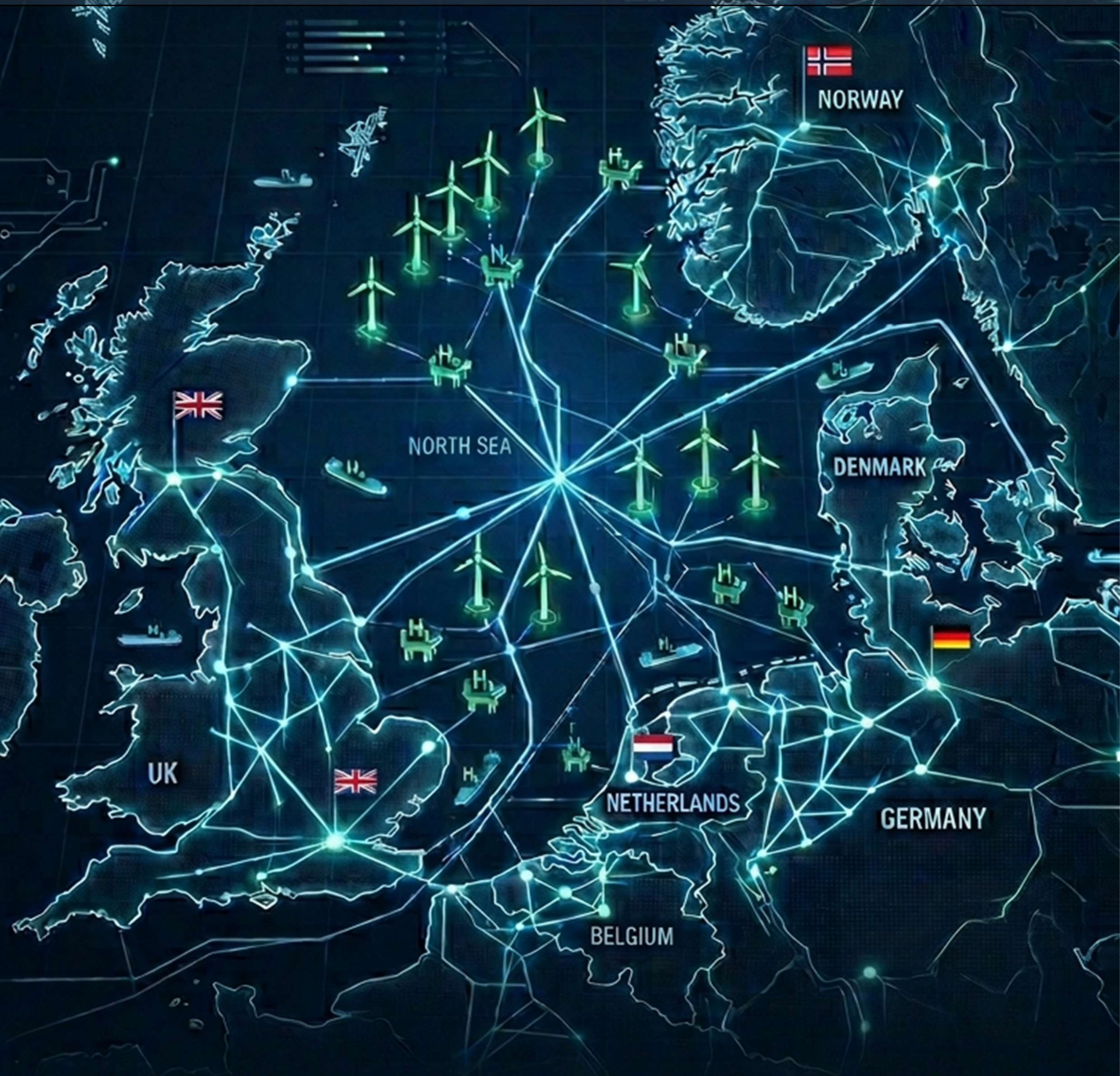
EXPLORING THE EVOLUTION OF OFFSHORE WIND BASED HYDROGEN TRANSPORT PIPELINE NETWORK IN THE NORTH SEA



Master Thesis Report – Complex Systems Engineering and Management

Ligin George Thomas

For this thesis, Large Language Models such as ChatGPT was used as a supporting tool during various stages of the study. Gemini was used to generate the cover image. LLMs were used as a supporting tool for improving the Python code, summarizing contents and to re-structure and refine the texts for improvement. The output of the LLM tools were critically reviewed by the author and adapted accordingly to ensure the analytical and academic level of this thesis. The full responsibility of the content of this thesis remains with the author.

Exploring The Evolution Of Offshore Wind Based Hydrogen Transport Pipeline Network In The North Sea

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

(Track – Energy)

Faculty of Technology, Policy and Management

by

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ACKNOWLEDGEMENT

The title of my master thesis is “Exploring the evolution of offshore wind based hydrogen transport pipeline network in the North Sea”. This thesis report represents the conclusion of my Master Thesis which I have spent half a year working on. This final work concludes the educational and exciting time I had at Delft University of Technology. The Master Program - Complex Systems Engineering and Management – Energy Track interested me highly even before I joined as a student at the Faculty of Technology, Policy and Management. The excitement and joy in the pursuit of excellence through this program has not diminished even minutely from the beginning till the end. TU Delft and the community showed me excellence in achieving the best in all the circumstances both on an educational level and personal level. My thesis and the amazing experience at TU Delft would not have been the same without the following people to whom I would like to express my gratitude.

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EXECUTIVE SUMMARY

The North Sea has the potential to become Europe's most important renewable energy hub with its ambitious offshore wind expansion target of up to 300 GW offshore wind capacity by the year 2050. Beyond electricity generation, this vast offshore wind potential creates the opportunity to produce large quantities of green hydrogen and to develop a dedicated offshore hydrogen transport infrastructure. This thesis addresses the main research question of how an offshore wind based hydrogen transport pipeline network may evolve in the North Sea. In order to answer this question, this study integrates offshore wind farm deployment analysis, hydrogen production estimations, transport capacity assessments, infrastructure budgeting consideration and dynamic network evolution modelling across multiple North Sea regions.

An evaluation of offshore wind development projects demonstrates that there are around 215 offshore wind farms totalling approximately 237 GW of offshore wind capacity which are either in operational, consented or in the planning stage across the North Sea basin. The United Kingdom and Germany are currently leading in installed capacity, followed by the countries of Netherlands, Belgium, Denmark, Norway and France. A large share of this identified wind capacity remains within the development zones which extends to the year 2050. This reflects both the strong political ambition and the significant uncertainty that remains regarding realization timelines. If full deployment is taken into considerations, the offshore wind farms have the potential to significantly transform the North Sea into Europe's "Green Power Plant". This transformation could enable both direct electricity exports and large scale hydrogen production.

Hydrogen production potential depends strongly on the electrolyser configuration and operational assumptions. Using representative case studies and extrapolating the results to the full offshore wind portfolio, annual hydrogen potential of the North Sea is found to be ranging between approximately 20 million tonnes and 27 million tonnes which also depend on whether alkaline (AE), proton exchange membrane (PEM), or solid oxide electrolysis (SOEC) technologies is deployed. SOEC demonstrates the highest theoretical production potential under assumed conditions. Even though the actual output will be determined by wind variability, operational flexibility and system integration constraints, these results provides an upper bound estimate which is suitable for strategic infrastructure planning. The scale of this production implies the substantial offshore hydrogen transport pipeline size requirements, with individual 600 MW wind farms requiring approximately DN200 pipelines and 1 GW installations requiring DN250 pipelines. Aggregated flows which may connect multiple wind farms or clusters will need large trunk lines potentially exceeding DN600. Investment capacity will further constrain the infrastructure development, with realistic annual offshore hydrogen pipeline budget estimated between EUR 2 Billion and EUR 8 Billion corresponding to roughly 400 km to 1600 km of pipeline construction per year.

To explore how such infrastructure could evolve under the constraints of participation, coordination and availability, a network based modelling framework was developed using NetworkX which is a python package for developing and studying the complex network systems. Offshore wind farms in the model were represented as hydrogen source nodes and demand centers as sink nodes which are connected through candidate pipeline edges. Network evolution was simulated across multiple North Sea regions of UK, France, Belgium, Netherlands and Norway over three time periods 2030, 2040 and 2050. The model evaluates infrastructure growth using four key metrics which includes, Total Pipeline Length (TPL), Average Source Sink Distance (ASSD), Fraction of Network Grown (FNG) and Delivered Hydrogen Potential (DHP). Pipeline prioritization in the model incorporates network metrics such as betweenness centrality, supply weighted flow, Euclidean distance and closeness centrality to ensure

that infrastructure investments reflect system wide efficiency, production relevance, spatial feasibility and accessibility. Multiple scenario classes were examined including balanced baseline growth with no dominant objective and full availability, random source selection to take into account of stochasticity, nearest neighbour source selection to consider regional coordination, availability constrained development (25%, 50% and 75%) to see effect of participation and availability followed by the project Improvement scenario with increasing availability over time due to learning effects and policy support.

Across different regions in multiple countries, network evolution shows consistent structural patterns. In regions which have early source activation, the total pipeline length and hydrogen delivery increases sharply between the years 2030 and 2040, followed by stabilization as the network approaches saturation by the year of 2050. In contrast, regions with late activation demonstrates more gradual incremental growth with significant infrastructure expansion occurring after the year 2040. Under the Balanced Baseline Scenario in which there is no single dominating objective, the total pipeline length increases steadily as new sources are integrated, while the average source to sink distance grows moderately as more distant sources connect to demand centers. The delivered hydrogen potential rises in parallel with expanding connectivity which confirms that the physical network growth directly translates into operational capacity. Over time, the fraction of network grown declines as expansion slows down and the system stabilizes.

Comparing the results of different source selection strategies reveals that the nearest neighbour selection strategy that gives priority to geographically closer production centers, generates networks that are nearly identical to the balanced baseline which indicates that the spatial proximity largely governs efficient network development. Random source selection strategy which incorporates stochasticity slightly accelerates early growth in some regions but it introduces variability without materially improving the long term outcomes. On the other hand, availability constraints strongly shape the network evolution. Lower availability fractions significantly reduces early TPL, ASSD and DHP which limits expansion and slows down the system maturation. As the availability increases, the network growth converges toward baseline levels. The project improvement scenario which gradually increases availability from 25% in 2030 to full activation by 2050 incorporates learning effect, technological maturity and policy support generates the most realistic development pathway, with phased expansion of both infrastructure and delivery capacity. This staged growth prevents excessive early overbuilding of the system while enabling long term system integration.

From the analysis and results, it has been observed that overall, the offshore wind based hydrogen pipeline network in the North Sea is very likely to evolve incrementally. Early regional clusters forms around active wind farms and demand centers. This is followed by the progressive interconnections as additional sources come online and trunk pipelines are reinforced. The network structure is strongly influenced by source availability and activation timing rather than by specific source selection algorithms. The available budget and physical pipeline capacity requirements will further influence the pace of expansion. Provided there are sufficient regional coordination, policy support and adequately budgeted development environment, the North Sea demonstrates the potential to be an integrated hydrogen transport network system that is capable of delivering up to 27 million tonnes of green hydrogen annually by the year of 2050. The evolution of this network will critically depend on synchronised offshore wind deployment, electrolyser technology choices, phased infrastructure investment and strategic system level planning across national boundaries.

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ACRONYMS

GHG – Green House Gas
AE – Alkaline Electrolysis
PEM – Proton Exchange Membrane
SOEC - Solid Oxide Electrolysis
EU – European Union
LOHC – Liquid Organic Hydrogen Carriers
NSEC – North Seas Energy Cooperation
EHB - European Hydrogen Backbone
TPL - Total Pipeline Length
ASSD - Average Source Sink Distance
FNG - Fraction of Network Grown

1. INTRODUCTION

This chapter introduces and delineates the problem after which the research objective is identified and defined.

1.1 – Problem Statement and Research Objective

Energy consumption has increased dramatically worldwide in recent decades driven by population growth and industrial development. The increase in energy demand is currently met in majority by the combustion of depleting fossil fuels which releases greenhouse gases (GHG) into the atmosphere thereby contributing towards global warming and air pollution. There is an urgent need to limit the rise in global temperature to under 1.5^{0}C in order to prevent irreversible climate impact on the global ecosystem(Mudhafar et al., 2025). Thus, fossil fuel depletion and the urgent need to reduce GHG emissions necessitates rapid transformation of the energy system by transitioning from fossil based energy sources into environmentally acceptable and low carbon intensive energy sources such as renewables(Vreeburg & Garcia-Navarro, 2025).

The main challenges with renewables are that they are intermittent and subject to weather conditions, for eg. solar irradiation and wind availability. In addition to these challenges, large volume of land resources needs to be occupied to install these systems due to which they often have limited public support(Glaum et al., 2024). Nevertheless, offshore wind farms are getting more attention in the recent years due to its ability to harness better wind resource above sea with higher wind speeds and location far from valuable land resources(Y. Wang et al., 2025). Yet the intermittent nature of offshore wind farms which are subjected to weather conditions doesn't always coincide with the electricity demand which means that it produces more power during weak demand or doesn't produce enough power when the demand is high. Another challenge is that the produced electricity is difficult to store economically and require expensive storage solutions for supplying later. This calls for an energy carrier which removes the constraints of fluctuations and can be stored. Hydrogen is a promising energy solution which is a good alternative to fossil fuels (Y. Wang et al., 2025) with high specific energy of 142 MJ/Kg (Joyo et al., 2025) and particularly relevant for sectors that are difficult to electrify(Glaum et al., 2024) and hard to abate such as steel making, aviation, industries and as feedstock for chemical industries(Franco et al., 2021; Singlitico et al., 2021). Both offshore wind energy and hydrogen are GHG emissions free and offers significant synergies together.

Hydrogen can be produced by number of ways such as natural gas reforming, water electrolysis and coal gasification(Lei et al., 2024). While natural gas reforming and coal gasification produces significant amount of GHG emissions, only water electrolysis is GHG emissions free which makes it an excellent choice to combine with offshore wind energy. Hydrogen may be produced directly by utilizing the generated electricity in the wind farm or partly produced when there is excess capacity of electricity.

The number of offshore wind farms in the EU is rising, see Figure 1 .The European Union (EU) envisions that around 300 GW of Offshore Wind will be deployed by 2050 predominantly in the North Sea(Vreeburg & Garcia-Navarro, 2025). A significant number of offshore wind farms are thus planned in the North Sea. Equipping hydrogen production with water electrolysers in these offshore wind farms is key to producing sufficient hydrogen to meet the increasing energy and feedstock demands mentioned earlier. The produced hydrogen needs to be transported to the demand centers on shore where it is consumed. Two main options for transporting hydrogen are ships and pipelines. Ships however can only transport limited load and therefore is not suitable to meet the high demand. Pipelines on the other hand can supply large volumes to meet the increasing demands and also offers line-pack storage(Dute et al., 2024).

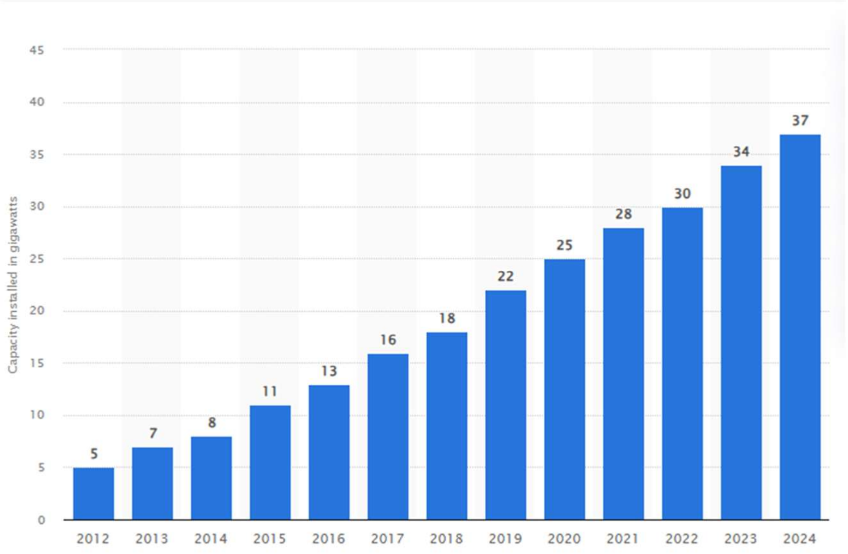


Figure 1 - Offshore Wind Capacity installation in Europe (Source - Statista 2026)

While there is clarity on the offshore wind farm developments in the North Sea, there is limited information and understanding on the development of a pipeline network system to transport the produced hydrogen back on shore. The situation is more complex as the windfarms have different production capacities, located far from each other, with different electrolyser types possible and belongs to different countries.

The development of offshore hydrogen pipeline infrastructure is a long term and capital intensive undertaking that requires strategic planning under substantial uncertainty. Key uncertainties arise from the speed at which the wind farms are deployed, the spatial distribution of offshore wind farm deployment, the timing and scale of hydrogen demand growth across different sectors and evolving policy, regulatory and market frameworks. The scale and location of hydrogen production over time is further influenced by technological advancements in electrolyser efficiency, capacity and cost reduction. Considering the long operational lifetimes and high upfront costs associated with pipeline infrastructures, early stage planning decisions will have lasting impacts on system performance and cost efficiency which will potentially lead to lock in effects constraining future expansion options.

Conventional infrastructure planning approaches often relies on static or single stage designs that assumes a fixed set of production and demand nodes. However, offshore hydrogen transport systems in the North Sea could emerge and expand incrementally. As new offshore wind farms are commissioned and hydrogen production capacities increase, it will result in the requirement of additional pipeline connections and capacity reinforcements. This evolutionary development could fundamentally alter network topology, flow distribution and utilization patterns over time. Further, infrastructure designed for early deployment stages could become sub optimal or under utilized as the system expands, highlighting the need for planning frameworks that explicitly considers network evolution rather than static end state designs.

Due to the international nature, North Sea presents a particularly complex environment for offshore hydrogen infrastructure. Offshore wind farms and prospective hydrogen pipelines lies across the jurisdictions of multiple countries. These countries have distinct national energy strategies, regulatory regimes and hydrogen market development plans. More importantly, there are differences in permitting processes, cost allocation mechanisms, and infrastructure ownership models which introduces additional layers of complexity for coordination across multiple border pipeline networks.

In addition to that, national priorities regarding domestic hydrogen use versus export can influence pipeline routing and capacity decisions. Therefore, the geopolitical and institutional factors could shape the evolution of hydrogen pipeline network over time.

In addition to the above mentioned challenges, there is spatial mismatch between offshore hydrogen production and onshore demand centers which can significantly influence the network design. While offshore wind farms are geographically dispersed across the North Sea, hydrogen demand is typically concentrated in specific industrial clusters, ports and energy hubs along the coast or inland. As the demand patterns changes and new hydrogen applications emerge, the relative importance of different demand centers will also likely change. Designing a pipeline network that can flexibly accommodate shifting supply demand relationships is therefore a crucial challenge in long term infrastructure planning.

The interaction between hydrogen production, transport capacity and demand further complicates the network evolution. The location and sizing of offshore electrolysers will also influence hydrogen flow volumes and temporal variability which in turn affect pipeline utilization and operational efficiency. Decisions regarding centralized versus distributed hydrogen production, as well as timing of the electrolyser deployment can lead to fundamentally different network configurations. These interdependencies underscore the importance of system level analysis which jointly considers production, transport and demand rather than treating them as independent planning problems.

Despite the strategic importance of offshore wind based hydrogen systems, there is limited understanding of how an offshore hydrogen pipeline network in the North Sea could evolve over time in response to the technical, spatial and institutional challenges. Existing studies focuses on isolated components or they assume static infrastructure layouts which provides limited insight into the long-term implications of incremental expansion as well as early investment decisions. Addressing this gap requires an explicit focus on the evolutionary development of pipeline network by taking into account of uncertainty, cross border interactions and the dynamic interplay between offshore hydrogen supply and onshore demand.

In light of the technical, spatial and institutional complexities associated with offshore wind based hydrogen transport system in the North Sea, this study aims to investigate the evolutionary development of an offshore hydrogen transport pipeline network under conditions of uncertainty.

Specifically, the research objective is to analyse and evaluate how the pipeline network, topology, capacity expansion and infrastructure investment decisions evolves over time in response to the phased deployment of offshore wind farms, the growth of hydrogen demand and cross border spatial constraints.

By adopting a dynamic perspective rather than a static end state design, this goal of this study is to identify efficient and flexible evolution pathways that minimizes long term system costs while reducing the risk of infrastructure lock in.

1.2 – Relevance to CoSEM

The Master's program in Complex Systems Engineering and Management with Energy Track at TU Delft teaches students to design innovative interventions in complex socio-technical systems in the real world such as large energy infrastructures. The problem that has been identified in the study, which is to understand the evolution of offshore wind farm based hydrogen pipeline transport network in the North Sea, is a complex socio-technical system with a variety of actors (multiple TSOs, countries), technologies (different production systems) and institutions (standards and directives etc). The hard to abate industries such as chemical industry, steel making and aviation etc cannot rely on electricity alone but sustainable fuel such as hydrogen which is now produced on shore and by non renewable sources and processes. Thus, meeting this demand is societally relevant with the inevitable need to transition to low carbon economy. This fits with the goal of CoSEM program to design innovative interventions for Complex Socio-Technical Systems with networked characteristics in the energy sector.

Transforming the current offshore windfarms to produce and transport hydrogen is a complex endeavour and transporting the produced green hydrogen efficiently is critical to meet the demands of the industries. This study is about proactively understanding how an offshore hydrogen pipeline may evolve in the North Sea. Strong coordination will be required between various actors and multiple countries to enable the development of the pipeline network.

Utilising the lessons learnt in CoSEM program, particularly the course on Design in Networked Systems (SEN 1241) and insights from Complex Systems Engineering (SEN1121), the complex offshore wind farm based hydrogen pipeline network can be studied and analysed to understand the evolution and it can be the starting point for network planning in the real world.

1.3 – Thesis Structure

The study is structured as follows. Starting with literature review, the knowledge gap is identified. The following chapter is Research Design with Main Research Question, Sub Questions and the Research Methodology. This is followed by the chapter on system decomposition where the main components of the offshore wind based hydrogen transport pipeline system is explored. Post the exploration of system components and the integrated system, a conceptual model is developed in the following chapter. Then the model is implemented in NetworkX to study the network evolution of the offshore hydrogen transport pipeline. Experiments are further designed to explore different scenarios and pathways followed by the results of the experiments. Discussion chapter looks into broader implication, stakeholder values and what the results mean for the hydrogen infrastructure planning in the larger system. The main research question is then answered in the Conclusion chapter along with scientific and societal relevance of this study.

- Having defined the problem which is the limited understanding of the development and evolution of an offshore hydrogen transport pipeline network in the North Sea, the research objective has been defined which is to investigate the evolutionary development of the offshore hydrogen transport system. The problem now needs to be looked into more detail in the literature and the knowledge gap have to be identified which will be performed in the next chapter.

2. LITERATURE REVIEW

This chapter provides a more detailed understanding of the problem for research. Beginning with a comprehensive review of existing research on central concepts, knowledge gaps are identified.

An extensive literature review has been executed to explore the existing research and knowledge gaps on Offshore Wind Farm and Hydrogen Pipeline Transportation Infrastructure in SCOPUS, TUDelft Library and Google Scholar databases. “Offshore Wind”, “Hydrogen”, “Pipeline”,“Transportation” and “Infrastructure” were the search terms using keyword “AND”. Further considering the network evolution of infrastructure aspect. The search terms were broadened by adding “Network Evolution” and “Infrastructure”

Search Term	Results in Scopus	Results in Google Scholar	Results in TU Delft Library
Offshore Wind AND Hydrogen AND Transportation	139	50,300	249
Offshore Wind AND Hydrogen AND Transportation AND Infrastructure	30	41,200	75
Offshore Wind AND Hydrogen AND Pipeline	115	27,400	65
Network Evolution AND Infrastructure	6,713	4,370,000	6,800

Table 1 - Search Terms and Results

The Table 1 above shows the number of results obtained which has a decreasing relevancy as results page move forward and after Top 50, most of the results differed vastly from the search terms. Hence the Top 50 relevant results of each category were looked at to be considered as well as to fit with the time constraints of this study. Due to the large volume of articles for “Network Evolution AND Infrastructure” search term, only articles that were relevant and recommended by the project supervisor is considered for the study.

Thus, the total results relevant for the initial screening is 430. The title is studied in the initial screening to exclude articles that were different from search terms and offshore wind based hydrogen transport. 402 articles were excluded after this stage and 28 articles which were related to the search terms or its synonyms were selected for abstract review. The abstract review looked at the articles to find researches related to offshore wind based hydrogen transport and pipeline network system. Of 28, 18 were selected as those articles included studies that considered offshore wind based hydrogen pipeline transportation infrastructure and its development. From the selected articles, using backward and forward snowballing, 5 more articles were discovered that had offshore wind farm based infrastructure design, which brings the total articles to be considered 23. The screening process and article count outcomes are shown in the Figure 2.

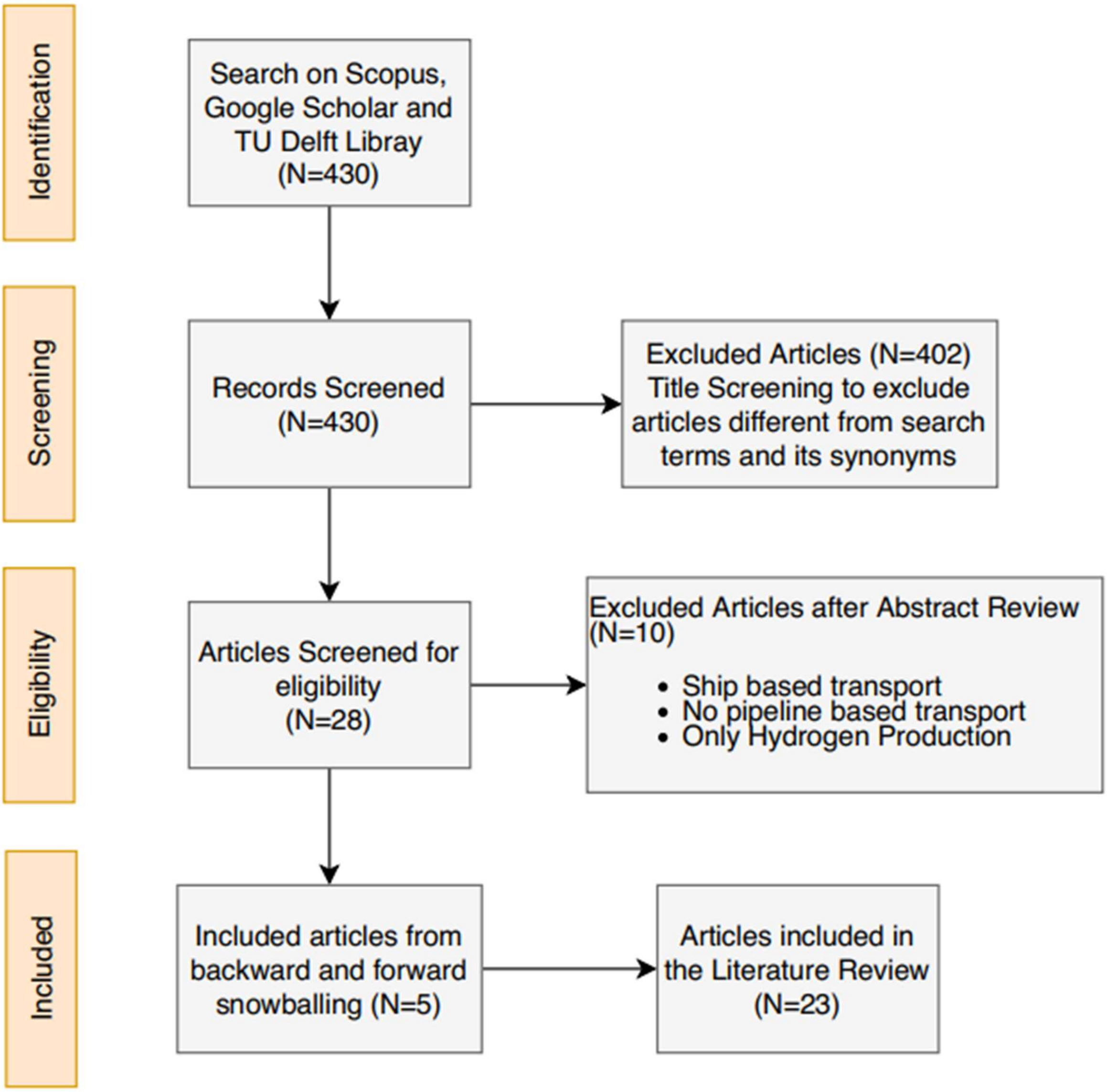


Figure 2 – Literature Screening Process

2.1 - Offshore Wind Hydrogen Transportation Infrastructure

While there is tremendous potential in developing hydrogen production in offshore wind farms, the literature regarding offshore electrolysis for production of hydrogen is limited(Singlitico et al., 2021). There are different electrolyser technologies available for producing hydrogen offshore. (Singlitico et al., 2021) in their study of different electrolysers for offshore application concluded that Alkaline Electrolyser (AE) is the most cost effective. Regarding placement of electrolysers, a comparison was made between in-turbine, offshore and onshore of which offshore placement was the most effective supported by economies of scale. (Singlitico et al., 2021) further underscores that offshore electrolysis has not achieved maturity in terms of required infrastructure especially in Giga Watt (GW) scale deployment.

The contemporary focus nowadays in offshore wind based hydrogen production is to prove the operation and technology readiness in the harsh and difficult offshore environment(Aloigi et al., 2024) and it has to be noted that offshore wind based hydrogen production infrastructure is at infancy(Kumar et al., 2023).

Considering the above, it is also important to underscore that the cost of producing hydrogen by water electrolysis is much higher than the conventional methods, with electricity cost as prime factor while the utilization rate and the demand are the key drivers of economic feasibility for such projects(Kumar et al., 2023). Thus high costs (Mudhafar et al., 2025), market demand and utilization rate are some of the economic challenges faced by offshore wind based hydrogen system. (Glaum et al., 2024) suggests that some of these economic challenges can be alleviated by utilizing a meshed network of hydrogen production from different wind farms thereby better improving economies of scale.

Offshore wind farm based hydrogen production can be of different architectural system which are mainly centralized and decentralized systems(Aloigi et al., 2024). Three different possibilities of configuration were studied by (Travaglini et al., 2025) for their costs and operational characteristics which included Centralized Onshore Electrolysis, Centralized Offshore Electrolysis and Decentralized Offshore Electrolysis. The study finds that Centralized Offshore Electrolysis with specifically Proton Exchange Membrane electrolysis is the most cost-effective configuration for deployment. It is also concurred by (C. Zhang et al., 2024) that centralized is the most applicable configuration for deployment in short to medium distances from onshore and Proton Exchange Membrane as the preferred electrolyser (Mudhafar et al., 2025).

The produced hydrogen has to be transported back onshore for consumption and further processing. Hydrogen can be transported in multiple forms such as compressed hydrogen, liquid hydrogen, hydrogen carriers such as ammonia and liquid organic hydrogen carrier (LOHC)(Giampieri et al., 2024). All these forms of hydrogen requires energy input to compress, liquify or convert into ammonia, methanol or other LOHC. (Giampieri et al., 2024) in their study of different forms for transportation finds that compressed hydrogen is the most cost-effective options for projects starting in 2025.

The produced hydrogen can be transported onshore by different methods such as pipelines and shipping vessels(Varotto et al., 2025). (Franco et al., 2021) studied different pathways to transport produced hydrogen from offshore wind farms in the form of compressed hydrogen, liquid hydrogen and ammonia and finds that the use of pipelines as the best solution especially for shorter distances onshore. This finding is concurred by (Dinh et al., 2024) in their study concluding that hydrogen transmission by pipelines is the most economical. (d'Amore-Domenech et al., 2023) and (Q. Wang et al., 2023) further agrees to the pipeline transportation method as the best option specially for distances up to 500 km. However it has to be underscored that there is no hydrogen pipeline in the subsea existing today (Aloigi et al., 2024). Further there is uncertainty in routing and sizing of pipeline networks as there is no clarity in the demand (Dinh et al., 2024).

Still, a detailed study identifying the possibilities of hydrogen pipeline transport infrastructure network especially in the North Sea with multiple farms and possible connections to different countries is missing (Y. Wang et al., 2025). Based on the case study of North Sea by (Bødal et al., 2024), it has been concluded that different countries take the role for exporting and importing, especially Norway, Denmark and UK as exporters and Germany and Netherlands as importers depending on the price of hydrogen while another study by (Durakovic et al., 2023) claims France, Norway and Germany as the main hydrogen producers. Yet it is not clear how a pipeline network would develop and future studies are required in order to promote the development of offshore wind based hydrogen industry(Y. Wang et al., 2025).

Hydrogen pipeline network from offshore windfarms are networked infrastructure and will evolve depending upon several factors. (Dunn et al., 2016) studied the spatial structure and evolution of such infrastructure networks utilizing clustering algorithms to generate nodal distributions having a variety of characteristics with similar properties to their real-world counterparts. The focus of the study was to generate spatial networks and the algorithm by (Dunn et al., 2016) is based upon a simplified cellular automata that requires only population density for the study area after which the initial conditions regarding the location and radius of the seed nodes of the network was determined. This strategy can be applied to generate hydrogen pipeline transport network possibilities in the North Sea.

In order to plan the development of hydrogen pipeline transport network, it is critical to understand how the network will evolve gradually from one wind farm connecting to multiple wind farms and even countries. Since there are no established subsea hydrogen pipeline network, inspiration can be drawn from other infrastructure networks to study its evolution. (Borgogno, 2025) in their study of High Speed Rail (HSR) network for EU developed an iterative network growth model to understand how the networks are formed which has the highest economic potentials continuously updating network configurations and travel demand patterns subject to budget constraints. Their findings underscore a dynamic interaction between demand, costs and travel time gains thus shaping the networks in three phases which includes expansion between high demand centres, extension of the network and network densification. (Cats et al., 2020) studied the evolution of metropolitan public transport networks to model the growth based on demand and cost function. Their study of the network growth experiments resulted in networks that initially shows an expansion of the network followed by capacity increments in the network and finally new connections that leads to densification of the network. Thus, a network may evolve in different phases depending upon the demand and budget constraints.

The hydrogen pipeline network has several demand points like ports or industrial clusters in multiple countries with different economic characteristics. Thus the evolution of the hydrogen pipeline network will also be determined by factors such as competition with shipment or pipeline option, economic feasibility and demand. (Hong et al., 2024) studied a pipe plus ship transport option for minimizing the system annual cost by proposing a mixed integer linear programming model for decentralized offshore produced hydrogen, however they considered hydrogen gathering stations due to the decentral nature of production which will be different when centralized offshore production is considered. Thus, the transport network will depend on the spatial configuration of the hydrogen production system. There can be more systems connected to the hydrogen transport networks such as hydrogen refuelling systems to cater demands for hydrogen powered ships. (X. Zhang et al., 2025) developed an integrated offshore hydrogen network framework that included hydrogen refuelling, hydrogen gathering stations and decentralized hydrogen production and concluded that total costs is significantly determined by distance of offshore wind farm, its spatial layout and number of gathering stations. (X. Zhang et al., 2025) further compared hydrogen pipeline transport and ship transport and concluded that hydrogen pipeline is more cost effective, environment friendly for long distance and large-scale transportation outperforming ship-based transport.

