Geographical Information Management and Applications

Developing a methodology to draw and compare hydrogen pipelines in the Dutch EEZ in 2050

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June 2020

Universiteit Utrecht

TU Delft

UNIVERSITY OF TWENTE.

WAGENINGEN UR

GIMA MSc. Final Thesis
June 2020

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North Sea Energy offshore system integration

TNO innovation for life

Preface

This report presents the results of my research which is part of my master's degree in Geographical Information Management and Applications. I am grateful for all those who supported me in completing this thesis. However, I want to especially thank a couple of people.

Firstly, I want to thank Joris Koornneef for sharing is knowledge, his infectious enthusiasm and providing a spot in his team at TNO. Secondly, I would like to thank Barend Köbben for his useful advice and involvement in the project. Thirdly, I want to thank Logan Brunner for his time and effort and the programming skills that I learned from him. I also want to thank Peter van de Giessen for his critical feedback and wisdom. Finally, I would like to thank my family for their unconditional support and being a sounding board whenever I needed them.

Enjoy the read!

Executive Summary

In order to meet the Paris Agreement, countries worldwide are striving to limit global warming to well below 2°C. To reach this goal, the global energy system must undergo an extensive transformation from a predominantly fossil fuel based system to a fully renewable and efficient system. One of the main green alternatives for fossil fuels is wind energy. As a consequence, many wind energy projects are currently in development; in particular offshore where a lot of space is available and high wind speeds prevail. The North Sea is a primary candidate for when considering large scale offshore wind farms (OWF) in Northwestern Europe and as a result, a large increase of offshore wind power is expected. To manage all the extra power input from these OWFs, solutions in the energy grid are needed.

Hydrogen gas is seen as an important solution to transport and store the energy produced by the OWFs. However, for hydrogen to be applied on a large scale, an extensive infrastructural network is required. Since the North Sea is spatially dominated by many reserved areas and economic activities, this will cause challenges in the planning of the infrastructure; infrastructural elements like hydrogen pipelines are likely to intersect these areas, causing conflicting interests. For this reason, the strategic planning of North Sea Infrastructure is of great importance.

In order to make the most out of hydrogen's potential, a better understanding of the spatial implementation is required. As a result, a large number of initiatives and R&D projects have been undertaken in the past few years. This report is written in the framework of the North Sea Energy (NSE) program, which aims to identify and assess opportunities for synergies between energy sectors offshore.

To resolve the challenges concerning the future implementation of hydrogen infrastructure, most studies make use of system modelling and/or economical analyses. However, some questions cannot be solved without taking into account the spatial component of the data. This research focuses on solving some of those infrastructural challenges from a spatial perspective. The research question for this study is; **How to optimize the routing of hydrogen pipelines considering current use functions and existing infrastructure?** To answer this question a spatial model has to be developed. Therefore, the main objective of this research is: **To develop a model to compare straight pipeline trajectories with trajectories that take into account spatial use functions and infrastructure reuse potential on the North Sea.**

Literature shows that the North Sea knows many different uses with diverging interests. This emphasizes the importance of the development of a model that can take into account these interests in varying ways. The study also demonstrates the role of pipelines as a means of transport in the hydrogen production chain. Finally, the literature study showed that the product of this research should be seen as a planning support system making use of GIS, with a relatively high level of uncertainty.

After the literature study, a model was developed that integrates use function areas, expert use factors, source and sink locations and corridor and reuse trajectories in order to run Least-Cost Path (LCP) algorithms across use factor raster layers. The use factor can be described as a measure of discouragement or encouragement to cross a certain use function of the sea. A concept model was developed in the graphical modeler in QGIS, after which the model was further automated using Python. This model was run following three scenarios; Area Only, Corridor and Reuse. In the Area Only scenario only the surface areas with their corresponding use factors are taken into account. The Corridor and Reuse scenarios extend the Area Only scenario by either adding pipeline corridors or pipelines that are theoretically available for reuse. For each of these scenarios the model was also run for the minimum and maximum expert input factor values in order to investigate the influence of these factors on the trajectories.

When comparing the scenario results to straight line trajectories, in each scenario the length has increased, while the hypothetical costs have decreased to various extents. The relative differences of these results are dependent on the use factor, which are set by the user. The results also show that the Area Only scenario follows a relatively direct route, while the other scenarios tend to follow the existing infrastructure. The degree to which the infrastructure is followed depends on the factor assigned to the corridors and reuse pipelines; the lower the value, the closer these trajectories are followed. The Area Only scenario resulted in the shortest merged trajectory length; 769,3 km, a length increase of about 14,1% compared to the straight line reference. The Corridor and Reuse scenarios resulted in length increases of about 16,8% and 18,5% respectively. The percentages of intersected use functions decreased for all scenarios; ranging from -25% for the Corridor scenario to -35,1% for the Area Only scenario. The (hypothetical) costs also decreased: -17,3% for Area Only, -23,8% for Corridor and -28,7% for the Reuse scenario.

The model still has some shortcomings and limitations, like the imprecise input factors and limited directions of movement of the LCP. Also, the dependence on market and location for hydrogen pipelines is too high when using these kinds of scales and the reference year of 2050. Therefore, the model and methodology shows greater potential in earlier stages of planning as a supporting tool for stakeholders. From the results the following can be concluded; in the case of the routing of hydrogen pipelines, a sacrifice will have to be made either in the length, or in the amount of crossed use functions, depending on which is more important for the user. Next to that, the potential in application of the model combined with the relatively short development time of this research, show that a lot can be gained by approaching these kind of problems from a spatial perspective.

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Acronyms

BEV Battery Electric Vehicle

CAPEX Capital Expenditure

CCS Carbon Capture and Storage

EEZ Exclusive Economic Zone

FCEV Fuell Cell Electric Vehicle

GIS Geographical Information System

GUI Graphical User Interface

GW Gigawatt

IDE Integrated Development Environment

IMO International Maritime Organisation

LCP Least-Cost Path

MW Megawatt

NCP Nederlands Continentaal Plat

NSE North Sea Energy

OPEX Operational Expenditure

OWF Offshore Wind Farm

PSS Planning Support System

SDSS Spatial Decision Support System

SMR Steam Methane Reforming

1 Introduction

By signing the 2015 Paris Agreement, the countries that are part of the UNFCCC, "... recognize the need for an effective and progressive response to the urgent threat of climate change on the basis of the best available scientific knowledge, ..." (UNFCCC, 2015). In order to meet this agreement, countries worldwide are striving to limit global warming to well below 2°C. To reach this goal, the global energy system must undergo an extensive transformation from a predominantly fossil fuel based system to a fully renewable and efficient system. For this reason, the EU and other countries target to cut 40% of their greenhouse gas emissions before 2030 and aim to be climate-neutral by 2050 (European Commission, 2015). Following this, one of the main objectives of the Dutch Climate Act is to decrease CO_2 emissions with 49% in 2030 and with 95% in 2050 (all are compared to 1990 emission levels) (Rijksoverheid, 2020).

1.1 Large scale offshore wind energy production

One of the main green alternatives for fossil fuels is wind energy. Therefore, many wind energy projects are currently in development. These projects can be located either onshore or offshore, but since Northwestern Europe is densely populated, the placement of onshore wind turbines often comes with disadvantages; a lack of inexpensive land together with visual and noise pollution are reasons for large opposition against onshore wind turbines (Bilgili, Yasar, & Simsek, 2011). This is one of the reasons why governments have to resort to offshore possibilities for wind parks to try and meet their energy goals, another reason being the higher wind speeds.

The North Sea is a primary candidate when considering large scale offshore wind farms (OWF) due to it being the largest body of water in Northwestern Europe, its relatively shallow seabed and its favorable wind conditions. As a result, a large increase of offshore wind power is expected; Several OWFs have already been realised on the North Sea and many more are planned (European Union, 2017). This also applies to the Dutch part of the North Sea (See Figure 1.1); according to the PBL (2018a), the estimated offshore wind capacity can grow from the current 1 GW of energy to 15 GW in 2030 and 60 GW in 2050. To entirely decarbonize the power sector of the countries surrounding the North Sea, it is estimated that 180 GW of wind capacity is required (Ruijgrok & van Druten, 2019). An additional disadvantage of electricity production from renewable sources is the intermittent character of energy supply, which causes an imbalance with the energy demand. To manage all this extra power input and fluctuations, solutions in the energy grid are needed.

1.2 Hydrogen

Hydrogen gas is acknowledged to play an important supporting role in this task (TNO, 2019). The gas is a clean fuel that emits no toxic emissions when burned and can easily be applied for electricity generation or in the transport sector (Hosseini & Wahid, 2016). It is also seen as a safe energy carrier that can help store and transport all the newly produced

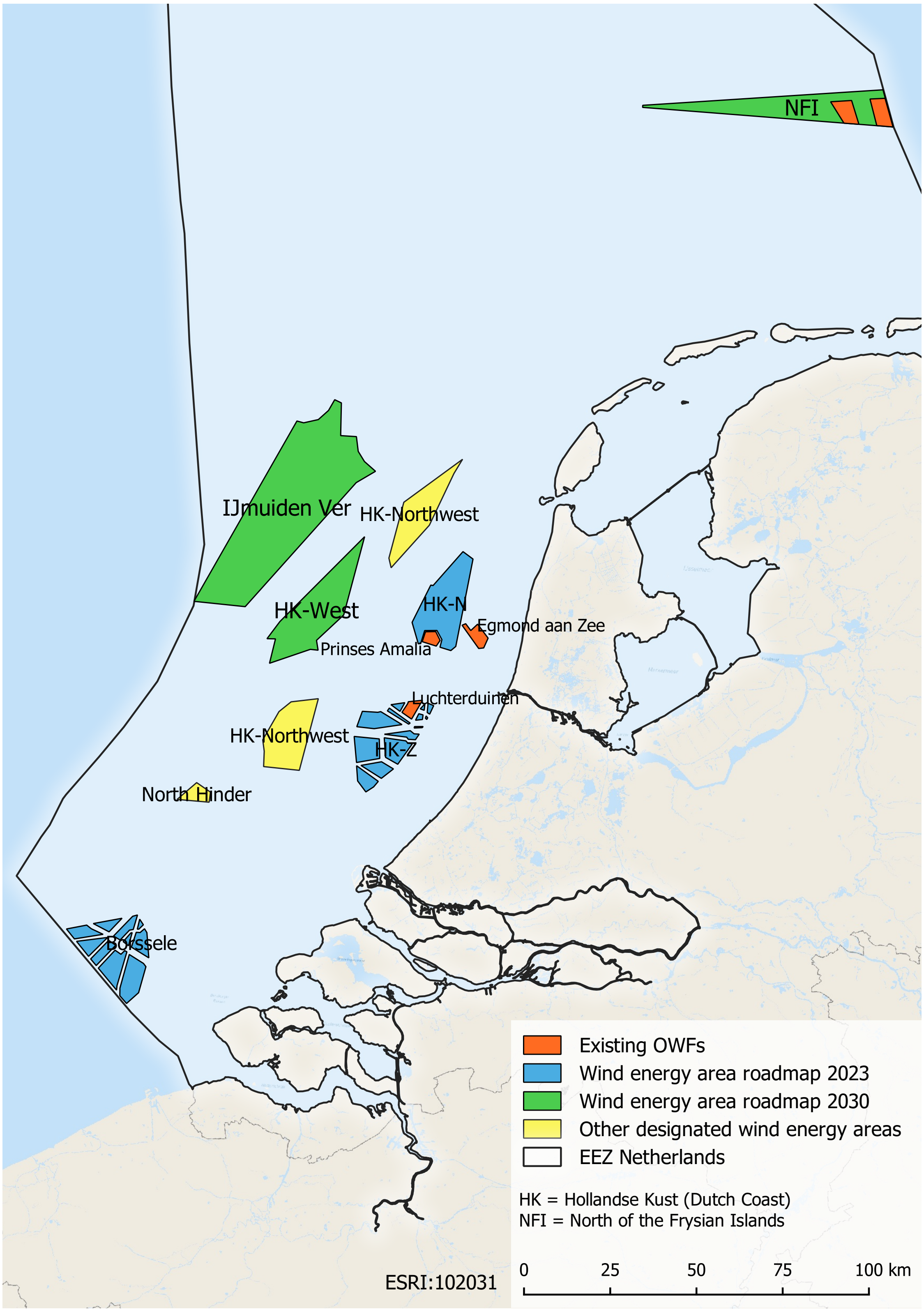


Figure 1.1: Overview of the current and planned OWFs on the Dutch continental shelf. Adapted from Ministerie EZK (2018).

energy from the OWFs (Hosseini & Wahid, 2016). This can be achieved when wind energy is used to convert water into hydrogen gas using electrolysers. These will be placed in or on top of hydrocarbon production platforms (North Sea Energy, 2020b). For this, also decommissioned hydrocarbon platforms might be used. This type of hydrogen along with hydrogen produced with other forms of renewable energy is called *green hydrogen*. Next to that, hydrogen can be produced from natural gas, of which large volumes are present on the North Sea. With this process, *grey* or *blue hydrogen* is produced (See Section 2.2).

