would flow through the system under different weather scenarios, which is one of the design goals of the future North Sea energy system (North Sea Wind Power Hub, 2024b).

As previously stated, flows in the model are based on various weather scenarios. In each scenario, the network must be capable of transporting the generated electricity to all connected countries. Therefore, the maximum flow observed on each cable across all scenarios will define its required capacity. These weather scenarios are modeled using weather-based capacity factors, which represent the power output of wind farms as a fraction of their maximum possible generation. Five scenarios are selected to capture the most demanding system conditions, as they are expected to produce the highest electricity flows across the network. These include: full generation, east-to-west, west-to-east, north-to-south, and south-to-north flows. These scenarios are presented in Table 9. By simulating full generation as well as directional imbalances from east to west, west to east, north to south, and south to north, the model will capture the maximum cable capacities that can be expected in a system designed for large scale electricity transmission (North Sea Wind Power Hub, 2024b). Table 10 shows the corresponding weather factors applied to each country under these scenarios. The values range from a minimum of 0.1 to a maximum of 1.0, representing very low to full wind generation. Countries located in the central North Sea region receive a weather factor of 0.6, the midpoint between these two extremes, reflecting moderate but consistent wind availability.

Table 9: Weather scenarios for capacity determination

Weather scenarios for determining cable capacity	
Full capacity	Everywhere wind is generated, excess capacity should go into hydrogen production.
west -> east	Wind from UK, will have to go to Germany/Denmark
East <- west	Wind from Denmark/Germany, will have to go to UK
North -> South	Wind will flow from Denmark and Norway to BE, NL and UK
South -> North	Wind will flow from BE, NL and UK to Denmark and Norway

Table 10: weather factors per nation in each of the weather scenarios

Country	Full capacity	West → East	East → West	North → South	South → North
Belgium	1	0.6	0.6	0.1	1.0
Denmark	1	0.2	1.0	1.0	0.1
Germany	1	0.2	1.0	0.6	0.6
Netherlands	1	0.6	0.6	0.1	1.0
Norway	1	0.6	0.6	1.0	0.1
United Kingdom	1	1.0	0.2	0.1	1.0

6.2.4. Offshore interconnection cables

There are a total of seven interconnection cables between countries in the North Sea region, all of which are incorporated into the model, as shown in Table 11. Each cable is manually added with a weight of 1 and its real transmission capacity. Assigning a weight of 1 causes the algorithm to treat these cables as extremely short, leading it to prioritize their use in the network. This is intentional, as these interconnections are already in place and should be utilized where possible to enhance efficiency. However, as shown in Table 11, the capacities of these existing interconnectors are relatively small compared to the expected energy flows within the future offshore hub and spoke system. Because the network must be capable of meeting and transporting the full electricity demand of all participating countries, these cables alone are not sufficient to form the backbone of the model. Their inclusion is therefore not intended as the starting point for the network design but rather as an acknowledgment of existing infrastructure that may contribute to the future North Sea energy system.

Table 11: Offshore interconnection cables and their capacity

name	country	country	Capacity (MW)	source
Skagerrak	Denmark	Norway	1700	(Skagerrak | Hitachi Energy, n.d.)
Nordlink	Germany	Norway	1400	(*NordLink, The North Sea (Norway-Germany)*, n.d.)
North Sea Link	United Kingdom	Norway	1400	(North Sea Link | National Grid, n.d.)
NorNED	Netherlands	Norway	700	(Tennet, n.d.-b)
BritNed	Netherlands	United Kingdom	1000	(BritNed | Access The UK And NL Electricity Markets, 2025)
COBRA	Netherlands	Denmark	700	(Tennet, n.d.-a)
Nemo	Belgium	United Kingdom	1000	(Pettigrew & National Grid, 2019)

6.3. Hydrogen capacity determination

To determine the required hydrogen production, we introduce a super consumer into the model. The super consumer represents the total electricity available for hydrogen production, absorbing only the excess electricity not used elsewhere. Analyzing the electricity flow to this super consumer helps identify the nodes that are expected to have excess electricity available for hydrogen generation. We can then allocate hydrogen production capacity to those key nodes. For the determination of green hydrogen generation capacity, we will look at an above average wind scenario combined with average demand. The average demand will be determined by multiplying the peak demand we acquired earlier by an average demand factor. For instance, if peak demand is 20GW and average demand is 15GW, then the demand factor should be multiplied by 0.75 to go from the peak to the average demand. The average demand factors in table 12 have been found by looking at data from Open Power System Data (2020).

Table 12: average demand as factor of peak demand per country

Country	Belgium	Denmark	Germany	Netherlands	Norway	United Kingdom
Average demand/ peak demand ratio	0.69	0.4	0.72	0.70	0.55	0.64

The green hydrogen production capacity should be designed for an above-average weather production scenario. Hydrogen is intended to be used during periods of excess renewable electricity generation (Dute et al., 2024). However, assuming a capacity factor of 1, which represents full production from all wind parks simultaneously, is unrealistic. It is rare that all wind farms in the North Sea operate at full capacity at the same time. The average wind capacity factor in the North Sea region typically ranges between 0.4 and 0.45 (Integration of Offshore Wind, n.d.). Therefore, it is reasonable to select a wind factor for hydrogen production capacity that lies between 0.4 and 1. We have chosen a factor of 0.65, slightly below the midpoint of 0.7, to represent an above-average but plausible production scenario. This value strikes a balance by avoiding the overly optimistic assumption of maximum output while capturing the potential for surplus electricity during favorable wind conditions. When the model is run using these demand and weather factors, it generates a surplus in electricity production, which provides an indication of the excess electricity available for hydrogen production under an average demand scenario combined with above-average wind conditions.

To determine where hydrogen electrolysis capacity should be installed within the North Sea energy system, this study uses the same above-average wind and average demand scenario described earlier. The super consumer is used to capture excess electricity, and by analyzing the electricity flows toward it, we identify which offshore wind parks generate surplus power. These parks are then considered the most suitable locations for hydrogen production infrastructure. For example, in the modular hydrogen implementation scenario with 2, 4, and 6 GW installations, a total of 12 GW of electrolysis capacity is to be distributed. If analysis shows that one wind park produces approximately 6 GW of excess electricity, another 4 GW, and a third 2 GW, then electrolysis capacity is allocated accordingly: 6 GW, 4 GW, and 2 GW, respectively. This proportional assignment ensures that electrolyzers are placed where excess electricity is available. Once the hydrogen production capacity is determined and subsequently allocated to the appropriate wind parks, the model is further tested using the weather-based production scenarios outlined in section 6.2.3. In these scenarios, electricity output varies depending on weather conditions, which may lead to varying amounts of excess electricity across the system. The model then evaluates whether hydrogen production should be activated under each scenario using the following logic:

1. **Is there excess electricity?**
   If no excess is available, electrolyzers remain inactive, and all generated electricity is directed to the grid.
2. **If there is excess electricity, is the amount less than the total installed electrolysis capacity?**
   If yes, electrolysis capacity is partially activated. Each node that has been allocated electrolysis capacity will reduce its electricity output in proportion to its share of the total installed capacity. For instance, if the total electrolysis capacity is 20 GW and 10 GW of excess electricity is available, then each electrolysis-enabled node will use half of its electrolysis capacity.
3. **If the excess electricity exceeds the total installed electrolysis capacity**, then each node will reduce its grid-connected generation up to the maximum of its electrolysis capacity. This means all available electrolyzers operate at full capacity to absorb the surplus.

This logic is implemented by modeling hydrogen production as a reduction in electricity sent from each node to the grid. The assumption here is that any electricity used for electrolysis is not available for direct transmission and is instead consumed locally for hydrogen production. This method allows the model to dynamically respond to system conditions while accurately representing the integration of hydrogen into the offshore grid. Although the modular hydrogen configuration is used to illustrate the allocation process, the same operational logic is applied to the other two hydrogen integration designs:

- In the **island-based configuration**, the total electrolysis capacity is fixed at 6 GW. The same activation logic applies, with the islands either partially or fully absorbing excess electricity up to their capacity.
- In the **onshore configuration**, hydrogen production occurs at the national landing points rather than offshore. Excess electricity, if available, is redirected to these landing points and used for hydrogen production according to the total demand previously determined. Activation follows the same rules, though capacity is treated as flexible demand rather than node-based infrastructure.

This unified modeling framework ensures that all hydrogen integration methods are assessed on an equal operational basis, allowing for consistent comparison across scenarios. In all cases, the conversion of electricity to hydrogen uses an efficiency factor of 0.65, meaning that 35 percent of the input energy is lost in the process (Leo, 2025). After assigning hydrogen production capacity, the producing nodes are connected to the landing points using pipelines, and the corresponding hydrogen flow capacities are calculated also using the Network Simplex algorithm(Brunovsky, 2023). To ensure a consistent and comparable assessment of hydrogen production potential across the different design scenarios, the pipelines between nodes are determined using a Minimum Spanning Tree (MST). This approach provides a uniform basis for evaluating total hydrogen pipeline capacity and production efficiency across all network configurations.

6.4. Model metrics

This study evaluates future North Sea energy networks using metrics that assess technical performance, spatial efficiency, robustness, and hydrogen integration. Key metrics include total edge length, total cable capacity, network diameter, installed hydrogen capacity, number of hydrogen nodes, hydrogen pipeline capacity, and essential edge percentage. These were selected instead of topological metrics such as node degree, network bridges, and betweenness centrality (NetworkX, 2025) because they more accurately represent physical and operational constraints, including cost-determining factors like cable length and cable capacity. The chosen metrics allow for direct comparisons between different edge designs, such as Delaunay and minimum spanning tree, as well as across various design scenarios. Below we will discuss each of the metrics included in this study.

6.4.1. Total model edge length

This metric measures the combined length of all transmission lines in the network. It serves as a valuable tool for evaluating the spatial efficiency of different network topologies, particularly when comparing Minimum Spanning Tree (MST) and Delaunay Triangulation designs. By analyzing this metric across various demand and capacity scenarios, we can assess each layout's physical scale, which are crucial determinators for total system costs. The comparison becomes particularly insightful when examining how high-capacity and low-capacity configurations affect total edge length. As discussed in Section 6.2, we anticipate the Delaunay network will demonstrate greater total length than the MST network. This metric therefore not only facilitates design comparisons but also helps validate our theoretical expectations regarding network topology performance.

6.4.2. Total model edge capacity

Total edge capacity measures the sum of all cable capacities in the network. It reflects the overall volume of energy the system is dimensioned to transport. Comparing this metric across MST and Delaunay layouts, and across different demand and capacity scenarios, helps identify which configurations are more capacity efficient.

6.4.3. Model diameter

The network diameter represents the longest shortest path between any two nodes in the system. This metric provides valuable insight into the network's spatial extent and degree of interconnectedness (NetworkX, 2025). It proves particularly useful when comparing Minimum Spanning Tree (MST) and Delaunay Triangulation layouts, as it reveals fundamental differences in connection directness between nodes, thereby helping evaluate overall network efficiency and robustness.

Based on the larger number of edges, we expect that the Delaunay network will exhibit a smaller diameter than the MST configuration due to its greater number of connections. This metric serves an additional diagnostic purpose by identifying anomalous scenarios where expected diameter relationships reverse - for instance, when the Delaunay network unexpectedly demonstrates a larger diameter than its MST counterpart. Such occurrences may indicate unusual network behavior worthy of further investigation.

6.4.4. Installed hydrogen capacity

This metric is particularly useful for comparing different demand and capacity situations to identify when hydrogen production will be highest and the lowest.

6.4.5. Number of hydrogen nodes

This counts how many distinct nodes in the network are allocated for hydrogen production or storage. It helps compare different hydrogen deployment strategies and scenarios, offering a view into how distributed or centralized the hydrogen infrastructure is under various planning assumptions.

6.4.6. Hydrogen pipeline capacity

Hydrogen pipeline capacity is a valuable metric for comparing hydrogen usage across different design scenarios. It represents the total infrastructure required to transport hydrogen from offshore production sites, to designated landing points. This metric is particularly useful for evaluating how the offshore hydrogen integration strategies, such as modular and island based, affect infrastructure requirements. Additionally, it provides insight into how variations in electricity generation, network configuration, and weather conditions influence the system’s capacity to convert and transport surplus electricity as hydrogen.

6.4.7. Essential edges percentage

The essential edge metric measures the proportion of cables that are critical for maintaining network performance in the event of a single cable failure, also known as an N -1 contingency. To assess this, the final set of electricity cables and their capacities is taken from the model. An average demand and production scenario is then simulated, and each cable is removed one at a time to test whether the remaining network can still meet demand. If the network remains feasible without a specific cable, that cable is considered non-essential under average conditions. Cables that connect nodes directly to landing points are excluded from this analysis, as their removal would automatically isolate part of the network and render the model infeasible.

This metric is expressed as a percentage of the total number of edges, allowing for meaningful comparison between MST and Delaunay networks, despite their differing network sizes. It offers insight into the structural robustness of each configuration and helps identify potential vulnerabilities. This supports a broader evaluation of system robustness across different design strategies and demand conditions. The generation and demand values used in this analysis are based on an average wind factor of 0.45 for the North Sea (Integration Of Offshore Wind, n.d.), and average national electricity demand relative to peak levels, as discussed in part 6.3.

7. Model scenario results

In this chapter, we present the results of the graph-based flow model developed for this research. As outlined in Chapters 5 and 6, the model was run using two different edge configurations across 8 scenarios. Each scenario represents a unique combination of installed generation capacity, hydrogen integration method, and electricity demand level.

Table 13: excess electricity generation for hydrogen production in each scenario

	Excess electricity generation for hydrogen production.			
Scenarios:	High capacity Demand * 1.6 (GW)	High capacity Demand * 1.3 (GW)	Low capacity Demand * 1.3 (GW)	Low capacity Demand * 1 (GW)
1 Medium build out **Base scenario**		**97.703**		
2 Small build out				**85.685**
3 Large build out	**58.373**			
4 Small onshore				**85.685**
5 medium onshore			**46.362**	
6 large onshore	**58.373**			
7 Few islands				**85.685**
8 Many islands		**97.703**		

Table 13 presents the results of the hydrogen capacity determination discussed in Section 6.3, which informs the electrolysis capacity to be installed in each scenario. In this chapter, we will focus on three specific scenarios, while the remaining scenarios are explained in Appendix C. The first is Scenario 1: Medium Build-out, which serves as the base scenario. The second is Scenario 5: Medium Onshore, which is of particular interest due to its combination of low generation capacity and a 30 percent increase in electricity demand, leading to distinctive system behavior. The third is Scenario 7: Few Islands, which displays similar trends to the base scenario but features lower installed capacity and reduced electricity demand.

7.1. Scenario 1: Medium build out

The first scenario we will discuss is the base case: Medium Build-Out. This scenario utilizes the modular hydrogen approach, meaning that nodes identified as having excess electricity generation in the hydrogen production scenario are allocated 2, 4, or 6 GW of electrolysis capacity. The result of the hydrogen determination scenario is shown in the figure below.

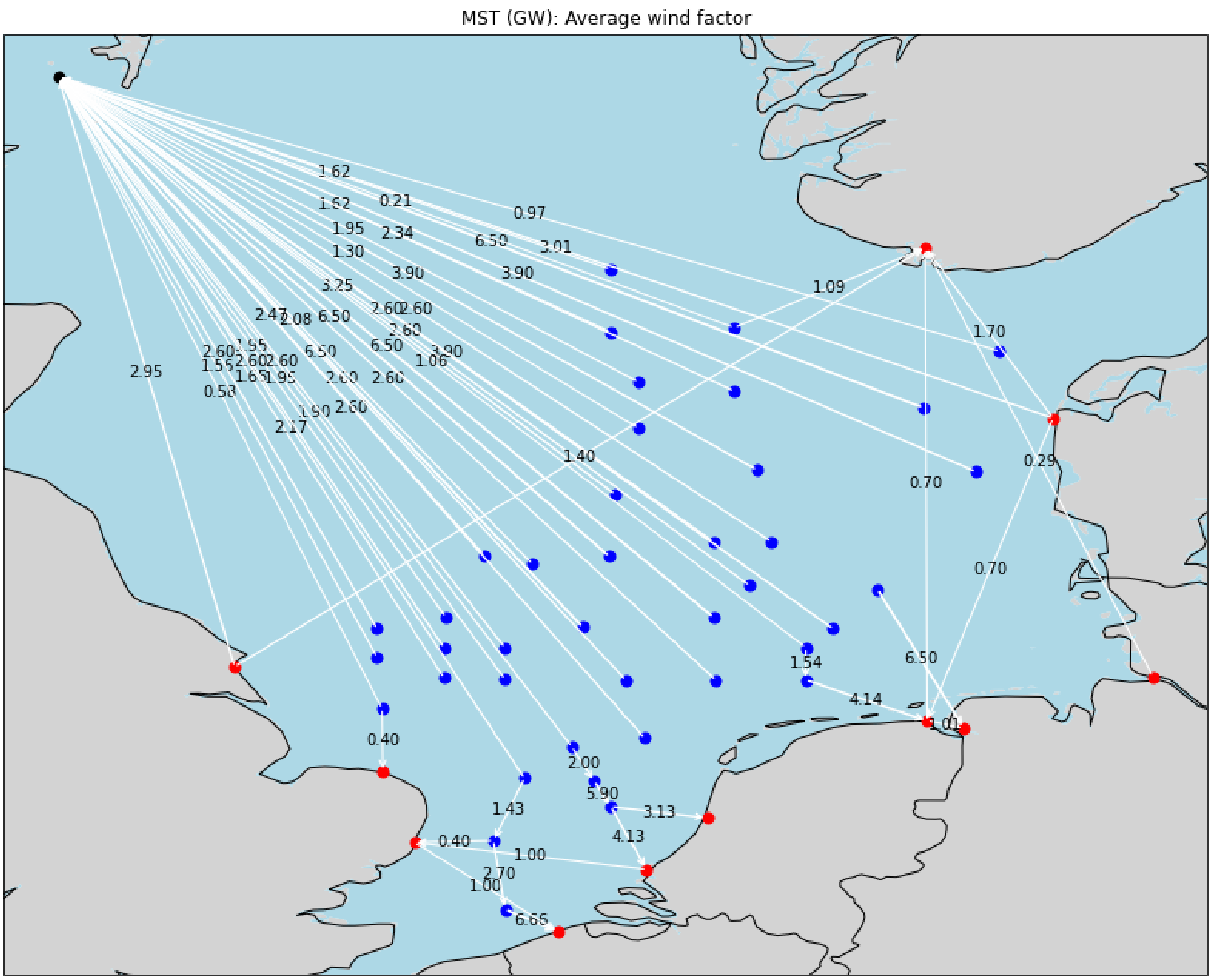

Figure 12: excess electricity production for hydrogen generation

Figure 12 shows the electricity flows throughout the model during the hydrogen determination scenario discussed in part 6.3. In this case, the total excess generation capacity is 97.703 GW. The super consumer node, located in the top left corner of Figure 12, receives this excess electricity. This node serves as an indicator of which offshore wind parks have surplus electricity available for hydrogen production. The specific hubs contributing to this excess and the corresponding flow values are detailed in Appendix B. With these hubs now identified, electrolysis capacity can be assigned to the nodes accordingly.

Table 14: Hydrogen generation capacity and hubs

Hydrogen Capacity (GW)	**# of Parks**	**Installed hydrogen capacity (GW)**
2	10	20
4	13	52
6	4	24
Total	27	96

Table 14 provides an overview of the total number of hubs allocated electrolysis capacities of 2, 4, or 6 GW in this scenario. As shown, various nodes are suitable for each capacity level. In total, 27 hydrogen production sites are identified, with a combined electrolysis capacity of 96 GW. This meets the objective that the total installed capacity should reflect the excess electricity observed in the hydrogen determination scenario. The specific hubs and their assigned electrolysis capacities can be found in Appendix B. With the electrolysis capacity now allocated, we can proceed to run the scenarios for edge capacity determination, as outlined in Section 6.2.3. The first step involves determining the optimization factor for reducing the Delaunay network, discussed in Section 6.2.2. When the optimization factor is set to 50, we obtain the shortest possible network, measuring 4003 km. Reducing the factor to 2.6 results in a network length of 6048 km. This satisfies the 1.5 times size ratio criterion mentioned in Section 6.2.2 concerning the Delaunay triangulation method.

Table 15: Scenario model results

	Delaunay	MST	differences
Diameter	1166 km	1353 km	+16.0%
Total length	6048 km	4830 km	-20.1%
Total capacity	1053.552 GW	1119.662 GW	+ 6.3%
Hydrogen capacity	183.874 GW		N/A
Number of essential edges	5	7	2
Essential edges percentage	9.80 %	17.07 %	7.27%

Table 15 presents the model results based on the metrics introduced in section 6.4. As expected, the Delaunay network has a smaller diameter but a longer total cable length compared to the Minimum Spanning Tree network. It also requires less overall transmission capacity. The Delaunay network has a significantly lower percentage of essential edges, which are cables critical for maintaining network operation under a single cable failure. This lower percentage indicates higher redundancy. In contrast, the Minimum Spanning Tree network's higher proportion of essential edges reflects its more minimal and less redundant design, making it more vulnerable to outages.

Figure 13 displays the final cable capacities for both the Delaunay and Minimum Spanning Tree networks in the top two images. Below these, the locations of essential edges for each network type are shown. These critical cables are primarily concentrated along key corridors from Belgium heading north, as well as in the region east of the United Kingdom. The identification of essential edges is based on simulations using average demand and average weather conditions, ensuring the analysis reflects typical operating scenarios. Notably, the Minimum Spanning Tree network includes an essential cable connecting Norway to the rest of the system. Since Norway relies on this single cable, a failure would isolate it from the network, highlighting the need for an additional connection to improve robustness. Overall, these results emphasize the trade-offs between network efficiency, cost, and reliability, with the Delaunay network offering greater robustness at the cost of increased cable length.