2.2 - Knowledge Gap

From the literature review, it has been concluded that offshore wind based hydrogen production infrastructure is at its infancy (Kumar et al., 2023). Further there are no subsea hydrogen pipelines existing today. While there are different studies on different offloading methods of produced hydrogen offshore (Franco et al., 2021), factors that drive the development of offshore hydrogen pipeline network is not yet described in the literature. Many of the studies looked into multi modal transport involving ships (Hong et al., 2024) and hydrogen carriers such as ammonia (Dinh et al., 2024), Liquid Organic Hydrogen Carriers (Seo et al., 2023). (Gondal, 2019) has looked at possible synergies with Natural Gas pipeline but there are limitations for its use due to process parameters. This study on the other hand will focus on hydrogen pipelines and compressed gaseous hydrogen as it is effective form to transport (Saborit et al., 2023) because from the literature review, it has been found that pipeline is the most economical means to transport hydrogen for short to medium distance (Abánades et al., 2025; Franco et al., 2021; Joyo et al., 2025).

There are studies that aim to optimize hydrogen pipeline network for single offshore wind farm, there is no study about connecting multiple offshore wind farm-based hydrogen production and its pipeline network. In the literature review, evolution of High Speed Rail network (Borgogno, 2025), public transport network (Cats et al., 2020) exists but there is no study on the evolution of offshore wind farm based hydrogen pipeline network and necessitates further study of it for the overall development of the offshore hydrogen industry (Y. Wang et al., 2025). This is the main knowledge gap this thesis aims to fulfil.

Taking the North Sea as the geographical area considering the existing offshore windfarms and tremendous potential to install new wind farms (Durakovic et al., 2023), this thesis will look into how hydrogen production in the offshore wind farms in the North Sea can lead to offshore pipeline networks connecting different demand centres in multiple countries and realistically how such a pipeline network could evolve considering the constraints of installation, availability and budget. Scenarios for its development has to be identified as well (Liu et al., 2024). This form of study to understand the different possible configuration of pipeline network and its evolution is novel and would add critical insights and can be starting point for planning such networks in the future.

- ➢ An extensive literature review has been performed along with the identification of the knowledge gaps. Now the research questions have to be defined along with research approach and methodology to answer the research questions. This is executed in the next chapter.

3. RESEARCH DESIGN

This chapter begins with the definition of research questions. The research approach and associated research methods that will be utilised to address the main research question and sub-questions is further discussed in this section. Then the research process is explained through a research flow diagram.

3.1 - Research Questions

The objective of this research is study how the offshore wind based hydrogen pipeline transport infrastructure in the North Sea could evolve.

The Main Research Question (MRQ) is as follows

How could the offshore wind based hydrogen transport pipeline network evolve in the North Sea?

In order to answer the main research question fully, it is broken down into Sub-Questions (SQ) that must be answered to reach a comprehensive understanding of the system as well as to answer the main research question finally.

SQ1) What are the offshore wind farms that are planned in the North Sea up till 2050?

SQ2) How much hydrogen can be produced in these wind farms depending upon the configuration?

SQ3) What is the capacity required to transport the produced hydrogen?

SQ4) What is a realistic budget for building offshore hydrogen pipeline each year and how many pipelines can be built in a year with this budget?

SQ5) How can network metrics be used to determine which pipelines to be built?

SQ6) What possible scenarios can help us understand hydrogen pipeline network evolution?

3.2 - Research Approach

The aim of this research is to understand the evolution of hydrogen transport pipeline network in the North Sea. The hydrogen pipeline transport network is complex in terms of technology, actors and various institutions that shape its development. A quantitative approach cannot capture the complexity of evolution as the goal of a quantitative approach is to quantify empirical setting through mathematics and statistics. As (Srivastava & Thomson, 2009) points out, quantitative research is suited for studies that typically asks “where”, “what” and “when” questions and do not necessarily answer “why” and “how” a phenomenon occurs. Qualitative research on the other hand, is a systematic approach of inquiring social phenomenon in its natural setting which includes but not limited to behaviour of actor(s), functioning of organizations and their relationships shaped by interactions (Teherani et al., 2015). However, for this study, the focus is on technological phenomenon on a future setting considering the evolution of hydrogen transport pipeline network and requires an approach that captures the technical aspects of the infrastructure and its evolving nature.

This project will therefore utilize a combination of design-oriented and modelling approach in order to capture the complexity and uncertainty of infrastructural development. (Dijkema et al., 2008) studied gas networks and suggests that networked infrastructures can be seen as complexsociotechnical systems with associated physical network and actor network showing the complexity. This design-oriented approach offers a structured way for developing a solution or intervention of a gap in the complex socio-technical system. Modelling approach is beneficial for this study as it captures the technical and networked aspects of the infrastructure that is to be developed for this study.

3.3 - Research Methods

3.3.1 - Literature Review and Desk Research

In order to build the technological basis for this study, literature review and desk research is utilized to obtain academic articles and industrial reports that are relevant to offshore hydrogen pipeline transport infrastructure. Considering that a physical offshore hydrogen pipeline doesn't exist today, relevant literature related to offshore natural gas pipeline networks can be useful to the study the development of hydrogen pipeline network. In the literature review and desk research study, attention is given to offshore hydrogen production, hydrogen demand and hydrogen pipeline transport.

Sub questions 1,2 and 3 can be answered using literature review and desk research to determine the details and location of offshore wind farms planned in the North Sea, to study and delineate production capability of each wind farm under different configurations and also to determine the capacity required to transport the produced hydrogen which can be formulated and calculated.

In order to answer the remaining questions, modelling with a design approach is required.

3.3.2 - Modelling with NetworkX

In order to analyse complex network such as hydrogen pipeline transport network, NetworkX is utilized here. NetworkX is a python language software package for creation, manipulation and exploration of structure, dynamics and functions of complex networks. The advantage of NetworkX is that it includes functions for computing network metrics such as betweenness centrality, clustering coefficients, degree distribution etc (Schult,2008). More applicable network metrics can be added depending upon the study. The NetworkX model can be utilized for generating possible network configuration for hydrogen pipeline transport and to study its evolution under different scenarios.

Sub questions 4, 5 and 6 can be answered by using a design and modelling approach to develop a conceptual model and the modelling the pipeline network infrastructure in NetworkX to understand the budget, annual installation capacity and utilizing different network metrics to determine the possible layouts. After that, the scenarios has to be designed that will help to explore the evolution of hydrogen pipeline network.

3.4 - Research Flow Diagram

The research flow diagram is shown in Figure 3. The process is described below of all the phases.

3.4.1 - Phase 1 Information Gathering

This phase is about exploration of the main research topic and building the fundamentals for this study. The main research method utilized in this phase is Literature Review and Desk Research. The goal of this phase is to gather sufficient information and data on offshore wind farms in the North Sea and the hydrogen production potential. Based on the explored information and analysing the data, sub questions 1 and 2 can be answered in this phase which will act as the foundation for the next phase. Data will be extracted from industry reports and academic literature regarding the latest development in Offshore Wind based Hydrogen Production and Transportation System.

3.4.2 - Phase 2 Model Conceptualization and Formulation

This phase is the design phase where the capacity requirements of offshore wind based hydrogen transport pipeline network is determined. After the capacity is estimated, this phase involves the formulation of conceptual model where the problem is again reconceptualised to accommodate the complex hydrogen transport infrastructure. The output of this stage is the conceptual model as well as the NetworkX model. Sub question 3 is answered in this phase with the capacity estimation.

3.4.3 - Phase 3 Model Implementation

After the model is formulated in this modelling phase, insights from existing literature and industry reports are utilized to determine the pipeline systems that can be built in a year. The model is then adjusted to incorporate possible pipeline system construction possibilities so as to find out how much pipeline system can be built each year. Thus, sub question 4 will be answered. The model is then verified for its data to ensure integrity with technical and economic aspects. The scenarios for input to the model are identified to be performed at the next phase.

3.4.4 - Phase 4 Model Use

In this modelling phase the data is analysed along with considerations of assumptions made and post desk research of academic literature, applicable network metrics are identified and compared to come up with appropriate network metrics to study the evolution of offshore hydrogen pipeline transport infrastructure in the model. Iterative steps will be taken to conform and refine the model to improve the applicability. Sub question 5 is answered in this phase.

3.4.5 - Phase 5 Conclusions and Recommendations

The resulted network will be incorporated in the model in this phase along with identified scenarios to gain insights into how the hydrogen pipeline network evolves. Thus, Sub Question 6 is answered in this phase. With all the sub-questions answered and based on insights from model output, the main research question is answered finally. The results and insights also further contribute towards the conclusion and recommendations of this study

- ➢ Having defined the research questions, research approach and research methodology along with the research flow diagram explaining the research process, the next chapter will focus on the offshore wind farm based hydrogen transportation pipeline network system and its components.

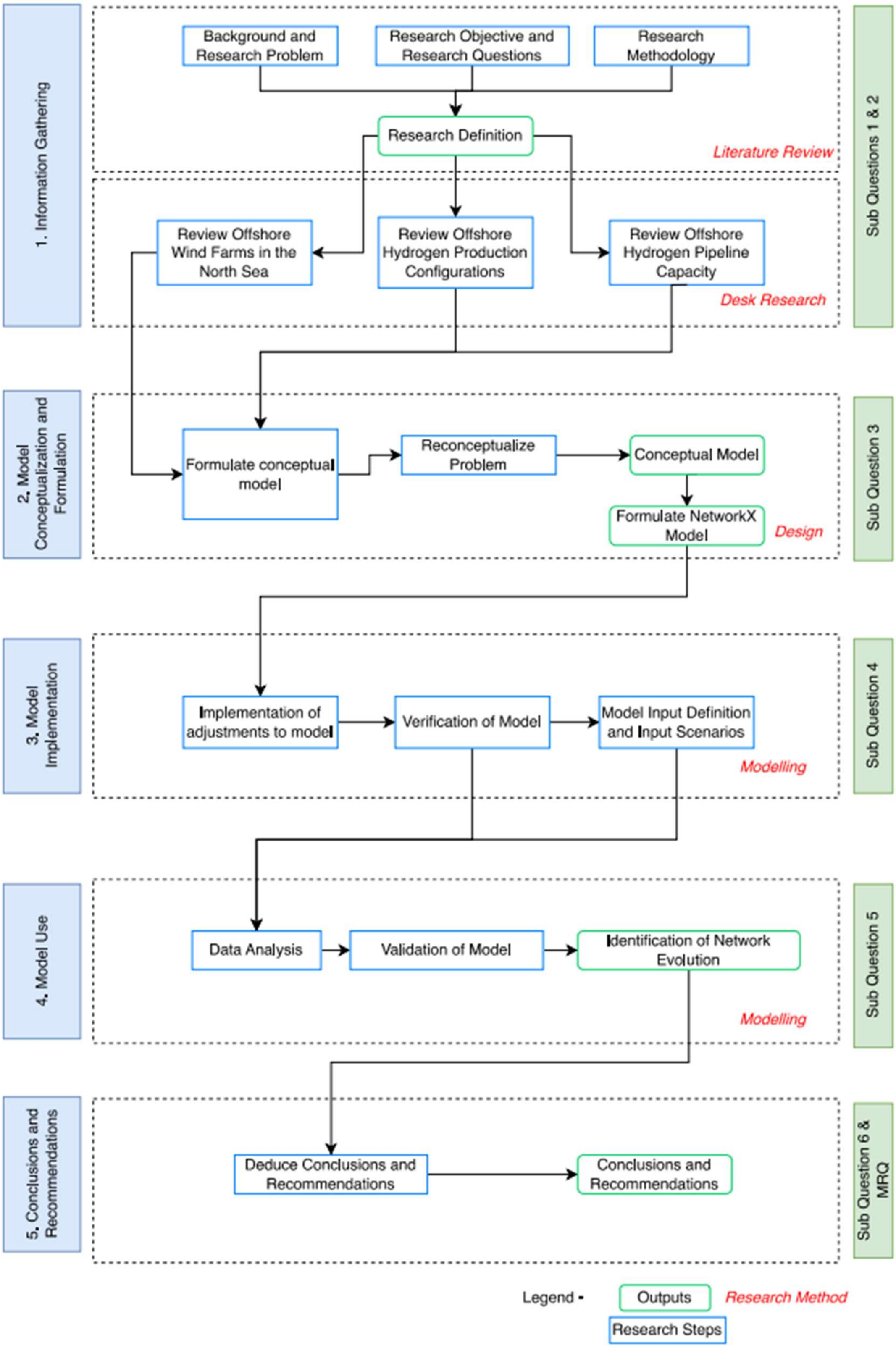


Figure 3 - Research Flow Diagram

4. SYSTEM IDENTIFICATION AND SYSTEM DECOMPOSITION

This chapter introduces the details of offshore wind farms in the North Sea. Then the focus shifts to potential hydrogen production that can be integrated with the offshore wind farms. After that the offshore hydrogen transport pipeline capacity requirements are evaluated. Existing projects related to offshore wind based hydrogen is described. An actor analysis is further performed to consider the views of the stakeholders. The section that follows it estimates the budget for offshore hydrogen pipeline. Finally, the last section delineates different network metrics that can prioritize pipeline growth are evaluated.

4.1 Offshore Wind Farms in the North Sea

Offshore wind planning is dynamic as the projects evolve through leasing, permitting and construction stages which are influenced by policy, economics and environmental factors. The countries that border the North Sea includes the United Kingdom, France, Belgium, the Netherlands, Germany, Denmark and Norway.

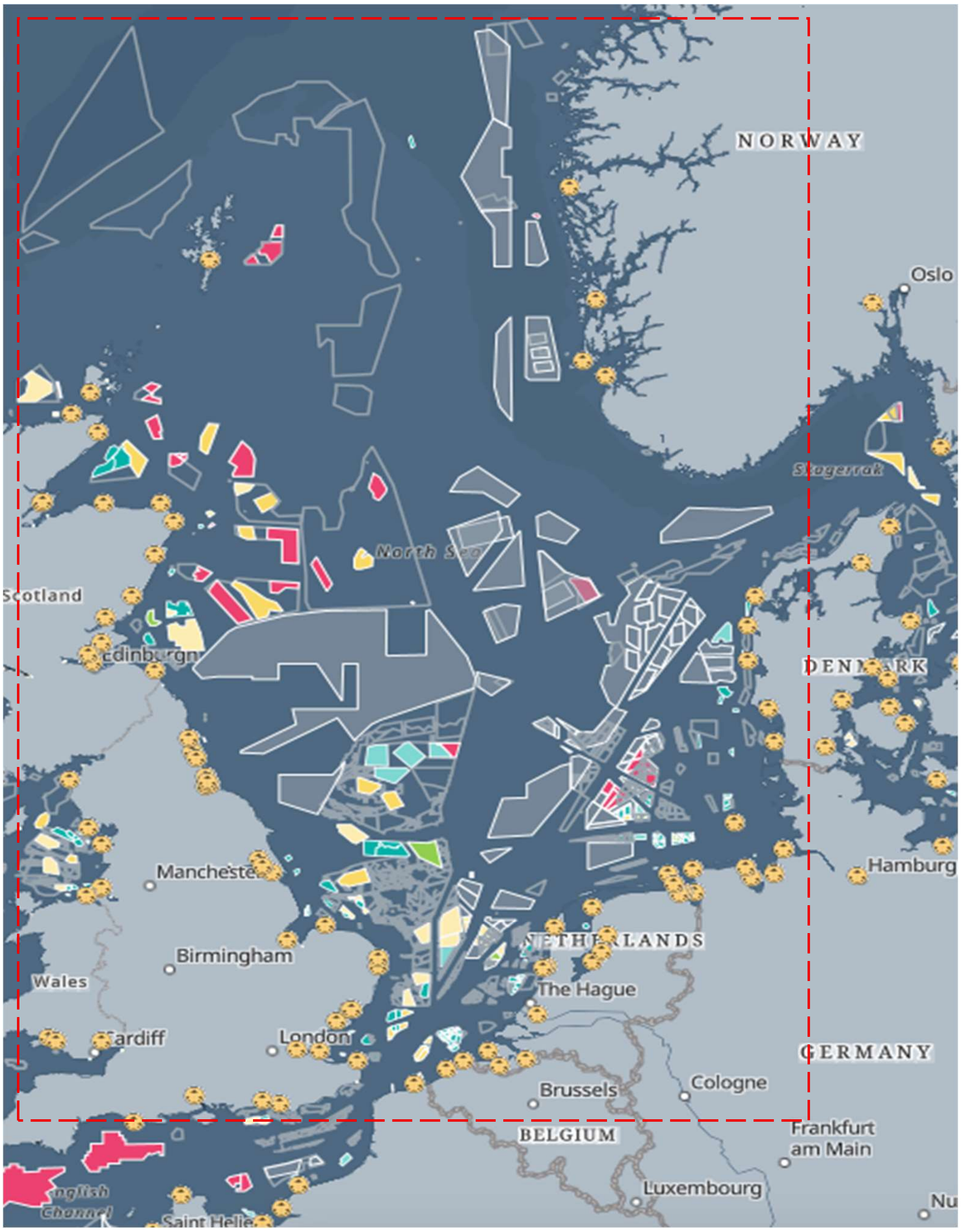


Figure 4 - Offshore Wind Farms planned in the North Sea (Source - 4C Offshore)

The Figure 4 shows different areas allocated for offshore wind farms in the North Sea by United Kingdom, France, Belgium, Netherlands, Germany, Denmark and Norway. The area under this study is marked by the red dashed box which covers the North Sea wind farms and the countries. The green elements indicate existing offshore wind farms while the grey and red zones are planned offshore wind farms. Many of the projects have also been cancelled or failed at tender phase. These were not considered for this study. The ports are marked yellow which can be the demand centres.

Utilizing (Offshore, 2025) mainly and official data sources, the data regarding offshore wind farms in the countries bordering North Sea, particularly its capacity and the current status are studied. The details are as follows.

Offshore Wind Farms in the United Kingdom

According to(Estate, 2025; Offshore, 2025; UK, 2025), the United Kingdom (UK) has around 13.5 Giga Watts (GW) of operational offshore windfarms in the North Sea. According to the data from (Offshore, 2025) approximately 9 GW of offshore wind farms are in the in the concept or early planning stage. 8GW of Offshore Wind Farms have their consent applications submitted while 14.8 GW of offshore wind farms consent has been authorised. The North East Area of Opportunity totalling 16 GW is in the development zone. 4GW of offshore wind farms is in the pre-construction stage while according to (Estate, 2024) 8 GW of offshore wind farms is in the construction stage.

Offshore Wind Farms in France

According to (Offshore, 2025) and (EDF, 2025) France has four operational wind farms with Two, Saint-Brieuc 496 MW and Fecamp 498 MW in the English Channel while Noirmoutier 488 MW and Saint Nazaire 480 MW in the Bay of Biscoy but they are not located in the North Sea. In the North Sea, According to (Dunkerque, 2025) a 600 MW offshore wind farm Dunkerque has its consent application submitted. 8 GW of new offshore wind farms in the North Sea are in the development zone.

Offshore Wind Farms in Belgium

According to (BE, 2025; Fulbright, 2025) and (Offshore, 2025) Belgium has 9 fully commissioned offshore wind farms in the North Sea generating 2.26 GW of energy. 3.5 GW of offshore wind farms have their consent applications submitted. Considering existing and planned zones, the total capacity of offshore wind in Belgium is expected to increase to 5.8 GW by 2030 almost tripling its current capacity (Fulbright, 2025). A further expansion totalling 8 GW is planned to be around 2040 (Fulbright, 2025).

Offshore Wind Farms in Germany

According to (Energy, 2025) 9.2 GW of offshore wind farms are in operation in the North Sea by Germany. According to (Offshore, 2025), 14.3 GW of offshore wind farms in German North Sea are in the Concept / Early planning stage. A consent application has been submitted for 630MW Nordlicht II offshore wind farm. Pre-construction has started for two offshore wind farms Norsee Cluster A and B with 435 MW and 420 MW respectively. Three offshore wind farms are currently under construction totalling 2 GW. The German Offshore Wind Energy Act defines the expansion targets for offshore wind energy in Germany. Plan is underway to install 50 GW by 2035 and 70 GW by the end of 2045(Energy, 2025).

Offshore Wind Farms in Denmark

According to (EU, 2025), Denmark has 2.7GW of offshore wind energy however as per (Offshore, 2025) there are currently only 4 fully commissioned offshore wind farms in the Danish North Sea totalling 1.2 GW. A 1 GW offshore wind farm Thor is under construction and is expected to be operational by 2027 (RWE, 2025b). 20 GW of offshore wind farms are in the development zone for future projects(Offshore, 2025). The ambition of Denmark currently is to have 14 GW by 2030 and 52 GW by 2050(EU, 2025).

Offshore Wind Farms in Norway

According to (Offshore, 2025), Norway has commissioned only 1 operational wind farm in the North Sea, Hywind Tampen which is the world’s largest floating offshore wind with a capacity of 95 MW. Around 1.8 GW of offshore wind farms are currently in the concept / early planning stage. 21.6 GW of offshore wind farms are currently in the development zone for future projects (Offshore, 2025).

Offshore Wind Farms in the Netherlands

According to (Offshore, 2025) and (Agency, 2025), Netherlands has commissioned 10 offshore wind farms totalling the capacity to 4.76 GW. Oranjewind with a capacity of 795 MW is in pre-construction stage. Consent has been authorized for 5.9 GW offshore wind farms. Netherlands has released a roadmap (Agency, 2025) for 21 GW of production up to 2030 with planned capacity of 11.5 GW adjacent to existing wind farms and Northern Netherlands, see Figure 5. Around 52 GW of offshore wind farm is in the development zone for future projects.

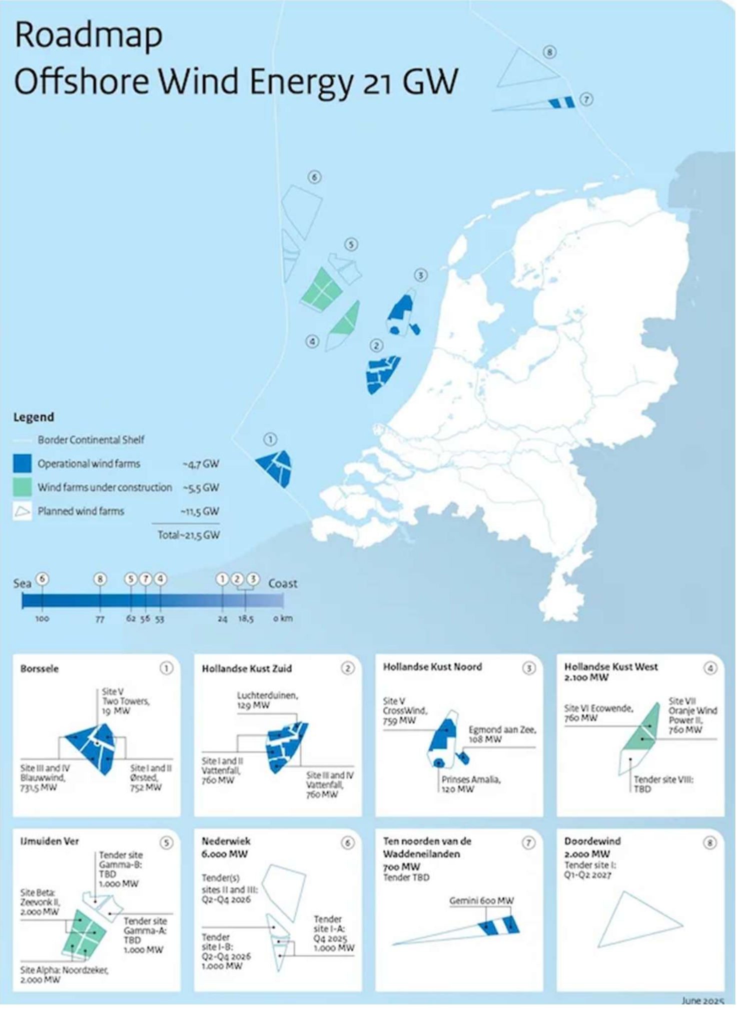


Figure 5 - Offshore Wind Roadmap – Netherlands (Source Netherlands Enterprise Agency)

Offshore Wind Farms in the North Sea up to 2050.

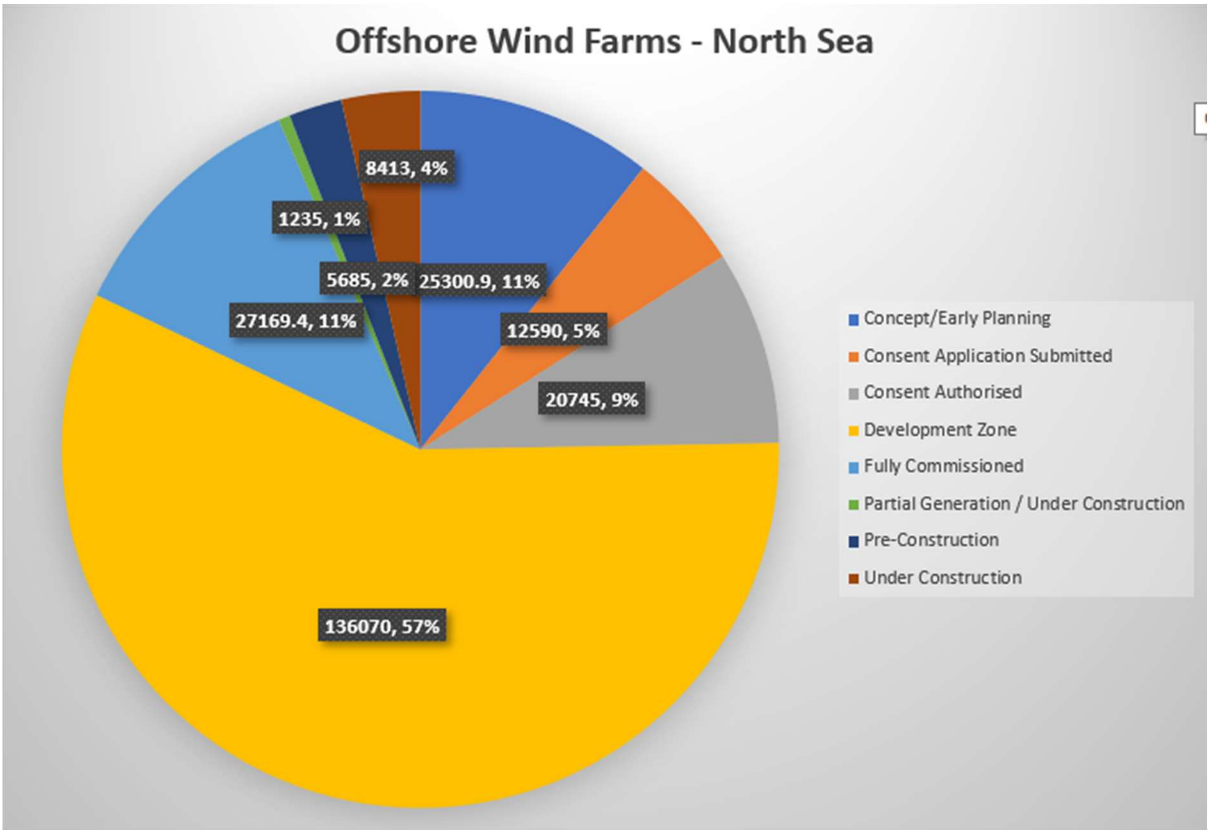


Figure 6 - Current status of offshore wind farms in the North Sea

The figure 6 shows at a glance the current status of offshore wind farms in the North Sea. Around 27GW are existing offshore wind farms accounting for 11% of the offshore wind farms. 57% of offshore wind farms are in the development stage.

215 offshore wind farms total 237 GW including existing and planned have been identified which may serve as the nodes for hydrogen production in the North Sea. The list of offshore wind farms, country, their capacity and current status are given in the table in appendix.

Answering Sub-Question 1 - What are the offshore wind farms that are planned in the North Sea up till 2050?

The countries which are bordering the North Sea includes the United Kingdom, France, Belgium, Netherlands, Germany, Denmark and Norway. The United Kingdom is leading with the largest installed capacity in the North Sea which is approximately 13.5 GW of offshore wind energy. Followed by Germany with 9.2 GW. Netherlands has installed 4.76 GW of offshore wind energy while Belgium has installed 2.26 GW. It is followed by Denmark having installed 1.2 GW capacity. The lowest capacity of offshore wind energy in the North Sea are of Norway with 95 MW and France of 0 MW. All the wind farms that are existing and planned are listed in the table in the appendix.

All the countries have ambitious plans to increase the share of offshore wind energy in their energy portfolio. 215 offshore wind farm areas have been identified with 27 GW of existing wind farms accounting to 11% of the total wind farms. Further 11% of wind farms are in concept or early planning stage. Consent application for 12.6 GW has been submitted to the authorities for further process while 20.7 GW of offshore wind farms have their consent authorized. Most notable here is that 57% of the offshore wind farms accounting to 136 GW identified are in the development zone for the years until 2050.

The North Sea countries are collaborating under the North Seas Energy Cooperation (NSEC) in order support and facilitate the development of offshore wind electricity and hydrogen grid development (European Commission, 2024). The member countries include Belgium, Denmark, Netherlands, Norway, Luxembourg, France, Ireland and the political body European Commission. As per NSEC, the goal is to have at least 260 GW of offshore wind energy by 2050. The EU however has put a target of 300 GW by 2050 which is far larger than the sum of currently announced projects. This means many future wind farms remain to be defined especially via national auctions. There are mega projects with more than 1 GW capacity by the bordering countries which helps move toward the long term target.

However, there are still uncertainties such as timing and success of future auctions, supply chain issues, cable grid infrastructure development and evolving technology for eg. Floating offshore wind etc. Because many wind farms are not yet clearly defined and technological, regulatory or economic conditions may change, the ultimate year 2050 scenario is flexible.

In conclusion, 215 offshore wind farms totalling 237 GW of energy that includes existing are planned for the North Sea up to 2050 with United Kingdom, Germany and Netherlands contributing to the majority of wind farms. Many details are often zonal (Development Zones) multi farm areas rather than named projects due to ongoing spatial planning. Such large infrastructure enables not only electricity export but also the possibility to integrate with hydrogen production including cross border sharing. The North Sea’s 300GW ambition positions it as Europe’s “Green Power Plant” enabling the possibility for net-zero by 2050. However, the success will hinge on accelerated tenders, planning, grid investments and stakeholder collaboration to mitigate any delays. What stakeholders could consider is to prioritize multi use zoning combining offshore electricity and hydrogen production to balance energy, ecology and economy.

4.2 Hydrogen Production in Offshore Wind Farms

Integrating offshore wind energy with hydrogen production represents a pivotal strategy for the decarbonization of energy system in Europe. As identified earlier, the North Sea region possesses one of the world’s largest concentrations of offshore wind farms supported by the surrounding countries ambitious plans for continued energy expansion. A climate neutral Europe requires not only electricity but also an energy carrier like hydrogen that is environment friendly and can be stored and meet the needs of particularly hard to electrify industries to use as feed stock and fuel as well as facilitate transnational energy exchange through pipelines.

In order to study the network evolution of offshore wind based hydrogen transport pipeline network and to evaluate the feasibility of such a network, it is essential to estimate how much hydrogen can be produced from the identified existing and planned offshore wind farms contingent upon the choice of electrolyser technology or configuration.

Various assumptions and choices have to made in advance to ensure the study can be completed within the timeframe of this project. This study assumes that the entirety of the generated electricity is dedicated to centralised offshore electrolysis for hydrogen production which is actually a simplification to estimate the maximum production potential. In the real world practice however, factors such as grid export, curtailment and hybrid operation would reduce this yield.

Hydrogen can easily be produced directly from electricity through water electrolyses which separates water into hydrogen and oxygen (Venugopalan Julio Garcia Navarro Lennert Buijs, 2024). The hydrogen produced is called green hydrogen as the source of the energy is from renewable energy sources which in this case is offshore wind energy.

Mainly there are three types of electrolysis technologies that can be considered

1) Alkaline Electrolysis (AE)
   Most mature of the electrolyser technology. The electrolyte used is alkaline water solution with electrodes being nickel, cobalt and iron. The Technological Readiness Level (TRL) is 9 and used in industrial scales at multiple MW. Advantage of alkaline electrolysis is that inexpensive materials are used and the cheapest option available for electrolysis (Venugopalan Julio Garcia Navarro Lennert Buijs, 2024).

2) Proton Exchange Membrane Electrolysis (PEM)
   PEM Electrolysis is gaining significant interest and there are small scale projects at MW scales. The electrolyte used here is an acidic polymer with platinum and iridium as electrodes which makes PEM electrolyser expensive. The distinguishing feature of PEM electrolyser is that it offers higher degree of operation flexibility compared to alkaline electrolysis which makes it the most suitable option for interconnection with renewables such as offshore wind energy. The TRL level is currently at 8(Venugopalan Julio Garcia Navarro Lennert Buijs, 2024).

3) Solid Oxide Electrolysis (SOEC)
   SOEC electrolysis is in continuous development and emerging with superior efficiency. It utilizes water and heat to produce hydrogen. Currently the SOEC electrolyser projects are in the pilot stages with scales of few kW. The TRL level is currently at 5. The electrolyte used here is an Oxide-conducting ceramic with nickel, zirconium, yttrium and lanthanum as electrodes. Since heat is used in this process, there is a lower requirement of electricity. SOEC is particularly suitable when there is availability of waste heat (Venugopalan Julio Garcia Navarro Lennert Buijs, 2024).

There are other types of electrolysers such as Anion Exchange Membrane (AEM) electrolysis which is in the development stage.

The minimum amount of energy needed for water electrolysis corresponds to the Higher Heating Value of hydrogen and is equal to 39.4 kWh/kgH_2(N. R. Council & of Engineering, 2004). This energy is exactly the same irrespective of which electrolysis technology is used while depending on the technology actual energy consumption may vary for eg, SOEC requires high operating temperatures (Venugopalan Julio Garcia Navarro Lennert Buijs, 2024).

4.2.1 - Factors affecting hydrogen production from an offshore wind farm

The major factors affecting hydrogen production from offshore wind farms include

a) Installed capacity of the wind farm

Larger the installed capacity of the wind farm, more is the electricity that can be generated annually. Hydrogen production scales proportionally with the electrical energy that is available for electrolysis.

b) Wind Resource Quality and Capacity Factor

The wind speed distribution at the site determines the capacity factor, i.e the percentage of time the wind farm operates at or near its rated power. Higher capacity factor translates to more electricity generated per MW which results in higher energy output. Advantage of offshore sites is that it will typically benefit from stronger and more consistent wind.

c) Electrolyser technology (AE, PEM, SOEC)

The efficiency of the electrolyser differs by type. Higher the efficiency, more the production of hydrogen from same electricity. For e.g. SOEC produces more hydrogen than PEM or AE for the same wind energy input.

d) Electrolyser capacity (MW)

The size of the electrolyser will determine the amount of wind energy which can be converted into hydrogen. If the electrolyser is undersized, excess wind power is curtailed which leads to lower hydrogen production. If oversized, more energy can be converted during periods of high wind leading to higher hydrogen production.

e) Electrolyser efficiency

The amount of electricity which is required to generate a kg of hydrogen is determined by the electrolyser efficiency. Lower energy consuming electrolyser can produce more hydrogen from the same wind energy.

f) Availability and Reliability of the electrolyser

Highly reliable system can maximize the hydrogen production. Maintenance as well as operational constraints can result in downtime which reduces the amount of hydrogen that is produced. The availability and reliability affect the operation and output of the electrolyser.

g) Curtailment and Grid Limitations

If export cables or grid capacity is limiting the power flow, the electricity could be curtailed leading to reduction in hydrogen production especially if the electrolyser is undersized.

h) Power conversion and Transmission losses

Losses in transformers, offshore substations, power electronics and cables reduce the net electricity delivered to the electrolyser which affects the hydrogen production output. The losses depend on distance and system design as in how the system is configured.

i) Water supply and Desalination requirements

Offshore hydrogen production requires desalinating seawater. The energy spent on desalination while essential can lower hydrogen production.

j) Temperature and Operating Conditions

Electrolyser performance depends on ambient temperature and operating pressure. Extreme conditions may reduce efficiency adding the requirement for additional heating or cooling energy.

k) Operational strategy and dispatch

Electrolysis can run as either constant load(base load) which requires buffering and oversized electrolyser or as flexible load following the wind conditions which produces variable output. Therefore, the strategy that is adoptd affects total hydrogen output. Thus, a number of factors determine the hydrogen production from offshore wind farms.