Currently, the large scale production of hydrogen at sea from wind energy is not financially competitive yet, due to high production costs and low efficiency rates. However, considering the fluctuating nature of wind energy, the growing amount of renewable energy that is fed into the electricity grid and increasing fossil fuel feedstock costs, it is expected that using hydrogen gas as a storage medium will become economic in the future (Bartels, Pate, & Olson, 2010). For hydrogen to be applied on a large scale, an extensive infrastructural network is needed. This network will enable the countries surrounding the North Sea to produce, transport, store and eventually make use of the gas.

1.3 Spatial Claims

Because future OWFs are planned further offshore ((International Energy Agency, 2019b), also see page 2), the hydrogen network will extend over a large area of the North Sea. And since the North Sea is spatially dominated by many reserved areas and economic activities (See Figure 1.2), this will cause challenges in the planning of the infrastructure; infrastructural elements, like hydrogen pipelines, are likely to intersect these areas, causing conflicting interests. These areas carry different functions, which include: Natura 2000 areas, military exercise areas, shipping routes and sand excavation areas. Each of these area functions comes with its own difficulties to take into account when constructing infrastructure. For this reason, the strategic planning of North Sea infrastructure is of great importance.

1.4 Challenges and Objectives

In order to make the most out of hydrogen's potential to play an essential role in a clean, safe and affordable energy future, a better understanding of the spatial implementation is required. This is affirmed by Agnolucci and Mcdowall (2013), who acknowledge that the further growth of hydrogen technologies, for example in the transport sector, is obstructed by the challenge of developing a large scale production and distribution infrastructure for hydrogen. This challenge is reflected in the scenario study of the Netherlands Environmental Assessment Agency (PBL, 2018b), where the following is stated as a knowledge gap addressed to knowledge institutes;

"Are hydrogen or other gases from offshore wind energy a realistic alternative (to natural gas)? For example, what are the expected cost developments of hydrogen production and its use for industry or energy generation?"

To answer this question, a large number of initiatives and R&D projects have been undertaken in the past few years (Groenenberg et al., 2019). One of these projects is the North Sea Energy (NSE) program, which is coordinated by TNO. The aim of the NSE program is to identify and assess opportunities for synergies between energy sectors offshore. Hereby taking into account low-carbon energy developments like Hydrogen infrastructure and addressing the potential for infrastructure reuse on the North Sea towards 2050. Another goal is to come up with engagements strategies for stakeholders and the general public (North Sea Energy, 2020b). It is intended to improve this engagement by the developing the North Sea Energy Atlas. The aim of this atlas is to optimize settled and future interests, initializing opportunities to speed up the energy transition and to bring new perspectives regarding our current and future offshore energy system (TNO, 2019). This report is written within the framework of the North Sea Energy Program.

To resolve the challenges concerning the future implementation of hydrogen infrastructure, most studies make use of system modelling and/or economical analyses. However, some questions cannot be solved without taking into account the spatial component of the data. Take for example the following passages by the Noordzeeloket;
'Based on the principle that space must be used efficiently, cables and pipelines should obstruct other uses as little as possible.' and *'... in principle cables and pipelines are positioned in such a way that they do not form an obstacle for other uses...'.* They provoke a question and contain a clear spatial component. The question that remains regarding the development of hydrogen infrastructure is;
How to optimize the routing of hydrogen pipelines considering current use functions and existing infrastructure?

To answer this question, first the different uses of the North Sea have to be identified. Each of these uses are likely to have different restrictions when considering the construction of cables and pipelines. In addition, also the reuse potential of existing infrastructure should be taken into account. Therefore, a model has to be developed to weigh these restriction levels up against each other, while still taking into account travel distance and direction to the destination of the pipeline. In order to test the results of this model, they can to be compared to the spatial input that is currently used in the system models. Therefore, the main objective of this research is:
To develop a model to compare straight pipeline trajectories with trajectories that take into account spatial use functions and infrastructure reuse potential on the North Sea.
This objective can be subdivided into the following sub-questions;

Sub-questions:

1. What are the use functions that influence the construction costs of hydrogen pipelines?
2. How to assess the influence of these use functions?
3. What is the impact on the route when the model is making use of corridors or decommissioned pipelines?
4. What are the length differences when comparing the calculated routes to the currently used straight lines?

5. What are the differences in amounts of intersected land-use compared to straight lines?

6. What are the estimated differences in costs when comparing straight lengths to the lengths that result from this model?

7. How suitable is the developed model for this type of application?

1.5 Scope and limitations

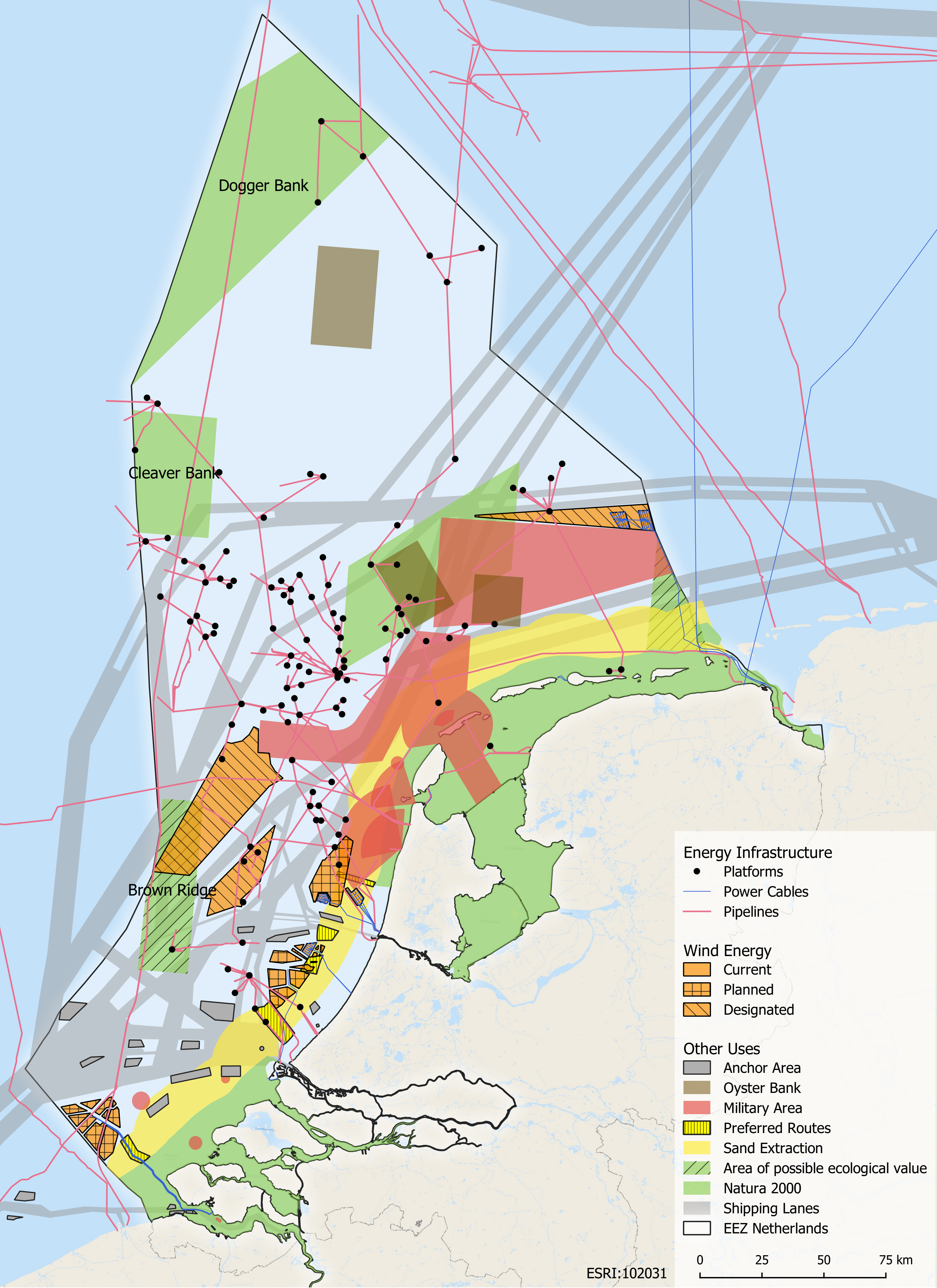
This research will at first focus only on the Dutch continental shelf due to the availability of Dutch spatial data. When a model has been developed, the spatial scope can be extended to the entire North Sea and the countries surrounding it (See Section 2.1). The reference year of this research is set to 2050, since this year is predominantly used in policy making (IRENA, 2019; PBL, 2018b; SER, 2013). The year 2030 is also often used, however it is thought that the realisation of infrastructure on the scale that is used in this research, is questionable within a decade. This is supported by the NSE program, who found that large scale offshore hydrogen production will not be of economic interest until 2030 (North Sea Energy, 2020b).

It should also be emphasized that this research does not aspire to give an advice on decision making; the results of the scenarios function as a proof of concept of the data and methodology. Therefore, the location selection together with cost results should be seen as indications rather than recommendations.

1.6 Report Outline

The structure of this report is as follows: Section 2 gives an overview of the theoretical framework for this research. Next, Section 3 describes the steps in the method and the used input data. In Section 4 an analysis is given of the results of the model. Discussion and conclusions of the methods and results are presented in Section 5 and Section 6 respectively. Finally, in Section 7 recommendations for future research are given.

Figure 1.2: Current Spatial claims on the Dutch EEZ.



2 Theoretical Framework

The idea of applying hydrogen in the energy system has been around for decades (Bockris, 2013). However, in recent years it has gained renewed interest due to the growing energy demand, the accompanying increase of greenhouse gas emissions and the resulting issue of global warming (da Silva Veras, Mozer, da Costa Rubim Messeder dos Santos, & da Silva César, 2017). Consequently, quite some research has been conducted by a number of consultancy firms and research institutes. In this chapter, the aspects that are of importance for this research are discussed; First the study area of the North Sea is introduced together with the current status and future prospects of spatial claims in the area. Then, the role of hydrogen, it's applications and technical requirements are explained. Lastly, comparable studies and related system- and spatial models are discussed.

2.1 Spatial claims of the North Sea

The study area for this research is the North Sea. It is located in the north-western part of Europe and has an area of 572,000 km^2. For the most part, the sea is defined by a shallow area on the European continental shelf with a mean depth of around 90m. The sea is bordered by Great Britain, Norway, Denmark, Germany, the Netherlands, Belgium and France, which all have their own Exclusive Economic Zone (EEZ). In their EEZ, each country has sovereign rights to explore, exploit, conserve and manage natural resources of the sea, seabed and subsoil (National Ocean Service, 2019). The surface area of the Dutch EEZ or Nederlands Continentaal Plat (NCP) takes up about 57,000 km^2 or 10% of the total North Sea area. Due to its location in Europe and the presence of large ports such as Rotterdam and Hamburg, shipping routes in the North Sea are among the busiest in the world (Barry, Elema, & Molen, 2006; NIOZ et al., 2015).

Although it seems vast, the North Sea is not an empty space (as is shown by Figure 1.2); Ruijgrok and van Druten (2019) state that there is only 13,000 km^2 or 10% (with a depth <55m) of the North Sea left that is not consumed by other use functions. Some of these use functions other than OWFs are; protected nature reserves, shipping routes, sand excavation areas, military zones, oil and gas platforms and pipelines for infrastructure reuse. As is summarised by de Vrees (2019), the Dutch government has focused increasingly on fostering a healthy, safe and profitable North Sea since the National Spatial Planning Policy was made in 2005. Since then it has become more clear that the realisation of these goals can lead to conflicts between the users of the sea.

The starting point of this study on multiple aspects is The Future of the North Sea report made by the PBL (PBL, 2018b). In this report, the PBL defines four scenarios by combining socioeconomic dimensions on the one hand and policy ambition on the other. The four scenarios are; *I) Slow Change, II) Pragmatic Sustainability, III) Rapid Development, IV) Sustainable Together*. These scenarios each represent different assumptions in the dimensions of ambition and development dynamics, with scenario I representing the most conservative and scenario IV the most progressive prospects. Although the scenarios differ a lot in their view of the future, the PBL study predicts an increase of spatial pressure on the North Sea in each of these scenarios, albeit to different extents (See Figure

2.1). In the next paragraphs the different uses of the North Sea, their future developments and the consequences for the construction of pipelines are discussed briefly.