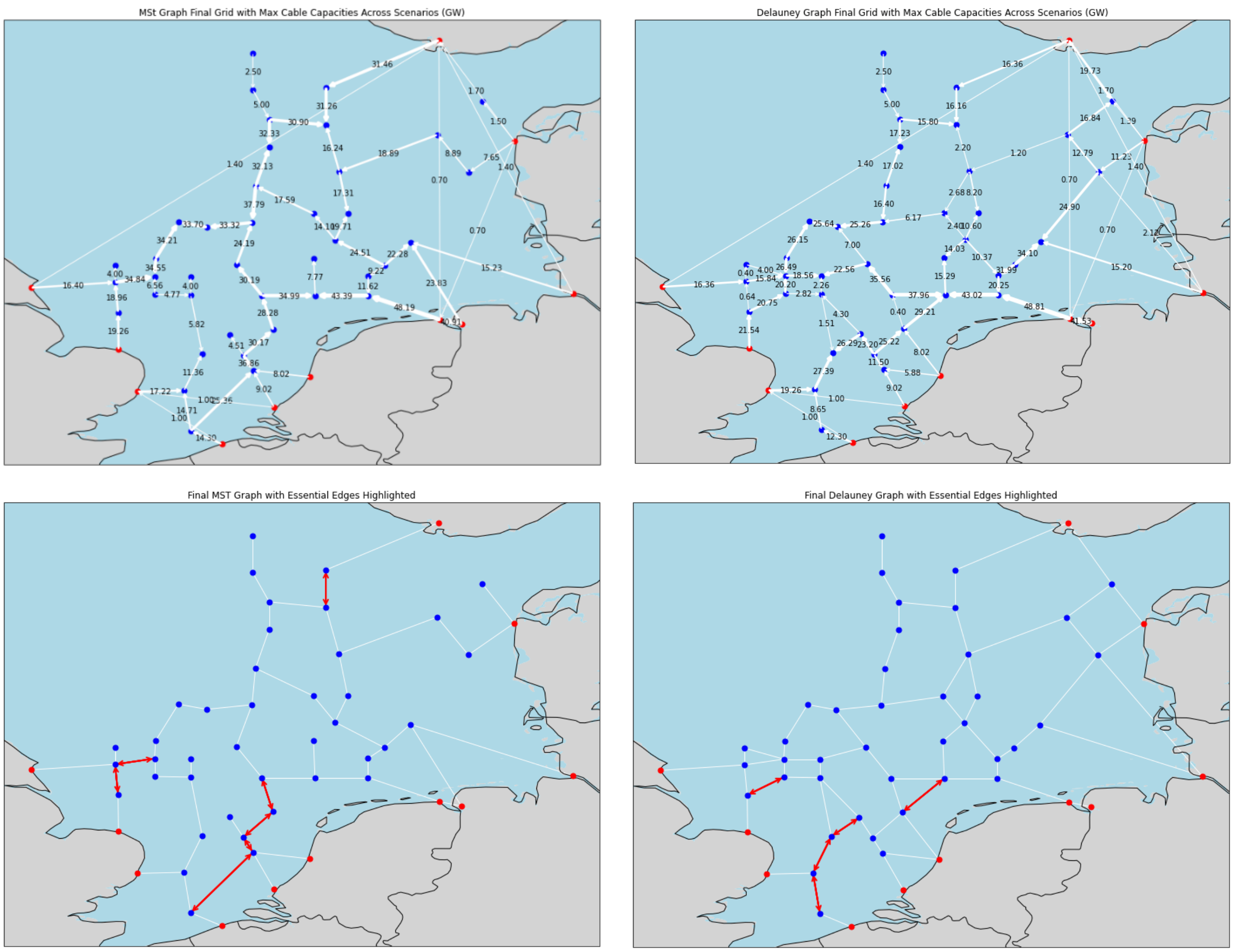

Figure 13: Overview of final cable capacities in the Minimum Spanning Tree and Delaunay models (top), alongside the spatial distribution of essential edges critical to network robustness (bottom).

7.2. Scenario 5: Medium onshore

The next scenario examined is the onshore hydrogen production case. In this scenario, the total hydrogen electrolysis capacity is evenly distributed among the landing nodes, increasing the electricity demand at each landing point accordingly. The hydrogen capacity allocation is based on the excess electricity generation identified in the hydrogen determination scenario. The result of the hydrogen determination scenario is shown in the figure below.

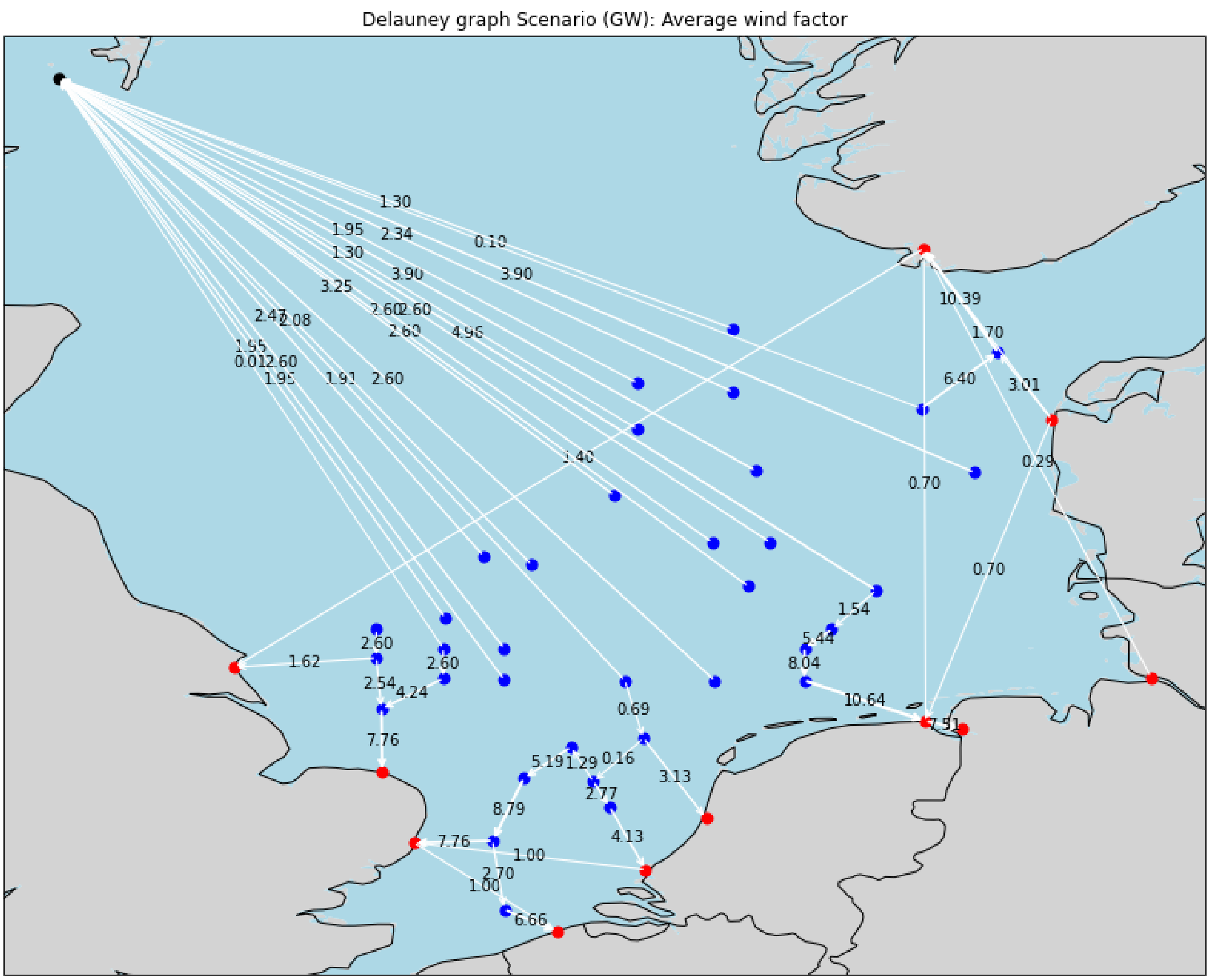

Figure 14: excess electricity production for hydrogen generation

Figure 14 shows the electricity flows throughout the model during the onshore hydrogen production scenario. In this case, the total excess generation capacity is 46.362 GW. This excess electricity is evenly distributed among the eleven landing points, increasing the electricity demand at each landing site. As a result, each landing point is allocated an additional 4.210 GW of electrolysis capacity to reflect this increased demand.

Table 16: Landing points and electrolysis capacity

Country	Name	Hydrogen generation capacity (GW)
Belgium	Wenduine landing	4.210
Denmark	Ferring landing	4.210
Germany	Emden landing	4.210
Germany	Büttel-Hamburg landing	4.210
Netherlands	Tweede maasvlakte landing	4.210
Netherlands	Ijmuiden Tata Steel landing	4.210
Netherlands	Eemshaven NorNed cable landing	4.210
United Kingdom	Cromer landing	4.210
United Kingdom	Leiston landing	4.210
United Kingdom	Ulrome landing	4.210
Norway	Feda landing	4.210

The first step is to determine the optimization factor for the Delaunay network. When set to 50, the model yields the shortest network length of 3741 km. Adjusting the optimization factor to 2.2 produces a longer network measuring 5687 km. This meets the 1.5 times size difference criterion discussed in Section 6.2.2 regarding the Delaunay triangulation method.

Table 17: scenario model results

	Delaunay	MST	differences
Diameter	1389 km	1318 km	-5.1%
Total length	5633 km	4492 km	-20.3%
Total capacity	684.475 GW	713.258 GW	+ 4.2%
Number of essential edges	45	36	9
Essential edges percentage	100 %	100 %	0 %

As shown in Table 17, the Delaunay network has a slightly larger diameter and longer total cable length compared to the Minimum Spanning Tree network. This higher diameter contradicts the estimate made in section 6.4. The Delaunay network also requires somewhat less total transmission capacity. Both network designs are fully vulnerable to edge failures, as indicated by 100% essential edges, meaning that every cable is critical to maintaining network functionality under the average demand and weather conditions used in this analysis.

This occurs because the increase in demand, without a corresponding rise in installed generation capacity, causes the network to operate more like a traditional park-to-country system rather than an interconnected grid facilitating electricity exchange between countries. Simply said: there is not enough electricity generated for transport between countries. As a result, the required transmission capacities decrease significantly compared to the previous scenario, since cross-country electricity flows are reduced across various weather conditions.

This effect is illustrated in Figure 15, where the Büttel-Hamburg node shows minimal capacity connections to the rest of the network. This node is located in the middle right of the figure, the rightmost landing point in Germany. In fact, in the Delaunay network, this node is disconnected from other nodes within Germany's maritime territory, leading to a larger network diameter compared to the MST network, where this connection is maintained.

In summary, the complete reliance on every edge in this scenario reflects the limited installed generation capacity relative to demand. As a result, the network operates more like isolated park-to-country connections rather than an interconnected system with significant electricity exchange between countries. This is because the available surplus electricity is insufficient to justify large cross-border electricity flows. The main insights into the effect of onshore hydrogen generation compared to offshore generation will be discussed in chapter 8, the discussion.

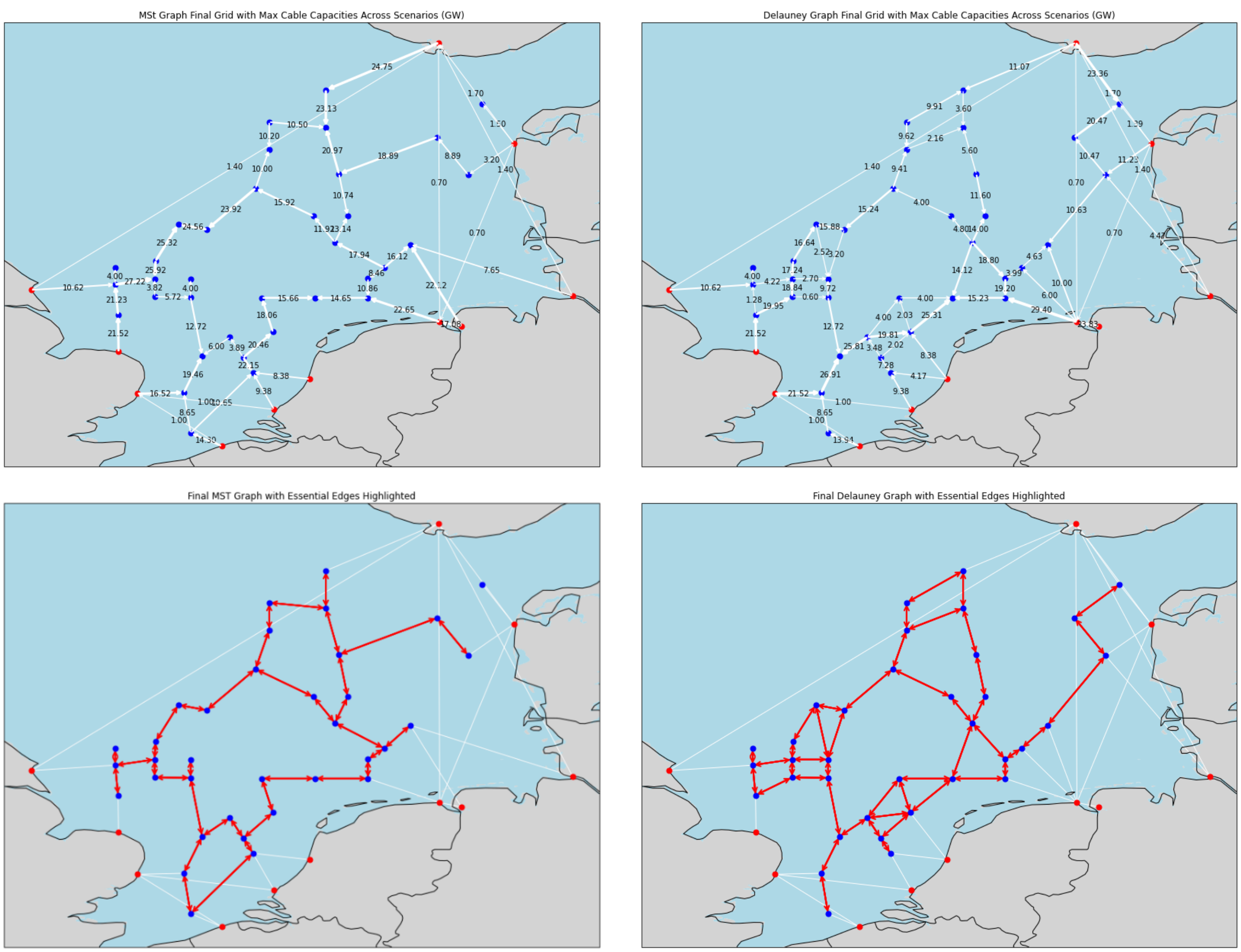

Figure 15: Overview of final cable capacities in the Minimum Spanning Tree and Delaunay models (top), alongside the spatial distribution of essential edges critical to network robustness (bottom).

7.3. Scenario 7: Few islands

In this section, we examine Scenario 7: Few Islands. This scenario applies the island-based hydrogen production approach, in which selected nodes with excess electricity generation are each assigned 6 GW of electrolysis capacity. The results of the hydrogen determination scenario are illustrated in the figure below.

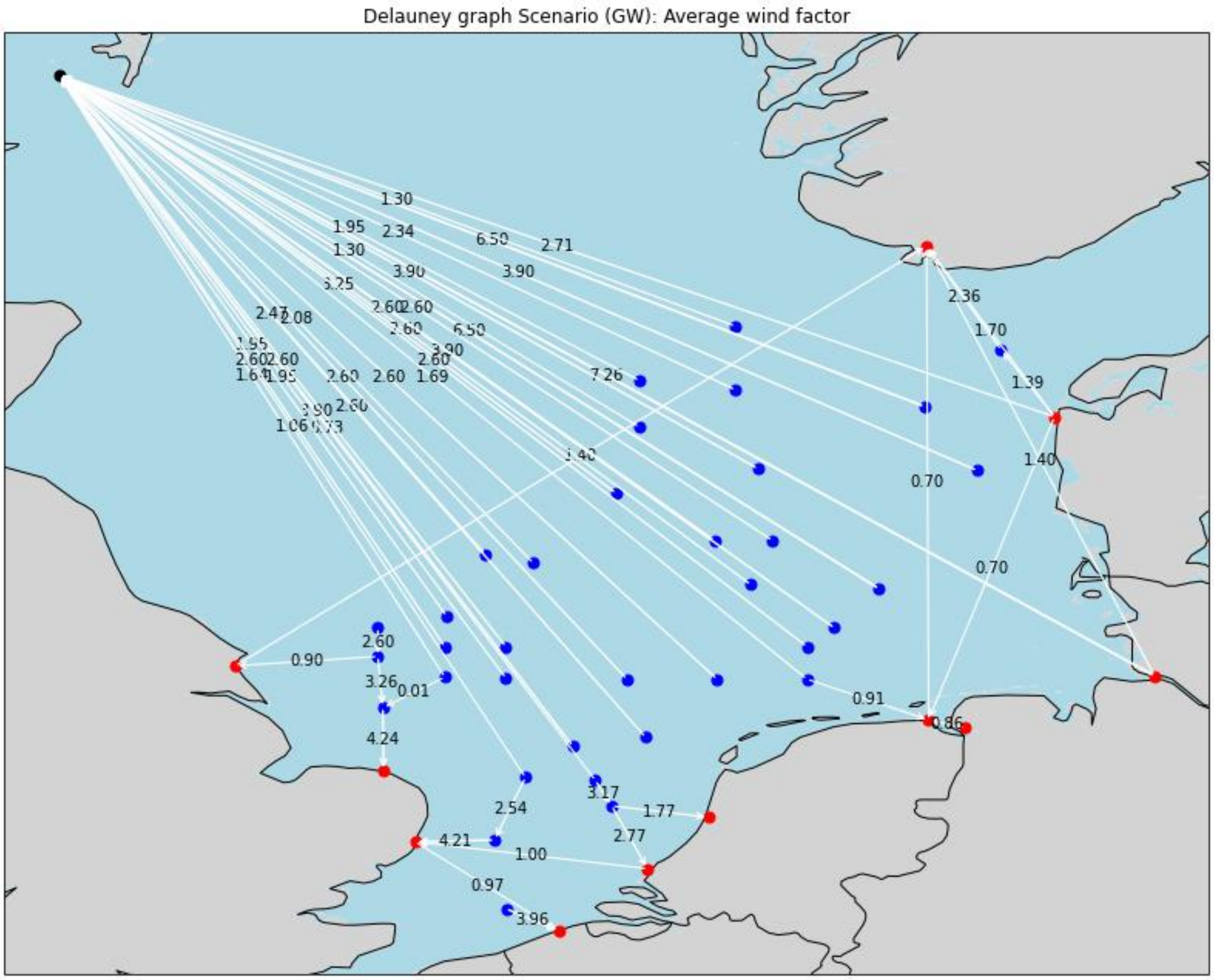

Figure 16: excess electricity production for hydrogen generation

Figure 16 shows the electricity flows throughout the model during the hydrogen determination scenario. In this case, the total excess electricity available for hydrogen production is 85.685 GW. Based on the generation patterns observed, specific offshore wind parks are selected to host electrolysis hubs of 6 GW each. These locations form the basis for assigning hydrogen production capacity.

Table 18: Hydrogen generation capacity and hubs

Hydrogen Capacity per island (GW)	**# of Parks**	**Installed hydrogen capacity (GW)**
6	14	84

As presented in Table 18, a total of 14 hubs have been identified as suitable for the allocation of 6 GW electrolysis capacity, leading to a combined hydrogen production capacity of 84 GW. The specific hubs selected for this capacity are listed in Appendix B. With these sites now designated for hydrogen production, the model proceeds to the next step: determining the required cable capacities through network scenario analysis.

First, we determine the optimization factor for the Delaunay network. Increasing the factor to 50 yields the shortest possible network length of 3741 km. Reducing the factor to 2.5 results in a network length of 5579 km, which satisfies the 1.5 times size difference criterion described in Section 6.2.2 concerning the Delaunay triangulation method.

Table 19: scenario model results

	Delaunay	MST	differences
Diameter	1197 km	1318 km	+15.3%
Total length	5579 km	4462 km	-19.8%
Total capacity	762.208 GW	789.121 GW	+ 4.3%
Hydrogen capacity	139.303 GW		N/A
Number of essential edges	4	5	1
Essential edges percentage	8.51 %	13.89 %	5.38 %

Table 19 summarizes the model results. As expected, the Delaunay network features a lower diameter but a longer total cable length compared to the Minimum Spanning Tree network. It also requires slightly less total transmission capacity and exhibits greater robustness, indicated by a lower percentage of essential edges.

Figure 17 displays the essential edges for both network types, which are mainly concentrated along key corridors from Belgium northward and in the region east of the United Kingdom. Consistent with scenario 1, the MST network includes an essential cable connecting Norway to the rest of the network. This highlights the ongoing need for an additional connection to prevent Norway from becoming isolated in the event of a cable failure.