4.2.2 - Methodological considerations.

To reduce the complexity and considering the time constraints of this study, an annual average energy based approach is utilized which provides a valid upper bound estimate of hydrogen potential.

The annual average method provides a straightforward estimate of potential hydrogen production but has limitations

- It ignores temporal variability of wind generation.
- It assumes full utilization of available electricity for hydrogen (i.e no electricity is diverted to the grid or curtailed)
- It does not account for electrical losses, electrolyser start or stop inefficiencies or balance of plant constraints.

Despite these simplifications, the method yields reasonable upper bound estimates for strategic planning and early stage feasibility analysis which is the case for this study. Further the data requirement is minimal while it directly ties wind energy to hydrogen potential.

4.2.3 - Hydrogen Production in existing wind farms

We can consider the case study of Gemini Wind Farm in the Netherlands to estimate the amount of hydrogen that can be produced in a year. The following case is applicable only for baseload hydrogen production case i.e the above calculation assumes that all the produced electricity is used for hydrogen generation. The case might be different if priority is given to electricity first and hydrogen production is only during weak electricity demand i.e peak shaving.

<u>Gemini Wind Farm Details</u>

Capacity – 600 MW

Annual electricity generation – 2.5 TWh/year (Gemini Wind Park, 2025)

Annual Hours – 8760 h/year

Capacity Factor =

$$CF = \frac{2.5\,TWh}{600MW \times 8760\,h} \approx \frac{2.5 \times 10^6\,MWh}{600 \times 8760} \approx 0.4756 \approx 48\%$$

PEM Electrolyser Efficiency = η_{PEM} = 0.8 (Shwe Sin et al., 2024)

AE Electrolyser Efficiency = η_{AE} = 0.7 (Nejadian et al., 2023)

SOEC Electrolyser Efficiency = η_{SOEC} = 0.9 (Nejadian et al., 2023)

Energy content of H_2 (LHV) = E_{H2} = 33.33 kWh / kg (N. R. Council & of Engineering, 2004)

Required electrical energy per kg of hydrogen for PEM = $\frac{E_{H2}}{\eta_{PEM}} = 41.66\ kWh/kg$

Required electrical energy per kg of hydrogen for AE = $\frac{E_{H2}}{\eta_{AE}} = 47.61\ kWh/kg$

Required electrical energy per kg of hydrogen for SOEC = $\frac{E_{H2}}{\eta_{SOEC}} = 37.03\ kWh/kg$

Average available power for the electrolyser

$P_{avg} = 600MW \ \times 0.48 = 288MW$

Since wind capacity factor is 48%

The electrolyser therefore will receive on average 288MW of power (because, sometimes the wind is below full output, sometimes above but limited to 600 MW)

The utilization factor thus for electrolyser is 48%

Hydrogen production rates for different electrolysers

a) PEM electrolyser

$$m_{H2} = \frac{P \ \times \ \eta_{PEM}}{E_{H2}} = \frac{288{,}000\ kW \ \times 0.8}{\frac{33.33\ kWh}{kg}} = 6{,}912.69\ kg\ H_2\ per\ hour$$

Annual Hydrogen Output from PEM Electrolyser – $6{,}912.69 \ \times 24 \times 365 \ \approx$ $60.55\ kilotonnes\ H_2 \ per\ year$

b) AE Electrolyser

$$m_{H2} = \frac{P \ \times \ \eta_{AE}}{E_{H2}} = \frac{288{,}000\ kW \ \times 0.7}{\frac{33.33\ kWh}{kg}} = 6{,}048.60\ kg\ H_2\ per\ hour$$

Annual Hydrogen Output from AE Electrolyser – $6{,}048.60 \times 24 \times 365 \ \approx$ $52.98\ kilotonnes\ H_2 \ per\ year$

c) SOEC Electrolyser

$$m_{H2} = \frac{P \ \times \ \eta_{SOEC}}{E_{H2}} = \frac{288{,}000\ kW \ \times 0.9}{\frac{33.33\ kWh}{kg}} = 7{,}776.78\ kg\ H_2\ per\ hour$$

Annual Hydrogen Output from SOEC Electrolyser – $7{,}776.78 \times 24 \times 365 \ \approx$ $68.12\ kilotonnes\ H_2 \ per\ year$

Thus, for the same wind farm and operating conditions, the hydrogen output per year varies depending on the configuration of the electrolysers with SOEC electrolyser having the highest production of 68.12 kilotonnes of hydrogen per year followed by PEM electrolyser with 60.55 kilotonnes and lowest production by AE electrolyser accounting for 52.98 kilotonnes of hydrogen per year.

4.2.4 - Total Hydrogen Production of planned and existing offshore wind farms

For 237 GW of offshore wind farms, assuming the same electrolysers and capacity factor, the total hydrogen production rate will be

starting with PEM electrolyser -

$$m_{H2} = \frac{P \times \eta}{E_{H2}} = \frac{113{,}760{,}000\ kW \ \times 0.8}{\underline{33.33\ kWh}\atop kg} = 2{,}730{,}513.05\ kg\ H_2\ per\ hour$$

Annual Hydrogen Output – $2{,}730{,}513.05\ \times 24 \times 365\ \approx 23.92\ million\ tonnes\ H_2\ \ per\ year$

For AE electrolyser

$$m_{H2} = \frac{P \times \eta}{E_{H2}} = \frac{113{,}760{,}000\ kW \ \times 0.7}{\underline{33.33\ kWh}\atop kg} = 2{,}389{,}198.92\ kg\ H_2\ per\ hour$$

Annual Hydrogen Output – $2{,}389{,}198.92 \times 24 \times 365\ \approx 20.92\ million\ tonnes\ H_2\ \ per\ year$

For SOEC electrolyser

$$m_{H2} = \frac{P \times \eta}{E_{H2}} = \frac{113{,}760{,}000\ kW \ \times 0.9}{\underline{33.33\ kWh}\atop kg} = 3{,}071{,}827.18\ kg\ H_2\ per\ hour$$

Annual Hydrogen Output – $3{,}071{,}872.18\ \times 24 \times 365\ \approx 26.91\ million\ tonnes\ H_2\ \ per\ year$

Answering Sub-Question 2 - How much hydrogen can be produced in these wind farms depending upon the configuration?

The results from the study shows that potential annual hydrogen production from the existing and planned offshore wind farms in the North Sea is not a fixed figure rather a variable outcome governed by the interplay between the stochastic nature of the wind resource and the dynamic efficiency or operational flexibility of the chosen electrolyser configuration. However, by simplifying and taking assumptions such as full availability of offshore wind for hydrogen production provides a reasonable upper bound estimate of hydrogen production potential which is sufficient for initial stage strategic planning.

Hydrogen production from offshore wind farms depends on a combination of wind resource characteristics, electrolyser system design, infrastructure configuration and operational constraints and the answer of potential production capacity is not straightforward. AE, PEM and SOEC electrolysers can be considered for determining the hydrogen production potential of an offshore wind farm.

Hence, taking the existing case study of Gemini wind farm in the Netherlands, the hydrogen production potential for different electrolyser configuration was estimated. The 600 MW wind farm produces 68.12 kilotonnes, 52.98 kilotonnes and 60.55 kilotonnes of hydrogen when configured with SOEC, AE and PEM electrolysers respectively.

Assuming the same conditions and configuration with same capacity factor, the case was extended for the entire offshore wind farm portfolio of 237 GW. The results show production possibility ranging from 20 million tonnes to 27 million tonnes of hydrogen per year depending upon the configuration.

The results underscore SOEC's superiority for maximizing hydrogen production.

North Sea offshore wind farms therefore have the potential to produce up to 27 million tonnes of hydrogen annually. Prioritising efficient technologies like SOEC will be key to realizing this potential.

4.3 Hydrogen Pipeline Capacity Requirements for Offshore Wind Electrolysis in the North Sea

The development of large scale offshore wind energy in the North Sea presents a significant opportunity for green hydrogen production through electrolysis. Previous chapters quantified the hydrogen production potential from existing and planned wind farms, demonstrating that offshore electrolysis can generate substantial volumes of hydrogen requiring efficient transport to on shore demand centres. This section builds on those findings by determining the required transport capacity specifically the subsea pipeline capacity needed to deliver the produced hydrogen to onshore demand centers.

Producing hydrogen at large scale is only the first step. Efficient transport infrastructure is critical to move hydrogen from offshore production sites to onshore demand centres and industrial consumers. Determining the required transport capacity moves the analysis from production potential to infrastructure design. The focus is on pipeline infrastructure as it offers the most efficient, large scale solution for gaseous transport over medium to long distances, particularly in the North Sea context where subsea pipelines can connect production sites directly to demand centres as mentioned earlier.

Unlike electricity transport, which is constrained by cable capacity, hydrogen pipeline capacity is a complex function of mass flow rate (kg/s), operating pressure, pipeline diameter and compression energy. The primary challenge is designing a network which can handle the high instantaneous flow variability that are inherent in offshore wind based production while remaining economically viable. Determining appropriate pipeline diameters and operating conditions is thus essential for designing a hydrogen backbone that is technically feasible and economically efficient.

This chapter applies established gas transport principles and engineering assumptions to estimate diameters for hydrogen produced by offshore wind farms. Two representative case studies of offshore windfarms Gemini (Netherlands) and Seagreen (United Kingdom) are analysed to illustrate the methodology. This approach provides a first order estimate of pipeline requirements and establishes a basis for system level hydrogen infrastructure planning.

4.3.1 - Theoretical Background for Gas Flow and Pipeline Transport

Hydrogen is characterised by low molecular weight, high compressibility and low density even at elevated pressures. These properties critically determine the pipeline design as volumetric flow requirements are much larger for hydrogen compared to natural gas for the same energy transport.

The pressures commonly considered for offshore hydrogen pipelines ranges between 80 bar and 150 bar. At these pressures, the density ranges from 7-10 kg/m3, depending on the temperature as well as compressibility factor (Z). For this study, a density of 7.8 kg/m3 at 100 bar is adopted following published values for isothermal hydrogen transport under North Sea ambient conditions.

Continuity Equation

For a steady, incompressible flow, the volumetric flow rate Q through a pipeline is expressed as

$$Q = Av = \frac{\pi D^2}{4}v$$

Where:

Q = volumetric flow rate (m3/s)

A = cross sectional area (m2)

D = internal pipeline diameter (m)

v = gas velocity (m/s)

Although hydrogen is compressible, this simplified equation is widely used for initial sizing and approximate transport capacity estimates considering that density assumptions are clearly stated.

Mass Flow and Volumetric Flow

Hydrogen mass flow rate m relates to volumetric flow as:

$$Q = \frac{m}{\rho}$$

where ρ is the gas density at operating conditions

Recommended Pipeline Velocities

Literature suggests safe operational velocities of 10-20 m/s for hydrogen transport (Genovese et al., 2024). A value of 15m/s is used for this study as a design reference, balancing pressure losses and pipeline lifetime considerations.

4.3.2 - Methodology

In order to estimate the capacity of the hydrogen pipeline, following four steps can be executed consecutively

1) Starting with the calculation of annual hydrogen production using AEP and HHV
2) Converting the annual hydrogen production to hourly rate and then to per second mass flow rate.
3) Then the mass flow rate of the hydrogen is converted to volumetric flow using density at the operating pressure.
4) Finally, applying the flow continuity equation to determine the required pipeline diameter.

A design margin of 25% is then added to account for operation variability, transient flow and to accommodate future scalability.

Case Study of two offshore wind farms

In order to determine the capacity required to transport the produced hydrogen, the Gemini Offshore Wind Farm in the Netherlands is considered as a case study first.

Assuming full production of hydrogen and zero electricity production.

Gemini Wind Farm Details:

Installed Capacity = 600 MW

Capacity Factor = 48% (determined earlier)

Annual Energy Production (AEP) = $600 \times 0.48 \times 8760 = 2.52\, TWh\, per\ year$

Electrolyser Details:

Rated Capacity = 600MW

Electrolyser Efficiency = η = 0.8 (Shwe Sin et al., 2024)

Energy content of H_2 (HHV) = E_{H2} = 39.4 kWh / kg (N. R. Council & of Engineering, 2004)

Pipeline Operating Pressure

Common Offshore H2 pipeline pressure = 100 bar (Cristello et al., 2023)

Hydrogen density at 100 bar = 7.8 kg/m^3 (Andersson & Grönkvist, 2019)

Pipeline Velocity

Recommended : 10 – 20 m/s (Genovese et al., 2024)

Using 15 m/s in this design case

Hydrogen Production Rate

$$H_{Annual} = \frac{AEP}{39.4} = \frac{2.52 \times 10^9}{39.4} \approx 63{,}960\ ton\ per\ year$$

Hourly hydrogen production

$$H_{Hourly} = \frac{63{,}960{,}000}{8760} \approx 7301\, kg\ per\ hour$$

In kg/s

$$m = \frac{7301}{3600} \approx 2.028\, kg/s$$

Considering a first order sizing with the following assumptions

a) Steady state
b) Isothermal gas
c) No friction loss
d) Constant density

Converting it into volumetric flow

$$Q\ = \frac{m}{\rho} = \frac{2.028}{7.8} \approx 0.26\, m^3/s$$

Where Q = Flow

Calculation of Pipeline Diameter

Using the flow continuity equation:

$$Q = \ Av = \frac{\pi D^2}{4} v$$

Solving for D:

$$D = \sqrt{\frac{4Q}{\pi v}}$$

Inserting Values

$$D = \sqrt{\frac{4\ \times 0.26}{\pi\ \times 15}} = 0.14855\, m$$

Therefore, the required pipeline inner diameter is approximately equal to 0.15m or 150 mm.

Pipelines however are subjected to transient flow and compression losses, overloading of electrolysers and possibility to accommodate future expansions. Therefore, an additional 25% design margin can be considered

$$D_{Design} = 1.25\ \times 0.15 \approx 0.186m$$

186mm will come under Nominal Diameter (DN) of 200 (Mass flow online, 2025)

Therefore, the capacity required for 600 MW Electrolyser in Gemini Windfarm is DN 200 (200mm inner diameter) pipe.

Similar calculation can be done on another offshore wind farm For e.g Seagreen in the United Kingdom

Seagreen Wind Farm Details:

Installed Capacity = 1075 MW

Capacity Factor = 48% (Assuming same as Gemini)

Annual Energy Production (AEP) = $1075 \times 0.48 \times 8760 = 4.52\ TWh\ per\ year$

Electrolyser Details:

Rated Capacity = 1000 MW (assumption)

Electrolyser Efficiency = η = 0.8 (Shwe Sin et al., 2024)

Energy content of H_2 (HHV) = E_{H2} = 39.4 kWh / kg (N. R. Council & of Engineering, 2004)

Pipeline Operating Pressure

Common Offshore H2 pipeline pressure = 100 bar (Cristello et al., 2023)

Hydrogen density at 100 bar = 7.8 kg/m^3 (Andersson & Grönkvist, 2019)

Pipeline Velocity

Recommended : 10 – 20 m/s (Genovese et al., 2024)

Using 15 m/s in this design case

Hydrogen Production Rate

$$H_{Annual} = \frac{AEP}{39.4} = \frac{4.52 \times 10^9}{39.4} \approx 114{,}721\ ton\ per\ year$$

Hourly hydrogen production

$$H_{Hourly} = \frac{114{,}721{,}000}{8760} \approx 13{,}096\ kg\ per\ hour$$

In kg/s

$$m = \frac{13{,}096}{3600} \approx 3.638\ kg/s$$

Converting it into volumetric flow

$$Q = \frac{m}{\rho} = \frac{3.638}{7.8} \approx 0.47\ m^3/s$$

Where Q = Flow

Calculation of Pipeline Diameter

Using the flow continuity equation:

$$Q = Av = \frac{\pi D^2}{4} v$$

Solving for D:

$$D = \sqrt{\frac{4Q}{\pi v}}$$

Inserting Values

$$D = \sqrt{\frac{4 \ \times 0.47}{\pi \ \times 15}} = 0.1997 \, m$$

Therefore, the required pipeline inner diameter is approximately equal to 0.2m or 200 mm.

Pipelines however are subjected to transient flow and compression losses, overloading of electrolysers and possibility to accommodate future expansions. Therefore, an additional 25% design margin can be considered

$$D_{Design} = 1.25 \ \times 0.2 \approx 0.25m$$

250mm will come under Nominal Diameter (DN) of 250 (Mass flow online, 2025)

Therefore, the capacity required for 1000 MW Electrolyser in Seagreen Windfarm is DN 250 (250mm inner diameter) pipe.

Answering Sub-Question 3 - What is the capacity required to transport the produced hydrogen?

The results demonstrate that pipeline diameter requirements scale nonlinearly with hydrogen production due to its relationship between flow, velocity and density. Even relatively modest increases in hydrogen flow requires noticeable increases in the internal diameter. This has implications for planning interconnected offshore hydrogen networks in the North Sea. Individual wind farms may require dedicated pipelines (eg. DN200 – DN250), while aggregating multiple wind farms would necessitate much larger trunk lines potentially DN600 or higher depending on future hydrogen production levels.

The simplified hydraulic approach adopted here does not account for friction losses or compression energy, which should be examined in later engineering design stages. Nevertheless, the presented method offers a clear, repeatable framework for estimating first order pipeline capacity requirements based on offshore wind hydrogen production potential and appropriate for conceptual pipeline sizing.

Using two representative case studies Gemini and Seagreen, it was demonstrated that hydrogen production from a 600 MW offshore wind farm requires a DN 200 pipeline and hydrogen production from a 1 GW wind farm requires a DN 250 pipeline. Thus, transport requirements scale significantly with production volume and must be considered early in offshore hydrogen system planning.

These results form a foundational component for modelling the offshore hydrogen transport network

4.4 Offshore Wind based Hydrogen Projects

There are several pilot projects related to offshore wind based hydrogen production and transport.

H_2opZee is a demonstration project in the Dutch part of the North Sea. The plan is to generate hydrogen far out at the sea by building electrolyser with capacity ranging from 300 to 500 MW (RWE, 2026b). The electrolysers will be powered by offshore wind energy to produce green hydrogen. The project is led by RWE and Neptune Energy (ETN, 2026).

NorthH2 is a partnership of Eneco, Equinor, RWE and Shell Netherlands. They are currently investigating the feasibility of large scale production, storage and transport of giga watt scale green hydrogen produced from offshore wind farms (NortH2, 2026). Initially the production of hydrogen will be at Eemshaven with plans to install large scale production in the sea (RWE, 2026c). The feasibility study has been completed successfully. Gasunie is working on the transport network for the produced hydrogen .

Aquaventus is another green hydrogen project in the German part of the North Sea. The aim is to utilize electricity from offshore wind farms to generate hydrogen in the sea on an industrial scale (RWE, 2026a). The plan is to install total capacity of 10 giga watts which can generate up to 1 million tonnes of green hydrogen by the year 2035. Aquaductus is the pipeline that will transport the produce hydrogen from the North Sea (AquaVentus, 2026). Aquaventus calls for continuous dialogues between industry, political and environmental associations to overcome the challenges of offshore hydrogen generation in the sea.

PosHYdon project is another offshore wind based hydrogen pilot project in the Dutch part of the North Sea. The plan is to produce hydrogen using electricity from offshore wind on an existing gas platform. It is a one year offshore pilot project starting with 1 MW seawater based electrolysis to demonstrate the viability of production and transport by existing pipeline(PosHYdon, 2026). This kind of project provides valuable research and system performance outputs to contribute towards assessment of economics of the system. The project is lead by consortium of Neptune Energy, Eneco, EBN and other partners (PosHYdon, 2025).

H_2Mare is another German project to produce hydrogen from offshore wind power. It is a research project and aims to generate hydrogen and power to X products such as methanol and ammonia (Federal Ministry of Research, 2023). This project also plan to pursue new technologies such as seawater electrolysis. The project is at a nascent stage and aims to contribute towards knowledge generation for large scale implementation.

SeaH_2Land is another offshore wind based hydrogen production project which is of 1 GW scale led by Ørsted (Orsted, 2026). The partners include Arcelor Mittal, Dow and Yara and primarily focuses on decarbonizing hard to abate industries such as steel making. The project aims to generate 580,000 tonnes of hydrogen. The 1 GW electrolyser will be connected to a new 2 GW offshore wind farm. The industrial beneficiaries is in talks with TSOs to develop the pipeline network for this project (Orsted, 2021). The project is in phases starting with 500 MW electrolyser and in the second phase it will be increased to 1 GW.

Gigastack is a renewable hydrogen project of the UK. The aim is to prove the economical viability of generating green hydrogen using offshore wind energy (Gigastack, 2026). The project plans to develop electrolyser technologies to produce at large scale. The goal of the project is to decarbonise large industrial clusters through close collaboration. Currently the project is on hold because of the need for further development and refinement (Power Technology, 2023). The project is led by Ørsted and Philips 66.

Deep Purple is a pilot project in Norway led by Technip FMC partnered with Actemium Sarpsborg. This project aims to use the surplus offshore wind energy to produce hydrogen and store it or export onshore via pipelines (FMC, 2026).

Hydrogen Offshore Production for Europe (HOPE) is another offshore wind based green hydrogen production in Belgium led by Lhyfe, a French green hydrogen producer. The two goals of this project include advancement of technology by developing and testing the 10MW offshore green hydrogen production system and to demonstrate the feasibility and financial viability of large scale hydrogen production concept and pipeline so as to deploy by 2028 (HOPE, 2026). The electrolyser that is adopted is 10 MW PEM electrolyser. The system also comprises of seawater treatment system and flexible composite thermoplastic subsea pipeline.

4.5 Actor Analysis

Developing an offshore wind-based hydrogen transport pipeline network constitutes a complex ecosystem of public and private actors across energy, industry, infrastructure, finance as well as regulation.

The main actors typically fall into the following categories

1) **Offshore Wind Developers**

   These are the companies that build and operate offshore wind farms which generates electricity. The generated electricity from the wind farms can be utilized to produce green hydrogen. The main goal of offshore wind developers currently is to produce and sell electricity. Hydrogen production from their offshore wind farm is yet to be incorporated into their business agenda.

2) **Hydrogen Infrastructure Developers (Transmission System Operators (TSOs))**

   Currently the TSOs focus on gas transmission through gas pipelines, however they are central because they will build, own and operate the hydrogen pipelines. The TSOs include but not limited to

   a) GASCADE, TSO of Germany
      GASCADE is a major gas transmission operator with operations across Germany. Gascade is leading the AquaDuctus project being the sole hydrogen pipeline planned for the German part of the North Sea (Gascade, 2023).
   b) Fluxys (Belgium)
      Fluxys is the biggest gas transmission operator in Belgium and currently building out a hydrogen transmission network. Fluxys has also joined the AquaDuctus project for offshore transmission of hydrogen (Gascade, 2023).
   c) Gasunie, TSO of Netherlands
      Gasunie is the major gas TSO in the Netherlands and currently working with Fluxys to build cross-border hydrogen infrastructure connecting Belgium and the Netherlands(Fluxys, 2022). Gasunie is also planning to connects its hydrogen network internationally with Denmark’s TSO Energinet (Gasunie, 2024).

d) Energienet (Denmark)
   Energinet is the Danish TSO transmitting gas across the country. Energinet is planning hydrogen pipeline networks.
e) GRTgaz (France)
   GRTgaz is the French TSO involved in gas transmission. GRTgaz is also involved in hydrogen infrastructures.
f) Gassco (Norway)
   Gassco is the gas transmission operator of Norway. Gassco has future plans to transport hydrogen to Germany(Gascade, 2024).
g) National Gas Transmission (United Kingdom)
   National Gas Transmission is the TSO owning and operating the British gas network. Natonal Gas Transmission is considering future opportunities in hydrogen transmission(National Gas Transmission, 2025).

3) **Offshore Wind to Hydrogen Initiatives**
   These are consortia, initiatives or project developers that combines offshore wind, electrolysis and pipeline transport. Some of the initiatives include
   a) Aquaventus
      The goal of Aquaventus project is to install 10 GW of green hydrogen production capacity from offshore wind in the German North Sea and develop associated pipeline transport infrastructure (Aquaventus, 2025)
   b) Hydrogen Scotland
      Aquaventus and Hydrogen Scotland have signed an MoU to cooperate on hydrogen production and infrastructure in the North Sea(H2 International, 2025)
   c) H_2opZee
      With the ambition of encouraging the development of hydrogen economy in the North Sea, H_2opZee is a hydrogen demonstration project in the Dutch North Sea with plans to install electrolysers up to 500 MW to produce hydrogen (RWE, 2025a).
   d) European Hydrogen Backbone (EHB)
      The EHB is an initiative consisting of energy infrastructure operators with a shared vision to reach climate neutral Europe using renewable and low carbon hydrogen market (EHB, 2026).

4) **Regional and Political Bodies**
   a) The North Seas Energy Cooperation (NSEC)
      NSEC is a collaboration among the North Seas countries that is supporting and facilitating the development of offshore electricity and hydrogen infrastructure grid. The members of this cooperation includes countries of Norway, Germany, Belgium, Denmark, France, Ireland, Luxembourg and the political body, European Commission (European Commission, 2024).
   b) European Commission and Other EU Institutions
      European Commission and other EU institutions facilitate the development of hydrogen infrastructure particularly through hydrogen policy support. For example AquaDuctus has been notified under Important Projects of Common European Interest (IPCEI) (Tube Tradefair, 2025)

5) **Offshore Construction and Engineering Contractors**
   In order to build and construct the offshore hydrogen infrastructure, the role played by these actors are critical. Examples of these companies include
   a) Van Oord – Offshore Wind Infrastructure Transportation and Installation company.
   b) DEME – Marine Engineering and Offshore Construction company active in Offshore Wind
   c) Allseas – Subsea construction company that specialized in offshore pipeline installation.

6) **Industrial Hydrogen Consumers and End Users**
   Downstream industrial users of hydrogen including steel manufacturing, chemical producers and refineries are important actors as they are directly involved in the consumption of produced hydrogen. The demand centres which are the industrial clusters and nearby ports will determine the offloading points.

7) **Financing and Investors**
   Private Investors such as energy companies, green energy investors or Infrastructure funds may participate in the offshore hydrogen infrastructure projects. Considering the strategic nature, governments, European Investment Bank, national banks and EU might provide public funding through grants, subsidies and favourable regulatory support.

4.5.1 - Strategic Importance of these actors

TSOs like Gasunie, GASCADE, Gasscom etc are infrastructure builders whose involvement ensures technical expertise, regulatory experience, transmission experience and existing pipeline networks that could be converted for potential use. Further, cross border TSOs and consortia are important as a multiple country connected network brings in higher economies of scale. Regional organizations such as NSEC helps align national ambitions, regulations and permits when multiple countries are involved. Engineering and construction firms can build offshore electrolysis and associated infrastructures such as pipelines thereby reducing the technology risks. Last but not the least, the capital-intensive undertaking needs public backing and financial support through consortiums or infrastructure funds.

4.5.2- Risks and Challenges for these actors

There is regulatory risk with uncertainty about hydrogen versus gas regulation and the necessary regulatory updates considering hydrogen as an energy carrier. Another risk is permitting such as marine permits, environmental assessments and safety approvals. Carrying hydrogen comes with its own technical risks such as material compatibility for pipelines and hydrogen embrittlement. The long pipelines need compression and robust safety requirements considering the harsh offshore environment. Another major risk would be the demand risk considering the uncertainty in demand as the hard to abate industries need to be transformed to accommodate hydrogen usage instead of fossil fuels. Last but not the least, there is financial risks considering large investment with long pay-back.

4.6 Budget for Offshore Wind based Hydrogen Pipeline Development

The development of a dedicated offshore wind based hydrogen pipeline network in the North Sea is a corner stone of Europe's strategy to harness offshore wind energy for green hydrogen production and achieve decarbonization targets under the EU Green Deal and REPowerEU plan. The transition toward large scale offshore wind powered hydrogen production in the North Sea necessitates a correspondingly robust transport infrastructure, particularly subsea hydrogen pipelines. These pipelines will serve to aggregate hydrogen from distributed offshore production sites and transport it to onshore demand centres. Acknowledging the nascent stage of dedicated offshore hydrogen pipelines compared to offshore natural gas pipeline systems, estimates need to be derived from recent industry studies, project specific data and analogous subsea infrastructure costs.

Building offshore hydrogen pipelines is an emerging field with almost zero or very limited operational examples today. Most hydrogen pipelines that are existing are onshore and the offshore (subsea) pipelines are primarily in the planning or early development stages. Realistic budgets and construction rates depend heavily on factors like pipeline diameter, length, water depth, route complexity, material specifications (hydrogen compatible steel with coatings to resist hydrogen embrittlement) and also whether the pipeline is new built or repurposed from existing gas infrastructure. According to a study performed by DNV particularly for gas grid operators, it has been observed that due to the different material and chemical properties of hydrogen compared to natural gas, the transportation of hydrogen is significantly different. The study also concluded that repurposing existing offshore pipelines is not really economical in most cases and unsuitable for the integrated hydrogen system connecting different wind farms(H2 International, 2023).

4.6.1 - Cost Estimates for Offshore Hydrogen Pipelines

Even though dedicated offshore hydrogen pipeline cost data are limited, a few credible benchmark exists. Capital expenditure (CAPEX) for new subsea hydrogen pipelines is found to be ranging from USD 4.7 Million to USD 7.1 Million per kilometer (Statista, 2021), based on recent data

- The Hydrogen Council estimates that up to USD 7.1 million per km (approximately EUR 6.5 million per km) is required for new subsea transmission lines supporting offshore wind based hydrogen transport (H. Council, 2021).
- Real world projects provides benchmarks which can be a basis for estimation. The H2Med (BarMar) subsea pipeline, a 400 km hydrogen dedicated subsea pipeline is budgeted at around EUR 2.135 billion for the underwater section, equation to roughly EUR 5.34 Million per km (H2MedProject, 2025).
- The European Hydrogen Backbone initiative notes that offshore pipeline costs nearly twice as onshore ones, with onshore new build costs rising to EUR 1 million to EUR 2 million per km for large diameter pipes due to inflation (European Hydrogen Backbone, 2023).
- Costs were calculated for offshore hydrogen backbone in the North Sea and assuming pipe diameters between 36 to 48 inches, the price were estimated to be between EUR 3 Million and EUR 4.5 Million per kilometer of pipeline (H2 International, 2023).

The above figures aligns with broader analyses indicating that subsea pipelines are estimated to be at EUR 4 Million to EUR 7 Million per km for high capacity hydrogen transport.

Typical offshore hydrogen pipelines in the current planning such as AquaDuctus in the North Sea are designed for distances of 200 km from wind farms to shore, with capacities supporting 1 GW of electrolysis (AquaDuctus, 2025) .

4.6.2 - Cost Components of Offshore Hydrogen Pipelines

Major cost components involved in offshore hydrogen pipeline construction includes the following :

- Material costs : For the pipelines, high strength steel pipe as well as composite material pipes that are suitable for external marine environment with adequate coating and cathodic protection are required.
- Manufacturing and fabrication costs : After the pipe material is selected the pipes have to be welded, coated and their joints prepared which adds more costs.
- Installation costs : In order to install the pipelines, specialized pipelay vessels are required for trenching, rock dumping and subsea engineering activities.
- Engineering, Procurement and Construction Management (EPCM) : The offshore hydrogen pipelines have to be designed and engineered to withstand the harsh offshore environment.
- Compression and Booster Stations adds additional costs to accommodate pressure requirements.
- Permitting, environmental assessment and survey costs
- Operation and Maintenance (O&M) costs over the pipeline’s lifetime
- Contingency and inflation allowance

Actual cost will depend also on the diameter, length, water depth, seabed conditions and regional labour & material prices.

Existing research consistently reports that offshore pipelines are more expensive per unit length than onshore equivalents (European Hydrogen Backbone, 2022). Levelized transport costs for offshore hydrogen pipelines have been estimated to be between 1.5 – 2 times more than onshore pipelines of similar diameter which reflects harsher installation conditions and specialized technology required for hydrogen service (European Hydrogen Backbone, 2022).

Due to the limited hydrogen specific cost data, offshore natural gas pipeline construction costs can be considered which acts as a proxy baseline before hydrogen specific premiums are applied. The historic industrial data suggests that the costs for subsea natural gas pipelines are around USD 2 million to USD 5 million per km depending on water depth and project complexity (Monitor, 2025). Further, from the industrial data, for offshore hydrogen transportation, the pipeline cost is estimated to be 1.5 – 2 times the cost of gas pipelines especially due to hydrogen specific material and welding specifications and additional compression requirements.

4.6.3 - Realistic Budget Scenarios

Given the cost uncertainty and economies of scale (pipeline size, diameter, depth and route complexity) three budget tiers for offshore hydrogen pipeline construction can be considered. Table 2 considers three different scenarios for annual budget with modest, intermediate and ambitious scale.

Budget Tier	Annual Budget (EUR)	Assumed Cost / km (EUR)	Approximate Offshore Pipeline Built per Year (km)
Modest	2 Billion	5 million / km	Around 400
Intermediate	4 Billion	5 million / km	Around 800
Ambitious	8 Billion	5 million / km	Around 1600

Table 2 Realistic Budget Scenarios

The approximation in offshore pipeline built per year reflects uncertainties and engineering complexity. Hydrogen pipeline costs could be more or less as technologies mature and projects scale.

Modest budgets could fund few hundred kilometers of dedicated offshore hydrogen pipeline annually and smaller diameter export lines from single wind hubs.

Intermediate budget resembles the capital intensity of other utility scale offshore energy infrastructure rollouts enabling deployment of several pipeline corridors annually.

Ambitious budget are consistent with multinational hydrogen projects like European Hydrogen Backbone (European Hydrogen Backbone, 2022) where pipelines form part of integrated systems linking multiple offshore wind sites across regions. It has to be noted that these budgets exclude electrolyser installation, offshore platforms, storage and onshore terminal costs. The focus is on pipeline CAPEX only.

4.6.4 - Annual Deployment Capacity

The number of distinct pipeline projects that could be completed annually will depend upon

1) Length of each project as in short branch lines or long trunk line
2) Availability of installation vessels and qualified crew
3) Regulatory and Permit timelines
4) Manufacturing capacity for specialized hydrogen compatible pipe and components

Consider the case of AquaDuctus (AquaDuctus, 2025) with 200 km long offshore hydrogen pipeline, then

- EUR 2 Billion might support 1 or 2 such pipeline per year
- EUR 4 Billion could support 3 to 5 such pipelines per year
- EUR 8 Billion could support 5 to 9 or more such pipelines per year

given economies of scale and overlapping vessel operations. Longer trunk network pipelines (e.g. 500+ km) would then count as one large project absorbing most of an annual budget under modest budgets.

4.6.5 - Key Uncertainties

Considering the nascent stage of offshore hydrogen pipeline network development, there are several uncertainties that has to be considered.

1) Technical factors
   Hydrogen embrittlement and material selection remain as active research area. The choice of suitable steel or composite materials will significantly affect costs. Placement of compressor and booster stations influence not only Capex but also the operating costs.