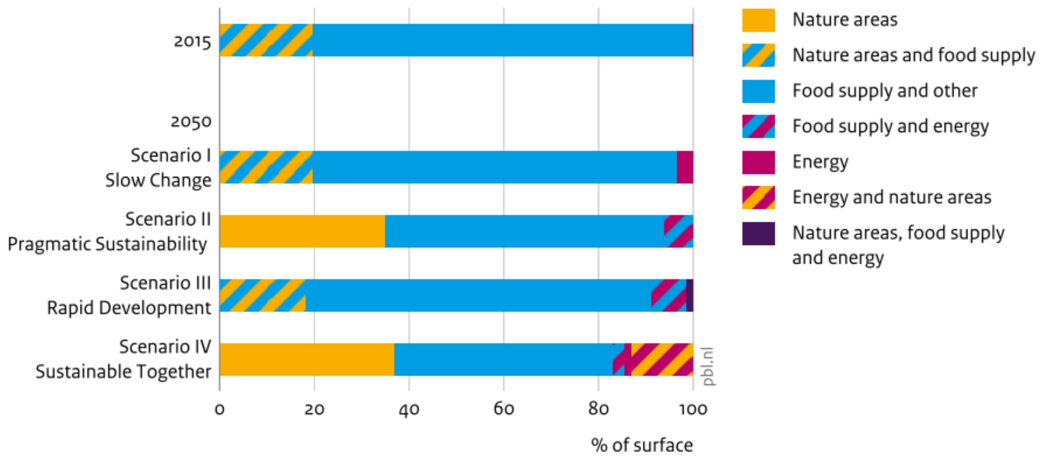


Figure 2.1: Space consumption at the North Sea for 2015 and 2050 (PBL, 2018b).

2.1.1 Wind Energy

As is acknowledged in the introduction, the offshore wind energy capacity of the Netherlands will increase drastically until 2050. The total offshore wind capacity for the Netherlands will grow from 1 GW in 2019 to 11,5 GW in 2030 (Rijksoverheid, 2016) and it was estimated by de Vrees (2019) that in 2050 the southern part of the North Sea has to provide towards 250 GW or 25000 turbines (10MW) to achieve a reduction of 80-95% in CO_2 emissions. However, according to Koivisto, Sørensen, Maule, and Traber (2017) the total amount of installed wind park capacities will be around 75 GW or 7500 turbines (10MW). Meanwhile, the PBL study estimates a capacity of 60 GW for 2050 in their most progressive scenario. The apparent discrepancy in these numbers signifies variation in projections of offshore wind capacities, which is also shown by the North Sea Energy (2018) review report. These variations imply that the outcomes of the scenarios used in each study are varying to a great extent and large margins should be taken into account in plan-making. Next to that, this also shows that even in the lowest estimations (60 GW in 2050 compared to 1 GW in 2019), substantial challenges still lie ahead to install the required capacity and reach our renewable energy goals.

If the planned and designated wind farms (Figure 1.1) are not taken into account, the scale and location of the wind farms differ substantially for each PBL scenario: in Scenario 1 and Scenario 2, the planned OWFs remain closest to the Dutch Coast, Scenario 3 also includes wind farms on the Doggersbank, which are connected to the land with large interconnecting cables, and Scenario 4 includes several more wind farms along the borders of the Dutch EEZ where the international connections are located.

2.1.2 Nature Reserves

Currently, the nature reserves on the north sea consist of Natura 2000 areas, like the Doggersbank, Cleaver Bank and Frisian Front and areas of particular ecological value, like the Central Oyster Grounds and the Brown Ridge. These reserves take up about 20% of the total area of the Dutch continental shelf (See Figure 2.1). Natura 2000 areas are already protected by the Birds and Habitats Directive. The other areas are currently being investigated to determine whether they qualify for different protection measures, like seabed protection (PBL, 2018b; Stichting De Noordzee, 2019). When looking at 2050, the percentage of surface reserved for nature will remain constant in scenario I and scenario III. In scenario II and scenario IV the amount of reserved surface increases drastically to about 35%. This is due to the realisation of an international nature network that interlinks the already existing nature reserves.

2.1.3 Oil and gas

Many oil and gas fields are located in the North Sea area. The Netherlands produce relatively little oil compared to the gas yields. Gas fields have been exploited since the 1970's and are still exploited today. To illustrate; the offshore gas production on the Netherlands Continental Shelf yielded about 14 billion m^3 in 2016 (TNO, 2019; EBN, 2017) or the equivalent of 10 million household heating devices. Many gas fields are still operational, however a number of them have been depleted and more and more platforms will be decommissioned as they reach the end of economic life. The North Sea Energy program is currently addressing the role and potential of reusing this decommissioned infrastructure for hydrogen as well as the reinjection of CO_2 in depleted reservoirs.

2.1.4 Shipping

Shipping on the North Sea is, and will remain a fundamental part of the Dutch economy. In fact, the transport of goods across the North Sea has been rising strongly for years (NIOZ et al., 2015). Sufficient space must remain to ensure safe corridors for this large amount of shipping traffic. The current shipping lanes are established by the International Maritime Organisation (IMO) and will therefore remain relatively constant, although it is expected that some adjustments will be made in the future. However, these adjustments are relatively insignificant in terms of change in surface area.

When considering pipelines, shipping lanes should be crossed perpendicularly and in the shortest possible way (Noordzeeloket, 2020). Also, since dredging is required for the navigability near ports, extra caution is required in these areas. Next to shipping lanes, also designated anchoring areas are of importance. These areas are mostly located close to the harbors of Rotterdam and Amsterdam/IJmuiden, adjacent to the shipping lanes (see figure 1.2). According to the Noordzeeloket, anchoring on cables and pipelines should be avoided wherever possible.

2.1.5 Sand Extraction

The sand extraction areas along the Dutch coast are located between the -20m depth line, which is also the border of the nature reserves along the coast, and the border of the Dutch territorial waters 12 nautical miles (22.2 km) off the coast (See Figure 1.2). The extracted sand is mostly used for coastal maintenance. Considering the anticipated sea level rise, it is expected that the demand for extracted sand will further increase in the coming decades (Noordzeeloket, 2020). Therefore, it is of importance to ensure efficient extraction and use of space. When a cable or pipeline is constructed in a sand extraction area, a financial compensation can be requested by the sand winning company to the cable or pipeline client.

2.1.6 Military

The Dutch military exercise areas on the North Sea are concentrated around the Den Helder area and the western Wadden Islands. These areas are available for other uses when no exercises are taking place. In principle, the construction of permanent structures is prohibited in the area for safety reasons, however cables and pipes can be constructed in coordination with the Ministry of Defence. The location of these areas is not likely to change drastically in the future and due to the increasing spatial pressure, the combined use of the areas will become more important. Only in scenario IV of the PBL study a large area north of the Wadden Islands is replaced by offshore wind farms.

2.1.7 Fishery & Aquaculture

Dutch fishery currently can take place across the entire EEZ, except for shipping lanes, Natura 2000 areas and wind farms. For this reason, fishing areas are not explicitly defined in this study. The fishing industry in the North Sea must comply to the EU Common Fisheries policy in order to maintain sustainable and healthy numbers of fish (Noordzeeloket, 2020). However, due to the growth of nature reserves and wind farms and the restriction for the fishery sector of a hard Brexit, the spatial pressure for fishery will further increase in the future. Therefore, the further application of aquaculture is considered, which can also take place in areas designated for nature or wind farms. This way, the North Sea can be shared by multiple uses at the same time.

2.1.8 Multiple Use Of Space

According to the PBL study, the multiple use of space will become more and more important in 2050 due to the increased spatial demands for both energy and nature. This can be accomplished in several ways; combining nature areas and food supply by allowing (some forms of) fishing and aquaculture in nature areas, combining wind energy and nature assuming the resilience of ecosystems, combining food supply and energy by allowing fishing with small vessels in wind farms or a combination of all uses. Several of these combinations are included in the scenarios with the largest growth of Wind energy (II, III, and IV). The Dutch government is striving to combine different uses where possible (IenM & EZ, 2015).

2.2 Hydrogen

In this section a hydrogen system is described in more detail from production to end-use in order to better understand future developments and the place of pipelines in the hydrogen production chain. A model of this system is depicted in Figure 2.2.

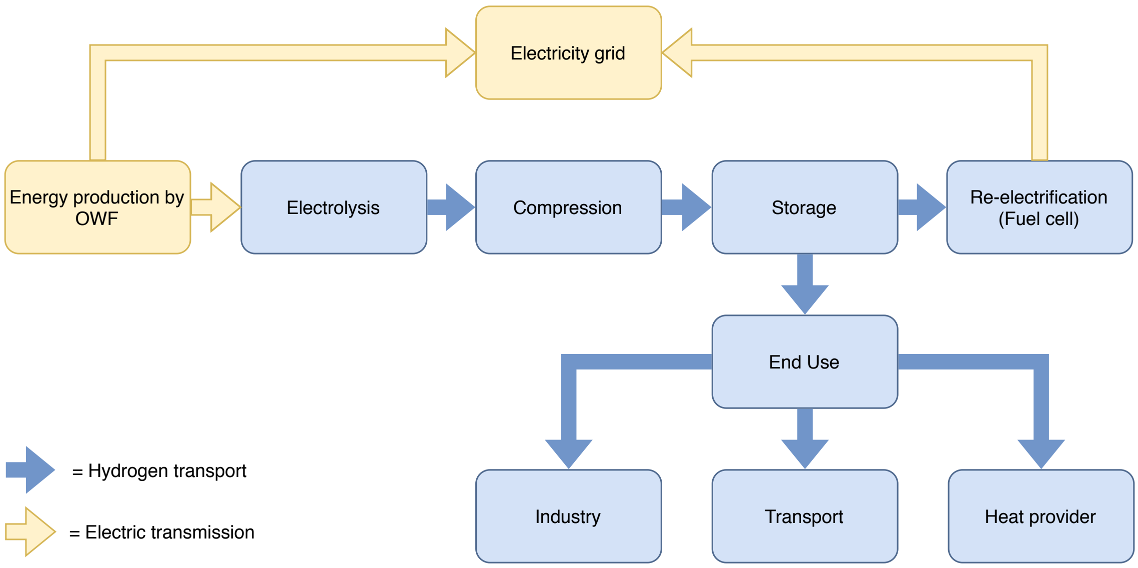


Figure 2.2: Scheme of a renewable hydrogen system. Adapted from Garcia et al. (2016).

2.2.1 Production

Hydrogen is produced when electricity is converted into hydrogen gas. For this, purified (sea)water is split into hydrogen and oxygen molecules with the use of electricity. This process is called **electrolysis** and takes place in an electrolyser. Hydrogen gas can be produced in three different types or ‘colors’. When ‘grey hydrogen’ is produced, Steam Methane Reforming (SMR) is used to convert natural gases into hydrogen. SMR is the most common way of producing hydrogen and greenhouse gases are still emitted (IRENA, 2018). ‘Blue hydrogen’ is produced when gas reforming is combined with Carbon Capture and Storage (CCS). With this method limited greenhouse gases are released into the atmosphere, although CO_2 is stored underground. The third variety of hydrogen is generated when making use of electrolysers powered by renewable energy. This type of hydrogen is called ‘green hydrogen’. In this process no greenhouse gases are produced or emitted (Juez-larré, Gessel, Dalman, Remmelts, & Groenenberg, 2019). However, a significant amount of the energy is lost in the process. At the moment the efficiency of electrolysers ranges from 60% to 81% (International Energy Agency, 2019a) and the CAPEX[1] for an electrolyser range from about 8,6 million euros (10 MW) to 51 million euros (100 MW)

[1](Capital Expenditure, or the initial investments needed to acquire assets. As opposed to OPEX, Operational Expenditure or the ongoing costs for running the asset)

for large scale production (NSE, 2020). After the hydrogen is produced, the gas has to be **compressed** in order to make storage more efficient. This compression also consumes energy.

The location of hydrogen production is variable and can take place offshore, onshore or on an artificial energy island (TNO, 2019). For offshore production, both operational or decommissioned hydrocarbon platforms can be used or reused. However, reuse of offshore platforms is limited; it is estimated that approximately 10% of the platforms in the Dutch EEZ are suitable for this purpose (Nexstep, 2019). To gain experience in offshore hydrogen production, a pilot project with the name PosHYdon was initiated (North Sea Energy, 2020b). It is expected that hydrogen production on this platform will start in 2021. Next to that, plans are currently initiated to develop an artificial island in the North Sea (TenneT, Gasunie, & DNV GL, 2018). The construction of an energy island however will be a large operation; the estimated CAPEX of the development of an energy island range from approx. 700 million (2GW wind capacity, 30% hydrogen) to approx. 1,75 billion (20GW, 70% H_2) euros (North Sea Energy, 2020a).

2.2.2 Storage

The storage of hydrogen gas can improve the flexibility of the energy system; Energy from wind has an intermittent character, due to continuously changing wind speeds. Previously, the difference in energy could be supplied by conventional power generation, but because of the increasing percentage of renewables in the energy supply, this will lead to an increased need for balancing power (Gahleitner, 2013). The production and storage of hydrogen can then be used to compensate inconsistencies in the energy supply in times of shortage (Gigler & Weeda, 2018).