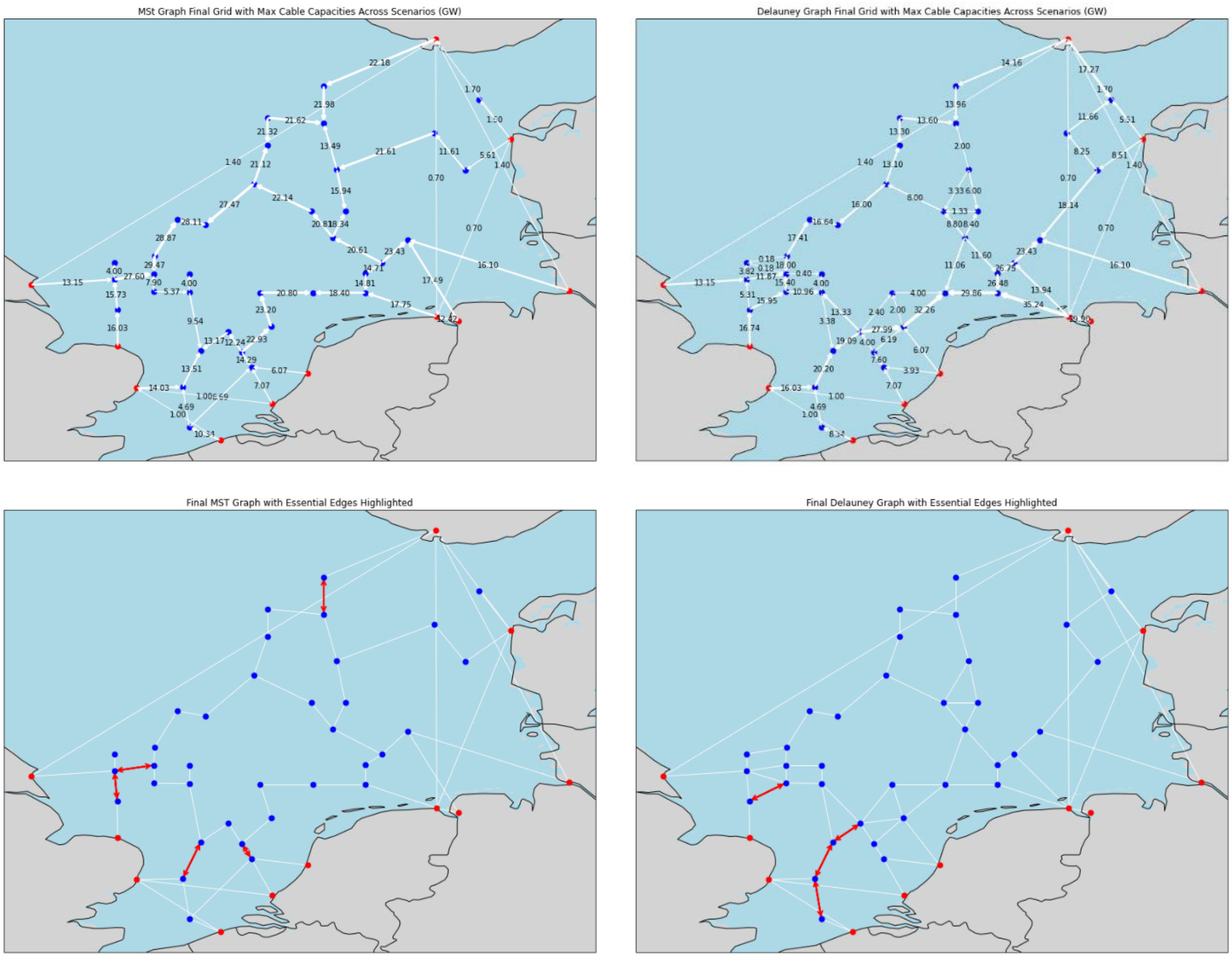

Figure 17: Overview of final cable capacities in the Minimum Spanning Tree and Delaunay models (top), alongside the spatial distribution of essential edges critical to network robustness (bottom).

7.4. Model results overview

Scenarios 1, 5, and 7 have been discussed in detail in the preceding sections. The results of the remaining scenarios are explained more extensively in Appendix C. With all eight scenarios now complete, we can begin to visualize and interpret the outcomes. Table 20 presents the key network performance metrics for each scenario, including total cable length, total transmission capacity, network diameter, and the number of essential edges. Table 21 summarizes the hydrogen-related metrics, including installed electrolysis capacity, the number of hydrogen production nodes, and the total pipeline capacity required. These tables serve as the foundation for the discussion and analysis in the following chapters.

Table 20: all scenarios model results

	Total network length (km)		Total network cable capacity (GW)		Network Diameter (km)		Essential edges percentage (%)	
Scenarios:	Delaunay	MST	Delaunay	MST	Delaunay	MST	Delaunay	MST
1 Medium build out **Base scenario**	6048	4830	1053.5	1119.6	1166	1353	9.80	17.07
2 Small build out	5687	4492	771.3	804.8	1197	1318	8.51	13.89
3 Large build out	6022	4830	1020.6	892.8	1173	1353	100	100
4 Small onshore	5687	4492	892.2	908.8	1235	1318	6.67	8.33
5 medium onshore	5633	4492	684.5	713.3	1389	1318	100	100
6 large onshore	6022	4830	1050.5	916.9	1173	1353	100	100
7 Few islands	5579	4492	762.2	789.1	1197	1318	8.51	13.89
8 Many islands	6048	4830	1053.4	1112.1	1166	1353	9.80	17.07

Table 21: all scenarios model hydrogen results

Hydrogen			
Scenarios:	Installed capacity (GW)	Number of nodes	Needed pipeline capacity (GW)
1 Medium build out **Base scenario**	96	27	183.9
2 Small build out	86	27	223.6
3 Large build out	60	17	115.1
4 Small onshore	85.685	11	N/A
5 medium onshore	46.362	11	N/A
6 large onshore	58.373	11	N/A
7 Few islands	84	14	139.3
8 Many islands	96	16	154.6

8. Discussion

In this chapter we will answer the last two sub questions, discuss the societal contributions of this research, possible policy recommendations for the creation of a North Sea energy system, and finally we will discuss the limitations of this research.

> *What is the effect of the hydrogen production methods and varying electricity demand on the total network length, total network cable capacity, Network diameter and hydrogen generation?*
>
> *What are the physical vulnerabilities of the hub and spoke network?*

We will answer these two questions together by firstly looking into the differences between the Delaunay and MST network, secondly by looking at the differences between the different capacity goals, thirdly we will look at the effects of different hydrogen inclusion methods, fourthly we will look at the effects of changing electricity demand.

8.1. MST VS Delaunay

A number of important distinctions become apparent when analyzing the differences between the Delaunay and MST networks. As expected, the **Delaunay networks are consistently longer**, with their total network length averaging about 1.25 times that of the MST networks. We already discussed and predicted this in part 6.2.2. as the MST network minimizes total edge length, whereas Delaunay network prioritizes spatial completeness and connection redundancy. The key thing about the length differences is how the longer Delaunay network uses this additional length compared to the MST network.

In most scenarios (1, 2, 4, 5, 7, and 8), the **Delaunay network exhibits a slightly lower total cable capacity** than the MST, with differences generally in the range of 4% to 7%. However, in scenarios 3 and 6, which combine high demand and large capacity objectives, the Delaunay network requires approximately 14% more installed capacity than the MST. This reversal likely results from the model's need to handle very large and variable electricity flows during various wind scenarios because of the high demand. We can also see this in the essential edge percentage of the networks in scenario 3 and 6. In both the percentage is 100%. We can therefore make up that the Delaunay network splits up the extremely large electricity flows over multiple paths in the various weather scenarios. While the MST network is forced to bundle its capacity over the existing edges. Leading to the situation that the total network capacity of the Delaunay network gets larger than the MST network when the electricity demand rises by 60%.

In all scenarios where the percentage of essential edges, defined as edges whose failure would prevent the network from meeting demand under average operation, is below 100 percent, the **Delaunay network demonstrates greater robustness** compared to the Minimum Spanning Tree network. Specifically, it outperforms the MST by 1.66 percent to 7.27 percent, a significant improvement especially considering that the Delaunay network achieves this enhanced robustness while using less total installed electricity cable capacity. This clearly indicates that a more meshed network topology offers greater robustness, making it the preferred choice from a vulnerability and reliability perspective.

As expected, the **Delaunay network generally exhibits a smaller network diameter** than the MST, meaning it offers more direct paths between nodes and stronger overall network connectivity. The only exception is Scenario 5, where the Delaunay network has a slightly larger diameter; this anomaly has been further addressed in the part 7.2., about the Medium onshore scenario results. When leaving this anomaly out we can see that generally the Delaunay network has a diameter of around 13% smaller than the MST network.

8.2. Effects of electricity demand

Now that we discussed the differences between the Delaunay and MST network we will look into the effects of changing the electricity demand. The first insight is that In scenarios with **a demand increase of 60% and high installed capacity, every edge in both MST and Delaunay networks becomes essential** for system operation. This is also true for the combination of 30% demand increase and the lower installed capacity. The reason for this is the lower installed capacity in these scenarios compared to scenarios with the same generation capacity and hydrogen inclusion method. This seems counterintuitive. Why does the **total electricity cable capacity decrease when electricity demand increases.** This is mainly because when electricity demand increases while the installed capacity stays the same, an interesting situation arises. The electricity generated in the various weather scenarios is not sufficient to satisfy the whole system demand, except for the full wind weather scenario. This means that most of the time there is **not enough excess electricity in the network to satisfy increases in demand**. The model will therefore start to function as an electricity generation model instead of an electricity transmission-model. For additional clarification we will compare Scenario 4 and 5. Both scenarios have the same installed capacity (low capacity goals) and have the same hydrogen inclusion method (onshore). As we can see in table 22, there is only an electricity surplus in the full wind scenario in scenario 5. While in scenario 4 with the lower demand there is excess electricity in 3 out of the 5 weather scenarios.

Table 22: Electricity excess or shortage in various weather scenarios for scenario 4 and 5

	Is there excess electricity in the weather scenario?				
	Full wind	West - East	East - West	South - North	North - South
Scenario 4 0% demand increase	Yes 48.617 Excess	No 35.556 GW Shortage	Yes 37.3475 GW Excess	Yes 27.693 GW Excess	No 45.877 GW Shortage
Scenario 5 30% demand increase	Yes 28.236 GW Excess	No 95.317 GW Shortage	No 22.387 GW Shortage	No 32.067 GW Shortage	No 105.638 GW Shortage

Because there is not enough electricity generation to satisfy demand in the higher demand scenario 5, there is no need for the model to create cables with large amounts of capacity. This also leads to the following insight: because the network has started to work more as a generation model instead of an electricity transmission model, the **essential edge percentage will become 100% in the case that demand rises** and installed capacity stays the same. Because the model will change its main approach it will become more vulnerable to edge failure. As the total edge capacity decreases, this will reduce the ability of the model to absorb cable failures and reallocate the capacity. Concludingly the model will start to function similarly to the current situation with existing wind parks, which are only connected to shore and not to each other, as there is no reason for transporting this electricity as there is not enough excess electricity. Additionally there will be **less hydrogen production capacity if electricity demand increases**. Because more electricity is used to meet demand directly, less electricity is available for hydrogen generation across different weather scenarios

We have discovered that with the various weather scenarios there is not a lot of spare generation capacity for hydrogen generation in high demand scenarios. However, we assumed that the model will operate in a no solar situation at night or in the winter. Considering that the countries around the North Sea have significant installed solar capacity, it follows that when both solar and wind generation are high, a substantial surplus of electricity will be available for hydrogen production. Thus, we can say something about the possible generation pattern of hydrogen in the future energy system of the North Sea. Namely, **Hydrogen production will follow solar generation patterns**, as the system will not reliably have enough excess electricity from wind power for hydrogen generation. In times when there is abundant sun and wind, there is a significant amount of excess electricity. However, when solar energy is not available, the system must cover the base demand across the North Sea region. This finding is in line with the scientific literature we discussed in chapter 2. This also means that future hydrogen generation and storage should focus mostly on seasonal differences such as the large generation of solar power in the summer. Then, this large excess of electricity in the summer period can then be converted into hydrogen and stored. This allows it to be used in the winter to generate electricity once again.

8.3. Capacity goal differences

In this part we will look at the effects of different installed capacities. Scenarios 1, 5, and 8 all share the same electricity demand level (30% increase), yet they show markedly different system behaviors. Scenario 5 has a much lower total system capacity compared to Scenarios 1 and 8. This difference is due to the low installed generation capacity in Scenario 5, which causes the system to function primarily as a local generation model, rather than a transmission-oriented model between countries. In this situation, there simply is not enough electricity being produced to require large transfers between regions. As a result, less cable capacity is needed overall. This shift in system behavior is also evident in the essential edge percentage: Scenario 5 shows 100% essential edges, indicating that this system is very vulnerable in the case of cable failure. In contrast, Scenarios 1 and 8 have an essential edge percentage of around 9 to 17%, reflecting the availability of surplus generation and thus the need for more cable capacity to facilitate the transfer of electricity. This highlights a key insight: the impact of different capacity goals (low vs. high installed generation) is highly dependent on the system's electricity demand. Therefore, **coordination between installed capacity and expected demand is critical** for effective infrastructure planning and system robustness.

8.4. Hydrogen layout implications

Available hydrogen capacity is strongly influenced by changes in electricity demand and installed generation capacity. **As electricity demand increases, less electricity is available for hydrogen production**. This effect is consistent across both low and high capacity configurations, where an increase in demand, either from a factor of 1.0 to 1.3 or from 1.3 to 1.6, leads to a reduction of approximately 39 GW in installed hydrogen capacity. A closer comparison of Scenarios 2, 4, and 7, which all share the same demand level and network layout but differ in their hydrogen strategies, highlights that the **onshore hydrogen configuration has a higher total system capacity** than either offshore hydrogen designs. Specifically, the onshore approach results in roughly 11% more system capacity. This is mainly because the system is designed to transmit electricity to shore for hydrogen production, which requires higher-capacity cables. As a result, the **onshore hydrogen networks have greater robustness compared to the offshore networks**. Moreover, the onshore scenario avoids the need for dedicated offshore hydrogen infrastructure. With a network which is 11% larger, the system is capable of transferring all the hydrogen production onshore, while also offering improved reliability.

Hydrogen is only produced under specific weather conditions. We touched upon this in the previous part about electricity demand. The comparison between Scenarios 4 and 5 illustrates this clearly. In Scenario 5, where demand is significantly higher (a 60% increase), there is virtually no excess electricity available for hydrogen production. As a result, hydrogen is only generated during the full wind weather scenario. In contrast, Scenario 4 shows that hydrogen can be produced in three out of five weather scenarios. **Since electricity is primarily used to meet base demand in most conditions, the influence of different hydrogen production strategies diminishes.** This effect is especially pronounced in high-demand cases like Scenario 5, where hydrogen is only generated in a full wind weather scenario. Consequently, the integration of additional renewable sources will significantly influence hydrogen generation patterns. This also supports the finding that Hydrogen generation patterns will follow generation patterns of other renewable energy sources, such as solar energy.

Finally, the analysis shows that **the difference between a modular hydrogen hub approach (using 2, 4, or 6 GW hubs) and an island-based approach with a single 6 GW hub is negligible** in terms of overall system performance. This will be demonstrated by comparing scenarios that share the same electricity demand but differ only in their hydrogen integration method.

Table 23: offshore hydrogen method scenario comparison

	Total network length (km)		Total network cable capacity (GW)		Network Diameter (km)		Essential edges percentage (%)	
Scenarios:	Delaunay	MST	Delaunay	MST	Delaunay	MST	Delaunay	MST
1 Medium build out **Base scenario**	6048	4830	1053.5	1119.6	1166	1353	9.80	17.07
2 Small build out	5687	4492	771.3	804.8	1197	1318	8.51	13.89
7 Few islands	5579	4492	762.2	789.1	1197	1318	8.51	13.89
8 Many islands	6048	4830	1053.4	1112.1	1166	1353	9.80	17.07

Scenarios 1 and 8 both feature a 30% increase in electricity demand combined with high installed generation capacity, while Scenarios 2 and 7 reflect stagnant demand and low installed capacity. As shown in Table 23, the differences in system performance between these scenarios are minimal. Key indicators such as network length, network diameter, and essential edge percentage are identical across these cases. Even the difference in total installed capacity is marginal, varying by only around 1%. This leads to the conclusion that the **decision between using offshore hydrogen islands or modular hydrogen production units is not driven by system performance, but rather by economic, environmental, and political considerations.** Since both approaches perform similarly in the model, we recommend adopting the modular hydrogen production strategy if offshore hydrogen generation is pursued. Modular units offer faster construction, greater flexibility in siting, and significantly reduced environmental impact, making them a more practical and scalable option for offshore implementation.

8.5. Societal contribution

This research provides valuable insights into the varied methods of hydrogen integration, electricity demand levels, and network capacities in the North Sea energy system. By illuminating how these different factors influence system design and performance, it equips policymakers with a more nuanced understanding that goes beyond one-size-fits-all solutions. This deeper knowledge enables more informed and flexible decision-making, helping to optimize infrastructure investments and reduce overall system costs. Furthermore, clarifying the preferred hydrogen production locations and their implications supports the strategic development of the carbon-neutral hydrogen sector. This, in turn, accelerates the transition to a sustainable energy future by lowering emissions and aligning infrastructure development with evolving market needs and national priorities.

8.6. Policy recommendations

To enable swift and coordinated development of a North Sea hydrogen infrastructure, a national approach offers a practical and politically feasible solution. As we discussed, the relationship between installed offshore wind capacity and electricity demand is essential for determining the required cable capacity. If electricity generation is insufficient relative to demand, there is little need for large-scale transmission infrastructure. By first developing national networks anchored to strategically chosen hubs, this approach maintains flexibility for future expansion. As the system evolves, additional interconnections can be added to enhance redundancy and reduce vulnerability without introducing unnecessary complexity during the early stages of coordination. This modular and scalable design allows governments to begin implementation while retaining the ability to adapt over time. By using this approach, initial costs are minimized, making it politically more advantageous to start development without waiting for broader international agreements.

Establishing initial hydrogen production capacity onshore provides a pragmatic and strategic entry point to the hydrogen economy. Onshore facilities are generally quicker and less complex to construct than offshore alternatives, allowing for faster deployment. They can also make immediate use of excess electricity from renewable sources such as wind and solar, helping to stabilize the power grid and avoid curtailment during periods of overproduction. This setup lays the foundation for a phased hydrogen market development strategy: initial onshore hydrogen supply helps stimulate early demand, which can then grow organically. As consumption increases and the hydrogen market matures, additional capacity, potentially offshore, can be planned based on real demand signals. This incremental, demand-responsive approach allows for learning-by-doing, reduces the risk of over investments by private companies, and ensures that long-term infrastructure development remains cost-effective and responsive to market needs.

8.7. Limitations

This study presents several areas requiring further investigation and model refinement. The first limitation we will discuss is the method of selecting the hydrogen generation capacity. In this study we have done this by using a weather factor of 0.65 and average electricity demand. This gave us a good estimate for comparing the different scenarios, however this method is not ideal. Preferably the installed hydrogen capacity should be derived through a time based model in which the model can use real time weather and demand data to estimate needed hydrogen capacity over a whole year. In such a time based model it will also become possible to estimate total needed hydrogen storage capacity.

Secondly, the system's reliance on surplus electricity for hydrogen production introduces significant sensitivity to fluctuations in electricity demand. The current model was designed primarily to estimate required cable capacities under various hydrogen integration strategies and is therefore based on worst-case (winter) conditions and peak demand scenarios. This modeling approach, while useful for conservative planning, may not accurately reflect the broader seasonal dynamics of energy availability and demand. Specifically, in the model scenarios where electricity demand increases more than the installed capacity, hydrogen production occurs only under full wind conditions. The model uses peak electricity demand as the baseline for calculating both energy flows and hydrogen generation, while in reality, average electricity demand is considerably lower. This discrepancy suggests that hydrogen generation potential may be underestimated in the model, particularly during periods of moderate demand and significant solar generation, which primarily is the case during the summer periods. To gain a more accurate understanding of the system's operational performance and hydrogen production potential, it is recommended to develop a time-resolved simulation model. Such a model should capture hourly fluctuations in both demand and renewable generation, particularly from solar sources, and would allow for the identification of surplus electricity windows suitable for hydrogen production and storage. This would enable a more nuanced and realistic assessment of system performance across seasonal and daily cycles.

Thirdly, the hydrogen network topology was modeled as a minimum spanning tree (MST), this was done to facilitate comparison across different weather scenarios and design configurations. Nonetheless, practical offshore hydrogen infrastructure is expected to exhibit a more meshed network structure to enhance system robustness and operational flexibility. In future research this should be addressed and integrated.

Fourthly, onshore interconnection capacity inside and between nations was not included in the current model, primarily due to constraints in time and data availability. Comprehensive information regarding the location, capacity, and length of existing onshore transmission infrastructure is often difficult to obtain. Moreover, incorporating existing interconnection routes between landing points under the assumption of unlimited internal cable capacity would have led the model to favor these pathways by default, since they would be treated as having no associated infrastructure costs. This could have biased the optimization results. Therefore, we recommend that future research explicitly integrates both offshore and onshore transmission infrastructure to enable identification of potential bottlenecks and to assess the feasibility of major energy transmission corridors across the region.

Lastly, this research concentrated exclusively on design variations without addressing the economic implications associated with the development of offshore wind parks and hydrogen production facilities. Because of the complexity and diversity of the cost components involved, such as infrastructure development, modular hydrogen hubs, onshore hydrogen production facilities, and transmission cabling, a full economic analysis was not included in this study. However, obtaining a clear and detailed understanding of these costs is essential for supporting future decision-making and for ensuring that deployment strategies are both effective and economically sustainable.

9. Conclusion

in this final chapter we will answer the main research question, go into the scientific contribution of this research, and finally address areas of future scientific research.

9.1. Main research question

In this research we looked at the following 5 sub research questions:

1. *What are the current goals and plans of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom regarding offshore wind power generation in the North Sea?*
2. *In which ways can hydrogen production be included into the North Sea hub and spoke energy system?*
3. *What are the different implementation scenarios of the hub and spoke energy system?*
4. *What is the effect of the hydrogen production methods and varying electricity demand on the total network length, total network cable capacity, Network diameter and hydrogen generation?*
5. *What are the physical vulnerabilities of the hub and spoke network?*

We started this research with sub question 1 and 2, these questions gave us insight into what the future energy system in the North sea could look like and all the different design variations. Then we continued with sub question 3, with which we created 8 scenarios that covered the uncertainties and possible designs that we found. After creating the model we could answer the final sub questions 4 and 5 by means of the model and its results. This has led us back to the main research question:

What are the possible structural configurations of the hub and spoke energy system in the North Sea, and how are they influenced by changes in capacity goals, electricity demand and hydrogen inclusion methods?

This research explored the possible configurations of the hub and spoke system for electricity and hydrogen production in the North Sea, considering the diverse goals of neighboring countries and the integration of emerging technologies like offshore hydrogen production. The findings highlight that the future energy system in the North Sea is not defined by a single optimal design but rather by a range of viable configurations, shaped by policy priorities, demand projections, and robustness requirements.

When comparing offshore modular hydrogen units with island-based electrolysis systems, the results demonstrate that there is no significant difference in network performance between the two. Scenarios with similar demand and different hydrogen integration show negligible variance in the network metrics. There are significant differences between onshore and offshore hydrogen production. Onshore hydrogen production requires about 11% more cable capacity, which also makes it less vulnerable to cable failures. Furthermore, onshore hydrogen production doesn't require other infrastructure investments, such as compressor stations, offshore pipelines, which are necessary for offshore hydrogen.

The design of the North Sea's hub and spoke energy system will be heavily influenced by future electricity demand. If electricity demand rises significantly, surplus power for hydrogen production will become scarce under most weather conditions. This implies that hydrogen generation will mirror the intermittent nature of other renewables like solar power. Additionally, higher electricity demand would reduce the need for extensive cross border cable infrastructure, as less excess electricity would be available to transmit across the network. In summary, there are two main scenarios regarding future demand and network behavior. If electricity demand remains stable or grows in line with installed capacity, the system will be able to supply power reliably to the surrounding North Sea countries. However, if demand outpaces capacity growth, the system will resemble a more traditional generation model, reducing the necessity large amounts of interconnection capacity.