2) Market and Policy Dynamics
Subsidies, hydrogen transmission tariffs and shared infrastructure mandates through strong policy support can critically alter project bankability and cost distribution among the stakeholders.

3) Regional Variability
The cost of pipeline infrastructure varies vastly by geography, water depth, regulatory environment and labour markets.

Answering Sub-Question 4 - What is a realistic budget for building offshore hydrogen pipeline each year and how many pipelines can be built in a year with this budget?

Given the current evidence and understanding of new pilot projects and established hydrogen pipeline estimates, offshore hydrogen pipeline construction remains highly capital intensive. The costs exceed traditional natural gas subsea pipelines when engineered for hydrogen service. This is mainly due to the additional safety and process requirements for transporting hydrogen. A realistic annual capital budget for dedicated offshore hydrogen pipeline can range from EUR 2 Billion to EUR 8 Billion which supports roughly 400 to 1600+ km of pipeline deployment per year depending on cost assumptions and project scale. The deployment rates of offshore hydrogen pipelines can accelerate with technological learning, policy support and standardization of hydrogen pipeline materials and installation practices.

These estimates provide a foundation basis for resource planning framework and strategic energy infrastructure modelling.

4.7 Network metrics to prioritize pipeline construction in offshore wind based hydrogen transport network

The large scale deployment of offshore wind energy in the North Sea presents a significant opportunity for the production of green hydrogen via electrolysis. The development of offshore wind based hydrogen production represents a critical pathway toward decarbonizing the energy system particularly in region such as North Sea with abundant wind resources. Hydrogen generated via electrolysis at offshore wind farms must be efficiently transported to onshore demand hubs or demand centers through dedicated pipeline networks. The development of a resilient and efficient hydrogen transport infrastructure is a critical planning challenge which involves diverse technologies, actors and transportation systems. Pipeline networks will have a central role in transporting hydrogen from offshore production hubs to onshore demand centres and industrial clusters.

Given the high capital costs as identified earlier, long lifetimes and path dependency associated with pipeline infrastructure development, strategic planning regarding which pipelines to build, in what order and at what scale are crucial to understanding the network evolution. Network system science provides a systematic framework to support such decisions. The hydrogen transport pipeline system can be represented in the form of a graph and with the application of network metrics, network planners can identify the critical connections, determine investment strategy and evaluate trade offs between costs, efficiency, robustness and future expansion potential. Rather than selecting pipelines based on geographic proximity, utilizing network metrics promotes system optimal infrastructure development.

4.7.1 Network Representation of Offshore Hydrogen Pipeline Systems

Graph Abstraction

The hydrogen pipeline can be represented as a graph $G = (V, E)$, where:

Nodes (V) represent offshore wind farm and hydrogen production hubs, onshore demand centers and industrial clusters

Edges(E) represent candidate hydrogen pipelines. Each edge may be directed or undirected depending on assumed flow reversibility.

Edge and Node Attributes

To support decision making, the graph includes attributes such as

Edge attributes

- Length
- Capital cost
- Transport Capacity
- Construction year or availability

Node attributes

- Hydrogen production capacity
- Hydrogen demand
- Location details
- Role (source or sink or intermediate)

This enriched network representation enables the application of both topological and weighted network metrics.

4.7.2 Network Metrics in Pipeline Network Growth Decisions

Network metrics quantify structural properties of the pipeline system. When applied to candidate pipeline configurations, these metrics helps in identifying which connections provide the highest system level value. An overview of the network metrics that can be considered is given in Table 3.

Metric	Type	What it measures	Planning / Evolution Insight
Degree Centrality	Node (topological)	Number of direct pipeline connections at a node	Identifies locally well connected hubs. It highlights nodes important for distributing hydrogen in multiple directions.
Weighted Degree (Node Strength)	Node (weighted)	Sum of edge weights (eg. Capacity, flow, cost) connected to a node	It reveals nodes critical for throughput rather than simple connectivity. It identifies trunk pipelines from local connections.

Betweenness Centrality	Node (flow oriented)	Frequency with which a node lies on shortest paths between other nodes	It identifies aggregation hubs and bottlenecks. It highlights critical nodes whose failure can strongly impact network performance.
Closeness Centrality	Node (distance based)	Average shortest path distance from a node to all other nodes	It indicates nodes with low transport cost and time to demand centers. It is useful for selecting efficient connection points.
Eigenvector Centrality	Node (hierarchical)	Importance of a node based on importance of its neighbours	It identifies strategically influential nodes connected to major hubs. It supports planning of long term backbone infrastructure.
Edge Betweenness Centrality	Edge (flow oriented)	Frequency with which an edge lies on the shortest paths	It highlights system critical pipelines and potential bottlenecks. It supports redundancy and prioritization of key connections.
Edge Weight Metrics	Edge (attributes)	Physical or economic attributes such as length, cost, pressure loss	Ground network analysis in engineering and economic realism. It strongly influences shortest paths and flow based metrics.
Capacity Utilization	Edge (operational)	Ratio of flow to maximum capacity	It identifies efficiently used pipelines and upgrade needs if any. It support prioritization of high value investments.
Shortest Path Length	Network (pairwise)	Minimum cost distance	It evaluates efficiency gains from new pipelines. It also highlights connections that reduce energy losses and operating costs.
Average Path Length	Network (global)	Mean shortest path distance across all node pairs	It measures overall system efficiency. It is also useful for assessing network wide benefits of new pipelines
Supply Weighted Flow	Node / Edge (flow weighted)	Flow weighted by production capacity of source nodes	It prioritizes pipelines that unlock large volumes. It aligns infrastructure with realistic generation scenarios.
Global Efficiency	Network (global)	Average inverse shortest path length across all node pairs	It captures how efficiently the flow can move through the system.
Clustering Coefficient	Node / Network (local structure)	Degree of local interconnectedness among neighbouring nodes	It identifies regional hubs as well as redundancy. It also helps assess balance between local optimization and system integration.

Euclidean Distance (Source to Sink)	Spatial / Edge	Straight line physical distance between nodes	It is a proxy for pipeline length, costs and losses. It ensures spatial and engineering feasibility in route selection.
Connected Components	Network (structural)	Group of mutually reachable nodes	It tracks network integration over time. It also highlights pipelines that connect isolated projects and deliver large systemic benefits

Table 3 - Network Metrics Overview

1) Degree Centrality

Degree centrality quantifies the number of direct connections that are connected to a node in the network (Hirsto, 2022). Degree centrality in the context of hydrogen pipeline network indicates the number of pipelines which are directly connected to a given node that can be either offshore wind farm based hydrogen production centers or demand centers. Nodes with high degree centrality acts as local hubs which facilitates multiple routing options for hydrogen transport. When we look at degree centrality from an infrastructure planning perspective, it provides insight into local connectivity and redundancy which highlights nodes that could play an important role in distributing hydrogen across multiple directions. It is important to note that degree centrality does not account for pipeline capacity, distance or flow but it mainly reflects structural connectivity rather than operational importance.

2) Weighted Degree (Node Strength)

Weighted degree is simply an extension of the degree centrality and it incorporates edge weights such as pipeline capacity, length, cost or hydrogen flow (Zhao & Sun, 2024). Instead of just simply counting connections, weighted degree on the other hand measures the cumulative importance of a node based on the characteristics of the connected pipelines. This metric provides a more realistic representation of node importance by distinguishing between nodes connected by high capacity trunk pipelines and nodes connected by smaller or less significant links in a hydrogen transport network. Weighted degree is especially relevant when pipeline capacities differ significantly as in the case of large offshore hydrogen pipeline systems where large export pipeline coexist with smaller regional connections. This metric helps to identify nodes that are critical in terms of throughput rather than just connectivity.

3) Betweenness Centrality

Betweenness centrality measures the extent to which a node lies on the shortest paths between other node pairs in the network (Easley & Kleinberg, 2010). Nodes which have high betweenness centrality acts as intermediaries or transit hubs through which a large fraction of hydrogen flows can pass through. In offshore wind based hydrogen pipeline networks, such nodes will result as aggregation hubs, junction platforms or strategically located entry points. A high betweenness centrality value indicates potential bottlenecks as the disruptions at these nodes could disproportionately affect the overall network performance. This metric therefore is crucial in order to identify critical infrastructure which may require redundancy, enhanced protection or capacity reinforcement. Betweenness centrality also have a critical role in understanding how network evolution redistributes flow paths over time.

4) Closeness Centrality

Closeness centrality determines how close a node is, on average, compared to all the other nodes in the network and it is based on the shortest path distances (Hansen et al., 2010). In the offshore hydrogen transport scenario, nodes with high closeness centrality could reach producers and consumers with relatively low transport cost and time. These nodes are attractive locations for new pipeline connections because they minimize hydrogen losses, compression requirements and operational costs. When deciding which pipelines to build, closeness centrality helps in identifying routes that reduces the overall distance hydrogen must travel across in the network. This metric therefore supports decisions aiming at improving global transport efficiency rather than local connectivity alone.

5) Eigenvector Centrality

Eigenvector centrality calculates the centrality of a node not only based on all of its direct connection but also based on the centrality of the nodes which are connected to it (Hansen et al., 2010). In the offshore hydrogen pipeline network case, a node that is connected to large production hub or key demand center could be very important even if it has relatively few connections. This metric captures the hierarchical structure and influence within the network which makes it useful for identifying emerging backbone nodes. Pipelines that are built to enhance eigenvector centrality could strengthen the core structure of the network and support long term scalability. Eigenvector centrality is particularly relevant when planning for infrastructure intended to become part of a future continental hydrogen backbone.

6) Edge Betweenness Centrality

Edge betweenness centrality measures how frequently a pipeline lies on shortest paths between pairs of nodes (Lu & Zhang, 2013). Pipelines which have high edge betweenness plays a disproportionate role in enabling hydrogen transport across the network. From a planning perspective, this metric helps in identifying which candidate pipelines would carry system critical flows when constructed. High edge betweenness pipelines may need higher design standards, redundancy, or early investment due to their significance. In addition to that, this metric also shows potential bottlenecks which can support decision making whether to add parallel pipelines or alternative routes to reduce congestion and systemic risk.

7) Edge Weight Metric

Edge weight metric represents physical as well as economic attributes of pipelines such as length, costs and pressure losses. These metrics are fundamental inputs instead of derived network measures yet they strongly influence all higher level metrics (Hevey, 2018). When evaluating which pipelines to are to be built, edge weight provides the possibility to compare between alternative routes connecting the same nodes. Pipelines which have lower pressure losses frequently has the potential to enhance the shortest path efficiency and overall network performance. Incorporating realistic edge weights may ensure that network evolution model will remain grounded on engineering and economic feasibility instead of purely topological considerations.

8) Capacity Utilization

Capacity utilization metric calculates the proportion of realized or expected hydrogen flow that passes through a pipeline to the maximum transport capacity of the pipeline (Fong et al., 2024). In the case of offshore hydrogen network planning, pipelines which have high expected utilization are strong candidates for construction because they offer efficient use of capital investment. This metric helps in understanding the difference between strategically important pipelines and those pipelines which add little functional value. In the long term, capacity utilization could also guide network evolution by signalling where upgrades or additional pipelines are needed.

9) Shortest Path Length

Shortest path length represents the minimum distance or cost that is required to transport hydrogen between two nodes (Mitchell, 2017). In offshore hydrogen pipeline networks, shorter paths normally corresponds to lower energy losses and operating costs. When evaluating new pipelines, planners can assess how much a proposed connection reduces the shortest path lengths between production and consumption nodes. Pipelines which significantly shorten paths often have a high system wide impact which can justify their higher upfront costs. This method therefore is central to decisions focused on efficiency and competitiveness of hydrogen transport.

10) Average Path Length

Average path length of the network is the mean shortest path distance between all pairs of nodes (Perez & Germon, 2016). This metric offers a global measure of transport efficiency across the entire offshore hydrogen transport system. A decrease in the average path length following the addition of new pipelines indicates improved connectivity and reduced transport effort. Pipelines which significantly lowers the average path length tend to benefit many nodes simultaneously, which makes this metric useful for evaluating system wide impact rather than localized improvements.

11) Supply weighted flow

Supply weighted flow is a measure of the amount of hydrogen transported through nodes or pipelines while clearly accounting for the amount of hydrogen supply available at each source node. In the case of an offshore wind based hydrogen pipeline network, this metric reflects not only the existence of transport pathways, but also their relevance to actual hydrogen production levels that may vary significantly between offshore wind farms. By assigning the network flows a weightage based on the supply capacity, this metric indicator evaluates and distinguishes pipelines which enable the transportation of large hydrogen volumes from major production hubs and also from those serving smaller or marginal sources (Bertagnolli et al., 2021). From the perspective of offshore hydrogen infrastructure planning, supply weighted flow offers insight into which pipeline connections are likely to experience high utilization and could deliver the greatest system value. It therefore supports decision making which is aimed at prioritizing pipelines that unlocks substantial offshore hydrogen production and ensures that transport infrastructure development remains aligned with realistic generation scenarios rather than just purely topological importance.

12) Global Efficiency

The global efficiency is measured to be the average inverse shortest path length between all pairs of nodes in the network (Ek et al., 2015). For the hydrogen transport network case, it directly corresponds to the efficiency of hydrogen transportation throughout the network. The key difference from average path length is that global efficiency emphasizes improvements in poorly connected regions. Pipelines which increases global efficiency are particularly valuable in integrating remote offshore wind farms into the broader hydrogen economy.

13) Clustering Coefficient

The clustering coefficient measures the propensity of nodes to form cluster in a tightly knit neighbourhood of nodes in the network (Hansen et al., 2010). In the case of an offshore hydrogen network , high clustering coefficient could represent regional hubs where multiple wind farms and pipelines are interconnected. High clustering may improve local reliability and flexibility but it may also indicate redundancy. The distinguishing feature of this metric is that it helps in identifying whether pipeline construction favours localized optimization or broader system integration of the pipeline network. It is particularly important when analyzing the emergence of regional hydrogen hubs in the North Sea.

14) Euclidean distance between source and sink

Euclidean distance between source and sink is calculated by the straight line physical distance that a hydrogen pipeline may stretch between production nodes and demand or aggregation nodes (Sohail et al., 2025). In the scenario of offshore hydrogen pipeline networks, this distance can serve as a proxy for pipeline length which may directly affect the capital expenditure, complexities in construction and energy losses. Shorter Euclidean distances normally accounts for lower investment and operating costs, particularly important for offshore environments where the installation and maintenance may be technically demanding. During the evaluation of candidate pipelines, this metric enables the comparison of possible routes where it highlights connections that minimizes physical transport distance while still maintaining full network functionality. From the perspective of infrastructure planning, utilizing Euclidean distance ensures that network evolution decisions are grounded in spatial and engineering feasibility complementing centrality based metrics that focuses primarily on structural or flow related importance.

15) Connected Components

Connected components identifies groups of nodes that are reachable from one another (Morrison et al., 2022). In the case of early hydrogen network development, multiple disconnected components may exist which corresponds to isolated projects. Pipelines which could connect separate components will often yield large benefits by enabling resource sharing and economies of scale. This metric is therefore important for prioritizing pipelines that could integrate isolated offshore assets into the main transport network. Further, component analysis also provides a clear indicator of network evolution over time.

Answering Sub-Question 5 - How can network metrics be used to determine which pipelines to be built?

Network metrics provide a quantitative framework to evaluate the system level impact of candidate pipeline investments beyond local or project specific considerations. In an offshore wind based hydrogen transport network, individual pipelines are not isolated assets rather their value depends on how they reshape connectivity, flow patterns, efficiency and resilience of the entire system. By the computation of different network metrics before and after the addition of candidate pipelines, network planners could systematically identify which connections contributes the greatest overall benefit which then should be prioritized for construction.

Network metrics can be used in three main ways:

1) Screening candidate pipelines by estimating their marginal contribution to network performance.
2) Ranking investments based on their impact on flow efficiency, accessibility and robustness.
3) Guiding network evolution i.e by showing how strategic importance shifts as new offshore wind farms and demand centers are integrated over time.

While many metrics can describe different aspects of network structure as reviewed earlier, only a subset is required to capture the dominant drivers of pipeline investment decisions in a large scale hydrogen transport system. For this study, four metrics are selected because they jointly capture flow criticality, demand supply relevance, spatial cost and system wide accessibility which are the key determinants of pipeline value.

Selected metrics include betweenness centrality (delta), supply weighted flow, Euclidean distance from source to sink and closeness centrality.

A) Betweenness Centrality

Betweenness centrality is used to identify pipelines and nodes that are critical for network wide hydrogen transport. In a hydrogen pipeline network, nodes or edges with high betweenness lie on a large fraction of shortest paths between production nodes (offshore wind farms producing hydrogen) and consuming nodes (onshore demand centers).

When applied to candidate pipelines, changes in betweenness centrality (delta) reveal whether a new connection creates a new strategic corridor for hydrogen flow, relieves congestion on existing routes or introduces potential bottlenecks that may require future reinforcement. Pipelines that significantly increase betweenness centrality are systemically important because they enable large scale redistribution of hydrogen across the network. Including betweenness centrality ensure that pipeline selection is guided by system level flow importance and not just local connectivity.

B) Supply weighted flow

Although the centrality metrics can help to identify structural importance, they do not necessarily incorporate where the hydrogen is actually produced. Supply weighted flow takes into account for this spatial distribution and amount of offshore hydrogen production by weighting the network flow according to the availability of supply at each source node. By using this metric, it is ensured that the pipelines are given priority based on their capacity to transport large volumes of hydrogen from the high capacity offshore wind farms, connecting major production hubs to demand centers efficiently and supporting realistic deployment scenarios instead of purely topological configurations.

In offshore wind based hydrogen systems, production is not always balanced and keeps changing over time. Supply weighted flow therefore aligns the infrastructure planning with actual energy system dynamics which ensures that the pipelines are built where they unlock the most usable hydrogen. This makes the metric particularly relevant for studying network evolution because it naturally adapts to changes in installed wind capacity.

C) Euclidean distance from source to sink

Euclidean distance serve as a proxy for physical pipeline length which is directly related to capital cost, compression requirements, energy losses and construction feasibility. In the offshore environments where longer pipelines imply higher installation and maintenance costs, increased pressure losses and operational complexity and also greater exposure to environmental and technical risks. By incorporating Euclidean distance from hydrogen sources to sinks, the network model can ensure that candidate pipelines are evaluated not only on network benefits but also on spatial realism. Pipelines that significantly reduce the transport distances between major production and consumption nodes offers stronger economic advantages and are more likely to be viable investments. This metric can therefore ground the network analysis in engineering and economic constraints, preventing the selection of pipelines which might appear attractive topologically but are impractical in real world offshore settings.

D) Closeness Centrality

Closeness centrality evaluates how easy it is for the hydrogen to be transported from a particular node to the rest of the network. Nodes having high closeness centrality are on average closer to all other nodes in terms of shortest path distance and it makes them attractive connection points for new pipelines. When applied to pipeline planning, closeness centrality helps in identifying connections that reduces overall transport distances across the system thereby improving accessibility of both producers and consumers, which in effect enhances global efficiency rather than local optimization alone. For the case of North Sea hydrogen network, increasing closeness centrality can help facilitate the development of well connected hubs which efficiently distributes hydrogen across market regions. With the inclusion of this metric, it is also ensured that pipeline construction contributes to a well connected and efficient network structure instead of reinforcing fragmented or regionally isolated systems.

The four selected metrics are complementary and together forms a balanced basis for pipeline selection. Betweenness Centrality (delta) evaluates the strategic importance and flow criticality. Supply weighted flow on the other hand ensures relevance to actual hydrogen production by also considering distance between source and the sink. Euclidean distance reflects physical and economic feasibility. Closeness centrality focuses on the global accessibility and efficiency. By evaluating candidate pipelines across these dimensions in a network evolution model, investments can be prioritized which are not only structurally important but also economically meaningful, spatially realistic and aligned with long term system integration goals.

- This chapter focused on system identification and decomposition. Starting with the identification of offshore wind farms in the North Sea, the production potential of the offshore wind farms to generate hydrogen has been assessed. Further the capacity requirements of the pipeline were calculated. Then a brief description of existing projects is discussed. This was followed by an actor analysis to understand the perspective of stakeholders. The offshore pipeline system has budgetary constraints which were explored. Then the network metrics that were most suitable to simulate offshore hydrogen pipeline network were identified and selected. The next chapter focuses on the development of a conceptual model to simulate network growth

5. CONCEPTUAL MODEL

This chapter focuses on capturing the logic of the model that has to be implemented in NetworkX and for that purpose a conceptual model is developed.

The conceptual model is in Figure 7 with the explanation below.

5.1 - Conceptual Overview of the Model

The model conceptualizes the offshore hydrogen transport system as a spatially embedded network that evolves over time. At its core, the system consists of three fundamental elements:

1) Hydrogen sources representing offshore wind farms equipped with electrolyzers.
2) Hydrogen sinks representing onshore demand centers
3) Pipeline infrastructure represented as edges connecting spatial nodes

Rather than predefining a complete pipeline layout, the network grows incrementally by adding pipeline segments based on multi criteria decision framework. At each growth step, candidate pipeline segments are evaluated according to their contribution to network connectivity, transport efficiency and hydrogen delivery potential. This approach allows the network topology to emerge endogenously from the interaction of spatial constraints, supply availability and strategic priorities.

The model is structured around three interacting dimensions which includes spatial structure defined by a two dimensional grid and regional boundaries, temporal evolution governed by discrete planning years and source commissioning years and finally decision logic that is implemented through a weighted scoring system that determines which pipeline segments are added to the network.

5.2 - Conceptual Model Description

A spatially explicit, time evolving conceptual model has been developed to explore the emergence of an offshore wind based hydrogen transport pipeline network in the North Sea. The model represents how the offshore hydrogen infrastructure could gradually form under different planning priorities as offshore production capacity and onshore demand evolve over time.

The offshore study area is first represented in the form of a grid and then further subdivided into regions to reflect geographical and planning boundaries. All grid locations are initially unconnected which represents the absence of hydrogen transport infrastructure in the North Sea. Specific grid locations are designated as hydrogen production sites, representing offshore wind powered electrolyser systems as source nodes, while other grid locations are designated as demand centers representing sink nodes. Each offshore wind based hydrogen production site is associated with a commissioning year, reflecting the temporal rollout of offshore wind projects.

The model progresses sequentially through predefined planning years. In each time period, only those sources whose commissioning year has been reached are considered to be active. To reflect the project uncertainty or phased deployment, the availability of active production sites can be constrained which will allow the model to represent delayed or partial realization of planned offshore capacity.

Within each region and planning period, the hydrogen pipeline network grows incrementally. Growth begins with the selection of an active production site that is not yet connected to any demand center. The selection of production sites may follow different strategies, such as fixed order, random selection or proximity based selection allowing alternative development pathways to be explored.

For a selected production site, the model identifies the part of the network which is already connected to that site and it evaluates potential pipeline extensions at the boundary of this connected area. Only physically adjacent extensions within the same region are considered which ensures that the network growth respects spatial realism and regional planning constraints.

Each potential pipeline extension is evaluated using multi criteria. These criteria capture different planning objectives such as the contribution of a pipeline to overall network structure, its ability to facilitate hydrogen transport from production to demand, its proximity to demand centers, and its effect on improving overall network accessibility. The relative importance of these criteria will vary across scenarios representing different planning philosophies.

To encourage the formation of a real world like backbone network, the model applies an adaptive connectivity incentive that favours extensions which connect previously separate parts of the network. This incentive is made to be strongest in early stages when the network is fragmented and gradually diminishes as the network becomes more integrated.

Based on the combined evaluation of all criteria, the highest performing pipeline extension is selected and permanently added to the network. The network state is updated after that and then the process is repeated iteratively. Once a production site becomes connected to at least one demand center, it is considered to be successfully integrated into the network. Then the focus shifts to other unconnected production sites.

Network growth within a region continues until one of three stopping conditions is reached. It includes, all active production sites are connected to demand centers, the regional pipeline construction limit is reached or no feasible pipeline extension remain. After the growth process for a planning period is completed, the resulting pipelines are classified according to their functional role within the network distinguishing between local connections, branch lines and trunk pipelines.

The evolved network is then evaluated using a set of performance indicators including total pipeline length, average transport distance between production and demand, the extent of network expansion over time and the potential amount of hydrogen that can be delivered to demand centers. These indicators allow systematic comparison across planning periods and scenario assumptions.

With repeated application of this process under alternative planning priorities and availability assumptions, the conceptual model enables the analysis of how different strategic choices could influence the long term structure and development of the offshore hydrogen transport network.

- A conceptual model to simulate the network growth and study its evolution has been developed. The next chapter will focus on its implementation in NetworkX.

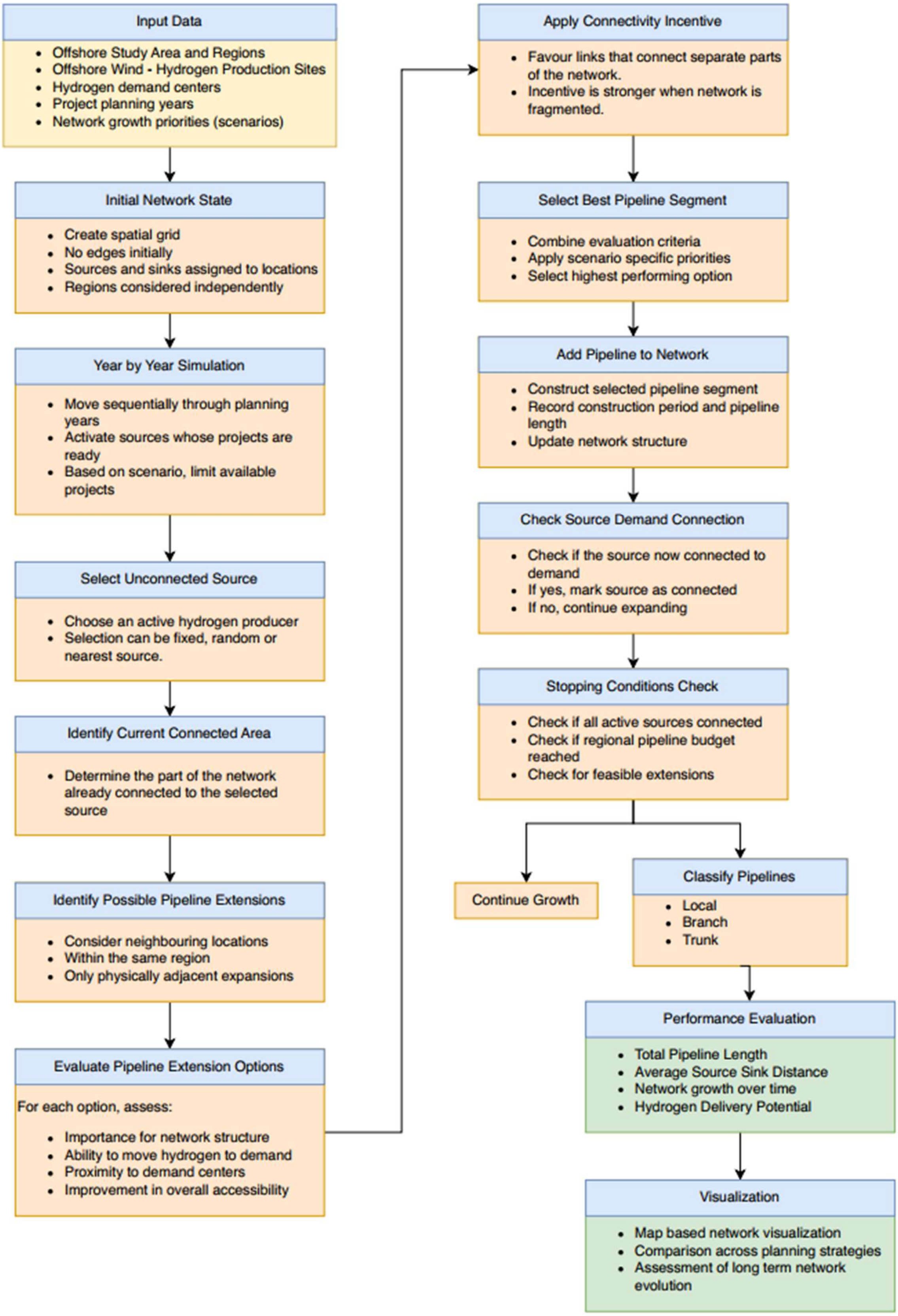


Figure 7 - Conceptual Model

6. MODEL DESIGN IN NETWORKX

This chapter focuses on the implementation of the conceptual model in NetworkX to simulate the offshore pipeline network growth and evolution.

The conceptual model described earlier is implemented using Python library NetworkX and adopts a heuristic, multi criteria growth approach rather than a single global optimization. The objective is not to identify a unique optimal network, but to explore how different design priorities, deployment strategies and availability assumptions influence the emerging network structure and performance. The model explicitly represents offshore wind farm based hydrogen production systems as sources, demand centers as sinks, and potential pipeline junctions as intermediate nodes all within a spatial grid. Network growth is simulated incrementally across multiple time periods (2030, 2040 and 2050) allowing the analysis of phased infrastructure development under different experimental scenarios. The offshore wind farms which are existing are expected to be generating hydrogen production in the year 2030. In order to simplify calculations, the commissioning years are assumed and defined. Offshore wind farms which are in the planning stage, consent application submitted and pre-construction stage are expected to generate hydrogen in the year 2040. The offshore wind farms in the development zones are expected to be operational by the year 2050.

6.1 - Network Representation

Graph Structure

The offshore wind based hydrogen transport pipeline network is modelled as an undirected, weighted graph $G = (V, E)$.

Here V represents the set of nodes while E represents the set of edges. The reason for using an undirected representation is because hydrogen pipelines allow bidirectional flow in principle. Further, the model focuses on connectivity and distance rather than directional flow control.

Each edge in the graph is attributed with a weight representing the Euclidean distance between its endpoints, which can serve as a proxy for pipeline length and installation cost. The graph will evolve over time as new edges are added. Edges are never removed once permanently constructed reflecting path dependent nature of pipeline infrastructure.

Spatial Grid and Node Placement

The spatial domain is categorized into a regular two dimensional grid, with each grid cell corresponding to a node in the graph which can be source, sink or intermediate node. Nodes are assigned Cartesian coordinates derived from the underlying map image of the North Sea which enables spatially explicit distance calculations and visualization.

Each node can belong to one of these three types:

a) Intermediate nodes which represents potential pipeline junctions
b) Source nodes which represents offshore wind farms producing hydrogen
c) Sink nodes which represents hydrogen demand centers

Intermediate nodes are initially inactive in terms of supply and demand but provides the spatial flexibility needed for routing pipelines realistically across the offshore environment.

Node Attributes

Each node in the network is associated with a set of attributes which governs its role in the model

- Pos : the spatial coordinates of the node
- Type: the node category (source, sink or intermediate)
- Supply: hydrogen production capacity (assigned only to sources)
- Year: commissioning year for hydrogen production assets
- Connected: a Boolean indicator of whether a source is connected to at least one sink

These attributes allows the model to distinguish between different functional roles and to activate sources dynamically over time.

Regional Decomposition

To manage spatial complexity and reflect regional planning considerations, the model divides the overall grid into multiple regions, each defined by rectangular spatial boundaries. Each region contains its own set of sources and sinks and is assigned a regional pipeline growth budget which can limit the number of edges that can be added.

Regional decomposition serves several purposes. First, it allows infrastructural development to be analyzed at a sub system level, which is particularly relevant for the North Sea where national planning strategies focus on region by region and the regulatory environment could be different for each country. Second, it reduces computational complexity by limiting the scope of network growth decisions to a subset of nodes. Finally, it enables comparative analysis between regions with different spatial characteristics, supply densities and demand patterns.

Even though the regions grow independently, they share the same underlying graph structure, ensuring consistency in spatial representation and allowing future extensions that consider inter regional connections.

Temporal Structure and Planning Horizons

The model incorporates time periods clearly through a set of discrete planning horizons: 2030, 2040 and 2050. As mentioned earlier, the availability of a source depends on the current status. These milestones reflect typically long term energy system planning frameworks and allow the staged deployment of hydrogen infrastructure to be analysed.

Hydrogen sources are assigned commissioning years and only those sources whose commissioning year is less than or equal to current simulation year are considered active. This mechanism enables the representation of phased offshore wind deployment and avoids unrealistic assumptions about spontaneous system availability.

Once constructed, pipeline segments remain in the network for all subsequent years, reflecting the cumulative and path dependent nature of infrastructure development.

6.2 - Network Growth Algorithm

Iterative Growth Logic

Network growth is implemented as an iterative process within each region and planning year. For a given region and year, pipeline segments are added one at a time until either the regional growth budget is exhausted or all active sources are connected to at least one sink.

At each iteration

1) An active source that is not yet connected to a sink is selected.
2) The connected component containing that source is identified.
3) Candidate edges are then generated at the boundary of this component temporarily.
4) Each candidate edge is further evaluated using a multi criteria scoring framework
5) The highest scoring edge is then added permanently to the network after removing the temporary edge.

This incremental approach of generating edges allows the network topology to evolve organically and it ensures that each investment decision is informed by the current state of the system

Source Selection Strategies

The model facilitates multiple source selection strategies to explore different development logics:

a) Deterministic selection, where the sources are connected in a fixed order
b) Random source selection, which introduces stochasticity into the growth process
c) Nearest neighbour source selection, where the sources geographically close to previously connected sources are given importance first.

These strategies are implemented as experimental scenarios and allows the sensitivity of network outcomes to planning heuristics to be assessed.

Candidate Edge Generation

Candidate pipeline segments are generated by examining the boundary between the connected component of the selected source and neighbouring unconnected nodes. Only edges that connects nodes within the same region, which do not already exist in the network and follows the predefined neighbourhood structure (all neighbours including diagonal connections) are considered. This ensures spatial continuity and it prevents unrealistic long distance jumps which otherwise would bypass intermediate routing options.

6.3 - Multi Criteria Edge Scoring Framework

Scoring Metrics

Each candidate edge is evaluated using a weighted combination of four metrics and an adaptive component bonus. The scoring metrics include

1) Change in betweenness centrality which captures the potential of the edge to create strategically important network nodes.
2) Change in closeness centrality which reflects improvements in overall network accessibility
3) Supply weighted flow potential, which favours edges that can enhance hydrogen delivery from sources to sinks
4) Inverse distance to nearest sink which encourages shorter and more direct routes in the network.
5) In order to reward edges that connect previously disconnected network components, an adaptive component bonus score is incorporated.

These metrics captures the complementary facets of network performance, balancing efficiency, robustness and connectivity.

Normalization and Weighting

As the metrics operates on different scales, all values are normalized prior to aggregation. A weighted sum is then used to compute a final score for each candidate edge. The weights assigned to each metric are defined experimentally which allows different planning priorities to be explored.

Adaptive Feedback and Connectivity

One of the important aspects of the model is its adaptive feedback mechanism. Following each edge additions, the number of connected components in the network is calculated again. Then the stability of the largest component is evaluated to determine the level of fragmentation. If the level is too high, the adaptive component bonus is increased which favours the merging of isolated sub networks. When the network becomes more interconnected, the bonus value is reduced which shifts the focus towards efficiency driven expansion. This feedback loop ensures that the early stage network growth gives importance to connectivity while later stage growth focuses on optimization.

Pipeline Attributes and Capacity Classification

Each pipeline segment is assigned a specific construction year along with a cost proportional to its length. After the network growth, pipeline segments are classified into three capacity categories – local, branch and trunk – based on their usage in shortest paths between sources and sinks. While these classes do not impose explicit flow constraints, they provide a structural interpretation of the network hierarchy and enable qualitative analysis of infrastructure roles.