This storage of hydrogen can be for a short period of time in order to produce energy directly or stored hydrogen can be used as a long-term energy buffer. Due to its high-energy density and good transportation properties, it is well-suited for strategic reserves of energy (van Wijk, 2017). Hydrogen can be stored in tanks (gaseous or liquid), in a gas network or underground in salt caverns, depleted gas fields or aquifers (Groenenberg et al., 2019; Juez-larré et al., 2019).

2.2.3 Transport

For smaller scale applications, hydrogen can be transported with truck, train or ship. For longer term, larger scale and larger distance projects, pipeline transport will be a more economical alternative. In these pipelines, the amount of transported gas is dependent on diameter pressure, temperature and flow speed numbers (Groenenberg et al., 2019). The relative CAPEX of a new pipeline is estimated by TNO to approx. 0.7 MEur/km for small scale- and to approx. 1 MEur/km for large scale green hydrogen production. Hydrogen transport can be organised in different forms; point-to-point connection between a production facility and a demand center, via a hub-spoke network or via a mature transport network (van den Broek et al., 2010). Comparable to CCS networks, these forms may be developed as following steps of a hydrogen network (McKinsey & Company, 2008). Considering the reference year of 2050, this research focuses predominantly on the early commercial and mature phases of a future hydrogen network.

The pipelines in these networks can be newly constructed, but the NSE Program also aims to address the potential of the reuse of natural gas infrastructure for hydrogen, because of economic benefits; CE Delft (2018) states that the conversion of an existing gas network will cost between 5-30% of the investments of a new gas network. Next to that, the option of hydrogen can bring the potential to avoid investments in the power network that will be needed when an increasing amount of renewable energy is added to the grid (TenneT et al., 2018). Pipelines can either be fully converted to transporting hydrogen only, or they can be used to transport a blend of hydrogen with natural gas or oil, also known as admixing. The feasibility of this technique was a matter of debate for a long time (Wietschel & Ball, 2009). However, recently it has been proven to be a possible alternative to full conversion (North Sea Energy, 2020b).

2.2.4 End Use

After the produced hydrogen is transported onshore, it can be directly marketed as a commodity or **re-electrified** and fed back into the **electricity grid** using a fuel cell (Garcia et al., 2016). The marketed hydrogen can be used in a number of sectors. The largest of these is the **industry** sector, where hydrogen can be used in a number of applications like; production of ammonia, oil refinery, metalworking, glass production and the electronics industry (International Energy Agency, 2019a; Hydrogen Europe, 2017). To illustrate this, the hydrogen demand shares for each industry sector are shown in Figure 2.3. The North Sea demand capacity by industrial sector is depicted in Figure 2.4. This strong industrial base is listed by the International Energy Agency (2019a) to be one of the features that make the North Sea an attractive starting point for scaling up hydrogen supply.

Next to the industry sector, the hydrogen can be applied in the **transport** sector; When green hydrogen is used in fuel cell electric vehicles (FCEVs), it can be a complementary green solution to battery electric vehicles (BEVs), which are currently becoming increasingly popular. The fuel cell technology can also expand the electric mobility market to long-range or high utilisation rate vehicles like; buses, trucks or boats (IRENA, 2018). Furthermore, recent studies have shown that hydrogen can be used as a direct **heat provider** for households and businesses by admixing hydrogen in existing natural gas grids or eventually even replacing natural gases in these grids (KIWA, 2018; DNV GL, 2017). This can cause cost reductions and an increase of competitiveness of hydrogen.

2.3 System Integration Options

The North Sea Energy Program not only investigates the integration of hydrogen into the grid, but also looks at other options for system integration. An overview of offshore system integration options is shown in Figure 2.5. In order to describe the framework which the hydrogen pipelines are part of, this section further examines two of these options; power-to-hydrogen and energy storage.

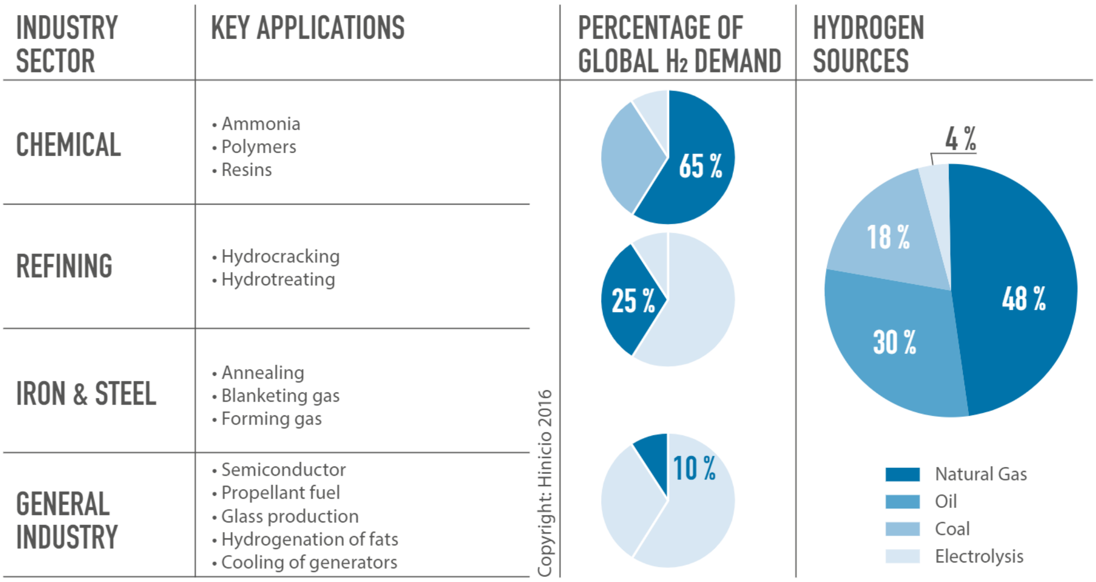


Figure 2.3: Global hydrogen demand and production sources (IRENA, 2018). The total global demand for hydrogen is estimated at around 74 MtH_2/yr (International Energy Agency, 2019a).

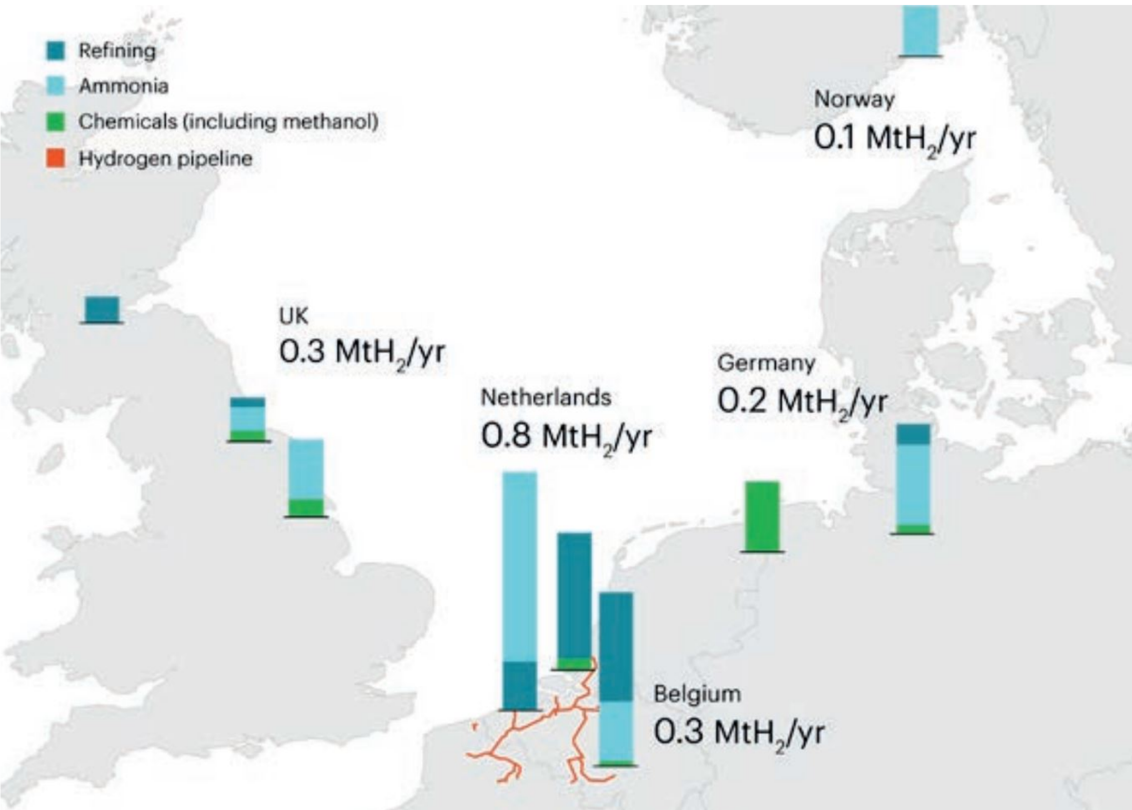


Figure 2.4: North Sea hydrogen demand capacity by sector and pipeline infrastructure (International Energy Agency, 2019a).

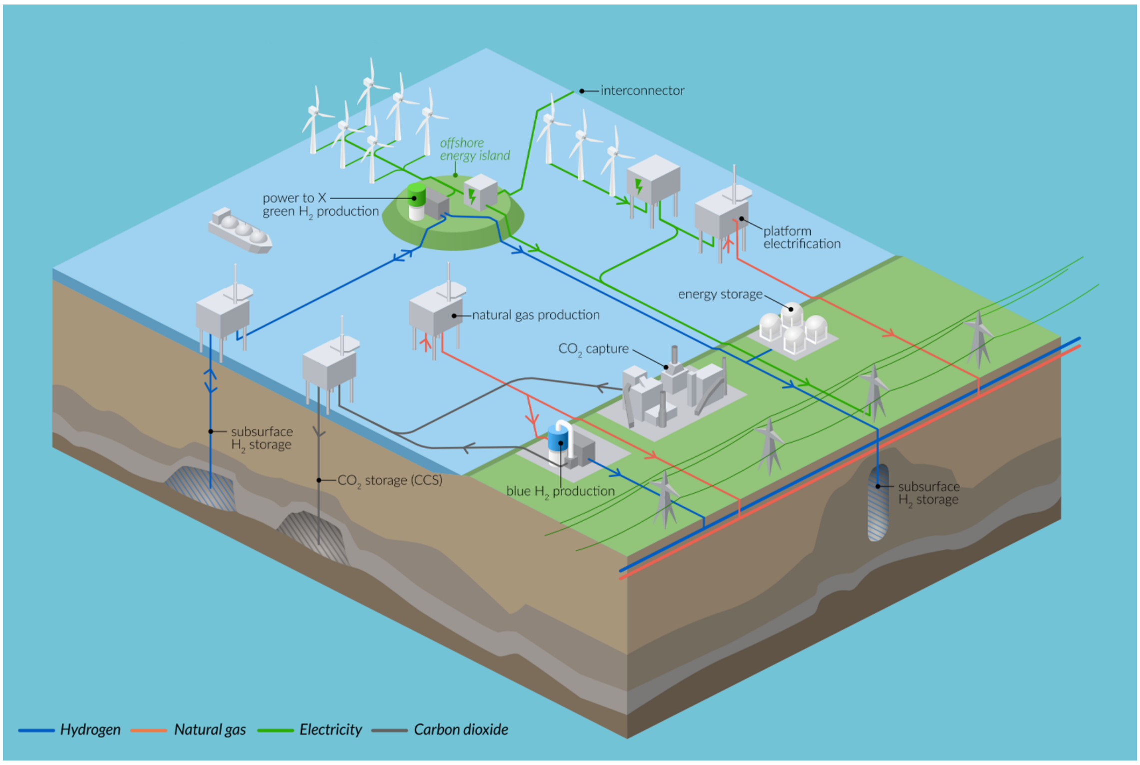


Figure 2.5: Offshore system integration concepts (North Sea Energy, 2020b).

2.3.1 Power-to-hydrogen

Power-to-hydrogen can be seen as the main system integration option of this research (Figure 2.6). In a power-to-hydrogen system, first the wind energy is led to a substation that collects energy from multiple OWFs. The substation is connected to a conversion platform on which an electrolyser is located. The electrolyser converts the electricity into hydrogen gas, after which the gas is compressed for transport or injection into the gas grid. This conversion can be located either offshore or onshore. However, according to the PBL study, new landing points are hard to realise and in times of high wind energy production, the onshore grid cannot handle these high amounts of energy. For this, the offshore conversion of power-to-hydrogen could be a solution.