Our analysis explored two fundamentally different strategies for designing the North Sea transmission network: the more meshed Delaunay triangulation method and the minimalist Minimum Spanning Tree (MST) approach. The Delaunay configuration results in a more extensive network with longer total cable length but requires less overall installed capacity than the MST alternative. It also offers better robustness, as its interconnected structure allows for better rerouting of electricity in the event of cable failures, increasing system robustness. This trade-off between minimizing cost drivers like network length and enhancing the network's robustness highlights a core complexity in designing the future North Sea energy system.

In conclusion, this study finds that there is no single optimal configuration for the North Sea's hub and spoke system. Instead, a spectrum of viable network designs emerges, each shaped by policy decisions, technological preferences, and future demand trajectories. The analysis underscores the need to balance technical performance with political feasibility, particularly when integrating international cooperation, hydrogen production strategies, and robustness considerations. These findings provide a valuable foundation for guiding future planning and development of the North Sea energy system in a way that is adaptable to diverse national priorities and evolving energy landscapes.

9.2. Scientific contribution

This research advances scientific understanding of energy system design in the North Sea by addressing several key knowledge gaps identified in the literature. One major contribution lies in clarifying the uncertainty surrounding the future location of green hydrogen production. As highlighted in the literature review in Chapter Two, there is significant variation in existing studies regarding the preferred location for hydrogen production. Some sources advocate for onshore production (Gea-Bermúdez et al., 2023; Bødal et al., 2024), others favor offshore alternatives (Glaum et al., 2024), while some express no clear preference (North Sea Wind Power Hub, 2024a). While earlier studies tend to lean toward one option or the other, this research offers a systematic comparison of both. It demonstrates that although offshore hydrogen production can reduce the required cable capacity, onshore production improves network robustness and eliminates the need for additional offshore infrastructure, such as pipelines and compressor stations.

Additionally, this study addresses the second key knowledge gap identified in Section 2.4 by combining the evolving and highly ambitious offshore wind capacity targets of North Sea countries with the intended dual role of the hub and spoke system in electricity generation and cross-border transmission. Although the North Sea Wind Power Hub (2024b) projects that 33 percent of all new transmission capacity by 2050 will support cross-border exchange, the implications of this dual role for overall system design have not been thoroughly explored in the scientific literature. This research fills that gap by showing how the relationship between electricity demand and installed capacity fundamentally influences system design, particularly in shaping the need for future transmission infrastructure.

Furthermore, this study addresses the significant variation in model inputs and assumptions observed in previous research. Studies such as those by Durakovic et al. (2022), Bødal et al. (2024), and Farahmand et al. (2024) often rely on a limited number of generation nodes and energy hubs, with disproportionately high offshore wind capacities assigned to each. These modeling choices differ markedly from the more distributed and moderate-scale hub configurations proposed by the North Sea Wind Power Hub organization (2024a, 2024b), making direct comparisons across studies difficult. Additionally, strict transmission capacity constraints in some models, such as those used by Durakovic et al. (2022), may bias results toward hydrogen infrastructure due to limited electricity transfer options. To provide a more consistent and systematic evaluation, this study explores a range of scenarios that vary hydrogen integration methods, electricity demand levels, and installed network capacities, offering a more robust understanding of how these factors shape system design and performance.

In summary, this research makes a meaningful contribution to the scientific understanding of integrated energy system design in the North Sea context. By addressing key gaps related to the location of green hydrogen production, the evolving role of the hub and spoke system, and the modeling assumptions used in previous studies, it offers a more comprehensive and realistic framework for future energy planning. The systematic comparison of scenarios and alignment with real-world policy targets provide general insights into system design that go beyond the specifics of any single model scenario. This research advances knowledge of how variations in hydrogen integration, electricity demand, and network capacity affect the future development and requirements of the North Sea energy system.

9.3. Future research recommendations

To further enhance the understanding and planning of the North Sea energy network, it is crucial to develop a time-based optimization model that can simulate system performance over an entire year, incorporating real demand profiles and weather fluctuations. This dynamic approach would provide much better insights into hydrogen generation patterns and more accurately determine the necessary installed capacity. Our current model indicates that hydrogen production is likely to follow solar generation patterns, primarily because in periods of low solar output, such as nighttime or winter, hydrogen generation occurs only under very windy circumstances. This interaction underscores how sensitive hydrogen production is to variations in electricity demand and renewable generation, making a comprehensive, time-resolved simulation essential for accurate future planning.

In addition to modeling improvements, there remains a significant gap in understanding the future electricity demand across the North Sea region. Accurate demand forecasts are critical for network design, capacity planning, and ensuring system robustness. Similarly, clearer projections of future hydrogen demand are needed to guide infrastructure investments and policy development. Both questions require coordinated research efforts involving governments, industry stakeholders, and academia to provide reliable data that can inform robust energy transition strategies.

In this research, a detailed economic analysis was not undertaken due to the complexity and uncertainty surrounding the many different cost components involved. These include expenses related to constructing offshore infrastructure such as hydrogen production islands and modular hubs, costs for building onshore hydrogen factories, and the installation of cables and pipelines, which vary depending on distance and capacity. Additionally electricity markets often operate on a marginal cost-based bidding system. When there is a large excess of wind electricity, prices frequently drop to zero or near zero. This market dynamic can significantly reduce incentives for private actors to develop the vast amounts of offshore wind capacity needed. Therefore, subsidies or other supportive policies could be necessary to encourage the build-out of offshore wind farms. Understanding these cost and market dynamics is essential for governments, industry, and research institutions because economics and finance play a crucial role in shaping infrastructure development and guiding policy decisions. A comprehensive understanding of these potential costs and market challenges will support more informed decision-making and help identify the most feasible and cost-effective design for the future North Sea energy system.

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Appendix

A. Selected articles literature review & hub generation determination

Table of all articles discussed in the literature review.

article	Authors	Subject area	Means of acquiring	Literature type
Determining onshore or offshore hydrogen storage for large offshore wind parks: The North Sea Wind Power Hub case	(Dute et al., 2024)	Hydrogen generation in the North Sea	Prisma search	Scientific article
Frequency Dynamics of the Northern European AC/DC Power System: A Look-Ahead Study	(Obradovic et al., 2022)	System design and specifications	Prisma search	Scientific article
North Sea Wind Power Hub Feasibility Study: Methodology for System Adequacy Design (Part I)	(Ismail et al., 2022)	System design and specifications	Prisma search	Scientific article
North Sea Wind Power Hub Feasibility Study: Methodology For Protection Design (part II)	(Zama et al., 2022)	System design and specifications	Prisma search	Scientific article
North Sea Wind Power Hub Feasibility Study: AC and DC Interconnection Comparison (Part III)	(Shinoda et al., 2022)	System design and specifications	Prisma search	Scientific article
Interconnection and generation from a North Sea power hub – A linear electricity model	(Alavirad et al., 2021	Legal and economic effects	Prisma search	Scientific article
A supra-national TSO to enhance offshore wind power development in the Baltic Sea? A legal and regulatory analysis	(Sunila et al., 2019)	Legal and economic effects	Prisma search	Scientific article
Comparative Assessment of Topologies for an Offshore Transnational Grid in the North Sea	(Chen et al., 2018)	System design and specifications	Prisma search	Scientific article
North Sea offshore network and energy storage for large scale integration of renewables	(Spro et al., 2015)	System design and specifications	Snowballing	Scientific article
Transmission expansion simulation for the European Northern Seas offshore grid	(Dedecca et al., 2017)	System design and specifications	Snowballing	Scientific article
Offshore power and hydrogen networks for Europe's North Sea	(Glaum et al., 2024)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Hydrogen for harvesting the potential of offshore wind: A North Sea case study	(Bødal et al., 2024)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Electrolysis as a flexibility resource on energy islands: The case of the North Sea	(Lüth et al., 2024)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Evaluating the offshore wind business case and green hydrogen production: A case study of a future North Sea Offshore Grid	(Farahmand et al., 2024)	Hydrogen generation in the North Sea	Snowballing	Scientific article

Going offshore or not: Where to generate hydrogen in future integrated energy systems?	(Gea-Bermúdez et al., 2023)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Powering Europe with North Sea offshore wind: The impact of hydrogen investments on grid infrastructure and power prices	(Durakovic et al., 2022).	System design and specifications	Snowballing	Scientific article
The future role of offshore renewable energy technologies in the North Sea energy system	(Santhakumar et al., 2024)	System design and specifications	Snowballing	Scientific article
Hydrogen as an energy vector	(Abdin et al., 2019)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies	(Ibrahim et al., 2022)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Feasibility of offshore wind turbines for linkage with onshore green hydrogen demands: A comparative economic analysis	(Kim et al., 2023)	Hydrogen generation in the North Sea	Snowballing	Scientific article
Grid-integrated offshore Power-to-Gas	(North Sea Wind Power Hub, 2022)	Hydrogen generation in the North Sea	Desk research	Government report
Offshore Energy Hubs: Blueprints with Offshore Electrolysis	(North Sea Wind Power Hub, 2024a)	Hydrogen generation in the North Sea	Desk research	Government report
Joint Statement on the North Seas Energy Cooperation	(North Sea Energy Cooperations, 2022)	Energy generation Targets	Desk Research/ snowballing	Government report
Pre-screening of potential environmental impacts	(North Sea Wind Power Hub, 2018)	System design and specifications	Desk Research	Government report
Cost Evaluation of North Sea Offshore Wind Post 2030	(North Sea Wind Power Hub (2019)	System design and specifications	Desk Research	Government report
Making headway towards hubs-and-spokes realisation	(North Sea Wind Power Hub, 2024b)	System design and specifications	Desk Research	Government report

Determination of all generation hubs in each country and the electricity demand for each country.

In this part we will determine the total offshore capacity of each country in the North Sea area. After this we will determine the amount of Offshore wind that is included in the hub and spoke system for each country. Additionally existing interconnection cables will be examined for inclusion in the system. And finally, the electricity demand for each country will be corrected for offshore and onshore wind generation outside of the model. These peak demands are the ones discovered in part 4.1. Additionally a weather factor will be added to the demand functions, this weather factor will show the productivity of the wind energy outside of the model in each nation. This weather factor will be the same as the factor used for each nation to calculate the cable capacities in part 6.2.

Belgium

The first country we will take a closer look at is Belgium. The existing wind farms of Belgium are located along the Dutch border and are connected with cables that only have the capacity for these wind farms. Therefore, it is not likely that these parks will be included in a future hub and spoke system. Especially when we look at the current plans of Belgium to create an energy island in their EEZ. This island will have 3 wind parks connected to it. These parks have an estimated wind capacity of 3.5GW (NedZero, 2024).

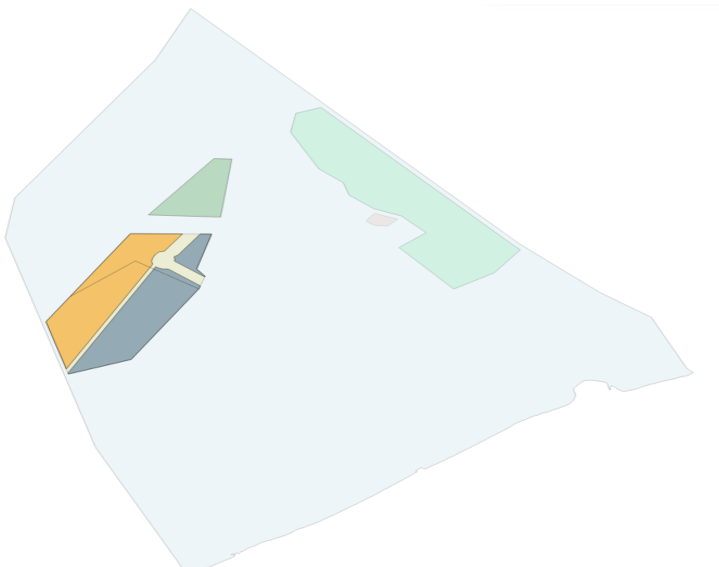

Figure A: current wind parks in the Belgian EEZ (FOD Economie, n.d.)

In figure A we see the current layout of the existing and planned offshore wind parks of Belgium. The region in the left part of the picture are the parks that will be connected to the previously mentioned energy island. When looking at the offshore wind goals of Belgium plans for an additional 2.4 GW will be needed to achieve these goals. This 2.4GW can be placed around this energy island and also connected to it. This would create an offshore energy hub of 5.9GW for Belgium. This hub will allow for transporting electricity to Belgium and elsewhere in the hub and spoke system. Furthermore, this hub is ideally suitable for hydrogen creation.

The electricity will go to Belgium at the connection point located at Wenduine. The Electricity demand for Belgium needs to be corrected for onshore wind generation and offshore wind generation which is outside of the hub and spoke system. Currently Belgium has 3.337 GW onshore wind and there is 3.1 GW offshore wind outside of the model (Statista Belgium, 2025). When we include this with the peak demand of 13.206GW we gain the following electricity demand formula for Belgium:

Wenduine landing = 13.206 * demand-factor – (3.337 + 3.1) * weather-factor

Denmark

Denmark currently has various offshore wind park developments planned. One of these locations is the Nordsoen1 area. This area has a planned capacity of 5 GW. The Thor wind park of 1 GW is located just above the Nordsoen1 area, as we can see in figure 10. We will therefore combine these two into a combined Nordsoen1 hub with a 6 GW capacity.

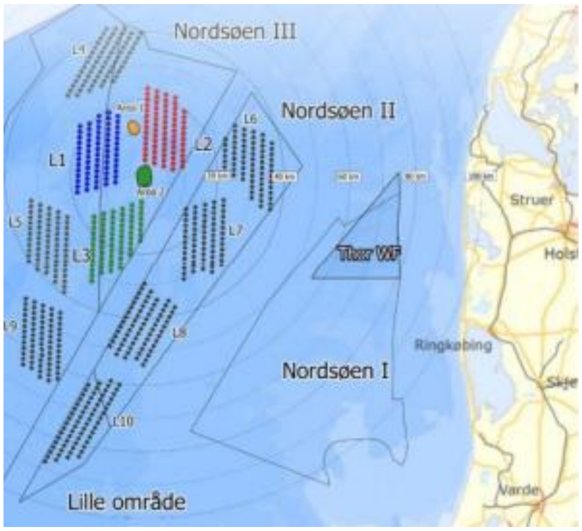

Figure B: Danish North Sea offshore wind developments (COWI & Poehler, 2022)

Additionally, we can see in figure B that Denmark intends to create the Nordsoen2&3 area. This area will have around 10 GW of connected wind power (COWI & Poehler, 2022). Additionally, this area could be used for the creation of an offshore island on which hydrogen can be created (COWI & Poehler, 2022). The 1.5GW offshore wind park Freya is located in a more remote place. This makes it not possible for this park to be combined with others for the creation of a larger hub. when we take into account the national goals

These parks which we can include in the model have a combined generation capacity of 17.5 GW. When we take into account the already existing offshore wind capacity in the North Sea and the 25GW expected capacity, we will need an additional 6.7 GW of offshore wind capacity to reach the 25GW wind power capacity goal in the North Sea area. This energy hub can be created further on the Danish part of the North Sea, as there are at this moment no current plans to create parks there.

The electricity will go to Denmark at the connection point located at Ferring. The Electricity demand for Denmark needs to be corrected for onshore wind generation and offshore wind generation which is outside of the hub and spoke system. Currently Denmark has 4.778 GW onshore wind and there is 10.8 GW offshore wind outside of the model (Statista Denmark, 2025). When we include this with the peak demand of 9.070GW we gain the following electricity demand formula for Denmark:

Ferring landing = 9.070 * demand-factor – (4.778 + 10.8) * weather-factor

Germany

Germany is a major consumer and an essential part of the hub and spoke system. Accordingly, Germany has created extensive plans for development of offshore wind in their part of the North Sea area.

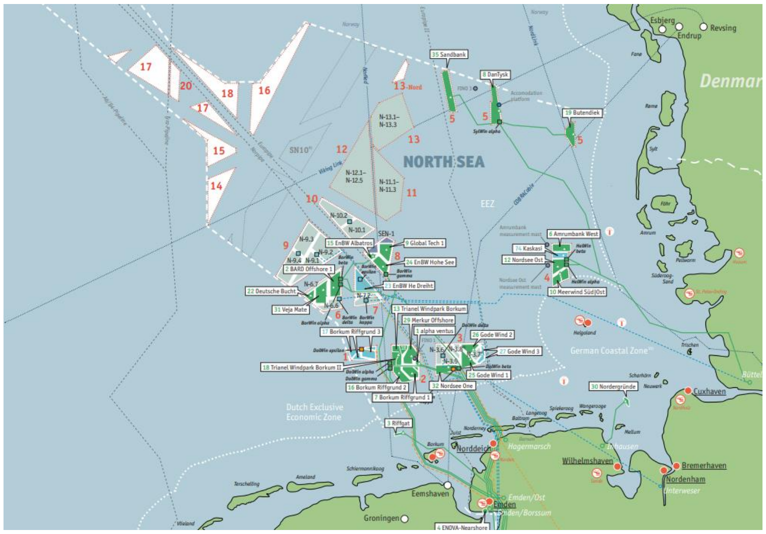

Figure C: Germany North Sea offshore wind park developments (WAB, 2021)

In figure C we see all the current wind park developments, and the future areas for expansion. Germany has divided these plans into different clusters. These clusters have various generation capacity and are therefore not all suitable for inclusion into the hub and spoke system. Especially as some of these clusters are already realized and the connecting cables are only designed for the loads of these wind parks. Below in table A we can see the exact capacity of each cluster.

Table A: German offshore wind cluster capacities (WAB, 2021)

Cluster:	Capacity (GW)
Cluster 1	1.303
Cluster 2	1.591
Cluster 3	2.716
Cluster 4	1.2204
Cluster 5	8.64
Cluster 6	1.952
Cluster 7	1.830
Cluster 8	1.0168
Cluster 9	4.000
Cluster 10	2.000
Cluster 11	2.667
Cluster 12	4.667
Cluster 13	2.667
Total Capacity	28.494

From this list the areas 9 and above can be included in the model as they are still to be developed. There are additional areas that can be used as can be seen in figure C. These areas are essential for reaching the 45GW of offshore wind in Germanys North Sea area. The clusters from 1 to 13 have a total capacity of 28.5 GW. When looking at the size of the areas 14 and above we estimate that the areas can produce a combined 17 GW. which gives a total offshore wind capacity of 45.5GW. some of these clusters are combined to create hubs with higher generation capacity.

Table B: German hub and spoke hubs and generation power

Clusters combined to form 1 hub	Power (GW)	Hub name in the model
9, 10	6	NEWGER1
11, 12, 13	10	NEWGER2
14, 15	4	NEWGER3
16, 18	4	NEWGER4
17, 20	4	NEWGER5
19	5	NEWGERDOG

The electricity will go to Germany at two different landing points. One located at Emden near the Dutch border, which is the current connection point for all North Sea wind farms. And another connection point located at Büttel, which is located near Hamburg. The German governments plans to connect these offshore wind farms to this place, and this place is also the location where the offshore cable form Germany to Norway comes ashore (WAB, 2021). The 77.508 GW electricity demand of Germany will be divided between these two landing points. Germany currently has an onshore wind capacity of 63.5GW, this capacity will be divided between the two landing points (Bundesverband WindEnergie (BWE), 2025). Germany has set a national offshore wind target of 70 GW. Of this, 45.5 GW is planned for the North Sea region, which implies that the remaining 24.5 GW will be developed in the Baltic Sea. As a result, the node located at Büttel will need to be adjusted to account for the offshore wind generation coming from the Baltic Sea. Similarly, the node at Emden needs to be corrected for the 12.5GW of offshore wind that is not inside the model. Taking this all into account we gain the following two demand functions for Germany.

Emden landing = 38.754* demand-factor – (12.5 + 31.75) * weather-factor

Büttel-Hamburg landing = 38.754 * demand-factor – (24.5 + 31.75) * weather-factor

Netherlands

The Netherlands is in the center of the North Sea area. And thus, the Netherlands will play a crucial role in the system. From transporting electricity from one side to the other, or by generating substantial amounts of electricity. Currently the Netherlands have various plans for offshore wind farms. As can be seen in figure 12, there is currently 4.7 GW of offshore wind operational in the Netherlands, 6.5 GW is under construction, and an additional 10 GW is planned. This gives a total of 21.5 GW offshore wind. However, the wind park Doordewind has had its plans altered and its capacity increased by 2GW (Rijksoverheid, n.d.). This then gives us a total of 23.5 GW of existing and planned offshore wind capacity.

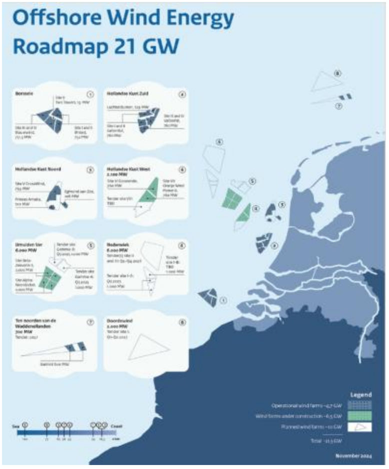

Figure D: Dutch North Sea offshore wind plans (Noordzeeloket, 2024)

As discussed in chapter 4, the Netherlands has a planned capacity goal of 40 GW or 70 GW depending on demand. This leads to a situation where in a low demand scenario 16.5 GW of additional offshore wind is needed to achieve the goals. And in the situation of high future demand 46.5 GW will be needed. Tennet the Transmission system operator of the Netherlands has created designs for 4 GW and 10 GW hubs (North Sea Wind Power Hub, 2024a). As can be seen in figure D, these additional hubs can be created to the north/east of the Nederwiek area, and to the north and west of the Doordewind area. We thus assume that the additional capacity will be realized in these areas. This gives us the following hubs and capacities in the 2 different demand scenarios.

Table C: Dutch hubs and their generation power

Hub name in model	Hub generation capacity
Ijmuiden Ver	6
Doordewind	4
Nederwiek	6
Hollandse Kust West	2.1
NEWNL1	4
NEWNL2	4
NEWNL3	4
NEWNL4	4
NEWNL5 (HIGH demand scenario)	10
NEWNL6 (HIGH demand scenario)	10
NEWNL7DOG (HIGH demand scenario)	10

The hubs in the low-capacity situation have a combined capacity of 34.1 GW. In the high-capacity situation 3 additional hubs of each 10 GW are added, bringing the total to 64.1 GW of additional capacity.