Performance Metrics

The mode computes four metrics to evaluate network performance

a) Total pipeline length (TPL) which is the total length of pipelines in the network.
b) Average source to sink distance which gives the average distance between sources and sinks in the network
c) Fraction of the network grown in each planning stage measures the network grown between each time period. This is calculated by comparing the number of edges between two time periods.
d) Delivered hydrogen potential measures how much hydrogen producing capacity is effectively reachable by demand centers through the current pipeline topology, discounted by transport distance.

These indicators facilitate comparative analysis across regions, years and experimental scenarios

Visualization and Interpretation

Visualization plays a central role in interpreting model outcomes. Nodes are colour coded by type, orange for sources, green for sinks and blue for intermediate nodes, edges are colour coded by construction year with colour red for 2030, yellow for 2040 and violet for 2050. Then edge widths are sized 1 for local lines, 2 for branch lines and 4 for trunk lines by their capacity class. Networks are overlaid on a geographical background map, enabling spatial patterns and development trajectories to be clearly identified.

Model Assumptions and Limitations

The model makes several simplifying assumptions, starting with full wind availability. There is no exclusion zones, bathymetric constraints and nature sensitive areas that were considered. Then the use of Euclidean distances for measuring the shortest straight line distance between sources and sinks. Also there is absence of flow, pressure and congestion parameters which on the real world networks matter. These assumptions though appropriate for exploratory scenario analysis should be considered when interpreting the results. The model structure is shown in Figure 8.

The code model alignment with detailed implementation mapping is given in the appendices.

- The focus of this chapter was on implementing the conceptual model in NetworkX. With the model developed in NetworkX, experiments need to be designed which can help in studying the network growth and evolution. That will be the goal of next chapter.

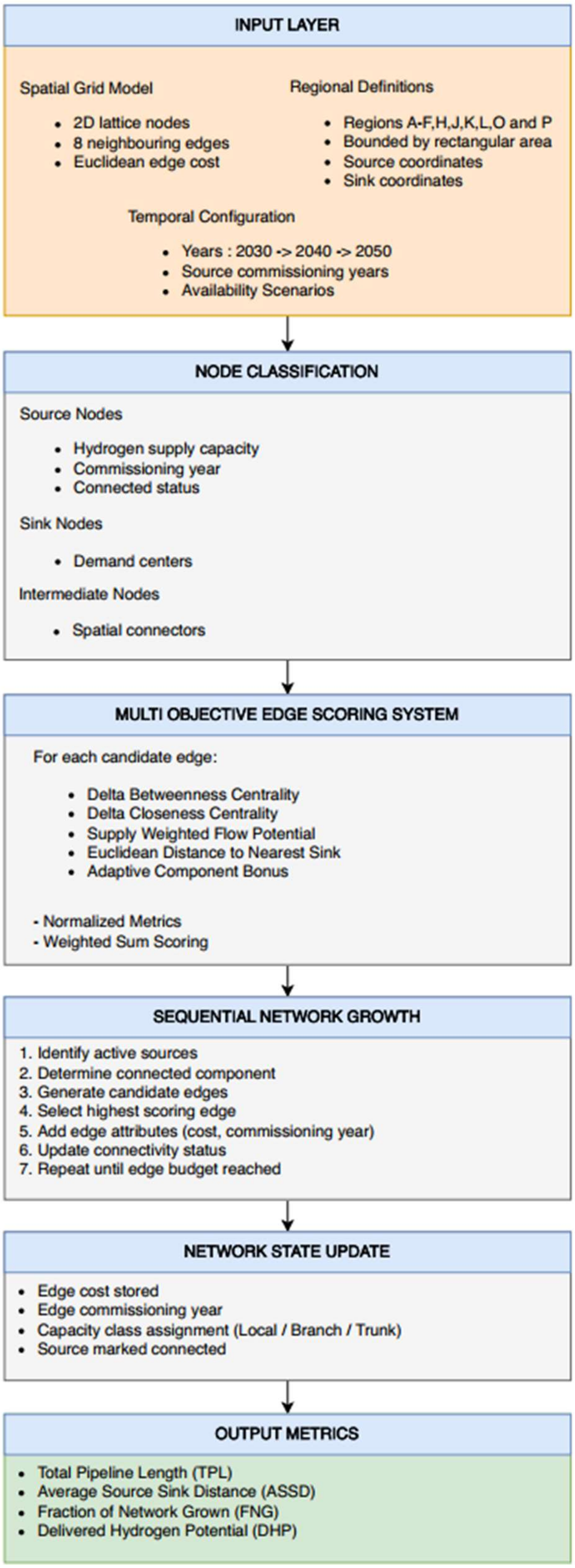


Figure 8 - Model Structure Diagram

7. EXPERIMENTATION

This chapter focuses on different experiments to study network evolution under different settings.

To systematically investigate the evolution of offshore wind based hydrogen transport infrastructure, a set of ten controlled experiments is designed and implemented in the NetworkX model. All the experiments are conducted under identical spatial, temporal and structural assumptions including fixed regional boundaries, source and sink locations, commissioning timelines and edge construction budget. The experiments differ only in the assumptions governing growth objectives, source selection behaviour and source availability over time. This approach enables a focused exploration of how alternative planning logics and uncertainty regimes influence the evolutionary pathways of large scale hydrogen pipeline networks.

The experiments are grouped into three broad categories. The first group explores alternative network growth priorities which examines how emphasizing structural robustness, transport functionality or spatial efficiency could shape emerging network topology. The second group investigates the role of source selection strategies by capturing the effects of coordination, randomness and spatial clustering in early infrastructure development. The third group introduces availability constraints representing uncertainty and phased realization of offshore wind based hydrogen projects and assessing how such constraints affect long term network evolution.

Exp	Name	Primary Focus	Key Assumption Tested	Network Evolution Insight
1	Balanced Baseline Growth	Multi objective growth	No single planning objective dominates	Reference benchmark for all comparisons
2	Topology Driven Growth	Structural importance	Connectivity and backbone formation prioritized	Emergence of hierarchical and robust network structures
3	Flow Driven Growth	Hydrogen transport potential	Functional efficiency dominates decisions	Demand oriented shaping of network topology
4	Distance Driven Growth	Spatial efficiency	Local cost minimization dominates	Effects of locally optimal decisions on global structure
5	Random Source Selection	Stochastic development order	Uncoordinated project realization	Sensitivity to initial conditions and path dependence
6	Nearest Neighbour Source Selection	Spatial clustering	Expansion follows geographic proximity	Formation of hubs, corridors and regional clusters
7	Fixed 25% Source Availability	High uncertainty	Strong constraints on project realization	Network formation under scarcity and delay
8	Fixed 50% Source Availability	Moderate uncertainty	Partial realization of planned capacity	Adaptive growth under incomplete participation
9	Fixed 75% Source Availability	Low uncertainty	Near complete realization with residual delays	Transitional behaviour toward fully developed networks
10	Project Improvement (25%-50%-100%)	Time varying availability	Gradual reduction of uncertainty over time	Long term impact of early constraints and learning effects

Table 4 - Experimentation Overview

An overview of all the experiments is given in Table 4. Together, these experiments provide a structured framework for analysing path dependency, efficiency and adaptability in the development of offshore hydrogen pipeline networks.

Experiment 1 : Balanced Baseline Growth

The balanced baseline experiment represents a reference configuration of network generation metrics in which the network growth is governed by a weighted combination of topological importance, hydrogen transport relevance, spatial efficiency and global accessibility. Particularly, the edge selection is influenced simultaneously by changes in betweenness centrality, supply weighted flow potential, Euclidean distance and closeness centrality. This experiment is designed to simulate a planning environment where there is no single objective which will dominate decision making and it reflects the reality of infrastructural development scenario where economic, operational and structural considerations must be balanced. From a network evolution perspective, this experiment provides a neutral calibration benchmark against which all other future experiments can be compared, allowing subsequent deviations in growth behaviour to be attributed directly to changes in assumptions rather than to underlying model structure.

Experiment 2 : Topology Driven Growth

The topology driven experiment assigns greater importance to betweenness centrality during edge selection. In this configuration, growth decisions prioritize improvements in overall connectivity as well as the strategic positioning of nodes within the network and with reduced emphasis on transport efficiency or spatial cost. This experiment is motivated by long term infrastructure planning philosophies that emphasizes robustness, redundancy and back bone formation over short term utilization. Its relevance to network evolution lies in examining how networks evolve when the growth is guided primarily by abstract structural properties rather than by immediate functional demand thus highlighting the role of betweenness centrality driven reinforcement and hierarchical structure formation in emerging infrastructure systems.

Experiment 3 : Flow Driven Growth

The flow driven experiment emphasizes on the hydrogen transport potential as the dominant criterion for network expansion. Edge selection in this case is guided primarily by the capacity of newly added connections which improves the potential movement of hydrogen from offshore wind sources to demand centers. This experimental setup reflects a development logic that focuses on early utilization, market activation and functional efficiency. In the context of network evolution, this experiment enables the study of how functional pressures shape the network topology over time and particularly how demand oriented growth influences the spatial alignment, directionality and integration of network components during successive stages of expansion.

Experiment 4 : Distance Driven Growth

In the distance driven experiment scenario, the Euclidean distance is the primary factor influencing the edge addition which approximates a cost minimization or least effort growth strategy. This experiment is designed so as to represent decentralized or incremental planning environments during which local construction costs dominate decision making. However it is potentially at the expense of global network consistency. Its relevance to network evolution lies in the exploration of how locally rational decisions accumulate over time to produce emergent large scale structures and also whether such growth mechanisms encourage fragmentation, path dependence or delayed backbone formation within the spatially embedded infrastructure networks.

The weight assumptions for experiment 1 to 4 are given in Table 5.

Experiments	Weight of Delta Betweenness Centrality	Weight of Supply Weighted Flow	Weight of Euclidean Distance	Weight of Closeness Centrality
Balanced Baseline	0.40	0.30	0.20	0.10
Topology Driven	0.60	0.10	0.10	0.20
Flow Driven	0.15	0.45	0.25	0.15
Distance Driven	0.05	0.15	0.65	0.15

Table 5- Weight Assumptions for Experiments 1 to 4

Selecting Experiment 1 (Balanced Baseline) as the baseline

Experiment 1 (Balanced Baseline) has been selected as the baseline because it represents a structurally neutral, multi objective reference configuration instead of an extreme planning logic. In experiment 1, edge selection is governed simultaneously by topological importance (Delta Betweenness), functional transport relevance (supply weighted flow potential), spatial efficiency (Euclidean distance) and global accessibility (closeness). Here, no single objective dominates the decision making process. This makes it an appropriate benchmark because it approximates how real world infrastructure planning typically operates viz through compromise among structural robustness, economic feasibility and operational efficiency. As a result of this, deviations observed in the other experiments can be interpreted as consequences of emphasizing a particular mechanism (topology, flow, cost, randomness or availability constraints), rather than artifacts of the underlying model. In the terms of methodology, the balanced baseline provides a controlled midpoint in the experimental design space against which directional biases in growth behaviour can be clearly analysed.

A hypothetical “perfect planning” design could in principle serve as a baseline, but in practice it is both conceptually and computationally problematic. A perfect design would require global foresight, complete information about future source realization, demand evolution and technology costs. And all these would likely involve solving a large scale dynamic optimization problem rather than a sequential growth heuristic. Such a solution would represent an idealized optimum under strong assumptions that are rarely attainable in real infrastructure development. Further, comparing heuristic growth processes to a fully optimized benchmark would risk conflating structural evolution dynamics with optimization performance. Since the model is explicitly evolutionary and path dependent, a heuristic baseline is more consistent with the current conceptual foundation. Considering all this, experiment 1 functions not as an “optimal” design but as a neutral and internally consistent reference point within the same modelling logic as the other experiments.

Experiment 5 : Random Source Selection

This experiment focuses on introducing stochasticity in the order in which offshore wind sources can connected in the network while retaining the balanced edge scoring logic. The random source selection strategy focuses on capturing the uncoordinated or market driven development scenario, where project realization is influenced by external factors which includes financing, permitting or developer specific strategies rather than by system wide optimization. From the viewpoint of network evolution, this experiment allows investigation of how randomness in early growth decisions could affect long term structural patterns thereby highlighting the sensitivity of evolving networks to its initial conditions and the degree of path dependency which are inherent in infrastructure development.

Experiment 6 : Nearest Neighbour Source Selection

The nearest neighbour source selection experiment imposes a spatial heuristic on the network growth process by prioritizing sources that are geographically close to previously connected sources. This experiment reflects the development dynamics where infrastructure expansion tends to cluster around existing assets owing to shared costs, logistical convenience as well as regional cooperation. This experiment is designed so as to explore the role of geographical proximity and localized decision making in shaping the network evolution. Further, it provides insight into how large scale structures such as network hubs, corridors and clusters could emerge organically through repeated local interactions even in the absence of explicit global coordination.

Experiment 7 : Fixed 25% availability across all periods

This experiment introduces a strong availability constraint by assuming that only 25% of the offshore wind projects are realized at their planned commissioning year along with temporal consistency in all the time periods. The experiment is designed so as to represent a highly uncertain development environment which is characterized by project delays, low participation, cancellations or restrictive regulatory system. Its relevance to the network evolution lies in examining how scarcity and uncertainty could constrain the early network formation thereby influencing which sources become structurally embedded. Further, this experiment also examines how the network adapts to limited participation initially while maintaining the potential for future expansion.

Experiment 8 : Fixed 50% availability across all periods

The fixed 50% availability experiment is a representation of a medium level of uncertainty, where only half of the expected offshore wind capacity will be available in each time period. This experiment portrays realistic development scenario where the participation of offshore wind farms are moderate as well as some projects abandoned or cancelled. In terms of network evolution, this experiment could help the analysis of adaptive network growth when there is partial realization. This experiment further sheds light on how evolving networks balance both flexibility and commitment, especially when future participation is uncertain but non negligible.

Experiment 9 : Fixed 75% availability across all periods

In the case of the fixed 75% availability experiment, there is an above average availability of planned sources that are assumed to be available, while a small fraction remains left out due to project cancellations or unwillingness to participate for hydrogen generation. This experiment setup is intended to simulate approximate near complete deployment scenarios while still retaining a small degree of uncertainty. The importance of this experiment to network evolution lies in the determination of transitional behaviours between constrained and fully realized system. In particular how residual uncertainty affects the timing, ordering and spatial distribution of network expansion during successive growth phases can be understood.

Experiment 10 : Project Improvement (25%-50%-100%)

The final experiment focuses on a dynamic improvement trajectory during which source availability increases over time which reflects learning effects, technological improvement, complementing investment conditions and strong policy support. Availability is assumed to be low during early periods and it progressively increases until full realization is achieved in the final period. This experiment is especially relevant for the study of network evolution under the changing source availability constraints over time as it enables the examination of early stage limitations which influences long term structural developments. Additionally, It also provides a framework to analyse path dependence, adaptability and the degree to which the early growth decisions could shape or restrict the future network configurations as the uncertainty diminishes.

Taken together these ten experiments provide a structured and comprehensive framework for analysing the development and evolution of offshore hydrogen pipeline network under different planning logics and regimes of uncertainty. The experimental framework will allow for the exploration of underlying mechanisms driving the development of the hydrogen network, irrespective of the realization of outcomes, by systematically varying the objectives of growth, source selection behaviour and availability constraints.

Relevance of combinations of variations in experiments

It has to be noted here that combinations of the experimental variations can be highly relevant and powerful methodologically speaking. While the current experiments isolate individual mechanisms such as growth objective, source selection order as well as availability constraints, in the real world however offshore hydrogen transport infrastructure is shaped by the interaction of these drivers than by any single factor operating independently. Combining variations for example, take the case of topology driven growth under 50% availability or the case of flow driven growth with nearest neighbour source selection, would allow the investigation of second order and interaction effects in network evolution. Such combinations has the potential to reveal whether structural planning priorities whether will amplify or dampen uncertainty effects. Also if stochastic early connections have stronger consequences under constrained availability and whether spatial clustering reinforces backbone formation under the flow driven logic for example. From the perspective of network science, these interaction experiments will enable the analysis to shift from single factor sensitivity testing towards a more systemic exploration of path dependence and emergent morphology. In essence, currently the design clearly establishes causal clarity through controlled variation but introducing selected combinations has the possibility to enhance realism and allow investigation of how multiple planning logics and uncertainty regimes jointly shape the long term structural configuration of the offshore hydrogen transport network.

Regions considered in this study

Region	**Country(s)**
A, B and C	France, Belgium and Netherlands
D, E and F	Netherlands
H	Norway
J, K, L, O and P	United Kingdom

Table 6 - Regions considered and their respective countries

The regions that are considered in the study are in Table 6 and they have been chosen to accommodate the computation limitations. The rectangular boundary grid determines the computational requirement for the algorithm to grow the network.

Answering Sub-Question 6 - What possible scenarios can help us understand hydrogen pipeline network evolution?

To comprehend the development and evolution of offshore wind based hydrogen pipeline networks, it is necessary to analyse the scenarios that consider the varying underlying drivers of network development rather than analysing a single optimal development scenario. For the purpose of this analysis, four broad categories of scenarios have been identified as being highly informative for understanding the mechanisms of network evolution in offshore wind based hydrogen transport infrastructure system.

First, the growth objective scenarios are critical in understanding how various planning priorities can shape network evolution. By varying the relative importance of topological structure, hydrogen flow potential and spatial efficiency, these scenarios explores how various decision making logics could influence the emergence of network connectivity, hierarchy and spatial organization over time.

Second, the source selection behaviour scenarios provides insight into the role of infrastructure developer behaviours and coordination in network evolution. Scenarios based on random or proximity driven source selection captures the effects of uncoordinated development, spatial clustering and path dependence which highlights how early decisions and local interactions could influence long term network structure.

Third, the availability constrained scenarios are important for examining the impact of uncertainty and partial participation or realization of planned infrastructure. Scenarios with fixed availability fraction represents uncertainty, while maintaining temporal consistency allows the network to evolve under long term constraints revealing how these networks adapt when only a subset of planned sources becomes available.

Finally, the temporal project improvement scenario is necessary to capture dynamic evolution under changing development conditions. Scenarios in which availability increases over time reflects learning effects, technological improvements, institutional maturation and improving investment conditions which enables the study of how early stage constraints could influence later network growth and whether networks can adapt as uncertainty diminishes.

Together, these scenario classes form a comprehensive framework for understanding hydrogen pipeline network evolution by isolating and examining the structural, behavioural and temporal mechanisms that drive the emergence and transformation of large scale infrastructure networks.

- This chapter focused on designing experiment scenarios to study the network growth and its evolution under different settings. The following chapter interprets, analyses and evaluates the results of the experiments run on the model.

8. RESULTS AND ANALYSIS

This chapter dives into the results and analysis of the experiments conducted on the model.

The first set of experiments that were conducted was for the following: -

Topology Driven

In the topology driven experiment, priority is given to betweenness centrality followed by closeness centrality. Consequently, the weights for the growth metrics are W_BC=0.60, W_FLOW=0.10, W_DIST=0.10 and W_CLOS=0.20.

Flow Driven

For the flow driven experiment, the weight of flow score is given priority followed by distance. The weights for the growth metrics in this experiment are W_BC=0.15, W_FLOW=0.45, W_DIST=0.25, W_CLOS=0.15

Distance Driven

In the distance driven experiment, priority is given to the Euclidean distance and lowest priority is betweenness centrality. The weights for the distance driven experiment are W_BC=0.05, W_FLOW=0.15, W_DIST=0.65 and W_CLOS=0.15.

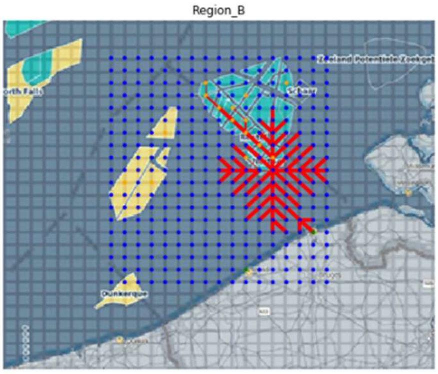
Balanced Baseline

In this experiment, the weights are given in equal steps for a balanced outcome. The weights for this experiment are W_BC=0.40, W_FLOW=0.30, W_DIST=0.20 and W_CLOS=0.10.

The first four experiments are designed to systematically investigate how different infrastructure planning priorities influence the evolutionary development of the offshore hydrogen pipeline network. Each experiment assigns distinct weights to the multi criteria edge selection mechanism, thereby prioritizing a specific decision logic. The topology driven experiment focuses on the structural centrality and network cohesion which encourages the formation of highly connected backbone structures. The flow driven scenario focuses on supply weighted hydrogen flow potential, encouraging network growth along routes that maximizes the hydrogen transport efficiency between sources and sinks. The distance driven experiment prioritizes the spatial proximity to the demand centers which leads to more geographically direct and potentially decentralized configurations. Finally, the balanced baseline scenario considers all these criteria with moderate weights, representing a more holistic planning approach and can be the baseline for future experiments to compare from. By analysing and comparing the resulting network topologies, expansion processes and performance metrics across these four configurations, the experiments aim to reveal how differing strategic priorities can shape the long term network structure, efficiency and potential lock in effects of the North Sea offshore hydrogen system.

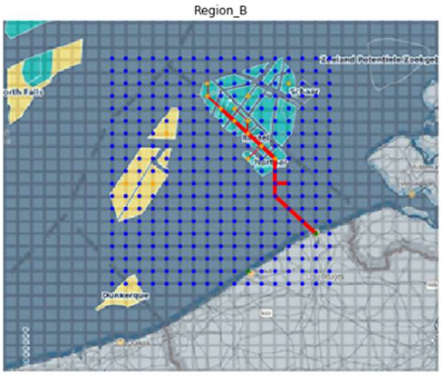
8.1 - Results of experiments (1 to 4)

The first set of four experiments were conducted on the French, Belgium and Netherlands map to generate networks for the years 2030, 2040 and 2050. The different regions under this study are shown in Figure 21 so as to understand where the analysis is taking place.



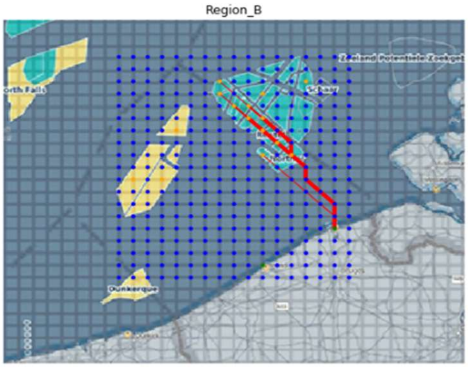
```
Metrics for Region_B in 2030:
Total pipeline length for Region_B in 2030: 2206.90
Average Source Sink Distance: 272.84
Fraction of Network Grown: 100.00%
```

Figure 9 - Topology Driven – (Region B) 2030



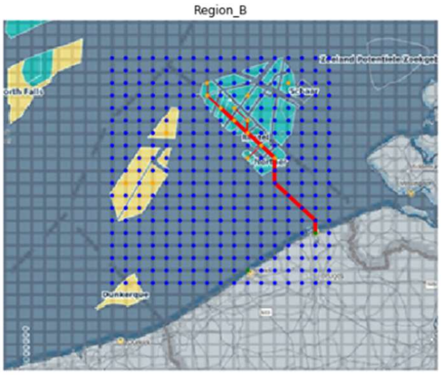
```
Metrics for Region_B in 2030:
Total pipeline length for Region_B in 2030: 491.40
Average Source Sink Distance: 276.11
Fraction of Network Grown: 100.00%
```

Figure 10 - Flow Driven – (Region B) 2030



```
Metrics for Region_B in 2030:
Total pipeline length for Region_B in 2030: 720.59
Average Source Sink Distance: 271.40
Fraction of Network Grown: 100.00%
```

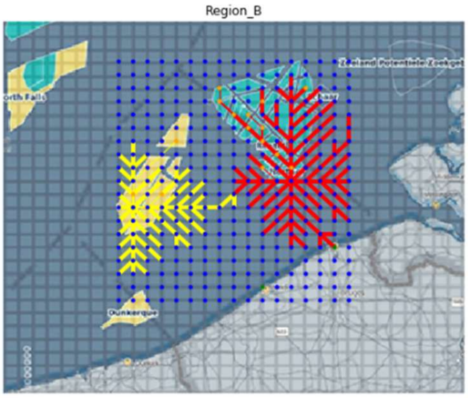
Figure 11 - Distance Driven (Region B) 2030



```
Metrics for Region_B in 2030:
Total pipeline length for Region_B in 2030: 465.80
Average Source Sink Distance: 276.11
Fraction of Network Grown: 100.00%
```

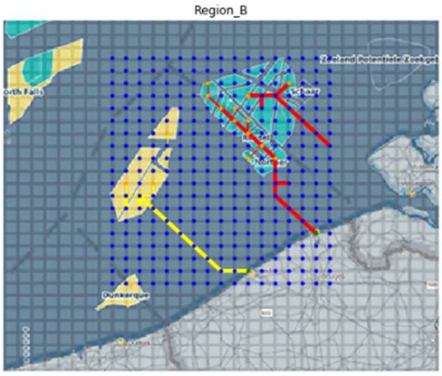
Figure 12 - Balanced Baseline (Region B) 2030

Analysing Figure 9 to Figure 12 for the time period 2030 in Region B, it is observed that for topology driven network, a pattern of pipeline network is emerged which is attributed to the high betweenness centrality for intermediate nodes. This is not particularly useful as a pipeline network as this is unrealistic and doesn't yield any contributing insight. The TPL for topology driven is the highest among the four experiments. The distance driven experiment results in the formation of multiple parallel lines converging at the sink with total pipeline length of 720.59. The flow driven and balanced baseline experiment resulted in similar networks however the flow driven has longer total pipeline length compared to balanced baseline. The flow driven network also has an additional unnecessary branch. Thus, balanced baseline experiment generated the best network with the lowest total pipeline length.



```
Metrics for Region_B in 2040:
Total pipeline length for Region_B in 2040: 4969.85
Average Source Sink Distance: 328.23
Fraction of Network Grown: 31.16%
```

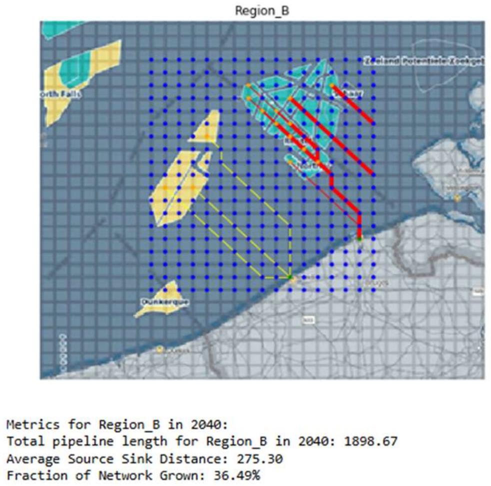
Figure 13 - Topology Driven (Region B) 2040



```
Metrics for Region_B in 2040:
Total pipeline length for Region_B in 2040: 1251.06
Average Source Sink Distance: 291.85
Fraction of Network Grown: 34.62%
```

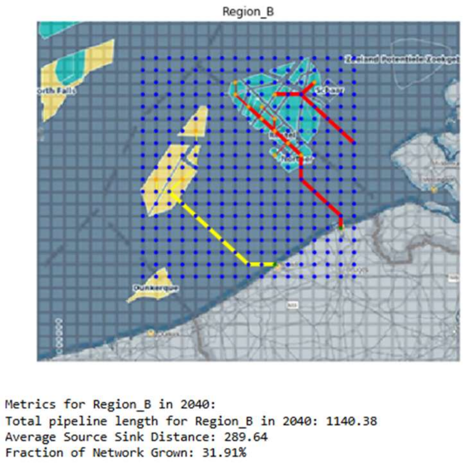
Figure 14 - Flow Driven (Region B) 2040

Similar result is also observed in the time period 2040 with the topology driven having a pattern like network. Flow driven is more compact but has extra branch to intermediate node.



```
Metrics for Region_B in 2040:
Total pipeline length for Region_B in 2040: 1898.67
Average Source Sink Distance: 275.30
Fraction of Network Grown: 36.49%
```

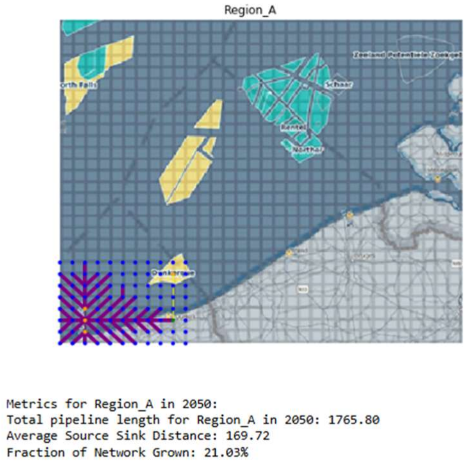
Figure 15 - Distance Driven 2040 (Region B)



```
Metrics for Region_B in 2040:
Total pipeline length for Region_B in 2040: 1140.38
Average Source Sink Distance: 289.64
Fraction of Network Grown: 31.91%
```

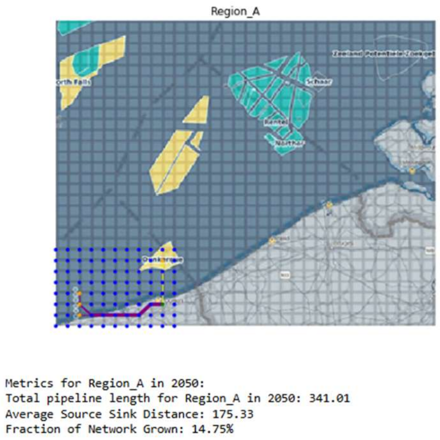
Figure 16 - Balanced Baseline 2040 (Region B)

From the Figure 15 and Figure 16 for distance driven and balanced baseline respectively, it can be observed that multiple parallel lines are formed for distance driven. On the other hand, balanced baseline shows compact network with the lowest total pipeline length which translates to lowest infrastructure cost.



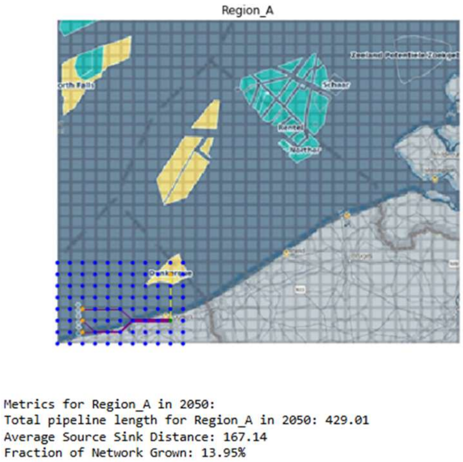
```
Metrics for Region_A in 2050:
Total pipeline length for Region_A in 2050: 1765.80
Average Source Sink Distance: 169.72
Fraction of Network Grown: 21.03%
```

Figure 17 - Topology Driven (Region C: 2050)



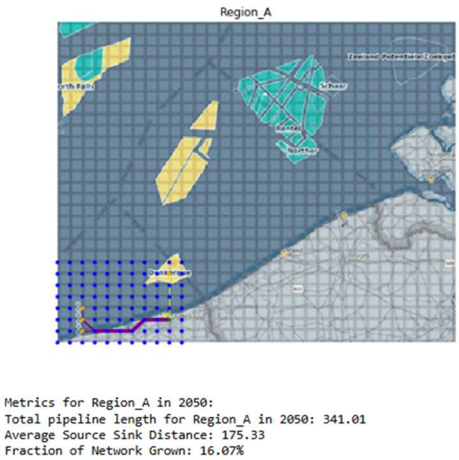
```
Metrics for Region_A in 2050:
Total pipeline length for Region_A in 2050: 341.01
Average Source Sink Distance: 175.33
Fraction of Network Grown: 14.75%
```

Figure 18 - Flow Driven (Region C: 2050)



```
Metrics for Region_A in 2050:
Total pipeline length for Region_A in 2050: 429.01
Average Source Sink Distance: 167.14
Fraction of Network Grown: 13.95%
```

Figure 19 - Distance Driven (Region C: 2050)



```
Metrics for Region_A in 2050:
Total pipeline length for Region_A in 2050: 341.01
Average Source Sink Distance: 175.33
Fraction of Network Grown: 16.07%
```

Figure 20 - Balanced Baseline (Region C: 2050)

From the Figure 17 to Figure 20 for region C in 2050, same results are observed. The topology driven gives a pattern like network while distance driven forms multiple parallel lines. The flow driven network and the balanced baseline forms identical network with similar scores on total pipeline length and average source to sink distance.

Thus, from the results of the initial four experiments, it has been observed that the balanced baseline weight configuration generates the most structurally consistent and representative evolution pathway for the offshore hydrogen pipeline network. It is because, while the topology driven, flow driven and distance driven scenarios each highlight extreme planning priorities, they tend to produce networks that are strongly inclined towards a single structural objective, potentially over emphasizing on centralization, transport efficiency or spatial proximity respectively. On the other hand, the balanced baseline experiment integrates all the decision criteria with moderate weighting which results in a network design that reflects more of a realistic balance between structural robustness, flow efficiency and spatial proximity. On the basis of this, the balanced baseline scenario can be selected as the reference configuration for future experiments. The balanced baseline scenario can also thus be used as a calibration benchmark against which alternative growth mechanisms, availability constraints and source selection strategies can be systematically studied. By using the balanced configuration as a baseline, it is also ensured that later comparisons reflect deviations from a structurally neutral and methodologically consistent planning based network instead of an intentionally extreme scenario.

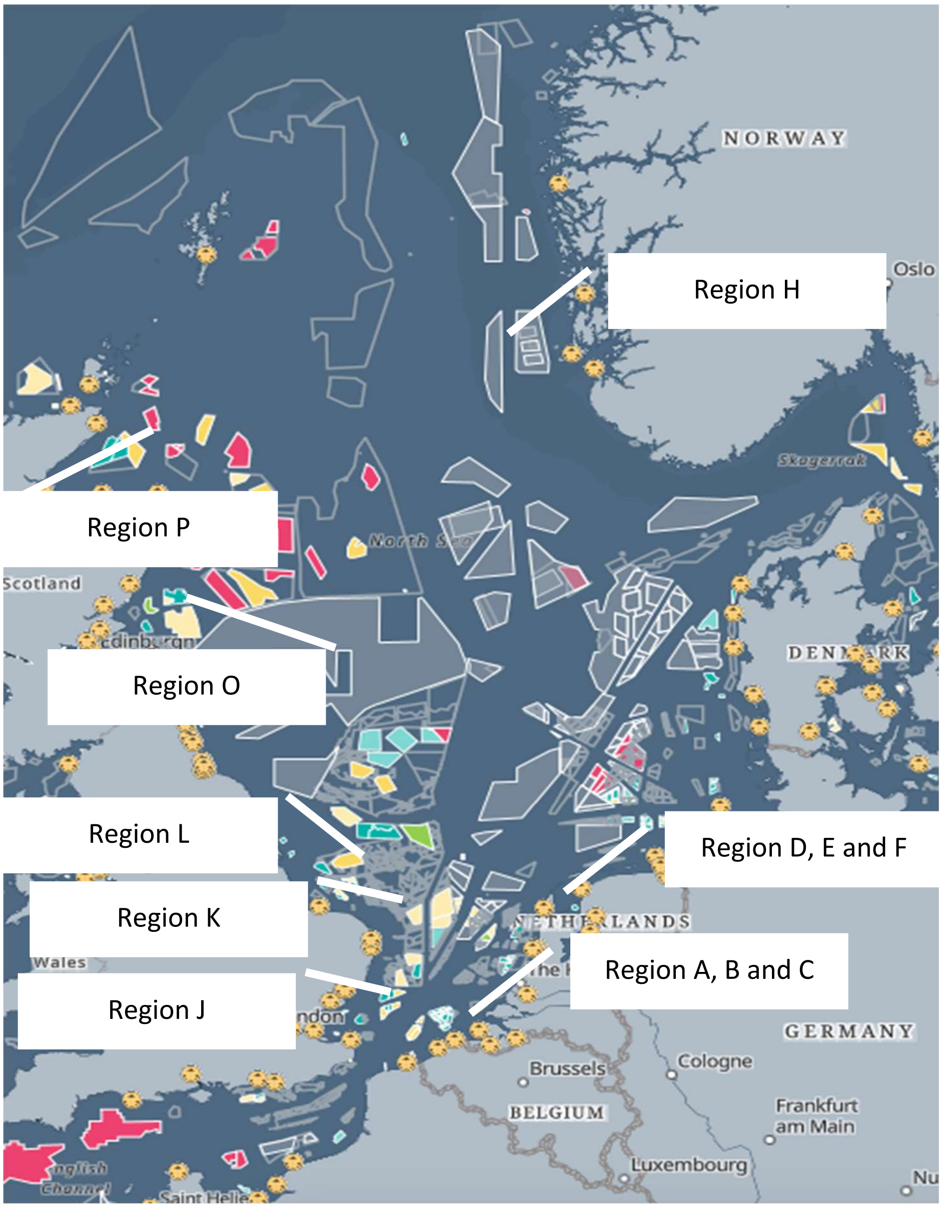


Figure 21 - Modelling Regions Map of the North Sea

The regions have been defined in no specific order, just that each region is given a unique name to identify. The North Sea is a large area with coastal lines appearing very small which poses challenges in region specification. The analysed regions were given a unique name to identify later which country it belongs to.