2.3.2 Energy Storage

Energy Storage is the second system integration option for which the tool can be applied and can be seen as an extension on the power-to-hydrogen option. In this option depleted gas fields or salt caverns are used for the storage of hydrogen produced with the energy generated by the OWFs. The HyUnder project has assessed the potential of large-scale underground hydrogen storage. The obtained results highlighted salt caverns as the primary option followed by depleted gas fields (Garcia et al., 2016). However, where platforms are located on top of gas fields, the salt structures located in the North Sea area are not developed yet, causing the need for new infrastructural investments. Furthermore, as depicted in Figure 2.7, large-scale underground hydrogen storage can be combined with offshore battery storage. The value of this combination will be assessed by TNO in the near future. When storing large amount of gas underground, a cushion gas is also required. Cushion gas is the volume of gas that is pumped into the reservoir required to maintain the operating pressure. This gas cannot be recovered until the end of the facility's lifetime and will therefore require an initial investment (Samsatli, Staffell, & Samsatli, 2016).

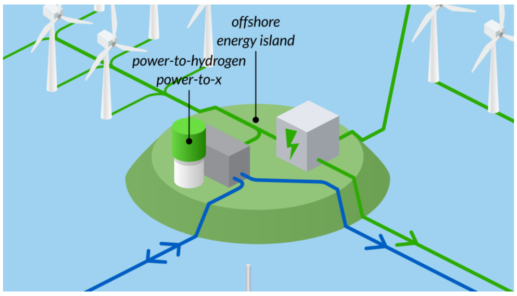


Figure 2.6: Power-to-hydrogen.

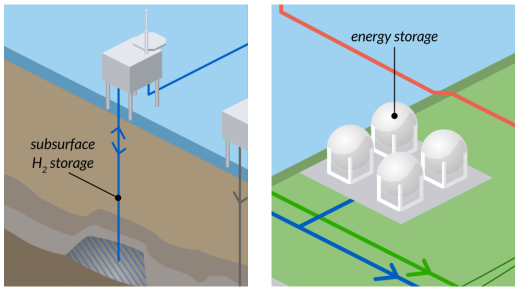


Figure 2.7: Energy Storage.

2.4 Hydrogen Infrastructure Modelling

As stated in the introduction, the main objective of this research is to develop a model to compare straight pipeline trajectories with trajectories that take into account spatial use functions and infrastructure reuse potential on the North Sea. The aim of this section is to determine the relative situation of this research in the modelling field by narrowing down the framework of related models. In order to define this modelling field, first a general description of several types of hydrogen infrastructure modelling according to literature are given. Hereby making use of an uncertainty typology. Then, the most closely related studies and models are discussed in more detail. Also, a distinction is made between planning support systems (PSS), spatial decision support systems (SDSS) and geographical information systems (GIS).

2.4.1 Hydrogen Supply Chain Models

According to Dagdougui (2012a) hydrogen supply chain models can be classified into three approaches, namely 1) optimization methods; 2) GIS based approaches; and 3) assessment plans toward the transition to hydrogen infrastructure. From these, the optimization methods are the most common. The aim of these models is to predict the future and find out optimal configurations when taking into account specific criteria by using optimization techniques such as linear-, dynamic- or stochastic programming. For this reason, they can be classified as Level 1 or Level 2 uncertainty models in the typology proposed by van Dorsser et al. (2018) shown in Figure 2.8. This typology was defined in order to link policy making to foresighting models. The second category studies use a spatial approach with GIS to develop a hydrogen infrastructure. These include for example the studies of Johnson, Yang, and Ogden (2008) and Stiller et al. (2010). In all of these studies, the data has a significant spatial character and as explained by Samson (1995), GIS should be applied when the spatial character of the data is significant in the data analysis. According to Dagdougui, these models cannot be considered as a general methodology for finding infrastructural configurations, because of their dependency on national or regional specific conditions. Also they often use probabilistic forecasting scenarios, which classifies this type of model as a Level 2 or Level 3 uncertainty. The third category of transition models aims to understand the behaviour of hydrogen supply chains when specific scenarios are assumed. Because of these assumptions, scenarios and behavioural character of theses studies, the current study should be included in this category, which can be classified as Level 3 or Level 4 uncertainty. It aims to discuss a multitude of plausible futures, which classifies it as a Level 3 uncertainty model according to van Dorsser et al. (2018).

It is advised by Agnolucci and Mcdowall (2013) to expand the classification with the studies that combine both spatial and optimization models. The study of van den Broek et al. (2010) should for example be included in this category. A first approach for this research was to also combine current optimization models from TNO with the resulting spatial model. However, not much research has yet been done in cost prediction for a hydrogen infrastructure driven by a spatial model. Or as stated by Resch et al. (2014); "...the integration of energy system models and GIS is still in its infancy." Also, the integration of system and spatial models can be seen as quite complex. Therefore, it is chosen for this study to use a spatial approach exclusively. In the next section different examples and types of spatial models and their characteristics are discussed.

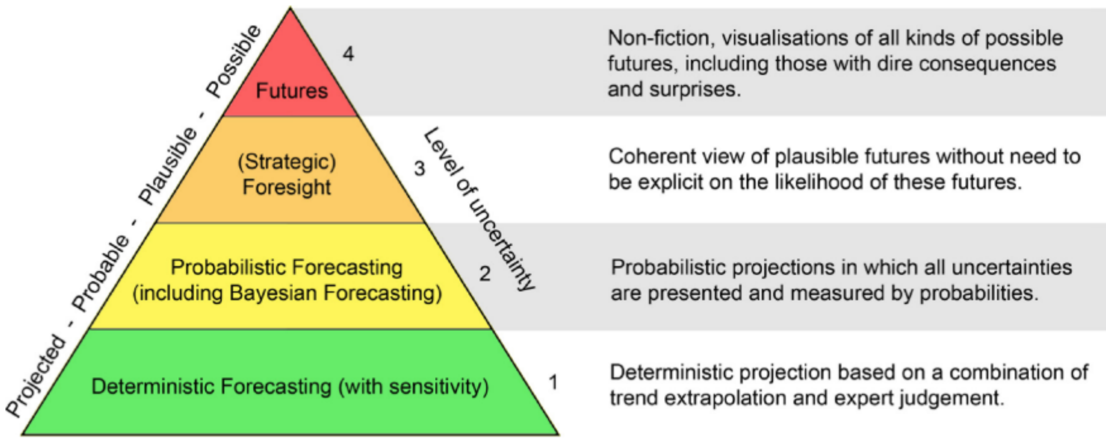


Figure 2.8: Model displaying the proposed four levels of uncertainty (van Dorsser et al., 2018).

2.4.2 Spatial Models

In the planning of energy systems not only the flow volumes from source to sink are of importance, ideally also the spatial aspect is taken into account. In the last decade, some research has been done on the economic feasibility of CCS with a spatial component (Neele, Hendriks, & Brandsma, 2009; van den Broek et al., 2010; Middleton, Kuby, Wei, Keating, & Pawar, 2012).

Johnson and Ogden (2012) developed a spatially explicit optimization model for long-term hydrogen pipeline planning. They found that none of the previously published models were able to optimize linking multiple production facilities and demand locations with capacitated[2] pipelines networks. So for this purpose the HyPAT model was developed. Differences between their method and this study are for example; the restriction of possible pipeline trajectories to a defined candidate pipeline network or the use of market penetration as an input variable.

Samsatli et al. (2016) also developed a model and included many of the elements this study includes, like; storage facilities, electrolyser and wind turbine sites. However, for their study the United Kingdom was divided into large discrete transmission zones. In this study, the aim is to develop a model that has no spatial discretisation.

A methodology that shares components with this study, is the study of van den Broek et al. (2010). In this research, a methodology was set up to use a Least-Cost Path (LCP) algorithm (as described by Adriaensen et al. (2003)), to calculate costs for CO_2 Carbon Capture and Storage (CCS) trunklines. This methodology can partially be applied to this research, since equivalent factors affect the costs of hydrogen trunklines. Because the cost of a pipeline is dependent on the type of use function and the presence of other pipelines, first the terrain and corridor factors are multiplied and assigned to each location in a raster of 100×100m. Next the least-cost path network analysis is applied to calculate the optimal route between a hub and a landing point.

To further pinpoint the situation of this research, a further classification of models spatial models has to be used. As explained by Geertman and Stillwell (2009) a distinction can be made between PSS's, DSS's and GIS in general.

Planning support system It is acknowledged that PSS's distinguish themselves by being focused on supporting specific planning tasks, where GIS's are general tools for capturing, manipulating, analysing, displaying and storing spatial data. However, many times a PSS will make use of a GIS because of the previously mentioned abilities. PSS's tend to focus on long range problems and strategic issues and consist of information, methods and instruments (among other things) integrated into a framework with a shared graphical user interface (GUI) (Geertman & Stillwell, 2003). With this, PSS's can enable planners to better handle the complexity of the planning processes, inspiring plans of better quality and saving a lot of time and resources (Geertman & Stillwell, 2009). They can even be designed explicitly to facilitate group interaction and discussion (Geertman & Stillwell, 2004). These properties correspond to a great extent with the goals set for this current research; it aims to develop an instrument which can be integrated in the shared NSE Atlas GUI. Also, one of the goals of this atlas is inspiring the user with ideas regarding the offshore energy system in the far future.

Decision support system DSS's are on many aspects related to PSS's, however DSS's are generally designed to support shorter term policy making done by business organisations or individuals. In this, the DSS fulfills a role of a tool that supports operational decision making instead of strategic planning. This means that DSS's have a relatively

[2] A pipeline network that includes capacity limitations based on pipeline diameters

low level of uncertainty compared to PSS's. For this reason, considering the relatively high level of uncertainty of this research, it can better be classified as a PSS.

Although differently classified, the current research is to some extent comparable to the decision support system developed by Neele et al. (2009). Although this DSS is focused on CCS and uses a stochastic approach, some of its functionality is similar to the one developed in this research, like; the capability of handling realistic scenarios and the use of multiple sources and storage locations. Also, the level of abstraction will be relatively high, since its main use will lie in a feasibility analysis at an early stage of the planning process.

In the manual designed by Neele (2008), which was developed for the CCS DSS it was stated that the Least-cost path algorithm was not used, because it was too complex, time-consuming and detailed. Therefore, a quicker solution was conceived making use of cost-effective networks of which the shapes and nodes could be adapted. However, it has been a decade since the CCS DSS was finished, in which a lot of technical progress within software and hardware is made. This makes it possible for this research to attempt to implement the Least-cost path algorithm and use functions while using the cost-effective networks as a starting point.

2.5 Conclusion

In this section it was shown that the North Sea knows many different uses with diverging interests. This emphasizes the importance of the development of a model that can take into account these interests in varying ways. After this, the role of the hydrogen pipeline in the production chain was explained. Section 2.4 showed that the product of this study should be seen as a planning support system making use of GIS, with a relatively high level of uncertainty.

3 Methods & Implementation

In this section, the method and implementation of this research are further explained. The method applied in this study can be summarised into **nine steps**, which are discussed separately in Section 3.3-3.9. These steps, the links in between steps and products are also depicted in a flowchart in Figure 3.1. These steps are:

1. User requirements workshop;
2. Inventory of use function areas;
3. Assessment of the use factors by a group of experts;
4. Inventory of Source and Sink locations;
5. Identification of potential corridor and reuse trajectories;
6. Development of a model using the graphical modeler in QGIS;
7. Further automating the model in Python;
8. Running the model for different scenarios;
9. Presentation and analysis of the results using QGIS and a spreadsheet interface.

3.1 User requirements workshop

As shown, first four experts from within TNO were consulted in a user requirement workshop. This workshop was organised to better understand the goals, decision criteria and constraints of the methodology. Also the desired functionalities of the tool had to be determined. The minutes of this workshop are available upon request.

3.2 Inventory of use function areas

For the spatial claims in this study, Scenario IV of the PBL study is used. This scenario assumes both high dynamics in economic, technological and climate developments as well as sustainable ambitions demanded by the Paris Climate Agreements. Scenario IV *Sustainable Together* was chosen, because it is the most radical in terms of spatial coverage on the North Sea. As is shown by the PBL, the spatial coverage of the North Sea for Scenario IV can increase up to 26% compared to a spatial coverage of up to 14% of Scenario III, which is the second most covered area. This makes Scenario IV the most interesting to research, since more coverage will likely cause more pronounced differences in outcomes. Next to that, in Scenario IV two energy islands are included in the Dutch EEZ together with high-capacity interconnecting trunklines. These can be used for this study as source points for hydrogen pipelines and corridor trajectories respectively. All map layers that are included in Scenario IV were acquired from the PBL by TNO.