The Netherlands has 3 connection points in the model. One at Eemshaven, which is the current connection point of the NorNed interconnection cable. One at the Tweede Maasvlakte. Which is a major energy consumption region and the connection point for the BritNed interconnection cable. And finally, one located at Ijmuiden, this location is close to the capital and has a large industrial cluster. Especially since a steel factory is located here, which will have a large future electrical and hydrogen demand. The 19.477 GW electricity demand will be divided between these 3 locations. Furthermore, the demand in these nodes need to be corrected for 6.932 GW onshore wind and 5.9 GW offshore wind generation that is not inside the hub and spoke system (Statista Netherlands, 2025). This gives the following node demand functions.

Eemshaven landing = 6.5 * demand-factor – (1.97 + 2.31) * weather-factor

Ijmuiden landing = 6.5 * demand-factor – (1.97 + 2.31) * weather-factor

Tweede Maasvlakte landing = 6.5 * demand-factor – (1.97 + 2.31) * weather-factor

Norway

Norway is planning several offshore wind developments in the southern North Sea, primarily grouped into the Sørvest and Sønnarvind areas. As shown in *Figure 13*, these regions include multiple designated zones for offshore wind deployment.

Figure E: Planned offshore wind areas in the Norwegian North Sea (McBride, 2023)

Of these, only the Sørvest areas are included in the model. The Sønnarvind A area is located farther east in significantly deeper waters, making it suitable only for floating offshore wind. Furthermore, there is opposition to the Sønnarvind A area, because this area is essential for local fishing communities. At present, only the Sørvest F area has concrete development plans, with a combined capacity of 3.6 GW. If Norway targets a total of between 10 and 15 GW of offshore wind capacity in this region, an additional 6.4–11.4 GW must be allocated across the remaining Sørvest zones. In the low-demand scenario, the model assumes development of Sørvest C (3 GW), Sørvest D (2 GW), and Sørvest E (2 GW), totaling 10.6 GW of capacity. In the high-demand scenario, development extends to Sørvest B and even Sønnarvind A, each with 2.5 GW, raising the modeled capacity to 15.6 GW.

All offshore electricity is routed to the Norwegian grid via a single landing point at Feda, which is also the connection point for the Skagerrak, NordLink, North Sea Link and the NordNed interconnection cables. The 24.930 GW electricity demand needs to be corrected for both the onshore wind and offshore wind that is located outside of the model in the 2 different capacity situations. Norway currently has 5.062 GW of onshore wind installed (Statista Norway, 2025). In the low-demand scenario, we estimate an additional 4.4 GW of offshore wind capacity located outside the model, while in the high-demand scenario, this value rises to 14.4 GW. This gives us the following demand functions:

High-capacity scenario:
Feda landing = 24.93 × demand-factor – (5.062 + 14.4) × weather-factor

Low-capacity scenario:
Feda landing = 24.93 × demand-factor – (5.062 + 4.4) × weather-factor

United Kingdom

The United Kingdom is expected to reach around 100 GW of offshore wind capacity by 2046, according to the Electricity System Operator (ESO, 2024). Of this total, approximately two thirds, or about 66 GW, is anticipated to come from fixed-bottom installations, which are better suited to shallower waters compared to floating wind farms (UK Floating Offshore Wind (FLOW) Task Force 2024). Based on the goal of 66GW and geographical suitability, we estimated that around 45 GW of this capacity will be located in the hub and spoke area of the North Sea. This means that an additional 11.176 GW needs to be created in the North Sea area. To streamline the network and facilitate interconnection, several offshore wind farms are grouped into larger energy hubs. These aggregated hubs not only simplify the system design but also support more efficient transmission planning. Dogger Bank C and D are combined into a single hub with a total capacity of 3.2 GW. Dogger Bank A and B, along with the Sofia wind farm, are merged to form a second hub with a combined capacity of 3.8 GW (Sofia, 2022). In the East Anglia region, Zone 3 (1.4 GW) is adjacent to both Norfolk Boreas (1.38 GW) and Norfolk Vanguard (2.76 GW). These three projects are consolidated into a single hub with a total generation capacity of 5.54 GW.

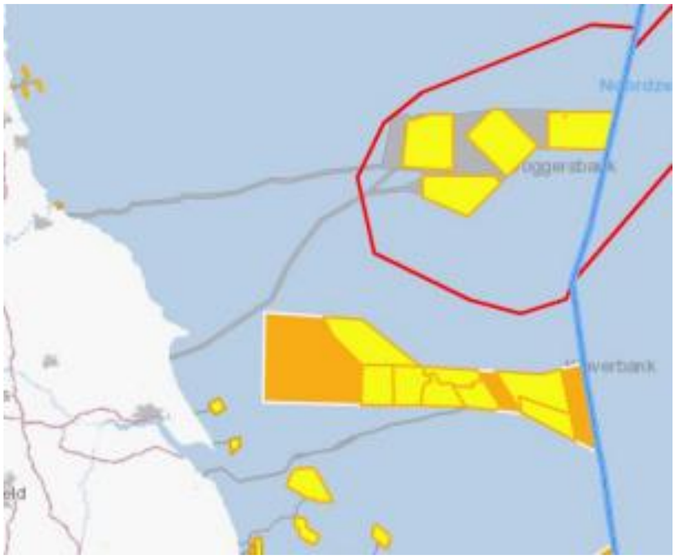

Figure F: United Kingdom offshore wind farm developments (Mulder, 2016)

As shown in Figure F, there is still available space south of the Dogger Bank region, and north of the Hornsea area that could accommodate additional offshore wind development. If the United Kingdom were to construct three new energy hubs of 4 GW each in these areas, it would fulfill the remaining 11.176 GW needed to reach its offshore wind capacity target.

One of the potential UK landing points is the Isle of Grain, which also serves as the connection point for the BritNed interconnector. However, this location is not directly connected to any of the offshore wind hubs included in the model. As such, the Isle of Grain is excluded from the modeled network. Instead, the model assumes a connection point at Leiston, which is situated closer to major offshore developments such as East Anglia, Norfolk Boreas, and Norfolk Vanguard. This location provides a more geographically representative and efficient connection for the modeled offshore infrastructure. This substitution is made under the assumption that the UK's internal grid can handle electricity transmission from actual landing points like the Isle of Grain to other parts of the country, allowing Leiston to serve as a proxy node for electricity flow in the model.

The United Kingdom has a projected peak electricity demand of 51.442 GW, which must be distributed across its various grid connection points. In modeling this demand, we also account for existing and planned onshore and offshore wind capacities. The UK currently has 15.418 GW of onshore wind capacity, with approximately 10 GW located in Scotland. This northern capacity is allocated to the northern node in the model (Renewable UK, 2024), while the remaining 5.418 GW is evenly distributed across the other two nodes.

Given the current peak demand of 51.442 GW, it is unlikely that the full 100 GW offshore wind target will be realized without significant demand growth. Therefore, we assume that in a low-demand scenario, only the 66 GW of fixed-bottom offshore capacity will be constructed. In a high-demand scenario, the full 100 GW, including floating offshore wind is developed. This gives us the following demand functions for the two different capacity/demand situations:

High-capacity demand functions:

Cromer landing = 17.15 * demand-factor – (20.15 + 2.7) * weather-factor

Leiston landing= 17.15 * demand-factor – (20.15 + 2.7) * weather-factor

Ulrome landing= 17.15 * demand-factor – (20.15 + 10) * weather-factor

Low-capacity demand functions:

Cromer landing = 17.15 * demand-factor – (8.82 + 2.7) * weather-factor

Leiston landing = 17.15 * demand-factor – (8.82 + 2.7) * weather-factor

Ulrome landing = 17.15 * demand-factor – (8.82 + 10) * weather-factor

Overview of offshore wind parks and landing points

With all the information we gathered about the hubs that can be included in the model we can create the following overview of hubs. As seen in table D below each hub will have a latitudinal and longitudinal coordinate, their generation capacity. Furthermore, in table E is an overview of all the landings, their coordinates and the associated demand functions.

Table D: Hub names, coordinates and generation capacity (WAB, 2021), (4C Offshore, n.d.)

Country	Windpark name	Latitudinal coordinate	Longitudinal coordinate	Generation capacity (GW)
Belgium	Princess Elisabeth	51.5264	2.5420	5.9
Denmark	Nordsoen 1	55.9809	7.3303	6
Denmark	Nordsoen 2+3	56.633	6.792	10
Denmark	Freya	57.2087	7.572	1.5
Denmark	NEWDK1	56	5.1	6.7
Germany	NEWGER1	54.38	5.88	6
Germany	NEWGER2	54.78	6.33	10
Germany	NEWGER3	54.82	5.03	4
Germany	NEWGER4	55.27	5.25	4
Germany	NEWGER5	55.27	4.66	4
Germany	NEWGERDOG	55.75	3.66	5
Netherlands	Ijmuiden Ver	52.83	3.45	6
Netherlands	Doordewind	54.1914	5.6	4
Netherlands	Nederwiek	53.18	3.22	6
Netherlands	Hollandse Kust West	52.57	3.616	2.1
Netherlands	NEWNL1	53.27	3.96	4
Netherlands	NEWNL2	53.86	3.77	4
Netherlands	NEWNL3	53.86	5.6	4
Netherlands	NEWNL4	53.86	4.685	4
Netherlands	NEWNL5	54.4	3.33	10

	(HIGH demand scenario)			
Netherlands	NEWNL6 (HIGH demand scenario)	54.5	4.66	10
Netherlands	NEWNL7DOG (HIGH demand scenario)	55.12	3.6	10
United Kingdom	East Anglia 1&2	52.2247	2.4242	2.574
United Kingdom	NorFolk + East Anglia 3	52.86	2.74	5.54
United Kingdom	Outer Dowsing	53.57	1.29	1.5
United Kingdom	Dogger Bank South Offshore	54.5007	1.938	3
United Kingdom	Dogger Bank C, D	55.04	2.82	3.2
United Kingdom	Dogger Bank A, B, Sofia	55.13	2.33	3.8
United Kingdom	Hornsea 1&2	53.88	1.92	2.538
United Kingdom	Hornsea 3	53.87	2.54	3
United Kingdom	Hornsea 4	54.09	1.24	2.4
United Kingdom	NEWUK1	54.38	1.24	4
United Kingdom	NEWUK2	54.19	1.92	4
United Kingdom	NEWUK3	54.19	2.54	4
Norway	Sorvest A (HIGH demand scenario)	58.0422	3.6118	2.5
Norway	Sorvest B (HIGH demand scenario)	57.4044	3.6118	2.5
Norway	Sorvest C	56.8955	3.8968	3
Norway	Sorvest D	56.4239	3.8968	2
Norway	Sorvest E	57.4477	4.8729	2
Norway	Sorvest F (Sorlige Nordsjo 2)	56.8011	4.8729	3.6

Table E: landing coordinates and their demand functions

Country	Latitudinal coordinate	Longitudinal coordinate	Node name and demand (GW)
Belgium	51.2995	3.0799	Wenduine = 13.206 * demand_factor – (3.337 + 3.1) * weather_factor
Denmark	56.5259	8.1164	Ferring = 9.070 * demand_factor – (4.778 + 10.8) * weather_factor
Germany	53.3676	7.2106	Emden = 38.754* demand_factor – (12.5 + 31.75) * weather_factor
Germany	53.8939	9.1308	Büttel-Hamburg = 38.754 * demand_factor – (24.5 + 31.75) * weather_factor
Netherlands	51.9327	3.9809	Eemshaven = 6.5* demand_factor – (1.97 + 2.31) * weather_factor
Netherlands	52.4574	4.5958	Ijmuiden Tata Steel = 6.5 * demand_factor – (1.97 + 2.31) * weather_factor
Netherlands	53.4449	6.8361	Tweede Maasvlakte = 6.5 * demand_factor – (1.97 + 2.31) * weather_factor
Norway high capacity	58.2635	6.8158	Feda = 24.93 * demand_factor – (5.062 + 14.4) * weather_factor
Norway low capacity	58.2635	6.8158	Feda = 24.93 * demand_factor – (5.062 + 4.4) * weather_factor
United Kingdom High capacity	52.9282	1.2982	romer = 17.15 * demand_factor – (20.15 + 2.7) * weather_factor
United Kingdom High capacity	52.2062	1.6205	Leiston = 17.15 * demand_factor – (20.15 + 2.7) * weather_factor
United Kingdom High capacity	53.9951	-0.2087	Ulrome = 17.15 * demand_factor – (20.15 + 10) * weather_factor
United Kingdom Low capacity	52.9282	1.2982	Cromer = 17.15 * demand_factor – (8.82 + 2.7) * weather_factor

United Kingdom Low capacity	52.2062	1.6205	Leiston = 17.15 * demand_factor – (8.82 + 2.7) * weather_factor
United Kingdom Low capacity	53.9951	-0.2087	Ulrome = 17.15 * demand_factor – (8.82 + 10) * weather_factor

these hubs and landings give the following possible design layouts for the different amounts of installed capacity in the system.

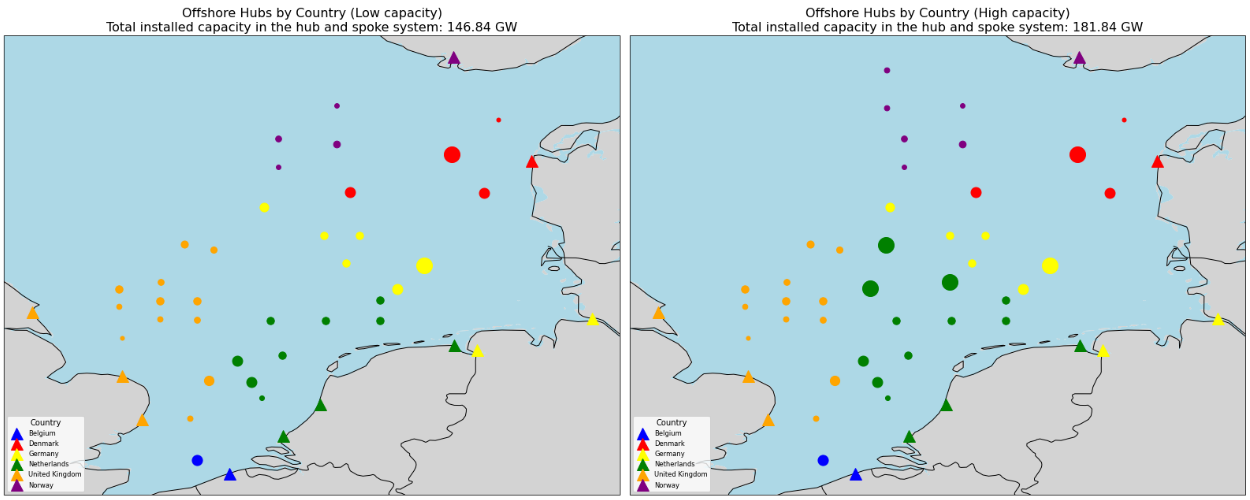

Figure G: High and low-capacity designs of the hubs in the model

B. Hydrogen hubs and model outputs

Hydrogen hubs scenario 1 medium buildout

Parks that have excess electricity	Excess electricity (GW)	To be installed hydrogen electrolysis capacity in node
Ferring landing	5.409	NO landing
Nordsoen 1	3.9	4
Nordsoen 2+3	6.5	6
Freya	0.975	To small
NEWDK1	2.366	2
Büttel-Hamburg landing	0.288	NO landing
NEWGER1	3.9	4
NEWGER3	2.6	4
NEWGER4	2.6	4
NEWGER5	2.6	4
NEWGERDOG	3.25	4
Doordewind	1.057	To small
Nederwiek	2.901	4
NEWNL1	2.6	4
NEWNL2	2.6	4
NEWNL4	2.6	4
NEWNL5 high demand	6.5	6
NEWNL6 high demand	6.5	6
NEWNL7DOG high demand	6.5	6
Ulrome landing	4.346	NO landing
Outer Dowsing	0.577	To small
Dogger Bank South Offshore	1.95	2
Dogger Bank C,D	2.08	2
Dogger Bank A,B, Sofia	2.47	2
Hornsea 1&2	1.649	2
Hornsea 3	1.95	2
Hornsea 4	1.56	2
Norfolk + East Anglia 3	1.175	To small
NEWUK1	2.6	4
NEWUK2	2.6	4
NEWUK3	2.6	4
Sorvest A	1.625	2
Sorvest B	1.625	2
Sorvest C	1.95	2
Sorvest D	1.3	To small

Model output 1 medium buildout Delaunay

Running scenario: Full Wind
  Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 153.547 GW
  there is a generation surplus of: 63.521 GW
  Hydrogen usage data is available.
Running scenario: West to East
  there is a generation shortage of: 34.327 GW
  No hydrogen usage data found.
Running scenario: East to West
  Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 11.411 GW
  there is a generation shortage of: 0.042 GW

Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 33.423 GW
there is a generation shortage of: 0.032 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 84.239 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1166 km
the total length of the network is : 6048 KM
the total capacity of the network is : 1053.552 GW
The total length of the hydrogen network is: 4476 KM
The total pipeline apacity of the hydrogen network is: 183.874 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 5.0

Model output 1 medium buildout MST

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 153.547 GW
there is a generation surplus of: 63.521 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 34.327 GW
No hydrogen usage data found.
Running scenario: East to West
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 11.411 GW
there is a generation shortage of: 0.042 GW
Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 33.423 GW
there is a generation shortage of: 0.032 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 84.239 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1353 km
the total length of the network is : 4830 KM
the total capacity of the network is : 1119.662 GW
The total length of the hydrogen network is: 4476 KM
The total pipeline capacity of the hydrogen network is: 183.874 GW
Removing edge ('Princess Elisabeth', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 7.0

Hydrogen hubs scenario 2 small buildout

Parks that have excess electricity	Excess electricity (GW)	To be installed hydrogen capacity in node
Ferring landing	2.704	NO LANDINGS
Büttel-Hamburg landing	7.259	NO LANDINGS
Nordsoen 1	3.9	4
Nordsoen 2+3	6.5	6
NEWDK1	3.9	4
NEWGER1	3.9	4
NEWGER2	6.5	6
NEWGER3	2.6	4
NEWGER4	2.6	2
NEWGER5	2.6	4
NEWGERDOG	3.25	4
Ijmuiden Ver	0.729	To Small
Doordewind	2.6	4
Nederwiek	3.9	4
NEWNL1	2.6	4
NEWNL2	2.6	2
NEWNL3	1.691	2
NEWNL4	2.6	4
Sorvest C	1.95	2
Sorvest D	1.3	2
Sorvest E	1.3	2
Sorvest F (Sorlige Nordsjo 2)	2.34	2
Dogger Bank South Offshore	1.95	2
Dogger Bank C,D	2.08	2
Dogger Bank A,B, Sofia	2.47	2
Hornsea 1&2	1.649	2
Hornsea 3	1.95	2
Norfolk + East Anglia 3	1.063	2
NEWUK2	2.6	4
NEWUK3	2.6	4

Model output 2 small buildout Delaunay

Running scenario: Full Wind
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 134.318 GW
    there is a generation surplus of: 48.291 GW
    Hydrogen usage data is available.
Running scenario: West to East
    there is a generation shortage of: 35.556 GW
    No hydrogen usage data found.
Running scenario: East to West
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 37.375 GW

there is a generation shortage of: 0.039 GW
Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 27.693 GW
there is a generation shortage of: 0.046 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 45.877 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1197 km
the total length of the network is : 5687 KM
the total capacity of the network is : 771.306 GW
The total length of the hydrogen network is: 4585 KM
The total pipeline capacity of the hydrogen network is: 223.62 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 4.0
the percentage of essential edges is: 8.51063829787234 %

Model output 2 small buildout MST

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 134.318 GW
there is a generation surplus of: 48.291 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 35.556 GW
No hydrogen usage data found.
Running scenario: East to West
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 37.375 GW
there is a generation shortage of: 0.039 GW
Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 27.693 GW
there is a generation shortage of: 0.046 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 45.877 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1318 km
the total length of the network is : 4492 KM
the total capacity of the network is : 804.828 GW
The total length of the hydrogen network is: 4585 KM
The total pipeline capacity of the hydrogen network is: 223.62 GW
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 5.0
the percentage of essential edges is: 13.88888888888889 %

Hydrogen hubs scenario 3 large buildout

Park Name	Excess Electricity	To be installed hydrogen electrolysis capacity in node
NEWDK1	3.9	4
NEWGER4	2.6	4
NEWGER5	2.6	4
NEWGERDOG	3.25	4
NEWNL2	0.293	To small
NEWNL4	0.146	To small
NEWNL5 high demand	6.5	6
NEWNL6 high demand	6.5	6
NEWNL7DOG high demand	6.5	6
Sorvest A	1.625	2
Sorvest B	1.625	2
Sorvest C	1.95	2
Sorvest D	1.3	To small
Sorvest E	1.3	To small
Sorvest F (Sorlige Nordsjo 2)	2.34	2
Dogger Bank South Offshore	1.95	2
Dogger Bank C,D	2.08	2
Dogger Bank A,B, Sofia	2.47	2
Hornsea 1&2	1.649	2
Hornsea 3	1.95	2
NEWUK1	0.645	To small
NEWUK2	2.6	4
NEWUK3	2.6	4
TOTAL	58.373	60

Model output 3 large buildout Delaunay

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 93.787 GW
there is a generation surplus of: 37.77 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 94.088 GW
No hydrogen usage data found.
Running scenario: East to West
there is a generation shortage of: 48.349 GW
No hydrogen usage data found.
Running scenario: South to North
there is a generation shortage of: 26.338 GW
No hydrogen usage data found.
Running scenario: North to South
there is a generation shortage of: 143.999 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1173 km
the total length of the network is : 6022 KM
the total capacity of the network is : 1020.567 GW
The total length of the hydrogen network is: 4830 KM
The total pipeline capacity of the hydrogen network is: 115.102 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Freya') makes the system infeasible in an average weather/demand situation.
Removing edge ('Freya', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWNL6 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL4') makes the system infeasible in an average weather/demand situation.