8.2 – Results of experiments 5 to 10

Experiments 5 to 10 are performed on multiple regions in the North Sea including Netherlands, France, Belgium, Norway and the United Kingdom. These experiments are designed to examine how different source selection strategies, participation dynamics, technological improvement and policy support can influence the evolutionary development of the offshore wind based hydrogen transport pipeline network. While the initial four experiments explored structural planning priorities through variations in weighting criteria, these subsequent experiments shifts the focus towards institutional behaviour, market participation and temporal availability of hydrogen production sources. The Random Source selection scenario represents a decentralized, market driven environment in which project participation is uncoordinated which can potentially lead to fragmented expansion pathways. On the other hand, the Nearest Neighbour Source Selection scenario focuses on situations where there is regional coordination during which geographically proximate projects aligns together to develop shared infrastructure, encouraging clustered growth and backbone formation. Experiments 7 to 9 systemically varies the level of source availability (25%, 50% and 75%) consistently across all time periods to assess how different degrees of market participation affects network connectivity and expansion speed. Finally, the Project Improvement scenario introduces increasing number of sources over the time periods that aligns with gradual technological maturation and strengthening policy support over time. Together, all these experiments aim to evaluate how varying degrees of coordination, participation intensity and temporal commitments shape long term network topology, investment efficiency and potential lock in effects, thereby providing insight into the sensitivity of offshore hydrogen infrastructure evolution to institutional and market conditions.

Experiment 5 is random source selection where the sources are randomly selected from a list of unconnected sources. This experiment as mentioned earlier simulates uncoordinated or market driven participation of sources.

Experiment 6 is nearest neighbor source selection where the sources nearest to the connected source is selected for network growth. This simulates the situation where there is regional coordination and participation where shared infrastructure can be developed.

Experiment 7 is 25% availability of sources for all the time periods. The temporal consistency is prevailed. This experiment simulates the condition where participation is low for hydrogen production in offshore wind farms.

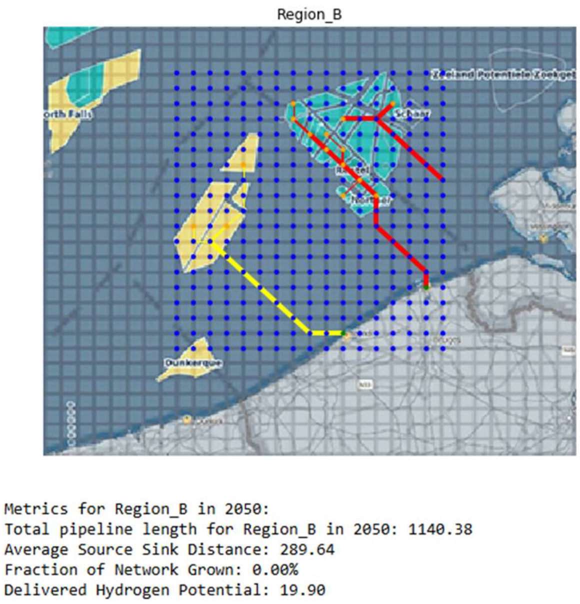
Experiment 8 is 50% availability of sources for all the time periods. This experiment simulates the situation where there is average participation by sources.

Experiment 9 is 75% availability of sources for all the time periods. This experiment simulates the situation where there is more than average participation by sources.

Experiment 10 is the project improvement scenario where there is initially less participation (25%), then due to policy support and technological improvement, there is 50% participation of sources in the year 2040. This is followed by 100% participation of sources in 2050 considering technological maturity and strong policy support.

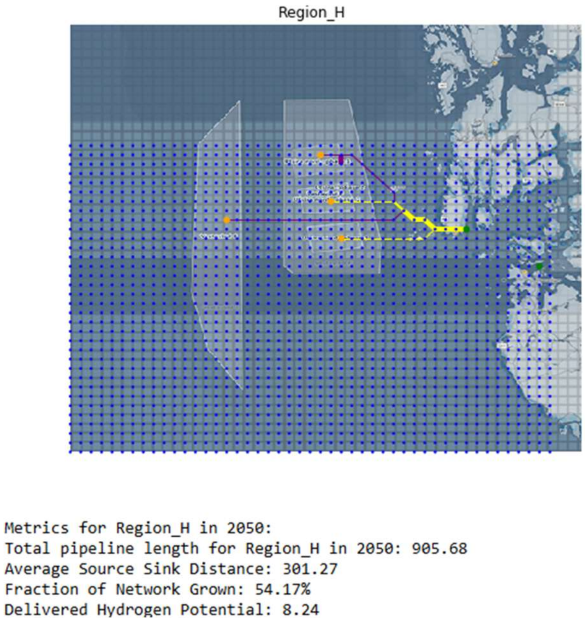
8.2.1 Analysis of results

The regions A,B,C,D,E,F,H,J,K,L,O and P are simulated to study the Network Evolution under different experiment scenarios. Regions A, B and C is for France, Belgium and part of Netherlands. The regions D,E and F are for the Northern part of Netherlands. The region H is of Norway. Region J, K, L, O and P are of the United Kingdom.



```
Metrics for Region_B in 2050:
Total pipeline length for Region_B in 2050: 1140.38
Average Source Sink Distance: 289.64
Fraction of Network Grown: 0.00%
Delivered Hydrogen Potential: 19.90
```

Figure 22 - Region B : Balanced Baseline 2050



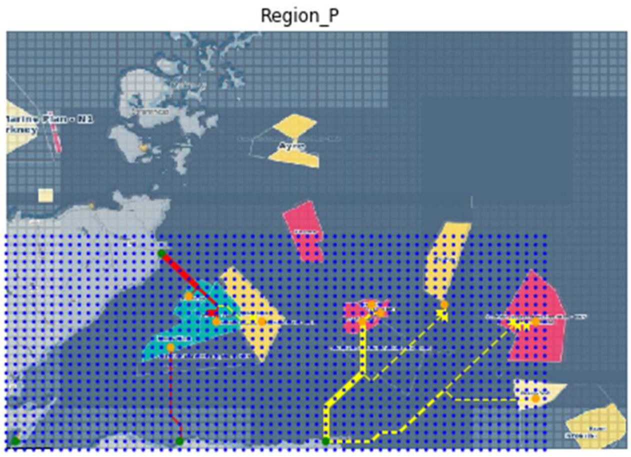
```
Metrics for Region_H in 2050:
Total pipeline length for Region_H in 2050: 905.68
Average Source Sink Distance: 301.27
Fraction of Network Grown: 54.17%
Delivered Hydrogen Potential: 8.24
```

Figure 23 -Region H : Balanced Baseline 2050

The analysis is considered through the lens of performance indicators which are Total Pipeline Length (TPL), Average Source Sink Distance (ASSD), Fraction of Network Grown (FNG) and Delivered Hydrogen Potential (DHP). All the results of the regions are given in the tables in the appendices.

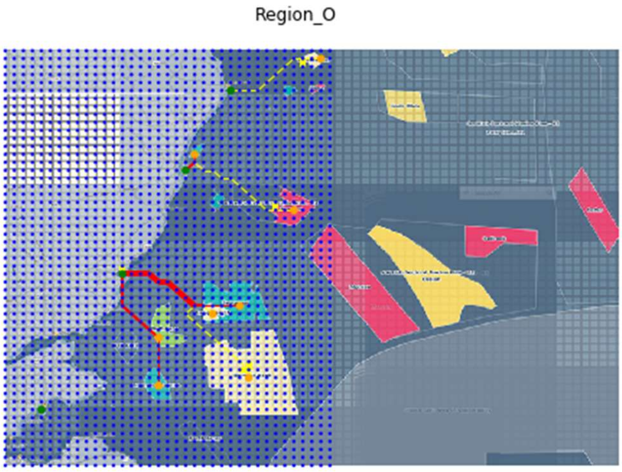
From the analysis of the results, starting with TPL and across all the regions, it is revealed that the network growth generally progresses over time, however the speed and timing differs depending upon source activation patterns and its availability. Regions such as B, C, J, L and P exhibits early network activity with the pipelines being already present in the first time period, see Figure 22. Regions A, H, K and O on the other hand shows delayed development with the TPL growth commencing in the second or third time periods, see Figure 23. Due to the stochastic connections, random source selection strategy tends to slightly increase TPL during early years, particularly in regions with early activation such as region B and region P yet by later periods, the TPL typically converges with the baseline scenario. The nearest neighbour source selection strategy is found to generate consistently networks that mirror baseline trends across all regions which highlights that the connection to closer sources doesn’t significantly affect the overall pipeline extent. Further, it has been observed that source availability strongly influences the TPL evolution. Low availability as expected will constrain the early growth of network and generates shorter pipelines during the initial years, whereas higher availability allows the network to expand more rapidly towards baseline levels. The project improvement scenario shows gradual staged growth of TPL, illustrating how the pashed source activation produces smoother and incremental network expansion.

The analysis of Average Source Sink Distance (ASSD) patterns helps to understand how the network reach evolves over time. In regions with early network activation such as B, C, J, L and P, the ASSD increases steadily considering more distant sources are integrated into the network. On the other hand in regions with delayed activation such as regions A, H, K and O, the ASSD rises sharply once pipelines come online which reflects the incorporation of long distance connections during the initial expansion. Random Source Selection is found to cause minor variations with occasionally decreasing early distances by linking sources closer to the sinks, on the other hand the nearest neighbour source selection produces almost identical results to the baseline scenario in all regions which confirms that the shortest path connections largely dictate network topology. Availability constraints play a critical role i.e lower source availability maintains smaller ASSD early on as only nearby sources are connected, while higher availability fractions results in larger average distances as the network incorporates more distant nodes. The Project improvement Scenario demonstrates a controlled and gradual increase in ASSD which is consistent with incremental network integration over time.



```
Metrics for Region_P in 2050:
Total pipeline length for Region_P in 2050: 1805.68
Average Source Sink Distance: 287.92
Fraction of Network Grown: 0.00%
Delivered Hydrogen Potential: 37.65
```

Figure 24 - Balanced Baseline : Region P 2050



```
Metrics for Region_O in 2050:
Total pipeline length for Region_O in 2050: 1201.94
Average Source Sink Distance: 202.77
Fraction of Network Grown: 0.00%
Delivered Hydrogen Potential: 37.28
```

Figure 25 – Balanced Baseline : Region O 2050

The results of the performance metric Fraction of Network Grown (FNG) shows that regions having early full connectivity such as regions B, J, L and P achieve 100% FNG in the initial periods, see Figure 24, whereas regions with delayed network activation such as regions A, H, K and O shows progressive growth over time, see Figure 25. The random source selection strategy slightly accelerates early FNG in regions with later activations such as regions A,C and H due to stochastic connections. Nearest neighbour selections strategy is found to mirror baseline values of FNG. Availability constraints reduces the FNG in the early time periods which slows the overall pace of network expansion. Higher availability is found to accelerate growth towards full network completion. The project improvement scenario presents gradual FNG evolution that closely follows staged source activation which highlights the benefits of phased network deployment.

The results of the Delivered Hydrogen Potential (DHP) is found to be closely following the dynamics of TPL and FNG. Regions which have early activations such as regions B, C, J, L and P reaches high DHP quickly reflecting their immediate operational capability once the pipelines are active, see Figure 26. Regions such as regions A, H, K and O, see figure 27, having delayed growth shows sharp DHP increases when the pipeline connections are finally established which demonstrates that hydrogen delivery is closely linked to network construction and source activation. The random source selection strategy offers a slightly improved early DHP by opportunistically connecting sources whereas nearest neighbour source selection strategy consistently produces similar results to the baseline scenario emphasizing that efficient shortest path connections supports hydrogen delivery without increasing variability. Availability constraint is the dominant factor which influences the FHP. Lower availability of sources slows down early delivery while higher or staged availability accelerates the hydrogen supply. In the case of project improvement scenario, smooth incremental increases in DHP is observed which reflects the impact of planned and phased source activation on operational potential.

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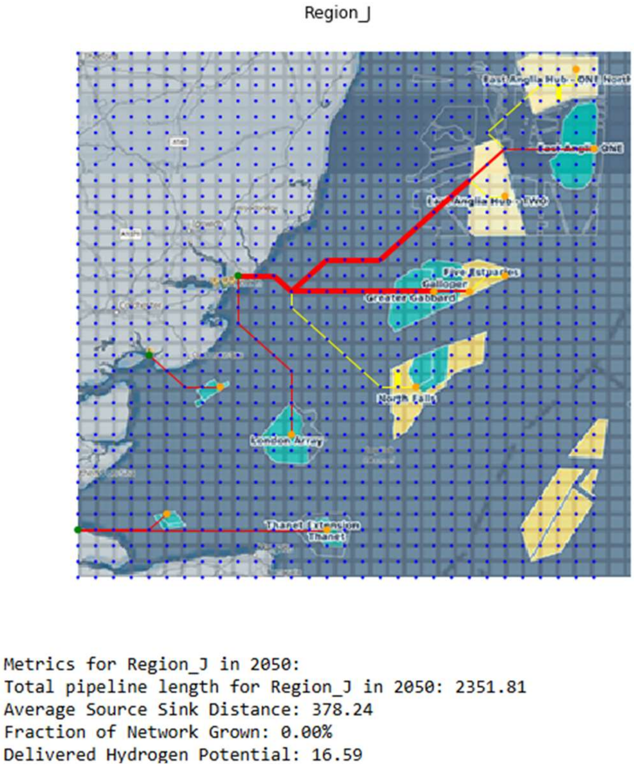
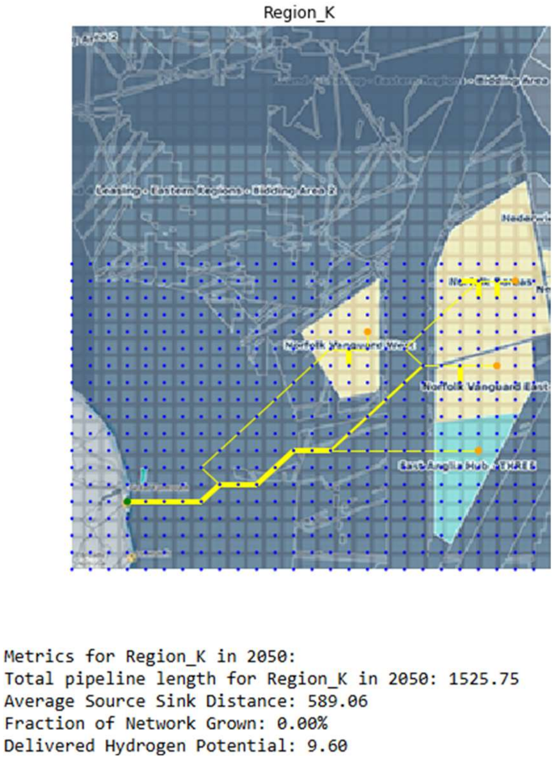


```
Metrics for Region_J in 2050:
Total pipeline length for Region_J in 2050: 2351.81
Average Source Sink Distance: 378.24
Fraction of Network Grown: 0.00%
Delivered Hydrogen Potential: 16.59
```

Figure 26 - Balanced Baseline : Region J 2050



```
Metrics for Region_K in 2050:
Total pipeline length for Region_K in 2050: 1525.75
Average Source Sink Distance: 589.06
Fraction of Network Grown: 0.00%
Delivered Hydrogen Potential: 9.60
```

Figure 27 – Balanced Baseline : Region K 2050

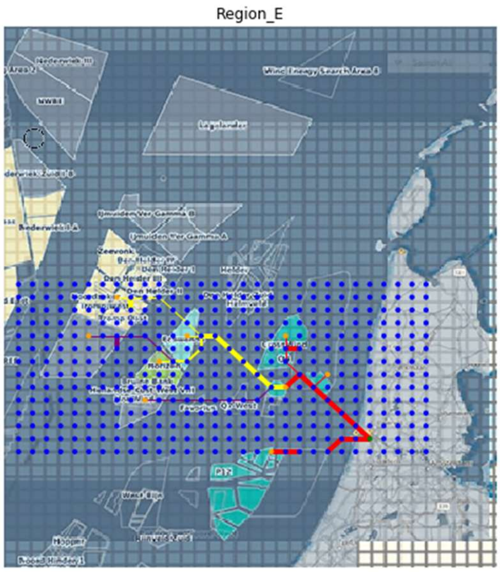
Considering all the performance metrics and the regions, several consistent patterns emerge. Source selection strategies showing minimum long term impact while the random source selection strategy mainly affects early network evolution. The nearest neighbour source selection strategy replicates baseline results. From the analysis, it can be concluded that source availability is the most critical factor which influences network growth and operational performance. Regions which have early activation tends to saturate rapidly reaching high TPL, ASSD, FNG and DHP quickly, whereas regions having delayed activation is found to be developing more gradually showing sharp increases once the pipelines and sources comes online. Project improvement scenarios across all the regions clearly demonstrates the benefits of staged network activation which produces controlled and incremental growth that balances infrastructure investment and operational efficiency.

Network Evolution Across Regions

Network evolution across the twelve regions demonstrates how both spatial and temporal planning of source activation strongly shapes the development of hydrogen transport infrastructure. Regions which have early source availability such as regions B, C, J, L and P, the network expands rapidly and reaches near maximum pipeline lengths by the second time period viz. 2040. The implication is that this rapid growth allows these regions to deliver hydrogen efficiently from early stages thus achieving high DHP by 2040, and with FNG declining quickly as the network gets saturated. ASSD is found to be gradually increasing as pipelines extents to more distant sources which reflects the comprehensive spatial coverage. On the other hand, regions which have delayed activation such as regions A, H, K and O demonstrates incremental growth, as it can be seen in the Figure 26 and Figure 27, with their TPL, ASSD, FNG and DHP remaining low during initial time periods and then rises sharply once the sources come online which further emphasizes the importance of both timing and phased deployment.

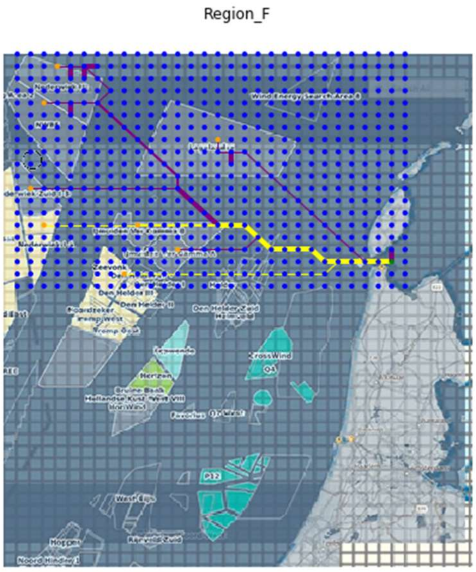
It has been observed across all regions that random source selection introduces slight variability, with slight acceleration of early TPL and DHP in certain cases (notably regions A, B and P). The nearest neighbour source selection strategy consistently mirrors the baseline results and confirms that the shortest path deterministic connections are optimal for infrastructure efficiency. The strongest determinant of network evolution from the analysis is of source availability. Low availability constrains pipeline growth, limiting network reach, with slow decreases in FNG, and delays of hydrogen delivery. On the other hand, higher availability or staged activation enables faster and controlled expansion. The project improvement scenario provides more realistic depiction of network development, demonstrating that the phased source activation results in smoother increases in pipeline length, connectivity and operation potential while avoiding overbuilding or underutilization. Together, these results from the analysis illustrates that an effective hydrogen network development strongly depend on careful coordination of source activation timing, availability and connection strategy. The phased planning of project improvement scenario offers the most controlled and efficient pathway for both infrastructure deployment and hydrogen delivery across diverse regional contexts.

The network evolution captured from the network generated for all the scenarios can clearly be observed if we compare the generated networks of regions E and F. See Figures 28 to Figure 41



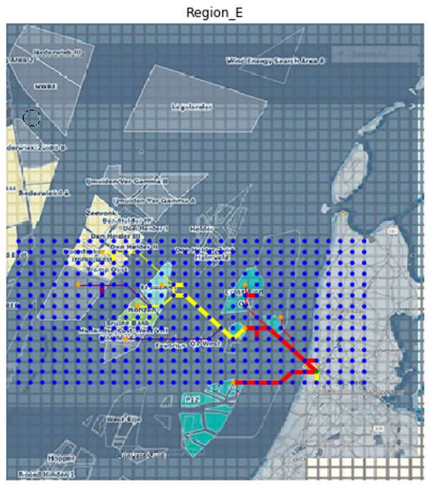
```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 1094.70
Average Source Sink Distance: 308.74
Fraction of Network Grown: 16.00%
Delivered Hydrogen Potential: 18.29
```

Figure 28 - Balanced Baseline (Region E) 2050



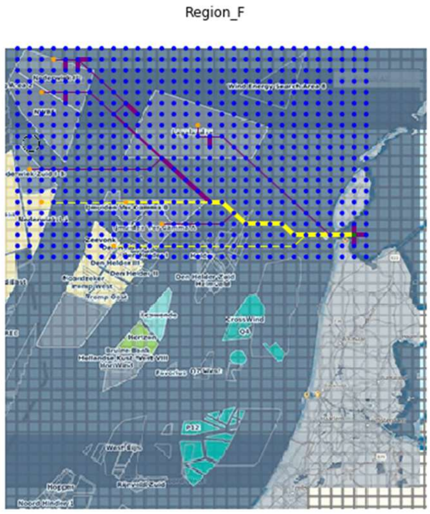
```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 2021.03
Average Source Sink Distance: 471.31
Fraction of Network Grown: 35.06%
Delivered Hydrogen Potential: 33.22
```

Figure 29 - Balanced Baseline (Region F) 2050



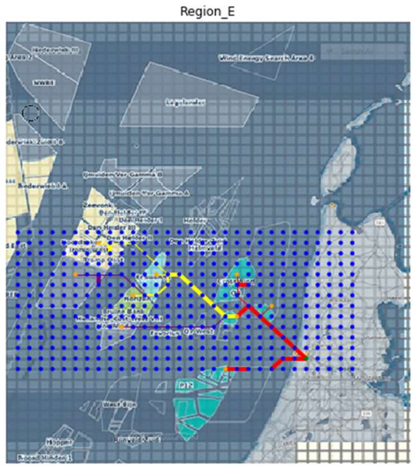
```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 1242.62
Average Source Sink Distance: 301.47
Fraction of Network Grown: 13.64%
Delivered Hydrogen Potential: 18.53
```

Figure 30 - Random Source Selection (Region E) 2050



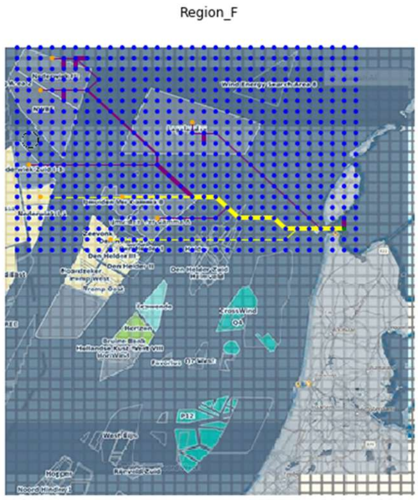
```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 2151.90
Average Source Sink Distance: 470.32
Fraction of Network Grown: 34.91%
Delivered Hydrogen Potential: 33.29
```

Figure 31 - Random Source Selection (Region F) 2050



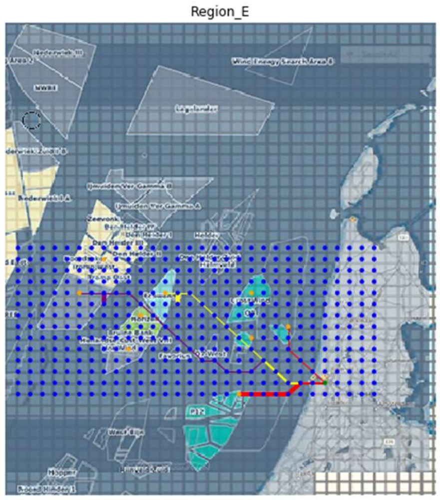
```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 1094.70
Average Source Sink Distance: 308.74
Fraction of Network Grown: 16.00%
Delivered Hydrogen Potential: 18.29
```

Figure 32 - Nearest Neighbour Source Selection (Region E) 2050



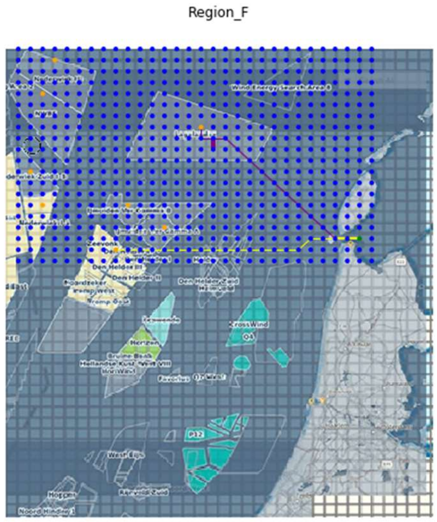
```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 2021.03
Average Source Sink Distance: 471.31
Fraction of Network Grown: 35.06%
Delivered Hydrogen Potential: 33.22
```

Figure 33 - Nearest Neighbour Source Selection (Region F) 2050



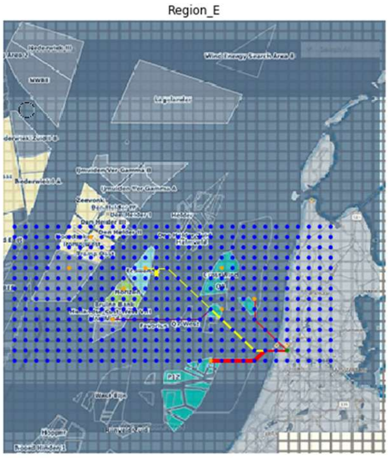
```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 903.20
Average Source Sink Distance: 291.58
Fraction of Network Grown: 26.67%
Delivered Hydrogen Potential: 5.34
```

Figure 34 - 25% Availability (Region E) 2050



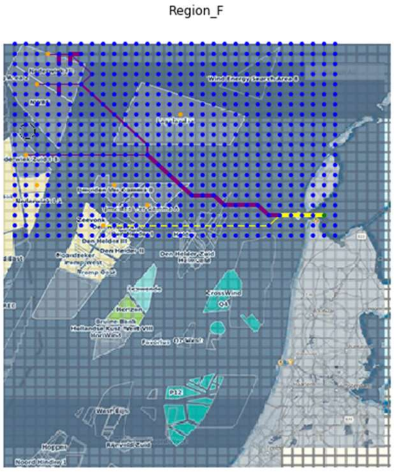
```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 702.69
Average Source Sink Distance: 361.82
Fraction of Network Grown: 17.81%
Delivered Hydrogen Potential: 17.19
```

Figure 35 - 25% Availability (Region F) 2050



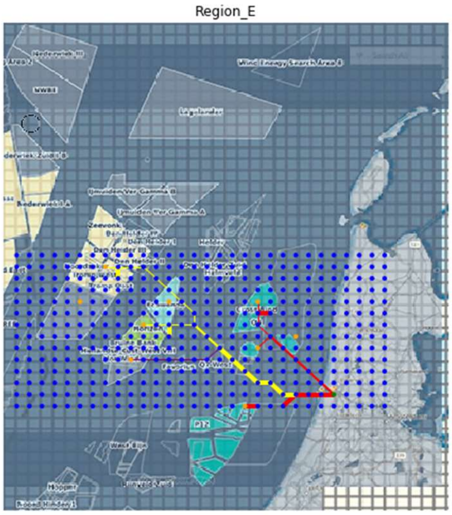
```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 721.62
Average Source Sink Distance: 254.39
Fraction of Network Grown: 16.98%
Delivered Hydrogen Potential: 5.47
```

Figure 36 - 50% Availability (Region E) 2050



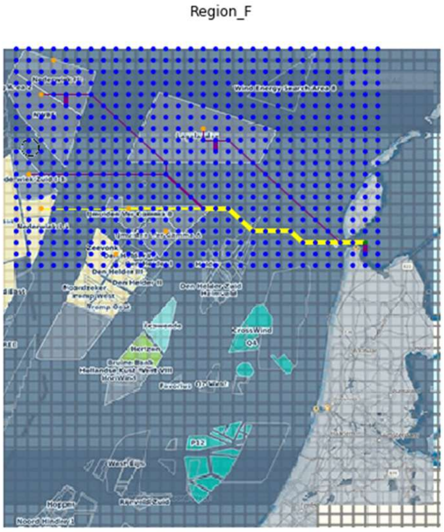
```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 1319.99
Average Source Sink Distance: 550.01
Fraction of Network Grown: 44.79%
Delivered Hydrogen Potential: 13.30
```

Figure 37 - 50% Availability (Region F) 2050



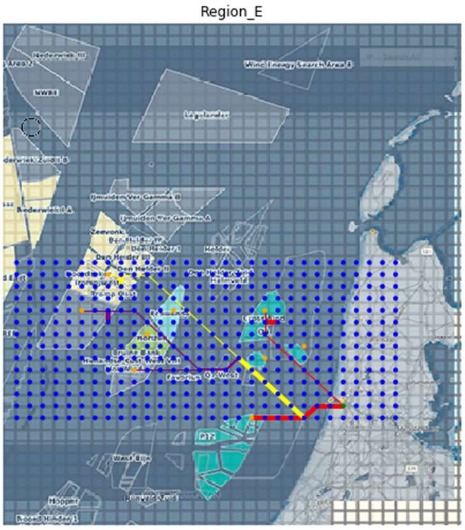
```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 971.95
Average Source Sink Distance: 291.52
Fraction of Network Grown: 9.09%
Delivered Hydrogen Potential: 13.76
```

Figure 38 - 75% Availability (Region E) 2050



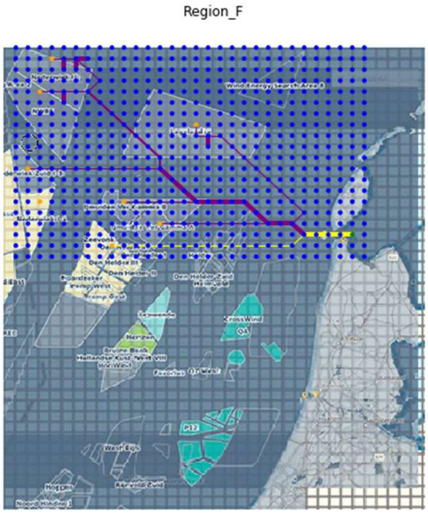
```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 1410.59
Average Source Sink Distance: 481.13
Fraction of Network Grown: 34.19%
Delivered Hydrogen Potential: 21.98
```

Figure 39 - 75% Availability (Region F) 2050



```
Metrics for Region_E in 2050:
Total pipeline length for Region_E in 2050: 1130.65
Average Source Sink Distance: 363.73
Fraction of Network Grown: 25.71%
Delivered Hydrogen Potential: 12.33
```

Figure 40 - Project Improvement (Region E) 2050



```
Metrics for Region_F in 2050:
Total pipeline length for Region_F in 2050: 1893.07
Average Source Sink Distance: 467.52
Fraction of Network Grown: 50.00%
Delivered Hydrogen Potential: 29.88
```

Figure 41- Project Improvement (Region F) 2050

As it can be observed from Figure 30, 36, 38 and 40, the source activation year and availability have a critical role in determining when and where the trunk lines will be built. There is also lock in effects as it can be observed in Figure 38 and Figure 40 where, depending on the availability of wind farms, the pipeline tends to be either trunk line or branch line.

Further it has to be noted that the regions of Germany and Denmark are extremely difficult to compute because the sources are far off in the North Sea and the grid is extremely dense, see Figure 42 and Figure 43 which requires enormous computation that cannot be completed during the timeframe of this study. However, the results of these areas will be similar to the results of other regions as the network metrics employed, modelling logic and calculation method is same.

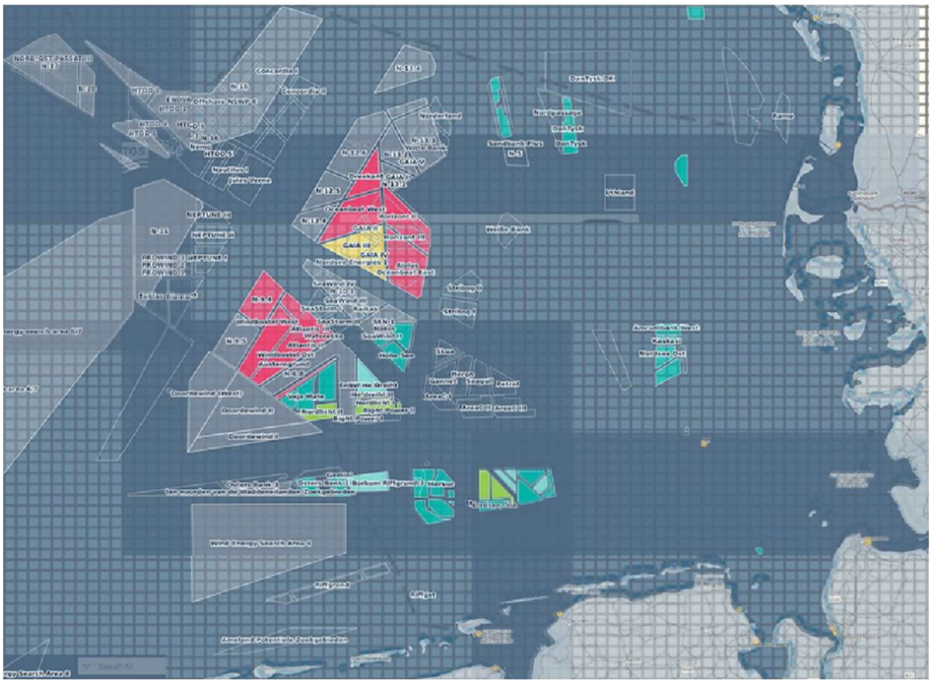


Figure 42 - Offshore Wind Farms of Germany

Figure 43 - Offshore Wind Farms of Denmark

Key Insights from the Results

In the experiments, for topology driven growth, pattern like highly interconnected structures with high TPL was observed. This demonstrates that maximizing structural centrality alone leads to over engineered networks. The model tries to make nodes "important" instead of "useful". In real hydrogen networks, the pipelines are not built to improve graph metrics rather to move molecules efficiently at minimum cost. Purely topology driven planning leads to unrealistic, economically inefficient infrastructure.