3.3 Assessment of use factors by a group of experts

Similar to the terrain and corridor factors used by van den Broek et al. (2010), the use factor in this study can be described as a measure of discouragement (>1) or encouragement (<1) to cross a certain use function of the sea. In order to be able to estimate the use factors from the map layers and to see how a group of stakeholders would handle the input, a

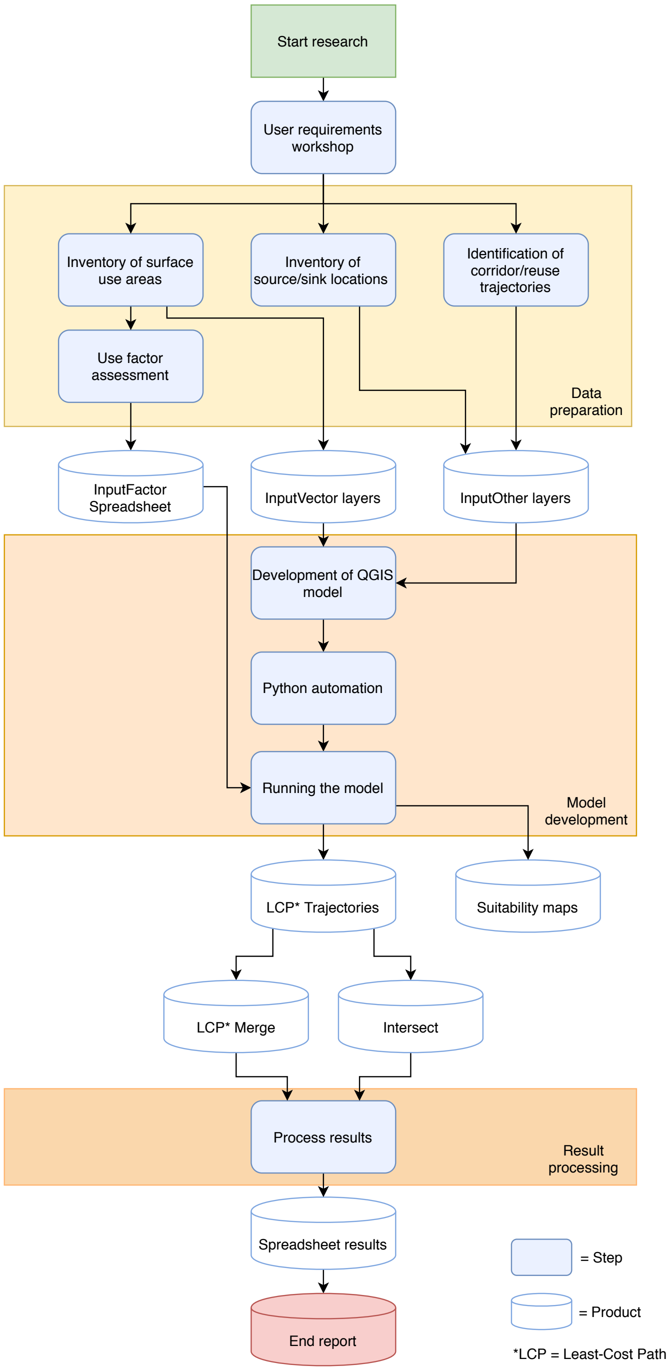


Figure 3.1: Chart displaying the method steps in this research.

form was created. At first it was believed that cost factors could be derived from existing literature and models, like the paper of van den Broek et al. (2010), the ECCO tool (NSE, 2020) or the CATO CONNECT tool (Hendriks, Koornneef, Brandsma, & Louw, 2012). In this case, the cost factor could be described as; the factor with which the standard costs/km for offshore pipelines has to be multiplied when a certain use function is crossed. This factor will often be higher than 1, since more often than not costs will increase when crossing a certain use function. In some cases, the factor can be lower than 1, when for example following a certain route will cause a decrease in costs.

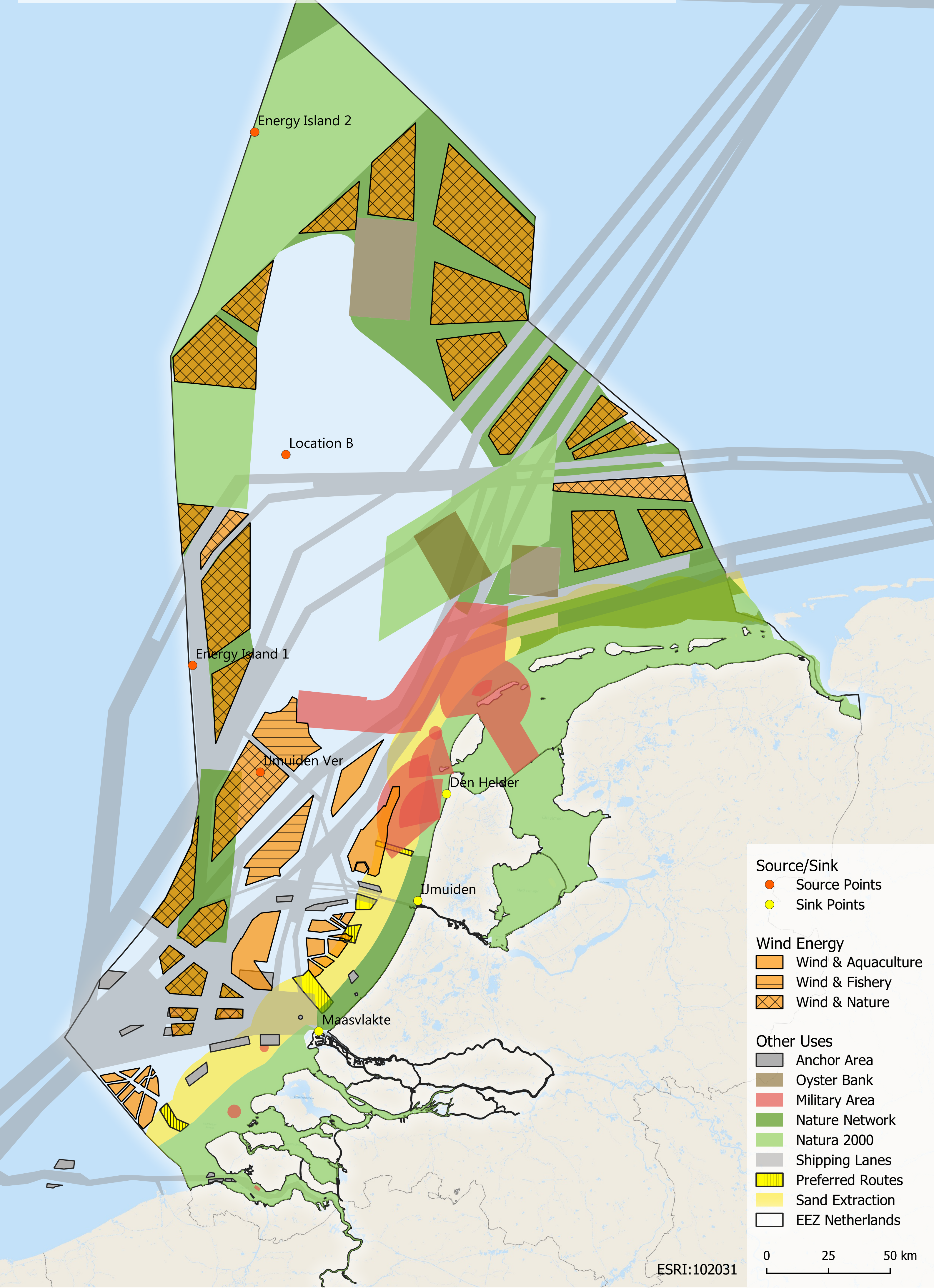
Extracting these factors from literature proved to be not yet possible. Only cost/km for pipelines with different diameters are known, together with costs for for example crossings of cables or shipping lanes. Inquiries were made at the consorting companies of DEME and Boskalis, which have a lot of expertise in laying pipelines. However, it was found that assigning generic cost factors does not do justice to the complexity and project/location specific conditions. This indicates a difference in project phase between the companies and this study; the companies are using tools and figures to realise projects, while this study uses tools as input for planning support systems, which tend to focus on long range problems. This study belongs therefore in an earlier phase of the project. In order to still have input factors for this study, a form with a question for each separate use function was developed (Appendix A) and sent out to a selection of five experts within the organisation of TNO. The results of the replies are shown in Table 1.

#	Use Function	Mean Use Factor
1	**Shipping lanes**	1.66
2	**Anchor areas**	3.42
3	**Natura 2000 areas**	5.10
4	**Nature Network areas**	3.70
5	**Oyster fields**	1.60
6	**Wind energy & Nature reserve**	2.00
7	**Wind energy & Fishing**	1.60
8	**Wind energy & Aquaculture**	1.13
9	**Military Areas**	1.53
10	**Sand Extraction area**	3.42[3]
12	**Pipeline Reuse**	0.58
12	**Corridors**	0.78

Table 1: Resulting mean use Factors derived from the Stakeholder form (N=5).

[3]The Sand Extraction Area factor was added in a later stage and made equal to the Anchor areas due to similar restrictions. This was done in consultation with TNO.

Figure 3.2: Hypothetical spatial claims on the Dutch EEZ according to Scenario IV of the PBL study.



In order to test sensitivity of the model to the change in use factor for the different scenarios, six extra factor sets were put together. In these factor sets only a single value is changed to the minimum or maximum value that was specified by one of the experts. These values are shown in Table 2. The shipping lane use function was chosen, because a change in factor for this use will be the most likely to cause the largest changes to the spatial distribution of pipeline trajectories due to the large presence and spread of shipping lanes across the Dutch EEZ. Also, the goals of the Dutch governments for crossing shipping lanes with pipelines are clearly specified (See Section 2.1).

#	Use Function	Mean	Min	Max
1	**Shipping Lanes**	1.66	1.00	2.00
10	**Pipeline Reuse**	0.58	0.10	0.80
11	**Corridors**	0.78	0.50	1.00

Table 2: Minimum and maximum values for the use factors.

3.4 Inventory of source/sink locations

To determine where and how many source and sink locations should be included in this study, an inventory of possible locations was made.

3.4.1 Sources

As mentioned in the previous section, two locations for hub-islands are already included in Scenario IV; One location at the border of the Dutch and English EEZ between the Cleaver Bank and the Brown Ridge (shown as Energy Island 1 on Figure 3.2) and another location in the middle of the North Sea on the Doggersbank (shown as Energy Island 2 on Figure 3.2). At first it was planned that both of these locations were going to be included in this study. However, when considering the effects of longer distances to the run time of the model it was chosen to drop the Doggersbank hub from the source locations. Also, the area directly in front of the Dutch coast is more diverse in terms of spatial coverage, which makes it a more interesting area to run the model over. Next to Energy Island 1, another location was selected; a platform or island in the IJmuiden Ver wind farm area (see Figure 3.2). This location was added because IJmuiden Ver is considered to be a major contribution to realize the additional wind energy capacity before 2030 (TenneT et al., 2018). Next to that, the resulting trajectories of this research can be compared to the configurations proposed by TenneT et al. (2018). Since there is no exact designated location for this source, the centroid of the whole IJmuiden Ver Windfarm area was taken. A centroid represents the mean position of all the points in the polygons, which makes it a logical starting point considering the even distribution of electricity cables to the island or platform.

3.4.2 Sinks

Included as landing points in this study are Rotterdam, IJmuiden and Den Helder. Of these, Rotterdam has the highest hydrogen demand and currently existing hydrogen network (CE Delft, 2018). Rotterdam and IJmuiden are furthermore part of the Gasunie Hydrogen-Backbone (Gasunie, 2018). This hydrogen-backbone is a plan for a pipeline network, which is realised in order to connect production sites with demand centers. Next to Rotterdam and IJmuiden, the Den Helder/Callantsoog landing point is included in the pipeline development strategy of the Dutch government (Structuurvisie Buisleidingen; Ministerie van Infrastructuur en Waterstaat (2012)). It is the landing point of, for example, the LOCAL, WGT, NOGAT and BBL pipelines. Although the landing points of Delfzijl and Sloe/Kanaalzone have high hydrogen demands (van Wijk, 2017; CE Delft, 2018), they are not taken into account in this study due to time limitations. Also, the Noordwijk landing point from the PBL study is included as an option in the model. However, the point was not used for this research, since it is not a hydrogen demand center nor a landing point for large gas pipelines and therefore less likely to be chosen for large-scale hydrogen infrastructure.

3.5 Identification of potential corridor and reuse trajectories

After the sources and sinks are located, a number of scenarios are defined. Each scenario describes a certain variation in implementation. Afterwards, the pipeline length and spatial variability of all three scenarios can be compared and conclusions can be drawn.

Scenarios:

1. Area Only Scenario: In this scenario, only the surface areas with their corresponding use factors are taken into account.
2. Corridor Scenario: This scenario extends the Area Only scenario by adding pipeline corridors to the used vector layers.
3. Reuse Scenario: This scenario uses pipelines available for reuse instead of known corridors.

Both the Corridor Scenario and the Reuse Scenario will be explained below.