Removing edge ('NEWNL2', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL6 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL6 high demand', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL6 high demand', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest A', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest A') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 52.0
the percentage of essential edges is: 100.0 %

Model output 3 large buildout MST

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 93.787 GW
there is a generation surplus of: 37.77 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 94.088 GW
No hydrogen usage data found.
Running scenario: East to West
there is a generation shortage of: 48.349 GW
No hydrogen usage data found.
Running scenario: South to North
there is a generation shortage of: 26.338 GW
No hydrogen usage data found.
Running scenario: North to South
there is a generation shortage of: 143.999 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1353 km
the total length of the network is : 4830 KM
the total capacity of the network is : 892.826 GW
The total length of the hydrogen network is: 4830 KM
The total pipeline capacity of the hydrogen network is: 115.102 GW
Removing edge ('Princess Elisabeth', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL6 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.

Removing edge ('NEWNL6 high demand', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest A', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest A') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 41.0
the percentage of essential edges is: 100.0 %

Hydrogen hubs scenario 4 small onshore

Parks that have excess electricity	Excess electricity (GW)
Ferring landing	2.704
Büttel-Hamburg landing	7.259
Nordsoen 1	3.9
Nordsoen 2+3	6.5
NEWDK1	3.9
NEWGER1	3.9
NEWGER2	6.5
NEWGER3	2.6
NEWGER4	2.6

NEWGER5	2.6
NEWGERDOG	3.25
Ijmuiden Ver	0.729
Doordewind	2.6
Nederwiek	3.9
NEWNL1	2.6
NEWNL2	2.6
NEWNL3	1.691
NEWNL4	2.6
Sorvest C	1.95
Sorvest D	1.3
Sorvest E	1.3
Sorvest F (Sorlige Nordsjo 2)	2.34
Dogger Bank South Offshore	1.95
Dogger Bank C,D	2.08
Dogger Bank A,B, Sofia	2.47
Hornsea 1&2	1.649
Hornsea 3	1.95
Norfolk + East Anglia 3	1.063
NEWUK2	2.6
NEWUK3	2.6

Model output 4 small onshore Delaunay

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 134.318 GW
there is a generation surplus of: 48.617 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 35.556 GW
No hydrogen usage data found.
Running scenario: East to West
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 37.375 GW
there is a generation shortage of: 0.006 GW
Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 27.693 GW
there is a generation shortage of: 0.005 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 45.877 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1235 km
the total length of the network is : 5687 KM
the total capacity of the network is : 892.216 GW
The total length of the hydrogen network is: 11943 KM
The total pipeline capacity of the hydrogen network is: 55.693 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.

the number of essential edges is 3.0
the percentage of essential edges is: 6.666666666666667 %

Model output 4 small onshore MST

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 134.318 GW
there is a generation surplus of: 48.617 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 35.556 GW
No hydrogen usage data found.
Running scenario: East to West
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 37.375 GW
there is a generation shortage of: 0.006 GW
Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 27.693 GW
there is a generation shortage of: 0.005 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 45.877 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1318 km
the total length of the network is : 4492 KM
the total capacity of the network is : 908.81 GW
The total length of the hydrogen network is: 11943 KM
The total pipeline capacity of the hydrogen network is: 55.693 GW
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 3.0
the percentage of essential edges is: 8.333333333333332 %

Hydrogen hubs scenario 5 medium onshore

Parks that have excess electricity	Excess electricity (GW)
Ferring landing	0.098
Nordsoen 1	3.9
Nordsoen 2+3	6.5
NEWDK1	3.9
NEWGER2	4.957
NEWGER3	2.6
NEWGER4	2.6
NEWGER5	2.6
NEWGERDOG	3.25
NEWNL2	1.912
NEWNL4	2.6
Sorvest C	1.95
Sorvest D	1.3
Sorvest E	1.3

Sorvest F (Sorlige Nordsjo 2)	2.34
Dogger Bank South Offshore	1.95
Dogger Bank C,D	2.08
Dogger Bank A,B, Sofia	2.47
Hornsea 3	1.95
NEWUK2	0.005
NEWUK3	2.6
Total	**52.862**

Model output 5 medium onshore Delaunay

Running scenario: Full Wind
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 74.557 GW
    there is a generation surplus of: 28.236 GW
    Hydrogen usage data is available.
Running scenario: West to East
    there is a generation shortage of: 95.317 GW
    No hydrogen usage data found.
Running scenario: East to West
    there is a generation shortage of: 22.387 GW
    No hydrogen usage data found.
Running scenario: South to North
    there is a generation shortage of: 32.067 GW
    No hydrogen usage data found.
Running scenario: North to South
    there is a generation shortage of: 105.638 GW
    No hydrogen usage data found.
The Diameter of the final graph is: 1389 km
the total length of the network is : 5633 KM
the total capacity of the network is : 684.475 GW
The total length of the hydrogen network is: 11943 KM
The total pipeline capacity of the hydrogen network is: 30.096 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Freya') makes the system infeasible in an average weather/demand situation.
Removing edge ('Freya', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER3') makes the system infeasible in an average weather/demand situation.

Removing edge ('Doordewind', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 45.0
the percentage of essential edges is: 100.0 %

Model output 5 medium onshore MST

Running scenario: Full Wind
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 74.557 GW
    there is a generation surplus of: 28.236 GW
    Hydrogen usage data is available.
Running scenario: West to East
    there is a generation shortage of: 95.317 GW
    No hydrogen usage data found.
Running scenario: East to West
    there is a generation shortage of: 22.387 GW
    No hydrogen usage data found.
Running scenario: South to North
    there is a generation shortage of: 32.067 GW
    No hydrogen usage data found.
Running scenario: North to South
    there is a generation shortage of: 105.638 GW
    No hydrogen usage data found.
The Diameter of the final graph is: 1318 km
the total length of the network is : 4492 KM
the total capacity of the network is : 713.258 GW
The total length of the hydrogen network is: 11943 KM
The total pipeline capacity of the hydrogen network is: 30.096 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Princess Elisabeth', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.

Removing edge ('Dogger Bank South Offshore', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 36.0
the percentage of essential edges is: 100.0 %

Hydrogen hubs scenario 6 large onshore

Parks that have excess electricity	Excess electricity (GW)
NEWDK1	3.9
NEWGER4	2.6
NEWGER5	2.6
NEWGERDOG	3.25
NEWNL2	0.293
NEWNL4	0.146
NEWNL5 high demand	6.5
NEWNL6 high demand	6.5
NEWNL7DOG high demand	6.5
Sorvest A	1.625
Sorvest B	1.625
Sorvest C	1.95
Sorvest D	1.3
Sorvest E	1.3
Sorvest F (Sorlige Nordsjo 2)	2.34
Dogger Bank South Offshore	1.95
Dogger Bank C,D	2.08
Dogger Bank A,B, Sofia	2.47

Hornsea 1&2	1.649
Hornsea 3	1.95
NEWUK1	0.645
NEWUK2	2.6
NEWUK3	2.6
Total	58.373

Model output 6 large onshore Delaunay

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 93.787 GW
there is a generation surplus of: 35.366 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 94.088 GW
No hydrogen usage data found.
Running scenario: East to West
there is a generation shortage of: 48.349 GW
No hydrogen usage data found.
Running scenario: South to North
there is a generation shortage of: 26.338 GW
No hydrogen usage data found.
Running scenario: North to South
there is a generation shortage of: 143.999 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1173 km
the total length of the network is : 6022 KM
the total capacity of the network is : 1050.456 GW
The total length of the hydrogen network is: 11943 KM
The total pipeline capacity of the hydrogen network is: 37.961 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Freya') makes the system infeasible in an average weather/demand situation.
Removing edge ('Freya', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWNL6 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER3') makes the system infeasible in an average weather/demand situation.

Removing edge ('Doordewind', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL6 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL6 high demand', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL6 high demand', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest A', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest A') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.

Removing edge ('NEWUK1', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 52.0
the percentage of essential edges is: 100.0 %

Model output 6 large onshore MST

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 93.787 GW
there is a generation surplus of: 35.366 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 94.088 GW
No hydrogen usage data found.
Running scenario: East to West
there is a generation shortage of: 48.349 GW
No hydrogen usage data found.
Running scenario: South to North
there is a generation shortage of: 26.338 GW
No hydrogen usage data found.
Running scenario: North to South
there is a generation shortage of: 143.999 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1353 km
the total length of the network is : 4830 KM
the total capacity of the network is : 916.927 GW
The total length of the hydrogen network is: 11943 KM
The total pipeline capacity of the hydrogen network is: 37.961 GW
Removing edge ('Princess Elisabeth', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'Nordsoen 1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nordsoen 2+3', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Nordsoen 2+3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWDK1', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER1', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER2', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER3', 'NEWGER4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER4', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGER3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGER5', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWGER5') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWGERDOG', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWGER1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Doordewind', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.

Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'Doordewind') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL3', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL6 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL5 high demand', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL6 high demand', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'NEWNL5 high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL7DOG high demand', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank South Offshore', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'NEWNL7DOG high demand') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank C,D', 'Dogger Bank A,B, Sofia') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('Dogger Bank A,B, Sofia', 'Dogger Bank C,D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'NEWUK3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 3', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK1', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Dogger Bank South Offshore') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK3', 'Hornsea 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest A', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest A') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest B', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest B') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest D') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest C', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'NEWGERDOG') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest D', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'NEWDK1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest C') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 41.0
the percentage of essential edges is: 100.0 %

Hydrogen hubs scenario 7 few islands

Parks that have excess electricity	Excess electricity (GW)	To be installed hydrogen capacity in node
Ferring landing	2.711	NO LANDINGS
Büttel-Hamburg landing	7.259	NO LANDINGS
Nordsoen 1	3.9	6
Nordsoen 2+3	6.5	6

NEWDK1	3.9	6
NEWGER1	3.9	6
NEWGER2	6.5	6
NEWGER3	2.6	6
NEWGER4	2.6	6
NEWGER5	2.6	6
NEWGERDOG	3.25	6
Ijmuiden Ver	0.729	To Small
Doordewind	2.6	6
Nederwiek	3.9	6
NEWNL1	2.6	6
NEWNL2	2.6	To Small
NEWNL3	1.691	To Small
NEWNL4	2.6	To Small
Sorvest C	1.95	To Small
Sorvest D	1.3	To Small
Sorvest E	1.3	To Small
Sorvest F (Sorlige Nordsjo 2)	2.34	To Small
Dogger Bank South Offshore	1.95	To Small
Dogger Bank C,D	2.08	To Small
Dogger Bank A,B, Sofia	2.47	To Small
Hornsea 1&2	1.642	To Small
Hornsea 3	1.95	To Small
Norfolk + East Anglia 3	1.063	To Small
NEWUK2	2.6	6
NEWUK3	2.6	6

Model output 7 few islands Delaunay

Running scenario: Full Wind
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 134.318 GW
    there is a generation surplus of: 50.304 GW
    Hydrogen usage data is available.
Running scenario: West to East
    there is a generation shortage of: 35.556 GW
    No hydrogen usage data found.
Running scenario: East to West
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 37.375 GW
    there is a generation shortage of: 0.015 GW
    Hydrogen usage data is available.
Running scenario: South to North
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 27.693 GW
    there is a generation shortage of: 0.024 GW
    Hydrogen usage data is available.
Running scenario: North to South
    there is a generation shortage of: 45.877 GW
    No hydrogen usage data found.
The Diameter of the final graph is: 1197 km
the total length of the network is : 5579 KM
the total capacity of the network is : 762.208 GW

The total length of the hydrogen network is: 4064 KM
The total pipeline capacity of the hydrogen network is: 139.303 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 4.0
the percentage of essential edges is: 8.51063829787234 %

Model output 7 few islands buildout MST

Running scenario: Full Wind
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 134.318 GW
there is a generation surplus of: 50.304 GW
Hydrogen usage data is available.
Running scenario: West to East
there is a generation shortage of: 35.556 GW
No hydrogen usage data found.
Running scenario: East to West
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 37.375 GW
there is a generation shortage of: 0.015 GW
Hydrogen usage data is available.
Running scenario: South to North
Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 27.693 GW
there is a generation shortage of: 0.024 GW
Hydrogen usage data is available.
Running scenario: North to South
there is a generation shortage of: 45.877 GW
No hydrogen usage data found.
The Diameter of the final graph is: 1318 km
the total length of the network is : 4492 KM
the total capacity of the network is : 789.121 GW
The total length of the hydrogen network is: 4064 KM
The total pipeline capacity of the hydrogen network is: 139.303 GW
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 5.0
the percentage of essential edges is: 13.88888888888889 %

Hydrogen hubs scenario 8 many islands

Parks that have excess electricity	Excess electricity (GW)	To be installed hydrogen capacity in node
Ferring landing	2.898	NO LANDINGS
Ulrome landing	2.946	NO LANDINGS
Nordsoen 1	3.9	6
Nordsoen 2+3	6.5	6
NEWDK1	3.9	6
NEWGER2	4.957	6
NEWGER3	2.6	6
NEWGER4	2.6	6

NEWGER5	2.6	6
NEWGERDOG	3.25	6
Nederwiek	3.9	6
NEWNL1	0.601	To small
NEWNL2	2.6	To small
NEWNL4	2.6	6
NEWNL5 high demand	6.5	6
NEWNL6 high demand	6.5	6
NEWNL7DOG high demand	6.5	6
Sorvest A	1.625	To small
Sorvest B	1.625	To small
Sorvest C	1.95	To small
Sorvest D	1.3	To small
Sorvest E	1.3	To small
Sorvest F (Sorlige Nordsjo 2)	2.34	To small
Outer Dowsing	0.577	To small
Dogger Bank South Offshore	1.95	To small
Dogger Bank C,D	2.08	To small
Dogger Bank A,B, Sofia	2.47	To small
Hornsea 1&2	1.649	To small
Hornsea 3	1.95	To small
Hornsea 4	1.56	To small
Norfolk + East Anglia 3	2.175	To small
NEWUK1	2.6	6
NEWUK2	2.6	6
NEWUK3	2.6	6
Total	97.703	96

Model output 8 many islands Delaunay

Running scenario: Full Wind
  Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 153.547 GW
  there is a generation surplus of: 57.531 GW
  Hydrogen usage data is available.
Running scenario: West to East
  there is a generation shortage of: 34.327 GW
  No hydrogen usage data found.
Running scenario: East to West
  Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 11.411 GW
  there is a generation shortage of: 0.029 GW
  Hydrogen usage data is available.
Running scenario: South to North
  Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 33.423 GW
  there is a generation shortage of: 0.014 GW
  Hydrogen usage data is available.
Running scenario: North to South
  there is a generation shortage of: 84.239 GW
  No hydrogen usage data found.

The Diameter of the final graph is: 1166 km
the total length of the network is : 6048 KM
the total capacity of the network is : 1053.374 GW
The total length of the hydrogen network is: 4266 KM
The total pipeline capacity of the hydrogen network is: 154.554 GW
Removing edge ('Princess Elisabeth', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Nederwiek', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL4') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL4', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('East Anglia 1&2', 'Norfolk + East Anglia 3') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 1&2') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 1&2', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'Nederwiek') makes the system infeasible in an average weather/demand situation.
Removing edge ('Norfolk + East Anglia 3', 'East Anglia 1&2') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 5.0
the percentage of essential edges is: 9.803921568627452 %

Model output 8 many islands MST

Running scenario: Full Wind
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 153.547 GW
    there is a generation surplus of: 57.531 GW
    Hydrogen usage data is available.
Running scenario: West to East
    there is a generation shortage of: 34.327 GW
    No hydrogen usage data found.
Running scenario: East to West
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 11.411 GW
    there is a generation shortage of: 0.029 GW
    Hydrogen usage data is available.
Running scenario: South to North
    Hydrogen is used in this weather scenario, before inclusion the excess electricity is: 33.423 GW
    there is a generation shortage of: 0.014 GW
    Hydrogen usage data is available.
Running scenario: North to South
    there is a generation shortage of: 84.239 GW
    No hydrogen usage data found.
The Diameter of the final graph is: 1353 km
the total length of the network is : 4830 KM
the total capacity of the network is : 1112.111 GW
The total length of the hydrogen network is: 4266 KM
The total pipeline capacity of the hydrogen network is: 154.554 GW
Removing edge ('Princess Elisabeth', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'Hollandse Kust West') makes the system infeasible in an average weather/demand situation.
Removing edge ('Ijmuiden Ver', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Princess Elisabeth') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hollandse Kust West', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'Ijmuiden Ver') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL1', 'NEWNL2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWNL2', 'NEWNL1') makes the system infeasible in an average weather/demand situation.
Removing edge ('Outer Dowsing', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'Outer Dowsing') makes the system infeasible in an average weather/demand situation.
Removing edge ('Hornsea 4', 'NEWUK2') makes the system infeasible in an average weather/demand situation.
Removing edge ('NEWUK2', 'Hornsea 4') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest E', 'Sorvest F (Sorlige Nordsjo 2)') makes the system infeasible in an average weather/demand situation.
Removing edge ('Sorvest F (Sorlige Nordsjo 2)', 'Sorvest E') makes the system infeasible in an average weather/demand situation.
the number of essential edges is 7.0
the percentage of essential edges is: 17.073170731707318 %

C. Scenario results

Scenario 2: Small build out

After running the model with the average demand factors and a weather factor of 0.65 we get as a result that there is 85.685 GW excess electricity. Thus, for this scenario hydrogen capacity should have around 85.685 GW of electrolysis capacity.

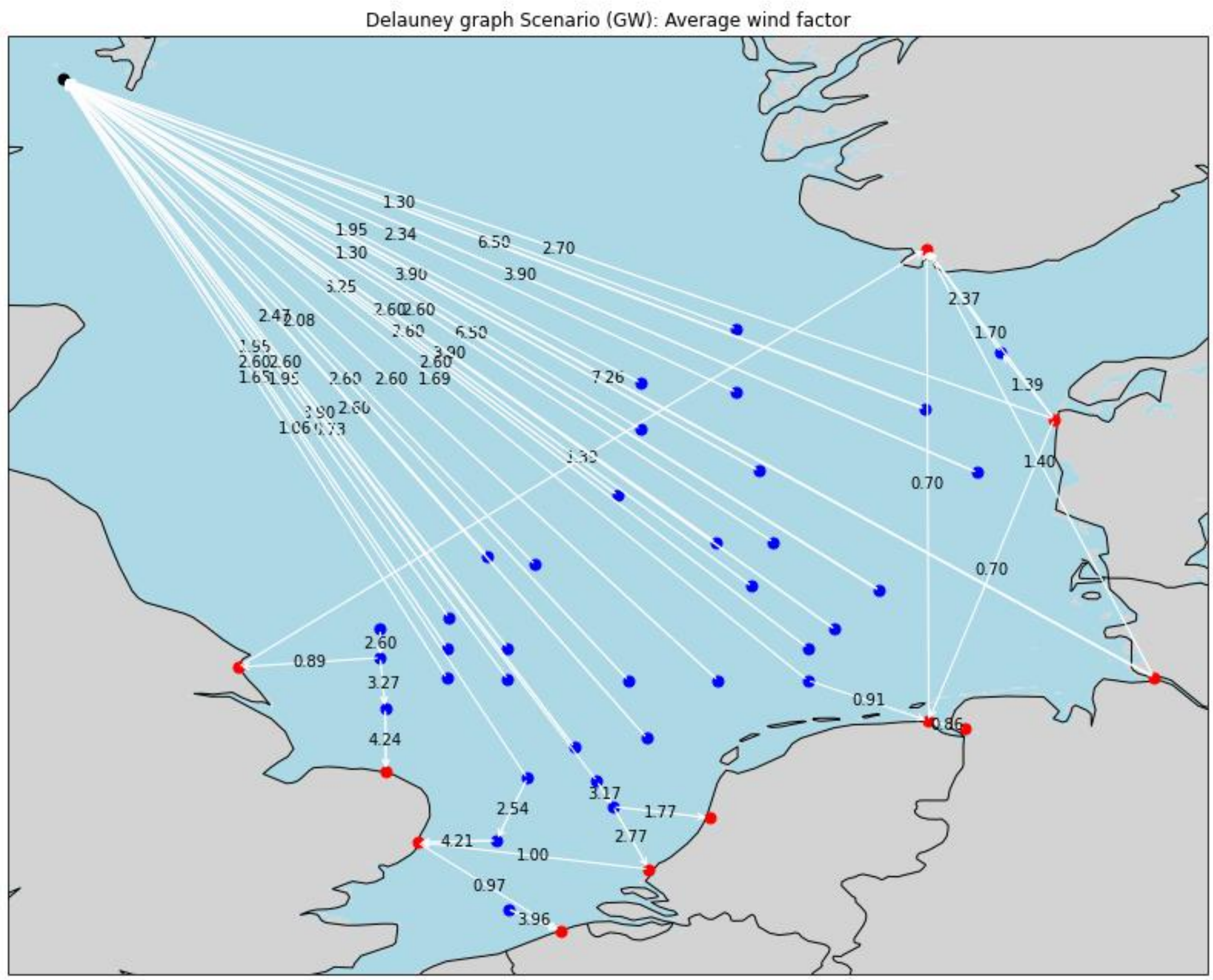

Figure 18: excess electricity production for hydrogen generation

In figure 18 we see the parks that generate this excess electricity. With the excess electricity of each park in this scenario, we determine which parks will get 2 GW, 4GW or 6GW of hydrogen generation capacity.

Table 24: Hydrogen generation capacity and hubs

Hydrogen Capacity (GW)	**# of Parks**	**Installed hydrogen capacity (GW)**

2	13	26
4	12	48
6	2	12
Total	27	86

As we can see from table 24, there are various nodes which are suitable for each of the generation capacity. These 27 locations of hydrogen production have a combined generation capacity of 86 GW. The specific hubs assigned electrolysis capacities of 2, 4, or 6 GW can be found in Appendix B. Now that we have located and added the hydrogen hubs we can start running the scenario. Firstly, we will determine the optimization factor for the Delaunay network. When the optimization factor is increased to 50, we find the shortest possible network, which is 3741 km. When we change the factor to 2.5 we gain a network of 5687km. This satisfies the 1.5 times size difference discussed in part 6.2.2. about the Delaunay triangulation method.

In table 25 the results of the model are visualized. We can see In table 22 that the Delaunay network has a lower diameter, higher total length, lower total capacity and is more resistant to edge failures, the exact essential edges for both the MST and Delaunay graph can be seen in figure 19 .we see that the essential edges are located in the same place in both the MST and Delaunay network, from Belgium to the north, in the area of the United Kingdom to the east. And the cable connecting Norway to the network. Just as in the previous scenario, we see that in the case of Norway an additional cable is needed to prevent Norway being cut off completely in the case of cable failure.