For distance driven growth, multiple parallel lines to sinks were observed showing strong spatial efficiency but lack of shared infrastructure. The network prioritizes shortest individual routes and not system efficiency. There is no incentive to reuse already made pipelines and duplication emerges. Minimizing distance alone thus can lead to infrastructure redundancy. In real world pipelines, parallel pipelines are expensive and rarely justified instead shared infrastructure is preferred. Distance driven optimization ignores economies of scale and can lead to redundant networks.

Flow driven growth shows better clustering around high supply nodes however there are occasionally unnecessary branches. The TPL is higher than the balanced baseline case. Prioritizing flow captures the demand supply logic however there is lack of spatial discipline and can over connect high supply areas. Flow alone creates locally optimal but globally inefficient networks. Flow based planning thus needs spatial and structural constraints to avoid over expansion.

In the balanced baseline case, as already mentioned, the network is compact with clear trunk and branch hierarchy. The TPL is also lowest and consistent across all regions and time. This implies that realistic infrastructure emerges from competing forces in equilibrium of cost (distance), demand (flow) and structure (connectivity). Therefore, the networks generated are multi objective compromises. Realistic pipeline systems thus are not optimized for one metric rather they are negotiated outcome between multiple constraints.

What evolution shows regarding the temporal growth patterns of early activation regions such as rapid TPL growth, high FNG and early high DHP is that the infrastructure forms quickly when supply is available and the network stabilizes early. These resembles early mover hydrogen hubs. Regarding the delayed activation regions, the pattern is minimal early growth, sudden expansion later and sharp increases in ASSD and DHP. Here the network jumps rather than growing gradually. This resembles late developing regions and the delayed investment could lead to rapid catch up expansion with potentially higher costs.

Regarding the path dependency and lock-in effects, it was observed that trunk and branch formation depends on early availability of wind farms able to generate hydrogen. This implies that early decisions constrain future structure. Once a trunk forms, future connection attaches to it and alternate layouts will become unlikely. Hydrogen infrastructure is thus path dependent and partially irreversible.

The model results thus in overall demonstrated that the offshore hydrogen pipeline network evolve as path dependent, supply driven systems in which realistic infrastructure may emerge only when the spatial efficiency, flow dynamics and structural connectivity are balanced. The dominant drivers of network growth and performance are source availability and activation timing.

Real World Implications

Offshore hydrogen networks must be planned as multi objective systems and not shortest path, highest flow or best topology. Instead it must be a balance of all three.

Early investment decisions creates long term lock in. The first trunk lines defines the future network shape. Poor early planning is difficult to be corrected. A policy implication here is that early stage planning must be strategic and not opportunistic.

Source availability is the primary trigger for offshore infrastructure development. Pipelines does not precede supply rather they respond to it. Coordinated rollout of offshore wind and hydrogen production is essential.

Phased development is superior to sudden expansion. When we look at the project improvement scenario, the network showed smoother growth, better utilization and less over building. Staged deployment thus reduces risk and improves efficiency.

Over optimization as seen earlier can lead to unrealistic systems. Topology focused resulted in highly complex and unrealistic network. Distance focused showed redundant networks and focusing only on flow lead to overbuilding of the network. Therefore, it is best to avoid single objective optimization frameworks.

It is also important to note here that infrastructure system was robust to local randomness. The random source selection scenario had limited long term impact. The macro scale is governed by system constraints and not local decisions.

9. DISCUSSION

This chapter discusses on the findings and looks into broader implications of the results. Model verification and validation is then discussed. This is followed by limitations of this study, future work and policy recommendations.

The results of this study provide a comprehensive understanding of the opportunities, challenges and the dynamics involved in the development of an offshore wind based hydrogen transport pipeline infrastructure in the North Sea. By integrating the insights obtained from the results of offshore wind farm deployment, potential of hydrogen production, capacity requirements for the hydrogen pipelines, network growth metrics and the scenario analysis, several key implications emerge for both energy planning and strategic infrastructure development.

Starting from the analysis of offshore wind farms planned for the North Sea, it is clearly evident that the North Sea represents a unique renewable energy with immense potential for green hydrogen production. The findings indicate that the existing and planned offshore wind capacity of around 237 GW can enable annual hydrogen production ranging from approximately 20 million tonnes to 27 million tonnes depending on the electrolyser technology employed. The SOEC electrolyser technology was found to be providing the highest output although several studies recommend PEM electrolysers. Therefore, the choice of electrolyser technology significantly influences the hydrogen production potential. This insight is particularly important for project developers. The results of hydrogen production potential considering the entire North Sea offshore wind capacity shows production volumes that could substantially contribute toward decarbonization goals while providing a reliable renewable hydrogen source to meet the hard to abate industrial demand, feedstocks and energy storage demand.

While there is immense potential for green hydrogen production in the North Sea, an effective hydrogen transport infrastructure is critical to unlock the benefits of the produced hydrogen. There are offshore natural gas pipelines in the North Sea however there are no offshore hydrogen pipelines in the North Sea or anywhere else. The results from this study demonstrates that the pipeline design and network capacity must be tailored for hydrogen production. Pipeline connecting a single wind farm are local lines requiring minimal diameter while the branch lines which connects two or more wind farms will require relatively larger diameter pipelines and trunk lines which connects more than three wind farms or cluster of wind farms will require larger DN600 or more diameter pipelines. There is a strong cost implication for this requirement. While there is limited data on the pipeline construction costs, estimate can be obtained with planned reference projects. A realistic annual investment budget can range from EUR 2 Billion to EUR 8 Billion which can build pipelines of approximately 400 km to 1600 km. The evolution of the network will also be determined by the locations of projects where the investment is made. Thus, there needs careful planning and prioritization to minimize overall costs. For this study, the network metrics adopted including betweenness centrality, supply weighted flow, Euclidean distance and closeness centrality offers a systematic approach to evaluate pipeline importance identifying the pipeline classes which helps guide investment towards routes that maximizes system wide overall efficiency, connectivity and economic feasibility.

The results from the experimental scenario analysis highlights the dynamic and staged nature of hydrogen network evolution. The networks generated in the balanced baseline, random source selection, nearest neighbour source selection, availability constrained experiments and project improvement scenario collectively demonstrate that the network growth is highly influenced by source activation timing, its availability and coordination. Regions with early source activation as mentioned earlier in the results shows rapid pipeline growth and high hydrogen delivery potential, whereas late developing regions shows gradual incremental growth. The nearest neighbour source selection scenario produces stable and predictable network highlighting the importance of coordination. The random source selection can accelerate early connectivity but it introduces variability in network structure and hydrogen delivery. The results of availability limited scenarios with 25%, 50% and 75% availability illustrates that constraining source activation can slow down network evolution reducing total pipeline length, average source sink distances and delivered hydrogen potential during the early periods. The results from project improvement scenario demonstrates that phased activation of sources and gradual network expansion produces more realistic and controlled growth while optimizing resource use as well as avoiding overbuilding. These insights provide critical guidance for infrastructure developers and policy makers to align deployment schedules with available budget, system priorities and technical capacity.

The results and the findings have several important implications from a stakeholder perspective. Project investors and infrastructural developers can use production capacity and pipeline capacity estimates to plan infrastructural deployment and assess return on their investments. Policy makers can leverage network metrics and insights from scenarios to prioritize project that offers the greatest system level benefits while balancing economic feasibility, energy security and decarbonization targets. Transmission system operators (TSO) can utilize the insights from the analysis to plan for scalable and flexible network that can accommodate uncertain future expansions in hydrogen production and demand. Further, realizing the full potential of North Sea hydrogen infrastructure and the shared benefits can only be attained by coordinated development, cross border collaboration and optimal allocation of resources. Even though the analysis is done on different regions of multiple countries, country specific recommendations are not included as each country have their own unique hydrogen strategies and energy plans. Integrating it is beyond the scope of this study. The results however stress the importance of regional coordination in order to develop shared pipeline infrastructure that can reduce overall costs.

9.1 Model Verification and Validation

Although the NetworkX based framework represents a heuristic and stylized abstraction of offshore hydrogen transport infrastructure development, several steps can be taken in order to verify and validate its internal logic and its structural behaviour. The model verification is ensured by systematically checking the correctness of the algorithmic implementation. It is also verified by confirming that edge additions respects spatial adjacency constraints. Further it is checked if the source activation follows commissioning years as well as performance metrics such as total pipeline length, average source sink distance and delivered hydrogen potential evolves consistently across time steps. Sensitivity analysis with different weighting schemes as well as different participation levels further supports the verification by showcasing that the model responds logically to parametric changes thereby producing structurally distinct yet interpretable network configurations. Validation is more challenging due to the forward looking and exploratory nature of this study. However, it can be approached through conceptual and structural validation rather than by empirical replication. The growth patterns of the model could also be compared qualitatively with established principles of infrastructure expansion such as back bone formation, hub emergence and clustering that occurs when there is coordinated development. In addition to that, plausibility checks can be carried out by comparing the results with published offshore energy planning studies and also the known aspects of large scale pipeline systems like in the case of offshore natural gas pipelines or it is also possible to compare it with offshore electricity cable lines as shown in Figure 44 and Figure 45 which is more relevant. A thorough validation thus cannot be performed considering the large uncertainty of hydrogen production and uncertain demand. It is pertinent to mention here that the aim of the model is not to predict the exact future layouts but instead the primary goal here is to investigate evolutionary pathways based on different strategic and institutional conditions. The validity of the model rests on its ability to generate consistent, explainable and policy relevant insights rather than precise forecasts.

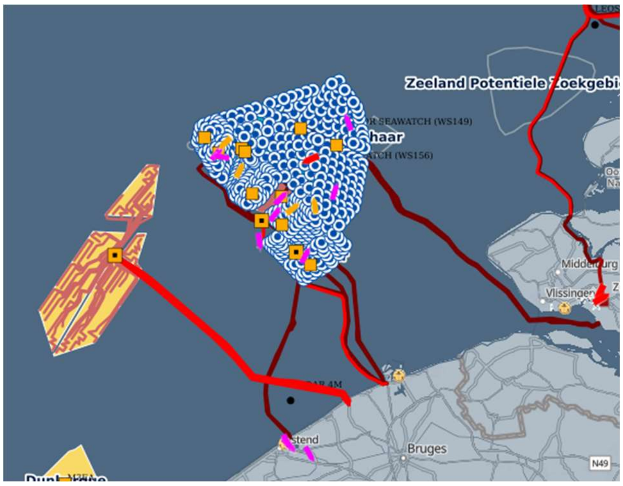


Figure 44 - Offshore Electricity Cable Lines - Belgium and Netherlands (Source = 4C Offshore)

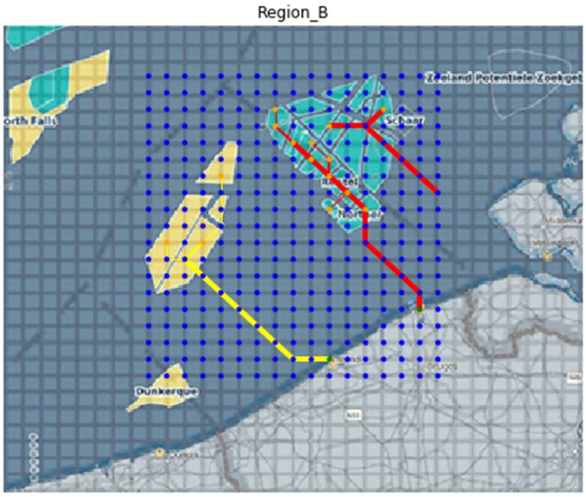


Figure 45 - Model Result of Offshore Hydrogen Transport Pipeline - Belgium and Netherlands

9.2 Limitations of the study

Despite the comprehensive nature of this study, there are several limitations that warrants further discussion. First of all, hydrogen production estimates that there is full wind availability and the electrolyser efficiency is simplified which may not capture temporal variability, downtime or maintenance constraints. Secondly, the pipeline capacity calculations omits friction losses, compression energy and other hydraulic complexities which are in the real world designs even though the current capacity calculation is sufficient for first order calculations. Third, the exclusive zones are not considered and demarcated, for e.g Military zones or Nature Protected Areas. Fourth, the network evolution scenarios are based on simplified network metric based growth rules and do not explicitly model regulatory, political or supply chain constraints that could delay deployment in the real world. Fifth, cross border connections are not considered as the focus of the study is on regional basis of respective countries. Cross border connections can emerge when there is sufficient advantage for shared infrastructures. Finally cost estimates, while grounded in current data, are subjected to technological learning, market fluctuations and policy changes over the next decades.

9.2 Future work

The limitations which are mentioned above highlights the opportunities for future work. Future studies can consider incorporating dynamic wind profiles, time dependent electrolyser performance, peak and off peak demand response production, more detailed hydraulic and energy loss modelling for pipelines. The environmental zones, economic constraints and technological uncertainties can be integrated in a multi objective optimization study to understand their effects on the overall network design of the offshore hydrogen system. Moreover, policy interventions, market dynamics and risk analysis can be included in scenario analysis to analyze the robustness of the system in extreme situations or delays. Finally, integrating hydrogen demand forecasts from multiple sectors would also enhance alignment between production, transport and consumption planning.

9.3 Policy Recommendation

This study suggests several actionable policy recommendations. The main recommendation is that the stakeholders should consider prioritizing coordinated spatial planning which integrates offshore wind electricity generation along with hydrogen production infrastructure. Even though this study doesn’t assess how much hydrogen is actually needed due to the large uncertainty in technology, demand and development aspects, the networks that were generated clearly demonstrated the necessity for shared planning which was clearly depicted in the form of trunk lines, branch lines and local lines emphasizing the advantages of shared infrastructure, further the coordinated planning which will result in large infrastructures has the potential to enable generation of potentially multi million tonnes of hydrogen as calculated in this study. This will help in the development of shared offshore hydrogen infrastructure which is critical for reducing the overall costs of the system. It is also important to consider multi-use zone to balance energy production, geological preservation and economic development. In order to ensure scalability and to maximize system wide connectivity, the network metrics enabled growth informs about the necessity for early investment in key trunk pipelines. While the initial cost will be high, there is flexibility to add more connections to the trunk lines which otherwise would require parallel lines resulting in cost overruns. The study also suggests development of policy frameworks that will support phased development aligned with realistic budget, incentivizing technology deployment such as SOEC electrolyser for high hydrogen yield and consider cross border collaboration to optimize shared infrastructure that will benefit the society more. Finally, the processes of systematic monitoring and adaptive planning will be essential in ensuring that the North Sea offshore wind based hydrogen network will evolve efficiently in response to technological, economic and environmental changes.

10. CONCLUSION

This chapter concludes this study by answering the main research question. The scientific and societal contributions are also described in this chapter.

This study set out to answer the main research question "How could the offshore wind based hydrogen transport pipeline network evolve in the North Sea?". To address this, six sub questions were formulated, focusing on offshore wind farm deployment, hydrogen production potential, transport capacity, realistic budget and pipeline deployment, network metric based prioritization and scenario based network evolution. By integrating empirical data, network modelling and scenario analysis, this research provides a detailed understanding of a large scale offshore hydrogen transport infrastructure may evolve in the North Sea.

Offshore Wind Farms in the North Sea (SQ1)

The North Sea currently has around 237 GW of offshore wind farms which are either existing, in consent stage, planning stage or in development zones. Thus, the North Sea has significant offshore wind potential for generating hydrogen. UK leads with 13.5 GW currently followed by Germany and Netherlands with 9.2 GW and 4.76 GW respectively in installed capacities. Collaborative efforts are undergoing under the North Seas Energy Cooperation (NSEC) as well as EU targets envisioning more than 300 GW by the year 2050 to position North Sea as a central hub for EU's green energy ambitions. However, there are uncertainties in the timings, auctions, supply chain constraints as well as technological uncertainties. For example, SOEC could develop into a mature stage as well as rising advancements in floating offshore wind turbines. Thus, there is flexibility in long term deployment that necessitates adaptive planning for the large scale hydrogen network.

Hydrogen Production Potential (SQ2)

The hydrogen production potential of a wind farm based hydrogen generation is highly dependent on the availability of wind, electrolyser technology and operation configuration of the system. A case study was conducted on the 600 MW Gemini Wind Farm to determine the production potential. From the study, it was determined that SOEC electrolyser yields maximum hydrogen compared to AE or PEM electrolyser systems. Extrapolating the results to the entire North Sea offshore wind portfolio, the annual hydrogen production was found to be between 20 million tonnes to 27 million tonnes as upper bound depending on the configuration and operational efficiency. The results underscore the enormous potential of the North Sea to generate sufficient hydrogen to supply domestic and international demands. The results also emphasize the need to prioritize high efficiency electrolyser technologies such as SOEC.

Hydrogen Transport Capacity (SQ3)

The produced hydrogen from offshore wind farm based hydrogen production platforms has to be transported via pipelines which has constraints due to process requirements. Depending on the flow volume, velocity and density, the capacity of the pipeline varies. Case studies of two wind farms with installed capacity of 600 MW and 1075 MW were analysed for the required diameter of the pipelines. The results demonstrated that diameter scales non linearly with hydrogen production. The 600 MW wind farm producing hydrogen required DN 200 pipeline while the 1075 MW wind farm required DN 250. Aggregating multiple wind farms will result in the requirement of larger trunk lines with diameters of DN600 or more. The conceptual hydraulic sizing provides a practical first order estimate in order to guide the early design of an integrated offshore hydrogen transport pipeline network.

Budget Constraints and Deployment Rates (SQ4)

It is important to note that there are currently no offshore hydrogen pipelines. Therefore, there is limited data regarding the costs or budget for construction of these pipelines. Still, there are projects that are in the planning stage which can give an estimate. Offshore hydrogen pipeline construction is highly capital intensive due to the extreme requirements. The costs will exceed traditional offshore natural gas pipelines due to higher process and safety requirements by hydrogen as the carrier. Budget could range from annually EUR 2 Billion to EUR 8 Billion which enables roughly 400 km to 800 km of pipeline deployment per year. The budget allocated will influence the network topology and its evolution as larger trunk lines are more expensive than branch lines or local lines.

Network Metrics for Pipeline Prioritization (SQ5)

In order to determine which pipelines to be built, network metrics can be utilized to systematically identify which pipeline connections contributes the highest overall benefit which prioritizes it as candidates for construction. There are several metrics that can be considered however, a selection has been made to include the most contributing metrics which can capture the dominant drivers of pipeline investment decisions. Betweenness centrality, Supply weighted flow, Euclidean distance and closeness centrality has been selected as they enable systematic prioritization of pipelines that could maximize system wide efficiency and accessibility. The main advantage of betweenness centrality is that it helps identify critical corridors while supply weighted flow aligns the infrastructure with production hubs incorporating capacity. Euclidean distance considers spatial realism and early cost estimates while the global accessibility is ensured by closeness centrality. Together, these metrics are critical in guiding the investments towards pipelines that are both technically viable and strategically important thereby to gain insights on network evolution.

Scenarios for Understanding Network Evolution (SQ6)

In order to understand the network evolution of offshore wind based hydrogen transport pipeline network, the scenarios have to designed in such a way that it captures different development pathways. Starting with varying the weights of the four metrics identified and selected earlier, how planning priorities can shape network evolution can be identified. These scenarios are grouped under growth objective scenario which also identifies the balanced baseline scenario for future experiments. Random or nearest neighbour source selection scenarios illustrates stochastic versus deterministic development patterns highlighting the importance of coordination and regional planning further enabling the development of shared infrastructures. Availability limited scenarios with 25%, 50% and 75% availability of hydrogen production in wind farms can reveal the impact of partial infrastructure realization and participation. Project Improvement scenarios show phased, adaptive growth illustrating the impact of technological maturation and strong policy support.

The results across different regions in multiple countries demonstrates that the network evolution is strongly dependent on source availability and temporal activation. The regions with early activation shows rapid pipeline growth and increased hydrogen delivery and saturates between the years 2040 and 2050. The regions with late activation shows gradual and incremental network development mirroring realistic staged deployment of hydrogen production. The random source selection scenario experiment shows acceleration of early growth marginally but the predictability of the network is maintained by nearest neighbour source selection strategy which demonstrates coordinated planning. The availability constraints limits the network expansion naturally, reducing the pipeline length, source sink distances and hydrogen delivery potential during early periods with limited availability.

The result of project improvement scenario illustrates phased and controlled growth that aligns with technological improvement and strong policy support.

Answering the Main Research Question

By synthesising the answers of all the sub questions, it is determined that the North Sea offers tremendous potential for offshore wind based hydrogen production with around 237 GW of wind farms including existing and in planning. Advancements in electrolyser technologies will significantly influence the hydrogen production potential and these electrolysers must be equipped to withstand harsh offshore environment. The configuration of offshore wind based hydrogen production system will also influence the proposed hydrogen transport pipeline network. Depending on the capacity of wind farms and electrolysers, the pipelines will have different capacities depending on whether it is a local pipeline connecting one wind farm, or branch line connecting two or three wind farms or a trunk line connecting more than three or four wind farms all producing hydrogen. The network metrics employed ensures that pipeline investments are strategically targeted which enhances overall system wide efficiency. The results of the experimentations with multiple scenarios based on growth, availability and project improvement demonstrates that the offshore wind based hydrogen transport pipeline network in the North Sea is expected to evolve gradually over multiple decades governed by the interplay between wind farm deployment, electrolyser capacity, pipeline sizing, budget availability and network connectivity. The initial expansion will be driven by existing wind farms which are the early hubs in high capacity region. Phased activation and project improvement scenarios depict the controlled integration of peripheral wind farms which are far located in the North Sea. The system will be capable of delivering tens of millions of tonnes of hydrogen annually. The top hydrogen producer will be the United Kingdom which has many giga watt scale of offshore wind farms, followed by Germany with closely located offshore wind farms of similar scales. Netherlands and Germany will likely lead the offshore wind based hydrogen production system as new pilot projects have been announced and are in planning stage. Considering all this, the network is highly likely to transition from a fragmented set of wind to hydrogen connections into a highly integrated and potentially cross border transport system by the year 2050. The developed framework also demonstrates that offshore hydrogen networks are not purely cost optimized artefacts but emergent systems whose topology is strongly influenced by timing, spatial clustering, financial and policy support and network structural properties. United Kingdom has the highest potential to lead in offshore hydrogen pipeline networks considering it has many operational and under construction large offshore wind farms. The pipeline network can mature early in the case of UK. Germany and Netherlands are most likely to follow the footsteps of UK with many offshore hydrogen pilot projects undergoing.

10.1 Scientific Contribution

This study contributes scientifically by developing a scenario based network evolution framework for offshore hydrogen transport incorporating stochastic and deterministic source selection, availability constraints and phased growth. Integrating network science metrics with energy infrastructure modelling provides a quantitative method to evaluate pipeline prioritization in large scale spatially distributed hydrogen system. Further this study makes a distinct scientific contribution by addressing a gap that existing literature has not previously filled which is the dynamic, temporally resolved modelling of network evolution of offshore wind based hydrogen transport pipeline network in the North Sea. While prior work has examined static infrastructure feasibility and cost optimization such as the European hydrogen backbone studies by (Van Wingerden et al., 2023) and the energy system optimization modelling of (Glaum et al., 2024), which demonstrated the cost advantages of offshore hydrogen pipeline transport over HVDC for remote wind farms, there is no existing modelling work on how such an offshore pipeline network actually evolves over time under different source availability and deployment conditions. Similarly (Kountouris et al., 2024) addressed unified European hydrogen infrastructure planning at a continental scale using myopic foresight optimisation but treated offshore pipeline evolution as a macro level outcome rather than a granular region by region developmental process. (Baufumé et al., 2013) in a foundational study on GIS based hydrogen pipeline network planning in Germany, demonstrated the value of spatially aware infrastructure modelling yet their framework was applied to onshore networks. This study further builds on the mentioned foundations and a novel multi metric network prioritization framework is introduced which integrates betweenness centrality, supply weighted flow, Euclidean distance and closeness centrality, applying it iteratively across different scenario experiments to simulate staged network growth. Betweenness centrality formalised by (Freeman, 1977)and subsequently applied to spatial infrastructure networks (Kirkley et al., 2018) has not previously been operationalised as a pipeline planning prioritization tool in an offshore hydrogen context. By combining existing data on offshore wind farms, capacity sizing and graph theoretic metrics within a unified scenario modelling framework, this research provides the first systematic account of how a North Sea offshore hydrogen pipeline network could plausibly evolve from a fragmented point to point connections towards an integrated system thereby contributing original methodological and applied knowledge to the emerging field of hydrogen infrastructure planning. Further this integration of energy systems modelling with infrastructure network science provides a novel methodological foundation for analysing large scale offshore hydrogen transport development under realistic transition constraints.

10.2 Societal Contribution

The analysis and results of this study offers key insights which can be taken for energy planners, hydrogen infrastructure developers and policy makers. The results underscores the importance of clear coordination in planning offshore hydrogen production deployment which can enable the development of shared infrastructure. The society can largely benefit from the reduction in construction costs because of shared infrastructures. In the infrastructure planning aspect, the study highlights possible optimal placement of pipelines to maximize hydrogen delivery while minimizing the costs. This study also demonstrates that large scale offshore hydrogen network can unlock the full potential of the North Sea's 237 GW wind portfolio supporting Europe's net zero goals by 2050. Further, this study helps regulators, developers and investors understand where to focus resources, which technologies to prioritize and how to phase infrastructure to balance risk, cost and benefit.

10.3 Reflection

While this study provided a structured framework for understanding the evolution of a offshore wind based hydrogen transport pipeline network in the North Sea, several simplifying assumptions defines its scope. Importantly, the model assumes that all the offshore wind capacity is directly available for hydrogen production. In reality, the case is different as only a fraction of total wind generation may be allocated for hydrogen production. Competing demands from direct electrification, grid export and power to X applications such as methanol or ammonia could likely limit the share of offshore wind energy diverted to electrolysis especially during the periods of high electricity market prices. As a result, hydrogen production potential in practice may be more dynamic and economically constrained than the upper bound estimates used in this study.

Further, the role of hydrogen in future energy systems will depend strongly on market conditions, infrastructure readiness as well as policy incentives. The rising electricity prices and evolving carbon pricing mechanisms may either strengthen hydrogen's competitiveness as a flexible energy carrier or limit its deployment compared to electrification pathways. Therefore, hydrogen is likely to function as part of a broader hybrid energy system rather than as sole determinant output of offshore wind. Yet, the hard to electrify industries need hydrogen or power to X fuels as energy source or feedstock.

Despite these limitations, the model remains valuable as a strategic planning tool, capturing the structural and temporal dynamics of network formation under different development scenarios. It provides insights into how the offshore hydrogen transport infrastructure could evolve under coordinated deployment. This is the case even if actual system outcomes will depend on economic optimization, market behaviour and regulatory frameworks that extends beyond the scope of the present modelling approach.

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APPENDICES

S.No	Country	Project Name	Status	Capacity (MW)
1	United Kingdom	Dogger Bank D (UK7V)	Concept/Early Planning	1500
2	United Kingdom	CampionWind (UK6B)	Concept/Early Planning	3000
3	United Kingdom	Cedar (UK7E)	Concept/Early Planning	1008
4	United Kingdom	Beech (UK5R)	Concept/Early Planning	1008
5	United Kingdom	Broadshore (UK6H)	Concept/Early Planning	900
6	United Kingdom	Sinclair (UK8C)	Concept/Early Planning	99.45
7	United Kingdom	Scaraben (UK8D)	Concept/Early Planning	99.45
8	United Kingdom	Stromar (UK6F)	Concept/Early Planning	1500
9	United Kingdom	Flora (UK8E)	Concept/Early Planning	50
10	United Kingdom	North Falls (UK4J)	Consent Application Submitted	504
11	United Kingdom	Five Estuaries (UK4I)	Consent Application Submitted	1100
12	United Kingdom	Dogger Bank South (DBS East) (UK4Y)	Consent Application Submitted	1500
13	United Kingdom	Dogger Bank South (DBS West) (UK4X)	Consent Application Submitted	1500
14	United Kingdom	Muir Mhor (UK6C)	Consent Application Submitted	798
15	United Kingdom	Buchan (UK6J)	Consent Application Submitted	960
16	United Kingdom	Outer Dowsing (UK4Z)	Consent Application Submitted	1500
17	United Kingdom	East Anglia Hub - TWO (UK39)	Consent Authorised	960
18	United Kingdom	East Anglia Hub - ONE North (UK2Q)	Consent Authorised	900
19	United Kingdom	Norfolk Vanguard (UK67)	Consent Authorised	2760
20	United Kingdom	Norfolk Boreas (UK69)	Consent Authorised	1380
21	United Kingdom	Hornsea Project Four (UK1J)	Consent Authorised	2400
22	United Kingdom	Berwick Bank (UK74)	Consent Authorised	4560

23	United Kingdom	Seagreen 1A (UK4P)	Consent Authorised	500
24	United Kingdom	Green Volt (UK94)	Consent Authorised	560
25	United Kingdom	Salamander (UK5F)	Consent Authorised	100
26	United Kingdom	Sheringham Shoal Extension (UK4H)	Fully Commissioned	317
27	United Kingdom	Dudgeon Extension (UK4G)	Fully Commissioned	402
28	United Kingdom	North East Area of Opportunity (UK8N)	Development Zone	16000
29	United Kingdom	Thanet (UK29)	Fully Commissioned	300
30	United Kingdom	London Array (UK14)	Fully Commissioned	630
31	United Kingdom	Gunfleet Sands 1 and 2 (UK07)	Fully Commissioned	172.8
32	United Kingdom	Gunfleet Sands 3 - Demonstration Project (UK73)	Fully Commissioned	12
33	United Kingdom	Kentish Flats (UK12)	Fully Commissioned	90
34	United Kingdom	Kentish Flats Extension (UK60)	Fully Commissioned	49.5
35	United Kingdom	Galloper (UK62)	Fully Commissioned	353
36	United Kingdom	Great Gabbard (UK05)	Fully Commissioned	504
37	United Kingdom	East Anglia ONE (UK64)	Fully Commissioned	714
38	United Kingdom	Scroby Sands	Fully Commissioned	60
39	United Kingdom	Humber Gateway	Fully Commissioned	219
40	United Kingdom	Westermost Rough	Fully Commissioned	210
41	United Kingdom	Teesside	Fully Commissioned	62.1
42	United Kingdom	Blyth Offshore Demonstrator – Phase 1	Fully Commissioned	41.5
43	United Kingdom	Methil Demo	Fully Commissioned	7
44	United Kingdom	Kincardine	Fully Commissioned	50
45	United Kingdom	Hornsea Project One (UK81)	Fully Commissioned	1218
46	United Kingdom	Hornsea Project Two (UK1U)	Fully Commissioned	1386

47	United Kingdom	Neart na Gaoithe (UK56)	Fully Commissioned	448
48	United Kingdom	Seagreen (UK44)	Fully Commissioned	1075
49	United Kingdom	Moray East (UK40)	Fully Commissioned	950
50	United Kingdom	Moray West (UK77)	Fully Commissioned	882
51	United Kingdom	Beatrice (UK53)	Fully Commissioned	588
52	United Kingdom	Inner Dowsing (UK11)	Fully Commissioned	97.2
53	United Kingdom	Lincs (UK13)	Fully Commissioned	270
54	United Kingdom	Lynn (UK15)	Fully Commissioned	97.2
55	United Kingdom	Race Bank (UK18)	Fully Commissioned	573.3
56	United Kingdom	Sheringham Shoal (UK27)	Fully Commissioned	316.8
57	United Kingdom	Dudgeon (UK04)	Fully Commissioned	402
58	United Kingdom	Triton Knoll (UK30)	Fully Commissioned	857
59	United Kingdom	Aberdeen (EOWDC)	Fully Commissioned	96.8
60	United Kingdom	Hywind Scotland Pilot Park	Fully Commissioned	30
61	United Kingdom	Dogger Bank A (UK80)	Partial Generation / Under Construction	1235
62	United Kingdom	Hornsea Project Three (UK1K)	Pre-Construction	2955
63	United Kingdom	Inch Cape (UK54)	Pre-Construction	1080
64	United Kingdom	East Anglia Hub - THREE (UK66)	Under Construction	1400
65	United Kingdom	Dogger Bank B (UK0V)	Under Construction	1235
66	United Kingdom	Sofia (UK1G)	Under Construction	1400
67	United Kingdom	Dogger Bank C (UK1F)	Under Construction	1200
68	Norway	GoliatVind	Concept/Early Planning	90
69	Norway	Windcatcher (NO74)	Concept/Early Planning	250
70	Norway	Sorlige Nordsjo II - phase 1 (NO40)	Concept/Early Planning	1500
71	Norway	Nordavind C (NO 77)	Development Zone	1000
72	Norway	Nordavind D	Development Zone	1000
73	Norway	Nordvest A (NO 79)	Development Zone	1000

74	Norway	Nordvest B (NO80)	Development Zone	1000
75	Norway	Nordvest C (NO81)	Development Zone	1000
76	Norway	Vestavind A (NO82)	Development Zone	1000
77	Norway	Vestavind B (NO83)	Development Zone	1000
78	Norway	Vestavind C (NO84)	Development Zone	1000
79	Norway	Vestavind D (NO85)	Development Zone	1000
80	Norway	Vestavind F (NO87)	Development Zone	1000
81	Norway	Vestavind E (NO86)	Development Zone	1000
82	Norway	Sonnavind A (NO94)	Development Zone	1000
83	Norway	Sorvest A (NO88)	Development Zone	1000
84	Norway	Sorvest E (NO92)	Development Zone	1000
85	Norway	Sorlige Nordsjo I (NO39)	Development Zone	1500
86	Norway	Sorvest B (NO89)	Development Zone	1000
87	Norway	Sorvest C (NP90)	Development Zone	1000
88	Norway	Sorvest D (NO91)	Development Zone	1000
89	Norway	Sorvest F (NO93)	Development Zone	1000
90	Norway	Sorlige Nordsjo II - phase 2 (NO66)	Development Zone	2100
91	Norway	Hywind Tampen (NO57)	Fully Commissioned	95
92	Netherlands	Ecowende (NL0O)	Consent Authorised	756
93	Netherlands	Ijmuiden Ver Alpha (NL0Q)	Consent Authorised	2000
94	Netherlands	Ijmuiden Ver Beta (NL0S)	Consent Authorised	2000
95	Netherlands	Nederwiek I-A (NL1T)	Consent Authorised	1150
96	Netherlands	Wind Energy Search Area 4 (NL1K)	Development Zone	4000
97	Netherlands	Ijmuiden Ver - Designated Wind Energy Area (NL0V)	Development Zone	867
98	Netherlands	Hollandse Kust West VIII (NL1F)	Development Zone	700
99	Netherlands	Lagelander	Development Zone	4000
100	Netherlands	Ijmuiden Ver Gamma B (NL3A)	Development Zone	1000
101	Netherlands	Ijmuiden Ver Gamma A (NL0X)	Development Zone	1000
102	Netherlands	Nederwiek Zuid I - B (NL2Z)	Development Zone	1000
103	Netherlands	NWBE (NL1S)	Development Zone	2000
104	Netherlands	Nederwiek III (NL1H)	Development Zone	2000
105	Netherlands	Netherlands - Future Tender A (NL0Y)	Development Zone	2500
106	Netherlands	Netherlands - Future Tender D (NL1B)	Development Zone	2500
107	Netherlands	Netherlands - Future Tender B (NL0Z)	Development Zone	2500
108	Netherlands	Netherlands - Future Tender E (NL1C)	Development Zone	2500