3.5.1 Corridor Scenario

Pipelines should be installed in a way that they do not impede other uses of the sea. Bundling pipelines will result in more efficient use of space and therefore will leave more space for other functions (Noordzeeloket, 2020). Placing pipelines along pipeline corridors also has legal and engineering advantages compared to constructing pipelines in new trajectories (Hendriks, Hagedoorn, & Warmenhoven, 2007). For this reason several pipeline corridors were defined for this study. For this research it was chosen to only use trajectories of current pipelines, which were acquired by the NSE program. The advantages of corridors are the highest in the sand excavation, nature reserve and beach areas, since the seabed is best protected here. This is also illustrated by the limited amount of landing points along the Dutch coast. Sand extraction is barely possible in the vicinity of cables and pipelines, the Dutch governments has assigned preferred routes (voorkeurtracé) for the cables and pipelines to cross the sand extraction area. These areas are depicted in yellow in Figure 3.2 and will also be included in the model as corridors.

3.5.2 Reuse Scenario

The selection of pipelines that have a potential to be reused is based on their diameter together with their evacuation route. For this research we assume a maximum capacity of 2 GW of wind energy per pipeline that will be converted into hydrogen. From this capacity 68% is converted into hydrogen by the electrolyser, when assuming the low heating value for hydrogen. This comes down to 1,36 GW of hydrogen that has to be transported. Entering this value into a basic engineering tool developed in the NSE program (NSE, 2020), results in a diameter of at least 14 inch. An evacuation route is the group of pipelines to which a single section of pipeline belongs. Each evacuation route transports the gas or oil to a different landing point. Therefore, the evacuation routes to the landing points that are not covered in this research should be filtered out. Combining these criteria results in four evacuation routes that are theoretically available for reuse; LOCAL and WGT for Den Helder, Q8 IJmuiden for IJmuiden and Maasvlakte for Rotterdam. With the Q8 IJmuiden route a remark has to be made that it has an actual diameter of 10 inch. However, this was the best option for IJmuiden since the Q8 Olie evacuation route transports oil, which makes it harder to admix hydrogen. Next to that it is often possible to increase the flow speed slightly if needed to reach the required capacity.

3.6 QGIS Graphical Modeler

After all the data and map layers are prepared, a proof of concept is developed in the form of a model to show the possibilities with the data and QGIS algorithms. In order to process multiple input vector layers into pipeline trajectories with geometric attributes, many processing steps have to be taken. To do this by hand using only the QGIS GUI takes a substantial amount of time. Next to that, for this research it was a requirement to be able to vary in input parameters or layers. A model offers the functionality of being able to run multiple steps subsequently together with the ability to easily change input variables. For this research, QGIS 3.10 was used as GIS. It offers comparable functionalities to the industry standard ArcGIS, but it is open source. Being open source means that QGIS is free to download and developers can design and add tooling themselves. Next to these benefits, if further research is to be done, there is no possibility of it to be restricted due to the lack of software licences. It is possible to extend the QGIS software package with plugins like; SAGA, GRASS or user-made plugins.

3.6.1 Algorithm modules

To create a first concept of which steps the model needs to make, a graphical model was created in the QGIS processing modeler. This model is shown in Figure 3.3. All input variables are shown in yellow, the processing algorithms are shown in white and the model output is shown in green. On the far left the input vector layers are shown. These are fed into a chain of 'Add autoincremental field', 'Rasterize' and 'Reclassify' algorithms respectively. The Add autoincremental field algorithm is required, because the rasterize algorithm is only able to use a field of integers to use as a burn-in value. In this algorithm a constant field name is used as input. Similarly, the raster extent, which is the extent of the Dutch EEZ, and raster cell size of 100m (following van den Broek et al. (2010)) are constants in the Rasterize algorithms. The raster cell size of the cables and pipelines can be set to a different value compared to the area raster cell size if needed. For these layers, also a Buffering algorithm with a buffer distance of 75m is added, since a line feature cannot directly be rasterized. In the reclassify algorithms all integers from the autoincremental field are replaced with the use function factors. In order to include all raster cells that are within the extent in the raster product, the NoData values are also converted to 1,0. If this conversion is not performed, only the areas where all raster layers have cells will remain in the raster product. The value of 1,0 is used since the NoData cells do not represent a use area and therefore should not influence the outcomes of the product when multiplied. After all rasters are multiplied in the raster product algorithm, the product raster is clipped with the Dutch EEZ polygon functioning as the mask layer. Next, in the Least-cost path algorithm, the Source and Sink points are introduced.

Least-Cost Path (LCP) An LCP is a result of the cost path analysis procedure for finding an optimal route between two points that minimizes cost (De Smith, Goodchild, & Longley, 2007; Adriaensen et al., 2003). First, a cost surface has to be defined. A cost surface, or cost raster gives the cost of travelling through each cell. Multiple types of cost can be combined to create a cost surface. From this cost surface, the cost distance raster is calculated, which is a raster that identifies the accumulated cost to travel to a certain source location. Next to this, a back-link raster is created. This raster consists of values (0-8) that mark the direction to each cells lowest cost neighbor (ESRI, 2020). Finally, an LCP can be computed by finding the corresponding destination cell in the back-link raster and following the path back to the source. The corresponding cell in the cost distance raster yields the total cost for the LCP. From this algorithm the output is used to join with a use function layer and a cables and pipelines layer to determine which features are crossed by the LCP. Geometric attributes are also added to be able to analyse the results. In this research the Europe Equidistant Conic (EPSG:102031) is used as a set coordinate reference system, because the cost results for pipelines are predominantly distance-dependent. Therefore it is important that distances are measured correctly.

In this research, as well as future applications, it is required to produce a multitude of LCPs. It is also beneficial to be able to view the results of a certain scenario at once. Therefore, iterations have to be made over sections of this graphical model after which the LCP trajectory layers can be merged. The iteration functionality is however not yet added to the QGIS Graphical Modeler. Fortunately, the QGIS processing modeler comes with the additional functionality of exporting the graphical model to python code. This can be done, because the graphical modeler is in essence a concatenation of separate native and third party processing algorithms together with input and output variables. The further

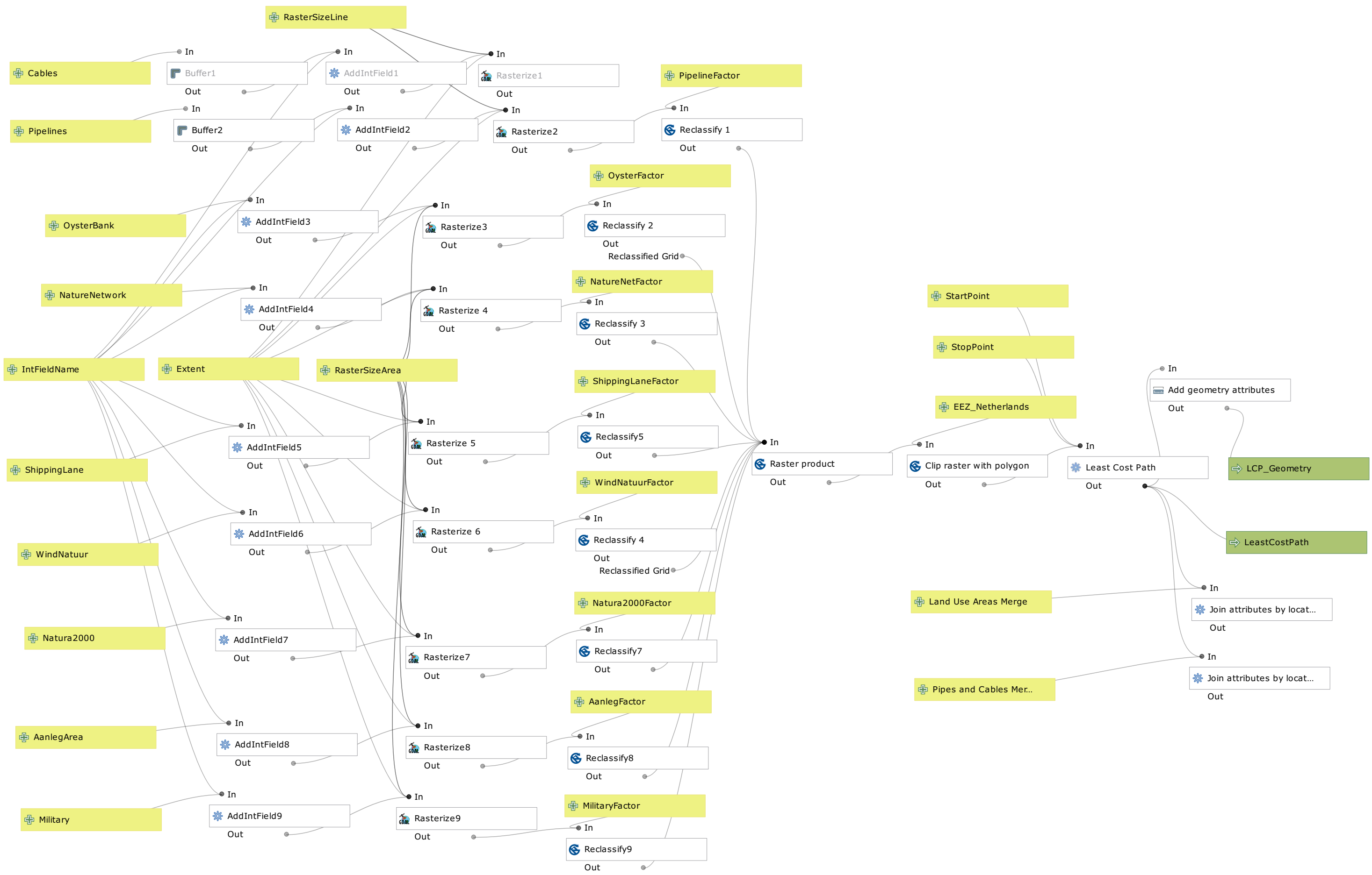


Figure 3.3: Graphical model created in the QGIS processing modeler

development of this python code is discussed in the next section.

3.7 Python Automation

After the graphical model is exported into python, the code is copied into Pycharm. Pycharm is used as an IDE (Integrated Development Environment) instead of coding directly into QGIS because of its convenient debugging features. Another benefit of developing the model outside QGIS, is the more convenient integration of Pycharm and Git. Git is used by TNO to track changes in source code during development of models. These models are uploaded to GitLab, which functions as a repository for these models. The current model has also been uploaded to GitLab. The Readme file with operating instructions and information about the model has been included in Appendix C.

The setup of the code is fairly straightforward; All required packages are imported first from the qgis.core library, secondly a class of the processing algorithm is defined together with the initialization of the algorithm. This initialization is done by adding parameter classes to its own class. These parameters can be set by the user, and consist of definable arguments like name, description and default value. The amount and names of the options from the factorset, source and sink parameters are read from the column name in the factor CSV file and attributes from the source and sink layers respectively. This adds to the use flexibility of the model. An example of this is shown in Listing 1. After this, the processAlgorithm function itself is defined using the initialization parameters as an argument. In the processAlgorithm function all algorithm modules specified in the graphical model are listed in the order of the time that a certain algorithm was added.

```
self.addParameter(QgsProcessingParameterEnum('FactorSet', 'Factor set to
    use:', options=factorcolumnlist, allowMultiple=True, defaultValue=None)
    )
```

Listing 1: Example line of code that enabled the user to select the factor set to use.

For each algorithm module, the name is given and the parameters are listed. Below each parameter list, the actual algorithm is run using the processing.run function. All outputs and results are then appended in the outputs[] and results[] lists. An example of an algorithm module is given in Listing 2. At the end of the code all results are returned.

```
1  # Rasterize11
2  alg_params = {
3      'BURN': 0,
4      'DATA_TYPE': 5,
5      'EXTENT': self.extent,
6      'FIELD': self.intfieldname,
7      'HEIGHT': 100,
8      'INIT': None,
9      'INPUT': outputs['Addintfield11']['OUTPUT'],
10     'INVERT': False,
11     'NODATA': 0,
12     'OPTIONS': '',
13     'UNITS': 1,
14     'WIDTH': 100,
15     'OUTPUT': outputpath + 'corridorras.gpkg'
16 }
17 outputs['Rasterize11'] = processing.run('gdal:rasterize', alg_params,
       context=context, feedback=feedback, is_child_algorithm=True)
```

Listing 2: Example algorithm module with algorithm name (line 1), parameter list (line 3-15) and statement that runs the actual algorithm (line 17).

3.7.1 Added automation and algorithm modules

To the bare-bone model exported from QGIS, automation steps and modules have been added to decrease the actions the user has to take to receive useful results. These steps are displayed as a flow chart in Appendix B. A number of automation steps will be discussed below.