Table 25: scenario model results

	Delaunay	MST	differences
Diameter	1197 km	1318 km	+10.1%
Total length	5687 km	4492 km	-21.0%
Total capacity	771.306 GW	804.828 GW	+ 4.3%
Hydrogen capacity	223.62 GW		N/A
Number of essential edges	4	5	1
Essential edges percentage	8.51 %	13.89 %	5.35 %

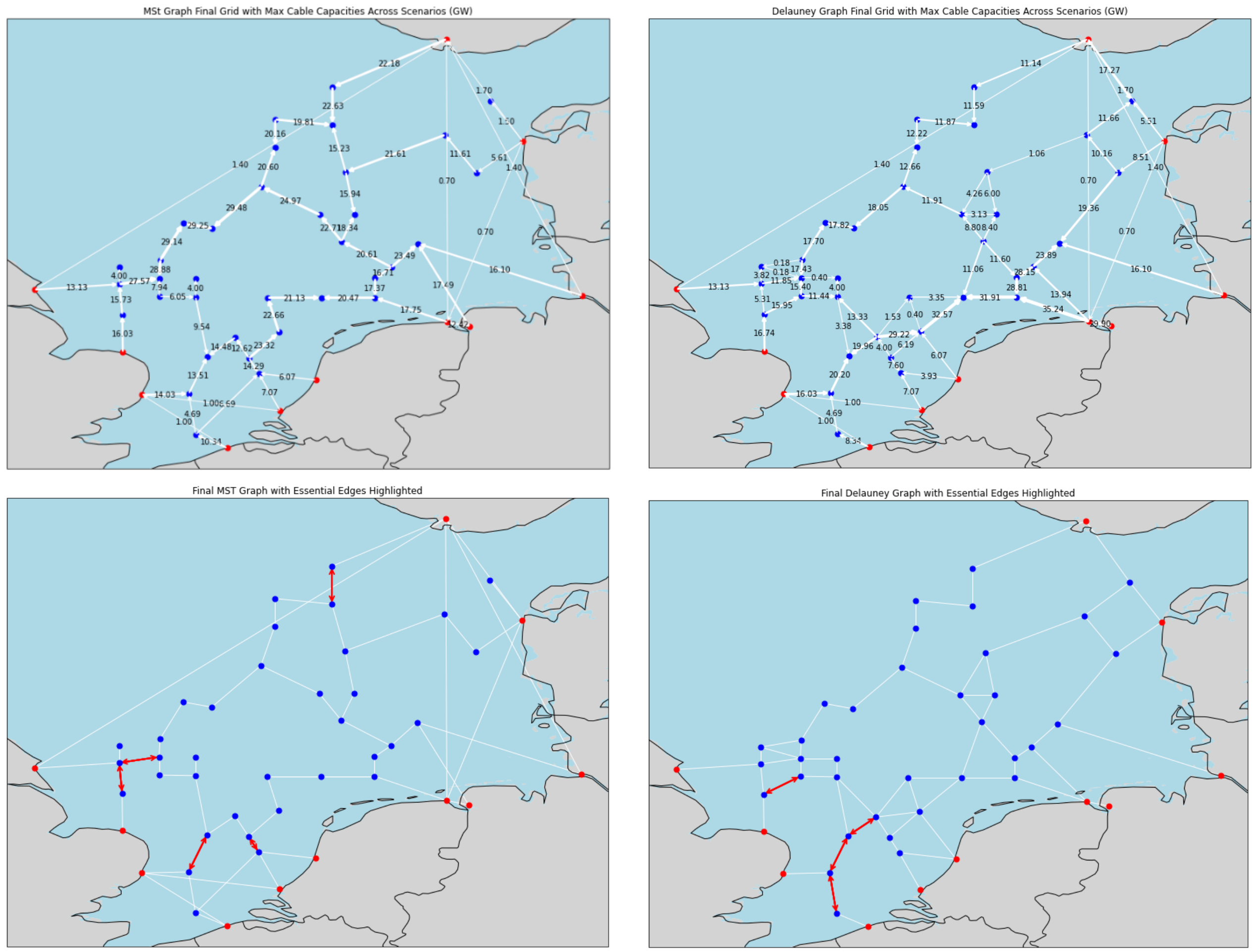

Figure 19: Final MST and Delauny model capacity and essential edges

Scenario 3: Large build out

After running the model with the average demand factors and a weather factor of 0.65 we get as a result that there is 58.373 GW of excess electricity. Thus, for this scenario hydrogen capacity should have around 58.373 GW of electrolysis capacity.

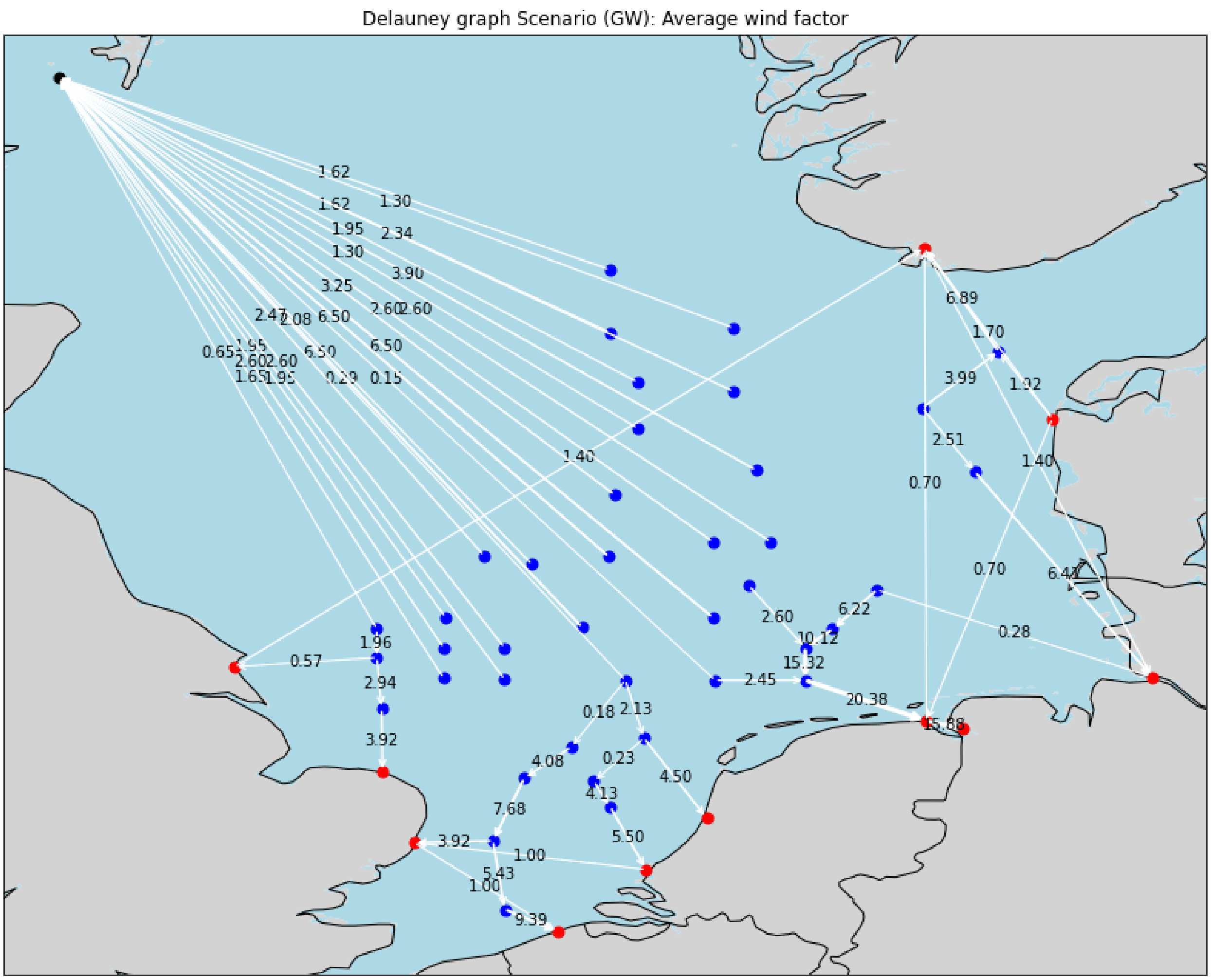

Figure 20: excess electricity production for hydrogen generation

In figure 20 we see the parks that generate this excess electricity. With the excess electricity of each park in this scenario, we determine which parks will get 2 GW, 4GW or 6GW of hydrogen generation capacity.

Table 26: Hydrogen generation capacity and hubs

Hydrogen Capacity	# of Parks	Installed hydrogen capacity

(GW)		(GW)
2	9	18
4	5	20
6	3	18
Total	17	60

As we can see in table 26, there are various nodes which are suitable for each of the generation capacity. These 17 locations of hydrogen production have a combined generation capacity of 60 GW. The specific hubs assigned electrolysis capacities of 2, 4, or 6 GW can be found in Appendix B. Now that we have located and added the hydrogen hubs we can start running the scenario. Firstly, we will determine the optimization factor for the Delaunay network. When the optimization factor is increased to 50, we find the shortest possible network, which is 4003 km. When we change the factor to 2.5 we gain a network of 6022km. This satisfies the 1.5 times size difference discussed in part 6.2.2. about the Delaunay triangulation method.

In table 27 the results of the model are visualized. We can see In table 27 that the Delaunay network has a lower diameter, higher total length, higher total capacity and that both designs are as vulnerable to edge failures. This is most likely due to the larger electricity flows throughout the network. In figure 21 both the edges capacity and essential edges are visualized. We see that in this scenario all edges are essential for the function of the model, the reason for this will be analyzed in the second part of this chapter

Table 27: scenario model results

	Delaunay	MST	differences
Diameter	1173 km	1353 km	+15.3%
Total length	6022 km	4830 km	-19.8%
Total capacity	1020.567 GW	892.826 GW	+ 4.3%
Hydrogen capacity	115.102 GW		N/A
Number of essential edges	52	41	1
Essential edges percentage	100 %	100 %	0 %

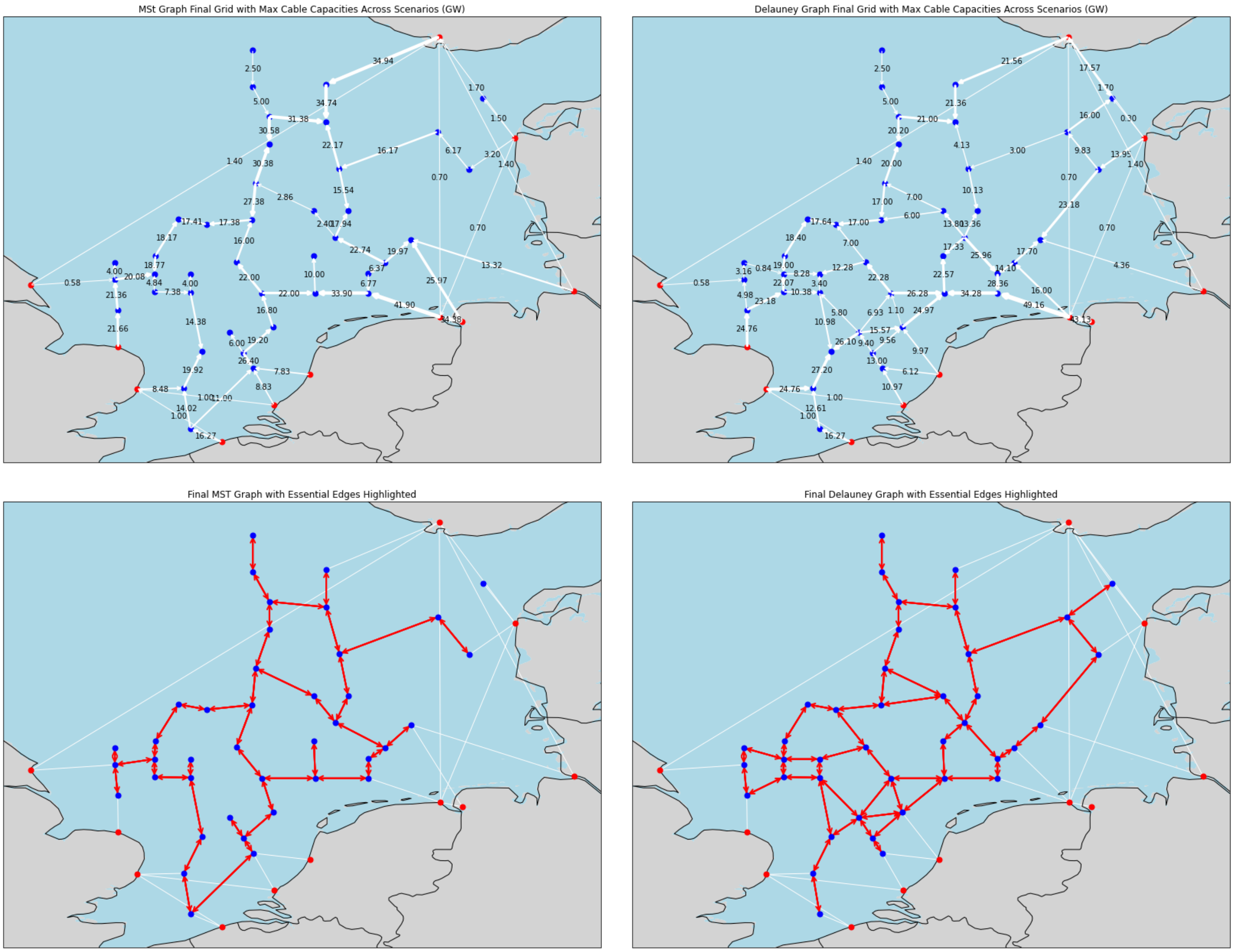

Figure 21: Final MST and Delauny model capacity and essential edges

Scenario 4: Small onshore

after running the model with the average demand factors and a weather factor of 0.65 we get as a result that there is 85.685 GW excess electricity. Thus for this scenario hydrogen capacity should have around 85.685 GW of electrolysis capacity.

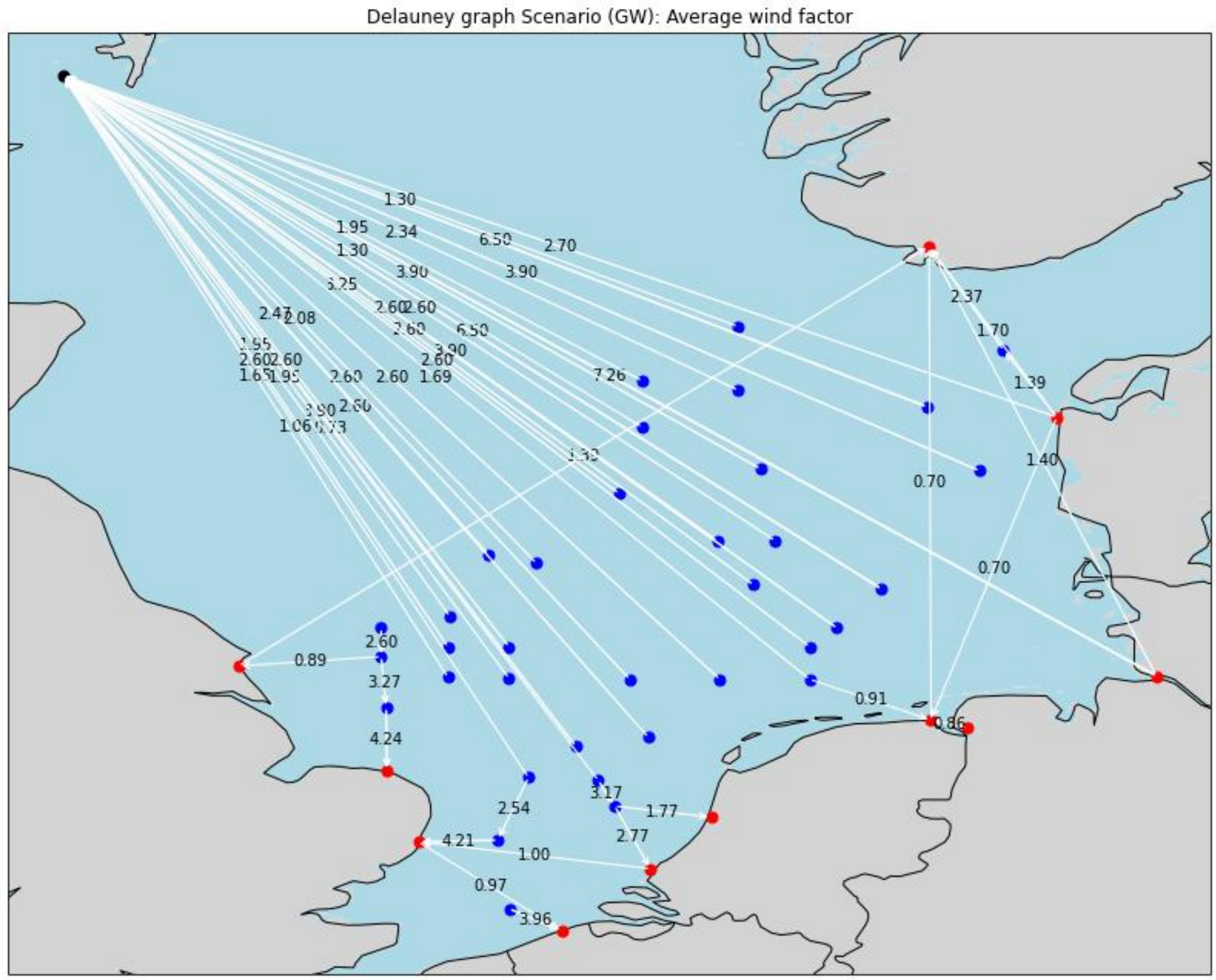

Figure 22: excess electricity production for hydrogen generation

In this scenario we will divide this 85.685 GW between the landing points, thus the demand at each landing point is increased. The additional electricity demand for electrolysis is 85.685 GW / 11 = 7.790 GW per landing point.

Table 28: landing points and electrolysis capacity

Country	Name	electrolysis capacity (GW)
Belgium	Wenduine landing	7.790
Denmark	Ferring landing	7.790
Germany	Emden landing	7.790

Germany	Büttel-Hamburg landing	7.790
Netherlands	Tweede maasvlakte landing	7.790
Netherlands	Ijmuiden Tata Steel landing	7.790
Netherlands	Eemshaven NorNed cable landing	7.790
United Kingdom	Cromer landing	7.790
United Kingdom	Leiston landing	7.790
United Kingdom	Ulrome landing	7.790
Norway	Feda landing	7.790

Firstly, we will determine the optimization factor for the Delaunay network. When the optimization factor is increased to 50, we find the shortest possible network, which is 3741 km. when we change the factor to 2.8 we gain a network of 5687km. This satisfies the 1.5 times size difference discussed in part 6.2.2. about the Delaunay triangulation method.

In table 29 the results of the model are visualized. We can see In table 29 that the Delaunay network has a lower diameter, higher total length, lower total capacity and is more resistant to edge failures, the exact essential edges for both the MST and Delaunay graph can be seen in figure 23 .we see that the essential edges are located in the same place in both the MST and Delaunay network, from Belgium to the north, in the area of the United Kingdom to the east. And the cable connecting Norway to the network. Just as in previous scenarios, we see that in the case of Norway an additional cable is needed to prevent Norway being cut off completely in the case of cable failure.

Table 29: scenario model results

	Delaunay	MST	differences
Diameter	1235 km	1318 km	+10.1%
Total length	5687 km	4492 km	-21.0%
Total capacity	892.216 GW	908.81GW	+ 4.3%
Number of essential edges	3	3	0
Essential edges percentage	6.67 %	13.89 %	5.35 %

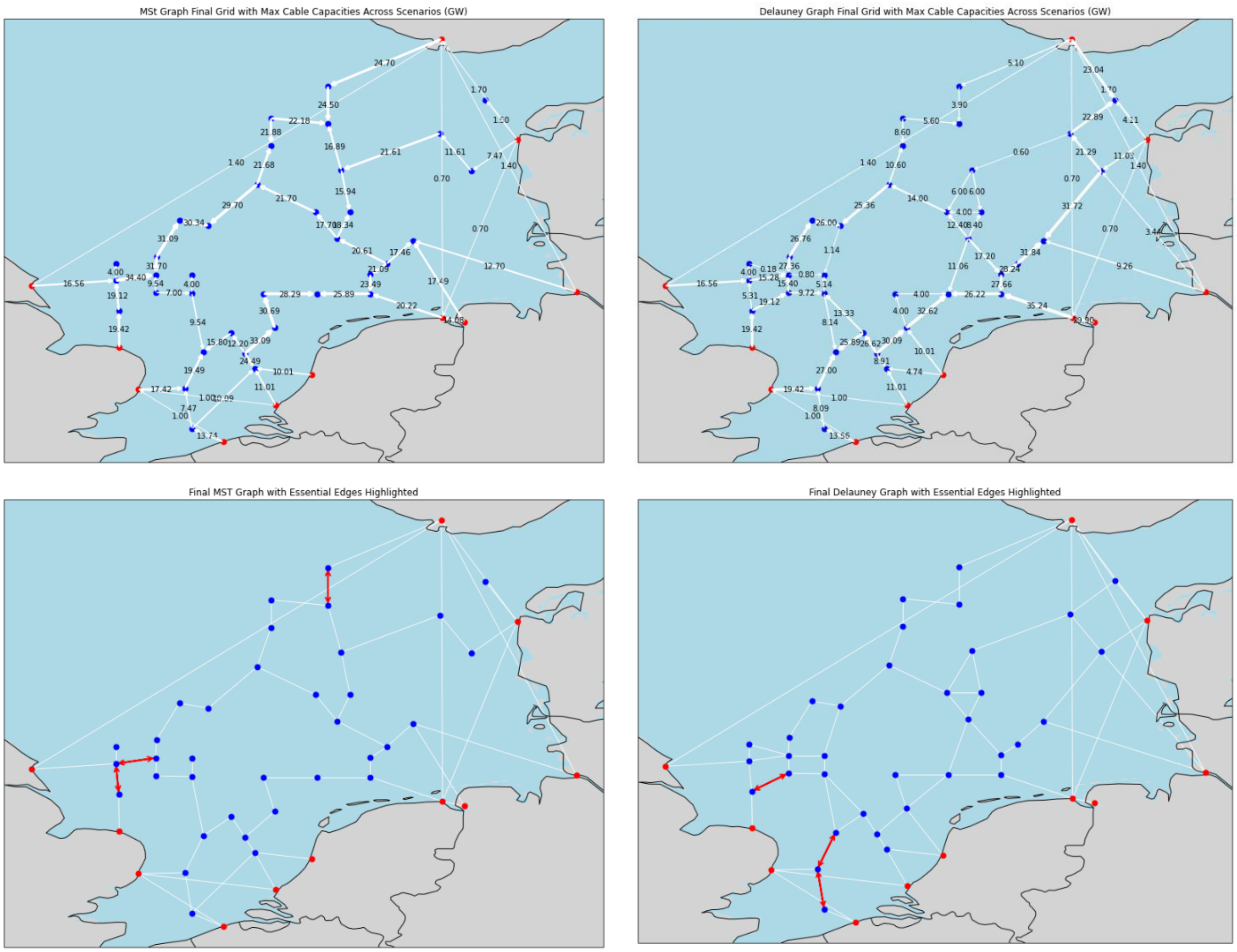

Figure 23: Final MST and Delauny model capacity and essential edges

Scenario 6: Large onshore

after running the model with the average demand factors and a weather factor of 0.65 we get as a result that there is 58.373 GW excess electricity. Thus for this scenario hydrogen capacity should have around 58.373 of electrolysis capacity.