109	Netherlands	Netherlands - Future Tender C (NL1A)	Development Zone	2500
110	Netherlands	Netherlands - Future Tender F (NL1D)	Development Zone	2500
111	Netherlands	Netherlands - Future Tender G (NL1V)	Development Zone	2500
112	Netherlands	Netherlands - Future Tender H (NL1W)	Development Zone	2500
113	Netherlands	Wind Energy Search Area 3 (NL1J)	Development Zone	2000
114	Netherlands	Wind Energy Search Area 6/7 (NL1N)	Development Zone	10000
115	Netherlands	Doordewind II (NL1U)	Development Zone	2000
116	Netherlands	Doordewind I (NL1M)	Development Zone	2000
117	Netherlands	Hollandse Kust Noord (NL0F)	Fully Commissioned	759
118	Netherlands	Egmond aan Zee (NL02)	Fully Commissioned	108
119	Netherlands	Prinses Amaliawindpark (NL01)	Fully Commissioned	120
120	Netherlands	Hollandse Kust Zuid Holland I and II (NL0D)	Fully Commissioned	770
121	Netherlands	Hollandse Kust Zuid Holland III and IV (NL0E)	Fully Commissioned	770
122	Netherlands	Eneco Luchterduinen (NL32)	Fully Commissioned	129
123	Netherlands	Gemini	Fully Commissioned	600
124	Netherlands	Borssele I - II	Fully Commissioned	752
125	Netherlands	Borssele III-IV	Fully Commissioned	731.5
126	Netherlands	Borssele V	Fully Commissioned	19
127	Netherlands	OranjeWind (NL1Q)	Pre-Construction	795
128	Germany	Oceanbeat West (DE3J)	Concept/Early Planning	2000
129	Germany	Dreekant (DE3K)	Concept/Early Planning	1000
130	Germany	Nordsee Energies 1 (DE3E)	Concept/Early Planning	2000
131	Germany	Oceanbeat East (DE3D)	Concept/Early Planning	2000
132	Germany	Nordsee Energies 2 (DE3O)	Concept/Early Planning	1500
133	Germany	Waterekke (DE3S)	Concept/Early Planning	1500
134	Germany	Windbostel Ost (DE3A)	Concept/Early Planning	2000
135	Germany	Windbostel West (DE3B)	Concept/Early Planning	2000
136	Germany	Waterkant (DE2W)	Concept/Early Planning	296
137	Germany	Nordlicht II (DE2V)	Consent Application Submitted	630
138	Germany	N-13.3 (DE3R)	Development Zone	2000
139	Germany	N-13.4 (DE4P)	Development Zone	2000
140	Germany	N-12.6 (DE4Q)	Development Zone	2000
141	Germany	N-12.5 (DE4R)	Development Zone	1000
142	Germany	N-12.4 (DE4Z)	Development Zone	1000
143	Germany	N-13.2 (DE3Q)	Development Zone	1000
144	Germany	N-13.1 (DE3F)	Development Zone	500

145	Germany	SEN-1 (DE2Z)	Development Zone	425
146	Germany	N-6.8 (DE4W)	Development Zone	2000
147	Germany	N-9.5 (DE4X)	Development Zone	1000
148	Germany	N-20 (DE4U)	Development Zone	1000
149	Germany	DanTysk (DE02)	Fully Commissioned	288
150	Germany	Sandbank (DE12)	Fully Commissioned	288
151	Germany	Albatros (DE39)	Fully Commissioned	112
152	Germany	Global Tech I (DE09)	Fully Commissioned	400
153	Germany	Hoho See (DE11)	Fully Commissioned	497
154	Germany	Amrumbank West (DE05)	Fully Commissioned	302
155	Germany	Kaskasi (DE33)	Fully Commissioned	342
156	Germany	Nordsee Ost (DE06)	Fully Commissioned	295.2
157	Germany	Meerwind Sud/Ost (DE07)	Fully Commissioned	288
158	Germany	Gode Wind 3 (DE0H)	Fully Commissioned	253
159	Germany	Gode Wind 1 and 2 (DE13)	Fully Commissioned	582
160	Germany	Nordsee One (DE28)	Fully Commissioned	332.1
161	Germany	Trianel Windpark Borkum I (DE27)	Fully Commissioned	200
162	Germany	Trianel Windpark Borkum II (DE0K)	Fully Commissioned	203
163	Germany	Merkur (DE26)	Fully Commissioned	396
164	Germany	Alpha Ventus (DE01)	Fully Commissioned	60
165	Germany	Borkum Riffgrund 1 (DE04)	Fully Commissioned	312
166	Germany	Borkum Riffgrund 2 (DE30)	Fully Commissioned	450
167	Germany	Riffgat (DE21)	Fully Commissioned	108
168	Germany	BARD Offshore 1 (DE23)	Fully Commissioned	400
169	Germany	Veja Mate (DE36)	Fully Commissioned	402
170	Germany	Deutsche Bucht (DE24)	Fully Commissioned	252
171	Germany	Nordsee Cluster A - N-3.8 (DE2T)	Pre-Construction	435
172	Germany	Nordsee Cluster B - N-3.5 (DE0O)	Pre-Construction	420
173	Germany	Nordsee Cluster A - N-3.7 (DE2S)	Under Construction	225
174	Germany	Borkum Riffgrund 3 (DE03)	Under Construction	913
175	Germany	EnBW He Dreiht (DE19)	Under Construction	960
176	France	Dunkerque (FR68)	Consent Application Submitted	598
177	France	France - Future Tender C (Fixed/Floating) (FR88)	Development Zone	2000
178	France	France - Future Tender B (Fixed/Floating) (FR80)	Development Zone	2000
179	France	France - Future Tender A (Fixed/Floating) (FR79)	Development Zone	2000
180	France	France - Future Tender E (Fixed/Floating) (FR96)	Development Zone	2000

181	France	France - Future Tender F (Fixed/Floating) (FR97)	Development Zone	2000
182	France	France - Future Tender G (Fixed/Floating) (FR98)	Development Zone	2000
183	Denmark	Nordsoen - Tender 4 (DK0Y)	Development Zone	1000
184	Denmark	Nordsoen - Tender 2 (DK0X)	Development Zone	1000
185	Denmark	Nordsoen - Tender 1 (DK0V)	Development Zone	1000
186	Denmark	Nordsoen - Tender 6 (DK1A)	Development Zone	1000
187	Denmark	Nordsoen - Tender 7 (DK1B)	Development Zone	1000
188	Denmark	Nordsoen - Tender 8 (DK1C)	Development Zone	1000
189	Denmark	Nordsoen - Tender 10 (DK1E)	Development Zone	1000
190	Denmark	Nordsoen - Tender 9 (DK1D)	Development Zone	1000
191	Denmark	Nordsoen - Tender 5 (DK0Z)	Development Zone	1000
192	Denmark	Nordsoen - Tender 3 (DK0W)	Development Zone	1000
193	Denmark	Nordsoen I - (Subarea 2) (DK2U)	Development Zone	6978
194	Denmark	Nordsoen I - A3 (DK0O)	Development Zone	1000
195	Denmark	Nordsoen I - A2 (DK2W)	Development Zone	1000
196	Denmark	Nordsoen I - A1 (DK2V)	Development Zone	1000
197	Denmark	Vesterhav Nord/Syd (DK48)	Fully Commissioned	344
198	Denmark	Horns Rev 3 (DK19)	Fully Commissioned	406.7
199	Denmark	Horns Rev 2 (DK10)	Fully Commissioned	209.3
200	Denmark	Horns Rev 1 (DK03)	Fully Commissioned	160
201	Denmark	Thor (DK22)	Under Construction	1080
202	Belgium	Princess Elisabeth Zone Lot 1 (BE14)	Consent Application Submitted	700
203	Belgium	Princess Elisabeth Zone Lot 2 (BE15)	Consent Application Submitted	1400
204	Belgium	Princess Elisabeth Zone Lot 3 (BE16)	Consent Application Submitted	1400
205	Belgium	Seamade (Mermaid) (BE07)	Fully Commissioned	235.2
206	Belgium	Northwester 2 (BE12)	Fully Commissioned	219
207	Belgium	Nobelwind (BE08)	Fully Commissioned	165
208	Belgium	Belwind (BE03)	Fully Commissioned	165
209	Belgium	Seamade (SeaStar) (BE06)	Fully Commissioned	252
210	Belgium	Northwind (BE02)	Fully Commissioned	216
211	Belgium	Rentel (BE05)	Fully Commissioned	309
212	Belgium	Thornton Bank - Phase II (BE09)	Fully Commissioned	184.5
213	Belgium	Thornton Bank - Phase I (BE01)	Fully Commissioned	30
214	Belgium	Thornton Bank - Phase III (BE10)	Fully Commissioned	110.7
215	Belgium	Norther (BE04)	Fully Commissioned	369.6

Table 7 - Offshore Wind Farms in North Sea

Code Model Alignment – Detailed Implementation Mapping

A) Experiment Configuration and Model Parameters

```
EXPERIMENTS = {

      “Balanced Baseline”: dict(W_BC=0.40, W_FLOW=0.30, W_DIST=0.20,
W_CLOS=0.10)
```

This block defines the multi criteria weighting schemes used in the edge scoring framework. Each experiment corresponds to a different planning philosophy, specifying the relative importance of

a) Topology driven (betweenness centrality)
b) Hydrogen delivery efficiency (flow potential)
c) Spatial efficiency (distance to sinks)
d) Overall accessibility (closeness centrality)

In the conceptual model, these weights implement the decision maker’s preferences, allowing scenario based exploration of alternative network growth strategies.

```
YEARS = [2030, 2040, 2050]

REGION_EDGE_BUDGET = 2000

BASE_COMPONENT_BONUS = 0.2
```

The above parameters defines the temporal structure and growth constraints of the model.

- YEARS which represents discrete planning time periods.
- REGION_EDGE_BUDGET limits the infrastructure expansion per region and year. It serves as a proxy for investment or construction constraints.
- BASE_COMPONENT_BONUS controls the strength of the adaptive feedback mechanism which promotes the network cohesion

B) Spatial Grid and Neighborhood Structure

```
def build_nbrs(grid_w, grid_h)
```

This function defines the spatial adjacency rules of the network. Each grid node may be connected to one of the eight neighbours (including both orthogonal and diagonal). This enables flexible routing of offshore pipelines. This also corresponds to the spatial discretization which is mentioned in the model design, wherein the pipelines can follow multiple plausible offshore paths instead of strict rectilinear routes.

C) Graph construction from Spatial Map

```
def build_graph(map_file, grid_w, grid_h):
```

This function starts by initialization of the base graph structure of the model. It first loads a background map for visualization. After that, a grid based graph is constructed where each node represents a potential pipeline junction. Next it assigns spatial coordinates (pos) for each node. At this stage, the graph contains no edges, representing a pre infrastructure baseline. All subsequent pipeline development emerges endogenously through the growth algorithm.

D) Regional Definition and Node selection

```
def region_nodes(region):
```

This function identifies the subset of nodes which belongs to a specific region. It then operationalizes the regional decomposition that is discussed in the conceptual model and allows each region to grow independently while sharing the same underlying spatial grid.

E) Metric Normalization

```
def normalize(values):
```

Normalization function ensures that heterogenous metrics (betweenness and closeness centrality changes, supply weighted flow and Euclidean distance) are comparable when aggregated into a single score. This ensures that no single metric overpowers the scoring. This directly supports the multi criteria decision making framework of the model.

F) Distance Precomputation

```
def precompute_edistances(G, region):
```

This function measures the Euclidean distance from each node to the nearest sink. It is used as a spatial efficiency metric. It also represents the intuitive planning preference for shorter pipeline routes to demand centers.

G) Hydrogen Flow Potential

```
def swfp(G, rG, v, sinks, sources):
```

This function quantifies the hydrogen delivery potential of a candidate node by combining both source supply capacity and network distance from source to sink through the candidate edge. This metric operationalizes the concept of service effectiveness by prioritizing edges which meaningfully improves the hydrogen transport performance rather than only improving topology.

H) Pipeline Capacity Classification

```
def assign_edge_cclasses(G, region)
```

After the network growth, edges are classified into local, branch and trunk pipelines based on how frequently they appear in the shortest paths between sources and sinks. Although there are no explicit flow constraints are imposed, this classification provides a structural interpretation of network hierarchy aligning with real world pipeline planning concepts.

I) Visualization

```
def visual_region(G, region, map_img):
```

Visualization function serves as both a validation tool and aids in the interpretation of the network. Color and width attributes allows the inspection of spatial growth patterns, temporal sequencing of investments and emerging pipeline hierarchies in order to evaluate network growth. This supports qualitative assessment alongside quantitative metrics.

J) Performance Metrics

```
def compute_tpl ():

def compute_assd ():

def compute_fng():

def compute_dhp():
```

These functions implement the evaluation of the networks generated in the model by measuring total pipeline length, average source sink distance, fraction of network grown and delivered hydrogen potential. These functions translates network structure into interpretable indicators of infrastructure scale, transport efficiency, growth dynamics and hydrogen delivery capability. These metrics then enables systematic comparison across scenarios and different time periods.

K) Core Network Growth Algorithm

```
def grow_region()
```

This function implements the core evolutionary logic of the model. It operationalizes the conceptual pseudocode almost directly starting with activation of sources based on commissioning year, followed by identification of the unconnected sources, then connected components are selected after which there is temporary edge insertion for metric evaluation. Then the multi criteria scoring is calculated which is followed by adaptive bonus score is added. Then the high scored edge is permanently added. Finally the connectivity of the source is updated. This iterative loop embodies the model’s path dependent infrastructure evolution where each decision reshapes future opportunities.

L) Regional and Temporal Simulation Loop

```
def run_map():
```

This function conducts the full simulation. First it initializes the graph and the regions. It then assigns sources and sink attributes. Then it iterates the processes over the planning years. Then the availability constraints are applied. The regional growth is then invoked to study the network generated. It represents the highest level abstraction of the model, linking spatial structure, temporal evolution and experimental design.

M) Experimentation

```
for exp_name, weights in EXPERIMENTS.items():
```

The experimentation function executes multiple experimental scenarios each with different decisions, weights or source selection strategies. The experiments are executed region by region. Fixed random seeds ensure reproducibility allowing differences in outcomes to be attributed to model logic rather than stochastic noise.

Model Results for regions A,B,C,D,E,F,H,J,K,L,O and P

Region D, E and F

	Metric	Region D	Region E	Region F
2030	TPL	292.25	367.48	0
	ASSD	188.4	160.11	NA
	FNG	100%	45.83%	0
	DHP	8.45	5.53	0
2040	TPL	318.43	766.95	838.64
	ASSD	188.40	269.95	434.49
	FNG	0%	42.86%	50%
	DHP	8.45	14.57	7.29
2050	TPL	318.43	1094.70	2021.03
	ASSD	188.40	308.74	471.31
	FNG	0	16%	35.06%
	DHP	8.45	18.29	33.22

Table 8 - Balanced Baseline

	Metric	Region D	Region E	Region F
2030	TPL	369.51	490.88	0
	ASSD	179.25	149.86	NA
	FNG	100%	48.48%	0
	DHP	8.74	5.73	0
2040	TPL	415	933.97	838.64
	ASSD	179.25	264.34	434.49
	FNG	0%	37.74%	44.21%
	DHP	8.74	14.72	7.29
2050	TPL	432.67	1242.62	2151.90
	ASSD	179.25	301.47	470.332
	FNG	0	13.64%	34.91%
	DHP	8.74	18.53	33.29

Table 9 - Random Source Selection

	Metric	Region D	Region E	Region F
2030	TPL	292.25	367.48	0
	ASSD	188.4	160.11	NA
	FNG	100%	45.83%	0
	DHP	8.45	5.53	0
2040	TPL	318.43	766.73	838.64
	ASSD	188.40	269.95	434.49
	FNG	0%	42.86%	50%
	DHP	8.45	14.57	7.29

2050	TPL	318.43	1094.70	2021.03
	ASSD	188.40	308.74	471.31
	FNG	0	16%	35.06%
	DHP	8.45	18.29	33.22

Table 10 - Nearest Neighbour Source Selection

	Metric	**Region D**	**Region E**	**Region F**
2030	TPL	142.06	255.92	0
	ASSD	142.06	113.86	NA
	FNG	100%	41.67%	0
	DHP	0.91	0.95	0
2040	TPL	168.24	540.93	393.15
	ASSD	142.06	209.92	393.15
	FNG	0%	50%	45.45
	DHP	0.91	3.43	5.09
2050	TPL	213.73	903.20	702.69
	ASSD	142.06	291.58	361.82
	FNG	0	26.67%	17.81%
	DHP	0.91	5.34	17.19

Table 11 – 25% Availability

	Metric	**Region D**	**Region E**	**Region F**
2030	TPL	142.06	255.92	0
	ASSD	142.06	113.86	NA
	FNG	100%	41.67%	0
	DHP	0.91	0.95	0
2040	TPL	168.24	540.93	393.15
	ASSD	142.06	209.92	393.15
	FNG	0%	50%	45.45%
	DHP	0.91	3.43	5.09
2050	TPL	213.73	721.62	1319.99
	ASSD	142.06	254.39	550.01
	FNG	0	16.98%	44.79%
	DHP	0.91	5.47	13.30

Table 12 – 50% Availability

	Metric	**Region D**	**Region E**	**Region F**
2030	TPL	259.22	341.31	0
	ASSD	184.75	174.72	NA
	FNG	100%	45.45%	0
	DHP	4.43	4.71	0
2040	TPL	285.39	829.89	522.75
	ASSD	184.75	278.56	455.15
	FNG	0%	50%	37.14%
	DHP	4.43	11.72	2.20
2050	TPL	350.20	971.95	1410.59
	ASSD	184.75	291.52	481.13
	FNG	0	9.09%	34.19%
	DHP	4.43	13.76	21.98

Table 13 – 75% Availability

	Metric	Region D	Region E	Region F
2030	TPL	142.06	353.76	0
	ASSD	142.06	192.39	NA
	FNG	100%	56.25%	0
	DHP	0.91	3.95	0
2040	TPL	168.24	743.48	393.15
	ASSD	142.06	314.62	393.15
	FNG	0%	50%	38.46%
	DHP	0.91	8.52	5.09
2050	TPL	220.59	1130.65	1893.07
	ASSD	142.06	363.73	467.52
	FNG	0	25.71%	50%
	DHP	0.91	12.33	29.88

Table 14 - Project Improvement

Region A, B and C

	Metric	Region A	Region B	Region C
2030	TPL	0	465.80	660.21
	ASSD	NA	276.11	372.53
	FNG	0	100%	46.43%
	DHP	0	8.87	3.99
2040	TPL	94.29	1140.38	660.21
	ASSD	94.29	289.64	372.53
	FNG	12.50%	31.91%	0.00%
	DHP	6.34	19.90	3.99
2050	TPL	341.01	1140.38	660.21
	ASSD	175.33	289.64	372.53
	FNG	16.07%	0.00%	0.00%
	DHP	65.91	19.90	3.99

Table 15 - Balanced Baseline

	Metric	Region A	Region B	Region C
2030	TPL	0	849.01	827.23
	ASSD	NA	280.02	354.13
	FNG	0	100%	31.11%
	DHP	0	8.82	4.22
2040	TPL	94.29	1623.05	827.23
	ASSD	94.29	291.40	354.13
	FNG	8.16%	28.99%	0.00%
	DHP	6.34	20.01	4.22
2050	TPL	569.33	1623.05	827.23
	ASSD	170.73	291.40	354.13
	FNG	20.69%	0.00%	0.00%
	DHP	67.69	20.01	4.22

Table 16 - Random Source Selection

	Metric	Region A	Region B	Region C
2030	TPL	0	465.80	660.21
	ASSD	NA	276.11	372.53

	FNG	0	100%	46.43%
	DHP	0	8.87	3.99
2040	TPL	94.29	1185.50	660.21
	ASSD	94.29	295.96	372.53
	FNG	12.50%	34.69%	0.00%
	DHP	6.34	18.47	3.99
2050	TPL	341.01	1185.50	660.21
	ASSD	175.33	295.96%	372.53
	FNG	15.52%	0.00%	0.00%
	DHP	65.91	18.47	3.99

Table 17 - Nearest Neighbour Source Selection

	Metric	**Region A**	**Region B**	**Region C**
2030	TPL	0	340.99	557.85
	ASSD	NA	274.40	380.73
	FNG	0	100.00%	50.00%
	DHP	0	1.19	1.92
2040	TPL	94.29	840.48	557.85
	ASSD	94.29	283.08	380.73
	FNG	14.29%	26.32%	0.00%
	DHP	6.34	5.71	1.92
2050	TPL	282.64	840.48	557.85
	ASSD	141.32	283.08	380.73
	FNG	15.56%	0.00%	0.00%
	DHP	27.58	5.71	1.92

Table 18 – 25% Availability

	Metric	**Region A**	**Region B**	**Region C**
2030	TPL	0	728.23	528.21
	ASSD	NA	314.82	327.52
	FNG	0	100.00%	28.95
	DHP	0	3.25	2.30
2040	TPL	94.29	1179.68	528.21
	ASSD	94.29	313.87	327.52
	FNG	9.52%	19.23%	0.00%
	DHP	6.34	7.78	2.30
2050	TPL	273.44	1179.68	528.21
	ASSD	136.72	313.87	327.52
	FNG	11.86%	0.00%	0.00%
	DHP	28.67	7.78	2.30

Table 19 – 50% Availability

	Metric	**Region A**	**Region B**	**Region C**
2030	TPL	0	750.68	586.58
	ASSD	NA	283.65	327.52
	FNG	0	100.00%	28.95%
	DHP	0	5.51	2.30
2040	TPL	94.29	1236.92	586.58
	ASSD	94.29	287.71	327.52

	FNG	9.52%	20.75%	0.00%
	DHP	6.34	14.79	2.30
2050	TPL	308.24	1236.92	586.58
	ASSD	153.93	287.71	327.52
	FNG	13.11%	0.00%	0.00%
	DHP	49.91	14.79	2.30

Table 20 – 75% Availability

	Metric	Region A	Region B	Region C
2030	TPL	0	340.99	557.85
	ASSD	NA	274.40	380.73
	FNG	0	100.00%	50.00%
	DHP	0	1.19	1.92
2040	TPL	94.29	840.48	557.85
	ASSD	94.29	283.08	380.73
	FNG	14.29%	26.32%	0.00%
	DHP	6.34	5.71	1.92
2050	TPL	341.01	840.48	557.85
	ASSD	175.33	283.08	380.73
	FNG	19.15%	0.00%	0.00%
	DHP	65.91	5.71	1.92

Table 21 -- Project Improvement

Region H

	Metric	Region H
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	416.13
	ASSD	234.79
	FNG	100.00%
	DHP	4.28
2050	TPL	905.68
	ASSD	301.27
	FNG	54.17%
	DHP	8.24

Table 22 - Balanced Baseline

	Metric	Region H
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	449.82
	ASSD	234.79
	FNG	100.00%

	DHP	4.28
2050	TPL	939.36
	ASSD	301.27
	FNG	52%
	DHP	8.24

Table 23 - Random Source Selection

	Metric	**Region H**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	416.13
	ASSD	234.79
	FNG	100.00%
	DHP	4.28
2050	TPL	905.68
	ASSD	301.27
	FNG	54.17%
	DHP	8.24

Table 24 - Nearest Neighbour Source Selection

	Metric	**Region H**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	219.84
	ASSD	219.84
	FNG	100.00%
	DHP	2.27
2050	TPL	480.03
	ASSD	258.81
	FNG	50.00%
	DHP	3.95

Table 25 – 25% Availability

	Metric	**Region H**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	219.84
	ASSD	219.84
	FNG	100.00%
	DHP	2.27
2050	TPL	480.03
	ASSD	258.81
	FNG	50.00%
	DHP	3.95

Table 26 – 50% Availability

	Metric	Region H
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	249.74
	ASSD	249.74
	FNG	100.00%
	DHP	2
2050	TPL	558.66
	ASSD	338.82
	FNG	56.67%
	DHP	4.34

Table 27 – 75% Availability

	Metric	Region H
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	219.84
	ASSD	219.84
	FNG	100.00%
	DHP	2.27
2050	TPL	806.77
	ASSD	315.17
	FNG	71.43%
	DHP	6.29

Table 28 - Project Improvement

Region J

	Metric	Region J
2030	TPL	1701.94
	ASSD	314.42
	FNG	100.00%
	DHP	9.26
2040	TPL	2351.81
	ASSD	378.24
	FNG	26.25%
	DHP	16.59
2050	TPL	2351.81
	ASSD	378.24
	FNG	0.00%
	DHP	16.59

Table 29 - Balanced Baseline

	Metric	Region J

2030	TPL	1699.11
	ASSD	314.42
	FNG	100.00%
	DHP	9.25
2040	TPL	2360.93
	ASSD	378.44
	FNG	26.25%
	DHP	16.55
2050	TPL	2360.93
	ASSD	378.44
	FNG	0.00%
	DHP	16.55

Table 30 - Random Source Selection

	Metric	**Region J**
2030	TPL	1701.94
	ASSD	314.42
	FNG	100.00%
	DHP	9.26
2040	TPL	2351.81
	ASSD	378.24
	FNG	26.25%
	DHP	16.59
2050	TPL	2351.81
	ASSD	378.24
	FNG	0.00%
	DHP	16.59

Table 31 - Nearest Neighbour Source Selection

	Metric	**Region J**
2030	TPL	302.92
	ASSD	302.92
	FNG	100.00%
	DHP	1.66
2040	TPL	583.24
	ASSD	324.30
	FNG	45.00%
	DHP	3.12
2050	TPL	583.24
	ASSD	324.30
	FNG	0.00%
	DHP	3.12

Table 32 – 25% Availability

	Metric	**Region J**
2030	TPL	1257.29
	ASSD	410.08
	FNG	100.00%
	DHP	2.97
2040	TPL	1612.09
	ASSD	407.26

	FNG	20.00%
	DHP	6.91
2050	TPL	1612.09
	ASSD	407.26
	FNG	0.00%
	DHP	6.91

Table 33 – 50% Availability

	Metric	Region J
2030	TPL	1160.21
	ASSD	310.48
	FNG	100%
	DHP	6.16
2040	TPL	1529.77
	ASSD	395.80
	FNG	23.53%
	DHP	12.04
2050	TPL	1529.77
	ASSD	395.80
	FNG	0.00%
	DHP	12.04

Table 34 – 75% Availability

	Metric	Region J
2030	TPL	373.94
	ASSD	373.94
	FNG	100%
	DHP	0.80
2040	TPL	1172.14
	ASSD	486.98
	FNG	65.00%
	DHP	4.36
2050	TPL	1172.14
	ASSD	486.98
	FNG	0.00%
	DHP	4.36

Table 35 - Project Improvement

Region K

	Metric	Region K
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	1525.75
	ASSD	589.06
	FNG	100%
	DHP	9.60
2050	TPL	1525.75

	ASSD	589.06
	FNG	0%
	DHP	9.60

Table 36 - Balanced Baseline

	Metric	**Region K**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	1568.59
	ASSD	589.99
	FNG	100%
	DHP	9.71
2050	TPL	1568.59
	ASSD	589.99
	FNG	0%
	DHP	9.71

Table 37 - Random Source Selection

	Metric	**Region K**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	1525.75
	ASSD	589.06
	FNG	100%
	DHP	9.60
2050	TPL	1525.75
	ASSD	589.06
	FNG	0%
	DHP	9.60

Table 38 - Nearest Neighbour Source Selection

	Metric	**Region K**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	624.49
	ASSD	600.39
	FNG	100%
	DHP	2.30
2050	TPL	624.49
	ASSD	600.39
	FNG	0%
	DHP	2.30

Table 39 – 25% Availability

	Metric	**Region K**

2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	1010.37
	ASSD	551.45
	FNG	100%
	DHP	5.04
2050	TPL	1010.37
	ASSD	551.45
	FNG	0%
	DHP	5.04

Table 40 – 50% Availability

	Metric	**Region K**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	1139.86
	ASSD	617.91
	FNG	100%
	DHP	6.85
2050	TPL	1139.86
	ASSD	617.91
	FNG	0%
	DHP	6.85

Table 41 – 75% Availability

	Metric	**Region K**
2030	TPL	0
	ASSD	NA
	FNG	0
	DHP	0
2040	TPL	834.64
	ASSD	563.82
	FNG	100%
	DHP	4.95
2050	TPL	834.64
	ASSD	563.82
	FNG	0%
	DHP	4.95

Table 42 - Project Improvement

Region L

	Metric	**Region L**
2030	TPL	1407.80
	ASSD	211.13
	FNG	100%

	DHP	13.60
2040	TPL	1960.56
	ASSD	272.70
	FNG	27.59%
	DHP	18.18
2050	TPL	1960.56
	ASSD	272.70
	FNG	0%
	DHP	18.18

Table 43 - Balanced Baseline

	Metric	**Region L**
2030	TPL	1495.85
	ASSD	218
	FNG	100%
	DHP	13.08
2040	TPL	2048.61
	ASSD	280.77
	FNG	26.23%
	DHP	17.56
2050	TPL	2048.61
	ASSD	280.77
	FNG	0%
	DHP	17.56

Table 44 - Random Source Selection

	Metric	**Region L**
2030	TPL	1407.80
	ASSD	211.13
	FNG	100%
	DHP	13.60
2040	TPL	1960.56
	ASSD	272.70
	FNG	27.59%
	DHP	18.18
2050	TPL	1960.56
	ASSD	272.70
	FNG	0%
	DHP	18.18

Table 45 - Nearest Neighbour Source Selection

	Metric	**Region L**
2030	TPL	457.78
	ASSD	212.14
	FNG	100%
	DHP	2.51
2040	TPL	1056.77
	ASSD	346.63
	FNG	58.06%
	DHP	4.95
2050	TPL	1056.77

	ASSD	346.63
	FNG	0%
	DHP	4.95

Table 46 – 25% Availability

	Metric	**Region L**
2030	TPL	345.26
	ASSD	111.68
	FNG	100%
	DHP	6.55
2040	TPL	749.89
	ASSD	164.77
	FNG	52.38%
	DHP	7.62
2050	TPL	749.89
	ASSD	164.77
	FNG	0%
	DHP	7.62

Table 47 – 50% Availability

	Metric	**Region L**
2030	TPL	1119.40
	ASSD	228.39
	FNG	100%
	DHP	9.88
2040	TPL	1792.78
	ASSD	284.47
	FNG	38.46%
	DHP	13.41
2050	TPL	1792.78
	ASSD	284.47
	FNG	0%
	DHP	13.41

Table 48 – 75% Availability

	Metric	**Region L**
2030	TPL	304.36
	ASSD	125.18
	FNG	100%
	DHP	3.74
2040	TPL	708.99
	ASSD	188.17
	FNG	55%
	DHP	4.81
2050	TPL	708.99
	ASSD	188.17
	FNG	0%
	DHP	4.81

Table 49 - Project Improvement

Region O

	Metric	Region O
2030	TPL	509.46
	ASSD	164.14
	FNG	100%
	DHP	9.42
2040	TPL	1201.94
	ASSD	202.77
	FNG	55.38%
	DHP	37.28
2050	TPL	1201.94
	ASSD	202.77
	FNG	0%
	DHP	37.28

Table 50 - Balanced Baseline

	Metric	Region O
2030	TPL	509.46
	ASSD	164.14
	FNG	100%
	DHP	9.42
2040	TPL	1201.94
	ASSD	202.77
	FNG	55.38%
	DHP	37.28
2050	TPL	1201.94
	ASSD	202.77
	FNG	0%
	DHP	37.28

Table 51 - Random Source Selection

	Metric	Region O
2030	TPL	509.46
	ASSD	164.14
	FNG	100%
	DHP	9.42
2040	TPL	1201.94
	ASSD	202.77
	FNG	55.38%
	DHP	37.28
2050	TPL	1201.94
	ASSD	202.77
	FNG	0%
	DHP	37.28

Table 52- Nearest Neighbour Source Selection

	Metric	Region O
2030	TPL	235.03
	ASSD	191.07
	FNG	100%

	DHP	1.91
2040	TPL	579.53
	ASSD	231.80
	FNG	54.84%
	DHP	16.46
2050	TPL	579.53
	ASSD	231.80
	FNG	0%
	DHP	16.46

Table 53 – 25% Availability

	Metric	**Region O**
2030	TPL	237.65
	ASSD	237.65
	FNG	100%
	DHP	4
2040	TPL	663.10
	ASSD	257.34
	FNG	62.86%
	DHP	18.49
2050	TPL	663.10
	ASSD	257.34
	FNG	0%
	DHP	18.49

Table 54 – 50% Availability

	Metric	**Region O**
2030	TPL	472.68
	ASSD	206.60
	FNG	100%
	DHP	6.70
2040	TPL	920.25
	ASSD	224.60
	FNG	46%
	DHP	22.98
2050	TPL	920.25
	ASSD	224.60
	FNG	0%
	DHP	22.98

Table 55 – 75% Availability

	Metric	**Region O**
2030	TPL	237.65
	ASSD	237.65
	FNG	100%
	DHP	4.8
2040	TPL	501.06
	ASSD	219.25
	FNG	51.85%
	DHP	11.83
2050	TPL	501.06

	ASSD	219.25
	FNG	0%
	DHP	11.83

Table 56 - Project Improvement

Region P

	Metric	Region P
2030	TPL	397.12
	ASSD	158.07
	FNG	100%
	DHP	15.28
2040	TPL	1805.68
	ASSD	287.92
	FNG	77.17%
	DHP	37.65
2050	TPL	1805.68
	ASSD	287.92
	FNG	0%
	DHP	37.65

Table 57 - Balanced Baseline

	Metric	Region P
2030	TPL	405.17
	ASSD	152.86
	FNG	100%
	DHP	16.04
2040	TPL	2016.93
	ASSD	287.67
	FNG	79.05%
	DHP	38.04
2050	TPL	2016.93
	ASSD	287.67
	FNG	0%
	DHP	38.04

Table 58 - Random Source Selection

	Metric	Region P
2030	TPL	397.12
	ASSD	158.07
	FNG	100%
	DHP	15.28
2040	TPL	1805.68
	ASSD	287.92
	FNG	77.17%
	DHP	37.65
2050	TPL	1805.68
	ASSD	287.92
	FNG	0%
	DHP	37.65

Table 59 - Nearest Neighbour Source Selection

	Metric	Region P
2030	TPL	182.23
	ASSD	182.23
	FNG	100%
	DHP	4.84
2040	TPL	570.79
	ASSD	268.69
	FNG	62.07%
	DHP	7.54
2050	TPL	570.79
	ASSD	268.69
	FNG	0%
	DHP	7.54

Table 60 – 25% Availability

	Metric	Region P
2030	TPL	182.23
	ASSD	182.23
	FNG	100%
	DHP	4.84
2040	TPL	1271.30
	ASSD	301.54
	FNG	83.08%
	DHP	19.58
2050	TPL	1271.30
	ASSD	301.54
	FNG	0%
	DHP	19.58

Table 61 – 50% Availability

	Metric	Region P
2030	TPL	373.46
	ASSD	177.95
	FNG	100%
	DHP	10.31
2040	TPL	1677.41
	ASSD	293.05
	FNG	76.19%
	DHP	27.88
2050	TPL	1677.41
	ASSD	293.05
	FNG	0%
	DHP	27.88

Table 62 – 75% Availability

	Metric	Region P
2030	TPL	191.23
	ASSD	173.67

	FNG	100%
	DHP	5.47
2040	TPL	1251.49
	ASSD	321.90
	FNG	85.71%
	DHP	9.58
2050	TPL	1251.49
	ASSD	321.90
	FNG	0%
	DHP	9.58

Table 63 - Project Improvement