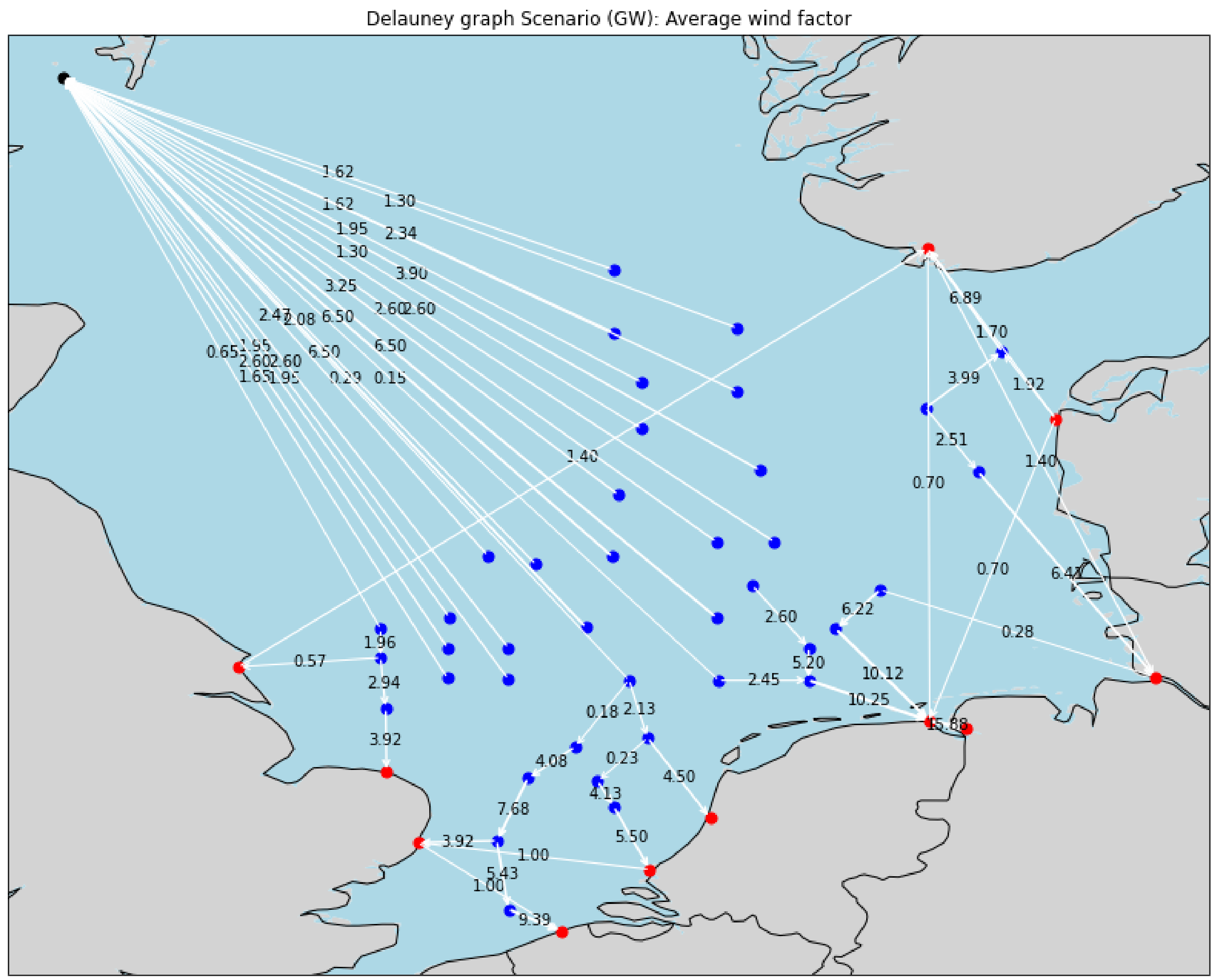

Figure 24: excess electricity production for hydrogen generation

In this scenario we will divide this 58.373 GW between the landing points, thus the demand at each landing point is increased. The additional electricity demand for electrolysis is 58.373 GW / 11 = 5.310 GW per landing point.

Table 30: landing points and electrolysis capacity

Country	Name	Hydrogen generation capacity (GW)
Belgium	Wenduine landing	5.310
Denmark	Ferring landing	5.310
Germany	Emden landing	5.310
Germany	Büttel-Hamburg landing	5.310
Netherlands	Tweede maasvlakte landing	5.310
Netherlands	Ijmuiden Tata Steel landing	5.310
Netherlands	Eemshaven NorNed cable landing	5.310
United Kingdom	Cromer landing	5.310
United Kingdom	Leiston landing	5.310
United Kingdom	Ulrome landing	5.310
Norway	Feda landing	5.310

Firstly we will determine the optimization factor for the Delaunay network. When the optimization factor is increased to 50 we find the shortest possible network, which is 4003 km. when we change the factor to 2.5 we gain a network of 6022km. This satisfies the 1.5 times size difference discussed in part 6.2.2. about the Delaunay triangulation method.

In table 31 the results of the model are visualized. We can see In table 31 that the Delaunay network has a smaller diameter, higher total length, and higher capacity and that both designs are as vulnerable to edge failures. This due to the situation that the demand is significantly higher than the installed capacity in the various weather scenarios. This has resulted in that the network is working as a more traditional park to country model, instead of a model in which electricity is mostly transported between countries. This leads to lower needed edge capacities as in the various weather scenarios the electricity flows between countries are diminished. Just like in the previous scenario. This effect has also caused the increase of needed capacity in the Delaunay network compared to the MST, as the network prefers the to use the many short connections with high capacity. And these connection primarily are located between hubs of a country, as can be seen in figure 25. We see that in this scenario all edges are essential for the function of the model, the reason for this will be analyzed in the second part of this chapter

Table 31: scenario model results

	Delaunay	MST	differences
Diameter	1173 km	1353 km	+ 15.3%
Total length	6022 km	4830 km	-19.8%
Total capacity	1050.456 GW	916.927 GW	+ 4.2%
Number of essential edges	52	41	9
Essential edges percentage	100 %	100 %	0 %

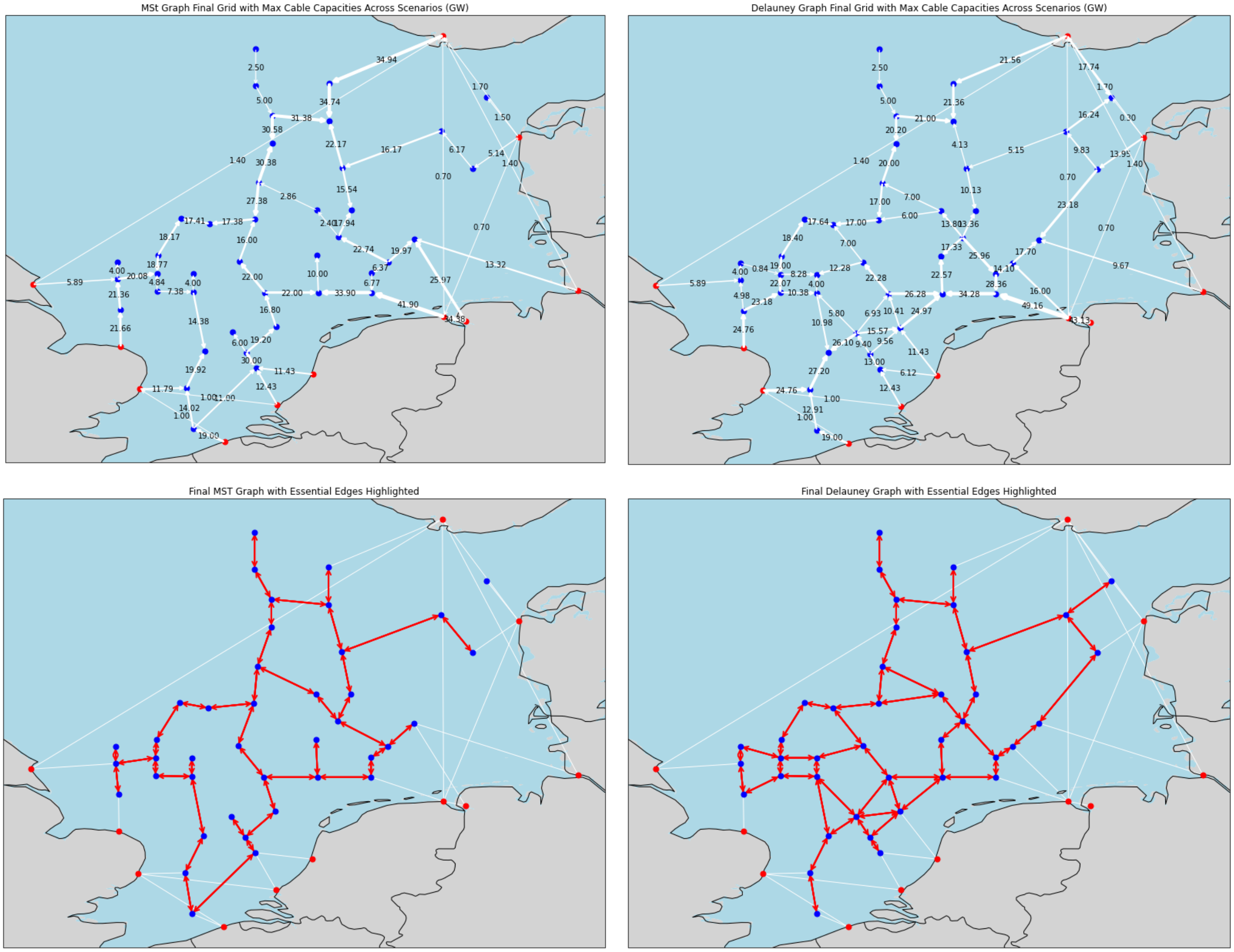

Figure 25: Final MST and Delauny model capacity and essential edges

Scenario 8: Many islands

after running the model with the average demand factors and a weather factor of 0.65 we get as a result that there is 97.703 GW excess electricity. Thus for this scenario hydrogen capacity should have around 97.703 GW of electrolysis capacity.

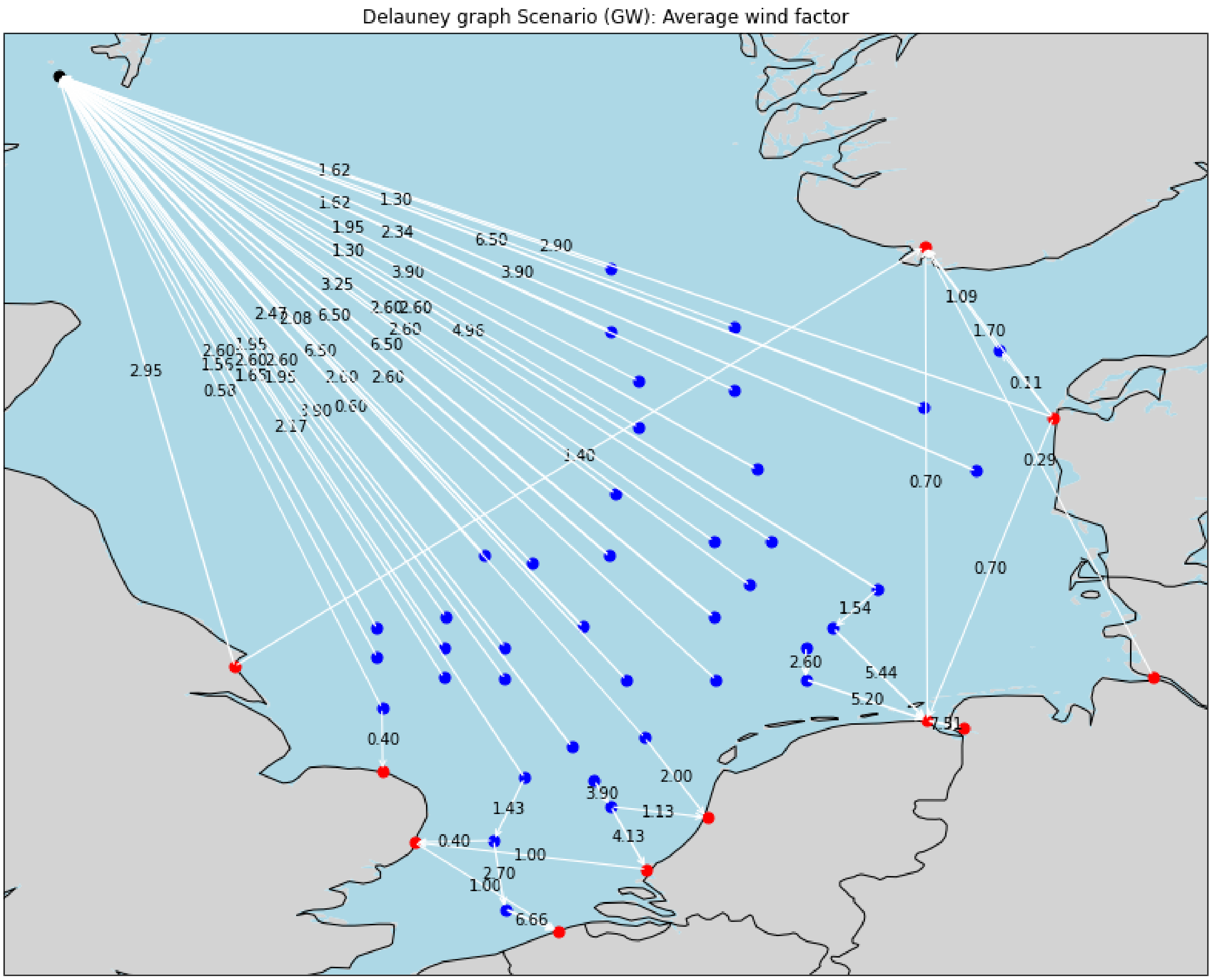

Figure 26: excess electricity production for hydrogen generation

In figure 26 we see the parks that generate this excess electricity. With the excess electricity generation of each park in this scenario, we determine which parks will get 6GW of hydrogen generation capacity.

Table 32: Hydrogen generation capacity and hubs

Hydrogen Capacity per island (GW)	# of Parks	Installed hydrogen capacity (GW)
6	16	96

As we can see in table 32, there are various nodes which are suitable for the electrolysis capacity of 6 GW. These 16 locations of hydrogen production have a combined generation capacity of 96 GW. The specific hubs assigned electrolysis capacity of 6 GW can be found in Appendix B. Now that we have located and added the hydrogen hubs we can start running the scenario. Firstly we will determine the optimization factor for the Delaunay network. When the optimization factor is increased to 50 we find the shortest possible network, which is 4003 km. when we change the factor to 2.6 we gain a network of 6048 km. This satisfies the 1.5 times size difference discussed in part 6.2.2. about the Delaunay triangulation method.

In table 33 the results of the model are visualized. We can see In table 33 that the Delaunay network has a lower diameter, higher total length, lower total capacity and is more resistant to edge failures, the exact essential edges for both the MST and Delaunay graph can be seen in figure 27 .We see that the essential edges are located in roughly the same place in both the MST and Delaunay network, from Belgium to the north, in the area of the United Kingdom to the east. And in the case of the MST the cable connecting Norway to the network. Just as in previous scenarios, we see that in the case of Norway an additional cable is needed to prevent Norway being cut off completely in the case of cable failure.

Table 33: scenario model results

	Delaunay	MST	differences
Diameter	1166 km	1353 km	+15.3%
Total length	6048 km	4830 km	-19.8%
Total capacity	1053.374 GW	1112.111 GW	+ 4.3%
Hydrogen capacity	154.554 GW		N/A
Number of essential edges	5	7	2
Essential edges percentage	9.80 %	17.07 %	7.27 %

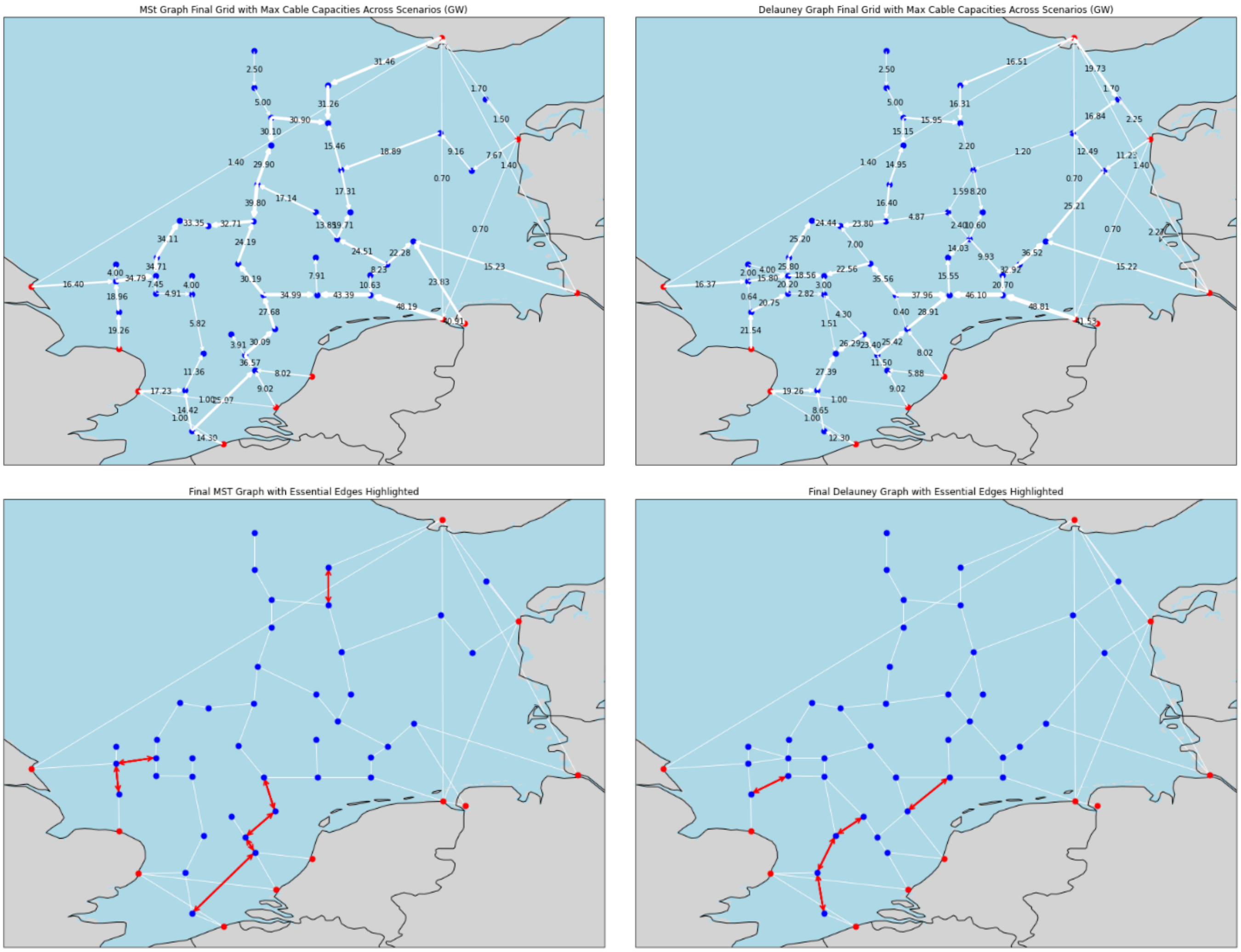

Figure 27: Final MST and Delauny model capacity and essential edges

D. Artificial intelligence statement

for the creation of this thesis artificial intelligence was used. The AI tool used was ChatGPT by OpenAI. This tool was used for three different purposes. Firstly to create text from a writing scheme I created. For example, in the case of the literature review, wrote down the key insights I required from each source, then I ordered them by subject, and then I would put a selection of the sources including the key insights into the AI tool with the assignment for it to create a flowing piece of text. This would give me an initial piece of text for me to work with, this allowed me to skip the often most difficult part of putting the first word on a page. This piece of text could then be easily altered and refined to my specific needs.

The second way that AI was used was during the coding phase of the research. For instance if you get an error and you really have no idea what is causing it? I copied my code into ChatGPT and it was able to find the mistake easily. Additionally it was used as a clever search engine to find functionalities in the various python libraries. For instance I wanted to plot the graphs on an accurate map of the North Sea region. I presented this wish to the AI tool and it explained about the Carthopy tool in python, and what inputs it needs and how you can use it. This usage of AI allowed my to better visualize my graphs and it increased the speed of the coding process considerably. However I realized soon in the coding process that the AI tool still has some severe knowledge gaps regarding the various algorithms. For instance, when creating the edge weights I used the length of the edges as weights for the network simplex algorithm. When I would run my model the algorithm which should work in just a few seconds would then be running for dozens of minutes with no sign of ever stopping and returning the results. When consoling the AI tool about the problem it gave various fixes, but none of these fixes was able to solve the problem. When looking at the working of the algorithm I found out that if the edge weights are not whole integers the algorithm could get stuck in a loop and run forever. When I altered my code to make sure the edge lengths were rounded to the next integer the problem was fixed.

The final way I used AI was for controlling spelling and grammar. For instance, if I was unhappy about a sentence because it was too long or the flow in the sentence was off, I would then put the sentence into the AI tool and order it to give me 3 variations of the sentence. These sentences the AI tool generated would often still be not what I was looking for, however doing this did give me inspiration for rewriting and altering the sentences.