Before each algorithm is run, a check is made whether the output already exists. If the output already exists, the file is set as the output of the algorithm. If not, the algorithm is run and the output is stored in the same way. The for-loops which the model uses to make iterations are shown schematically in the flow chart of Figure 3.4. The largest for-loop, which is responsible for iterating over different sets of use factors, is implemented to see what changes in these factors have on the spatial variability of the least-cost paths. This loop has to iterate over such a large part of the model, because for each different factor set a new raster product has to be composed over which the LCP algorithm is run. Similarly, the next largest for-loop is the loop that is responsible for running the LCP algorithm over the 3 different types of raster products; Area only, Areas with Corridors and Areas with optional reuse. For each of these types different merge, intersection and join layer are produced:

As discussed in Section 3.6.1, the LCP layers are merged to be able to easily view and further process all resulting trajectories of a single scenario at once. The intersection module is added to investigate the amount of distance that a pipeline trajectory crosses/intersects use areas. This can be expressed in the percentage of distance that a line is intersecting a use function area compared to the total length of the line. In the module, the merged LCP layers are used as an input together with an overlay layer. The overlay layer consists of all the surface area layers that were first merged and then dissolved. Finally, the join module is added to be able to see which use functions, cables or other pipelines are crossed by a single pipeline. Since these crossings can be costly, this can be useful information. The join module produces two line layers; one for use function areas and one for crossed cables and pipelines. In the attribute tables of these layers the crossed features are listed.

The smallest loops are the source and sink loops, since the sources and sinks are not dependent on other layers and are used as direct input for the LCP algorithm.

3.8 Running the model

When opening the model in QGIS and running it, a window appears where the user is prompted to select several parameters. These parameters are: The factor set to use, the required factor raster, the evacuation route name (only relevant when the areas and pipelines option is selected as factor raster), and the source and sink points. This window is shown in Figure 3.5 [4].

3.9 Processing the results

After the model has run, the processed single or merged LCP layers can be loaded into QGIS where they can be analysed further. For this research however, some more steps were needed to be able to compare the results and since these extra steps are not required for future use of the model, they are not implemented as a module in the python code. The comparison is done between the straight lines from source to landing point that were previously used in TNO models as well as the TenneT et al. (2018) study and the resulting lines of this model. The straight lines from source to sink can be defined by creating a virtual layer; In a virtual layer, an SQL query can be used to view vector layers in a certain

[4] In a later stadium, another functionality was added: the ability for the user to select input use function layers. The layers included in the model folder were however kept as a default.

way. The SQL query that was used to draw straight lines between the SourcePoints and SinkPoints geometries is shown in Listing 3. The 'where' statement on the third line was added to select only the IJmuiden ver and Energy Island 1 source points and exclude the Noordwijk landing pont.

```sql
select a.fid, b.fid, makeline(a.geometry, b.geometry) as geometry
from SourcePoints a, SinkPoints b
where (a.fid = '2' or a.fid='1') and not b.fid = '2'
```

Listing 3: SQL Query used to draw lines between source and sink points

Similar to the merged LCP layers, now the straight line virtual layer can also be used as an input layer in the intersection algorithm. After this, a virtual length field is added to the attributes of the intersection layers, which is filled using the field calculator and the $length expression. Hereafter, all summed lengths can be derived using the built-in statistics panel and compared to the total length resulting from the added geometric attributes in the LCP attribute tables. From the statistics panel also the total cost and sinuosity of the LCP layers can be derived. The total cost can be seen as a measure of difficulty for the pipeline construction of a specific route due to crossing a number of use functions. In contrast to the intersection length, the total cost does take into account crossing multiple different uses at a certain trajectory, because the cost figures of each use function are multiplied for each raster cell.

The total cost for the straight lines still have to be derived, since the lines were not calculated using the LCP algorithm. This was accomplished using the profile tool plugin from the external QGIS plugin database, which plots profile lines from raster layers along a line specified by the user. An example of a profile is shown in Figure 3.6, of which a table can be exported to Excel. To be able to compare the straight line total cost with the LCP layer total cost, the straight line cost derived from the profile has to be rewritten in the equivalent unit ($distance * \frac{cost}{100m}$), since the distance interval that the profile uses is not constant. Therefore, first the average cost has to be calculated in the spreadsheet after which it can be multiplied by the total length in hectometers.

An extra calculation is done for the total cost of the Areas only scenario; the estimated added costs for the expected increase in pipeline length when using the model. This is done to already have an idea about the cost reductions that have to result from using the model trajectory. This calculation is added to this scenario only, because in the other two scenarios the model is likely to use existing pipeline trajectories, which can result in even longer pipeline lengths. In this stage it is not possible yet to correct for these increased lengths with the cost advantage of following corridors or reusing pipelines. For this calculation, the cost figures from Nogepa (2009) can be followed.

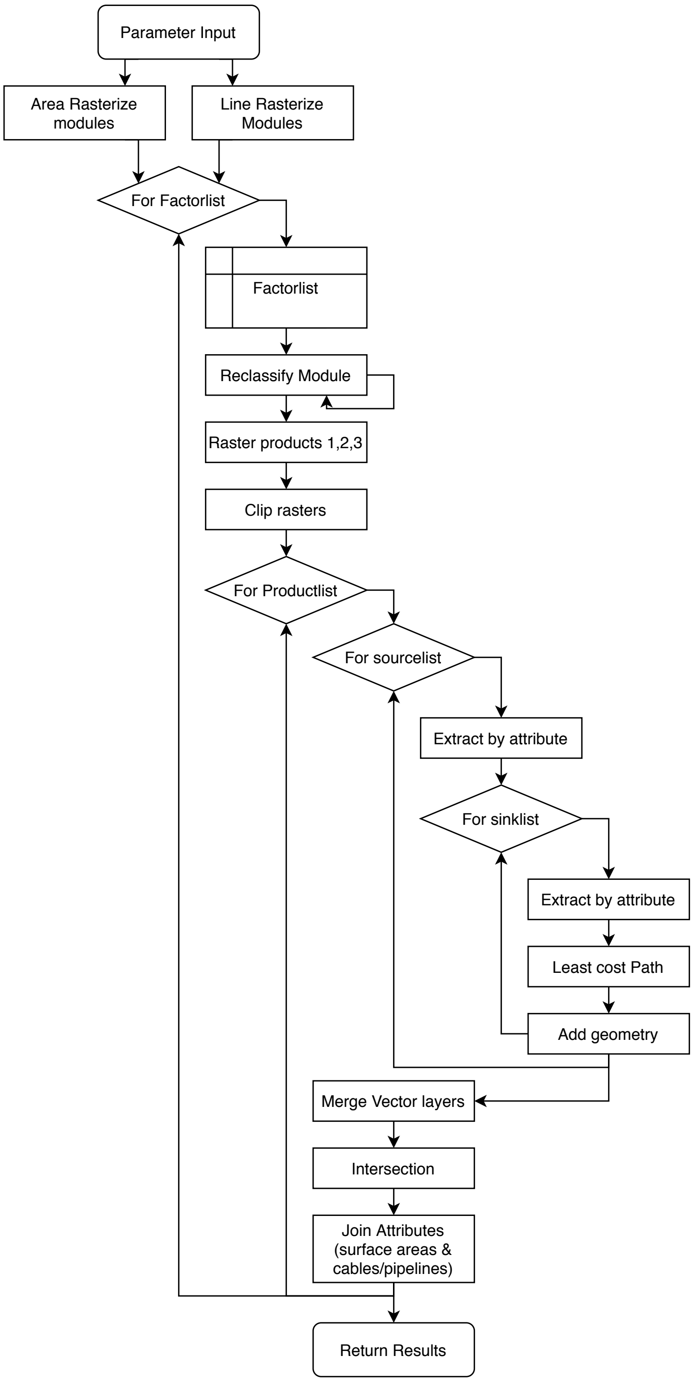


Figure 3.4: Schematic flow chart of the python model iterations

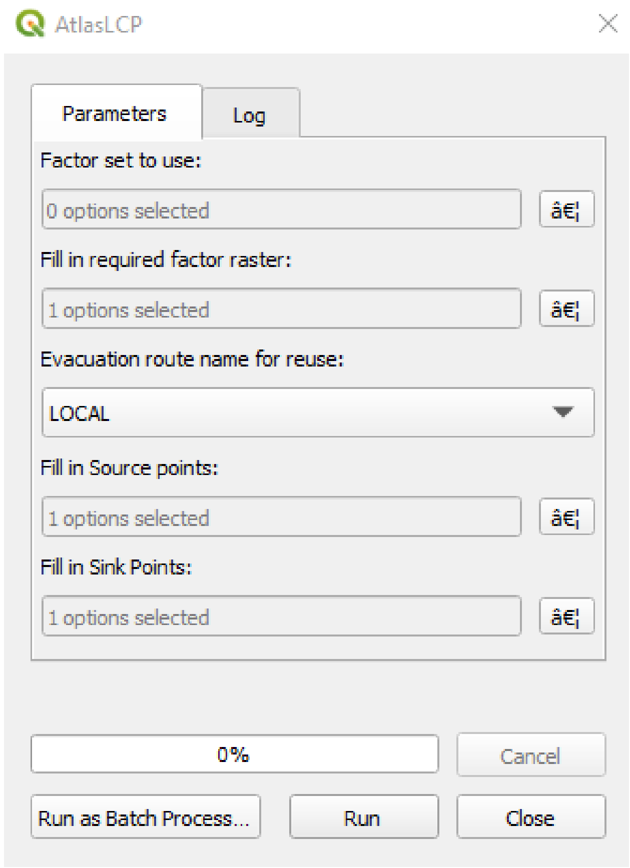


Figure 3.5: Model Parameter window

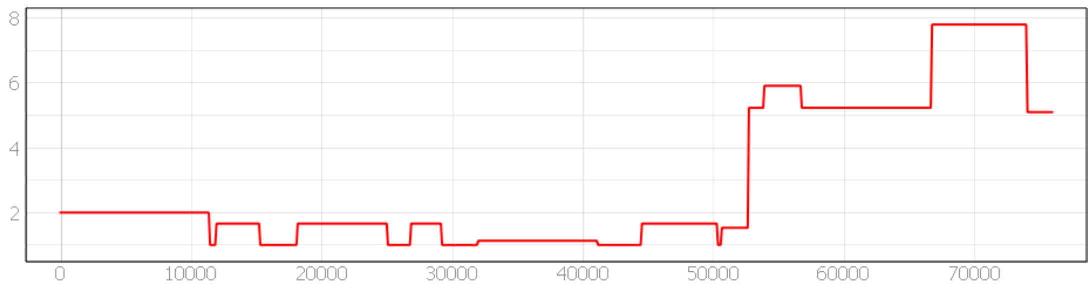


Figure 3.6: Example of a profile along a straight line from IJmuiden Ver to Den Helder with cost along the Y-axis and distance(m) along the X-axis

4 Results

In this section an analysis is made of the model results. This is done on the basis of research questions 2-5 and the scenarios listed in Section 3.5. In each subsection a sub-question is covered: the impact on the spatial distribution of the three main scenarios (Section 4.2) and the extreme use factor values (Section 4.3), the length differences when comparing the calculated routes to straight lines (Section 4.4), the difference in intersect lengths crossing use functions (Section 4.5) and the differences in total cost of each trajectory (Section 4.6). In these subsections the results of each scenario are compared; The model running over use areas only, the model running over use areas and corridors and the model running over use areas and reuse pipelines. For each scenario also the length is given when making use of the minimum and maximum factor values of each scenario (See Table 2).

The length, total cost and mean use factor of all resulting LCPs are shown in Appendix D. The summed lengths, intersect lengths, intersect percentages and summed total costs of the merged LCPs per scenario are shown in Appendix E. The column graphs in this section are based on the latter. Each column in these graphs represents a merged LCP trajectory layer consisting of six separate LCPs and a corresponding scenario. An example of such a layer is shown in Figure 4.1.

4.1 Individual LCP Differences

When comparing results from individual LCPs, several patterns can be identified. An example pattern visible in the table in Appendix D is the relatively high mean use factor of LCPs running to Den Helder. These values can be explained by the large military area off the coast of Den Helder, shown in dark blue in Figure 4.1. Contrarily, the mean use factor values of the LCPs running to Maasvlakte are relatively low due to a relatively large share of the trajectory running outside of the sand excavation area close to the shore. The mean use factors of the LCPs running from Energy Island 1 are lower on average for the same reason.

4.2 Scenario Differences

In Figure 4.2, a comparison has been made between the mean LCP trajectories of the Area Only, Corridor and Reuse scenarios. It shows that overall for the Area Only scenario (green line), a directer route is more cost-efficient compared to the Corridor and Reuse scenarios (orange and red line), which tend to follow the current infrastructure (black and grey lines) and thereby take larger detours. Of these latter two scenarios, the Reuse scenario appears to take the largest detour. Next to that, the Area Only scenario predominantly follows horizontal, diagonal or vertical directions in straight lines, while the other scenarios can also follow the curved lines of the current infrastructure. Contrarily, the Reuse LCP is able to take a shortcut from Energy Island 1 to Den Helder across the Wind energy & Nature area because of the lower mean cost factor for reuse. Although this pipeline is included as a corridor, the Corridor LCP does not run across this area. This is due to the availability of the more cost-efficient interconnecting pipeline trajectory from Den Helder

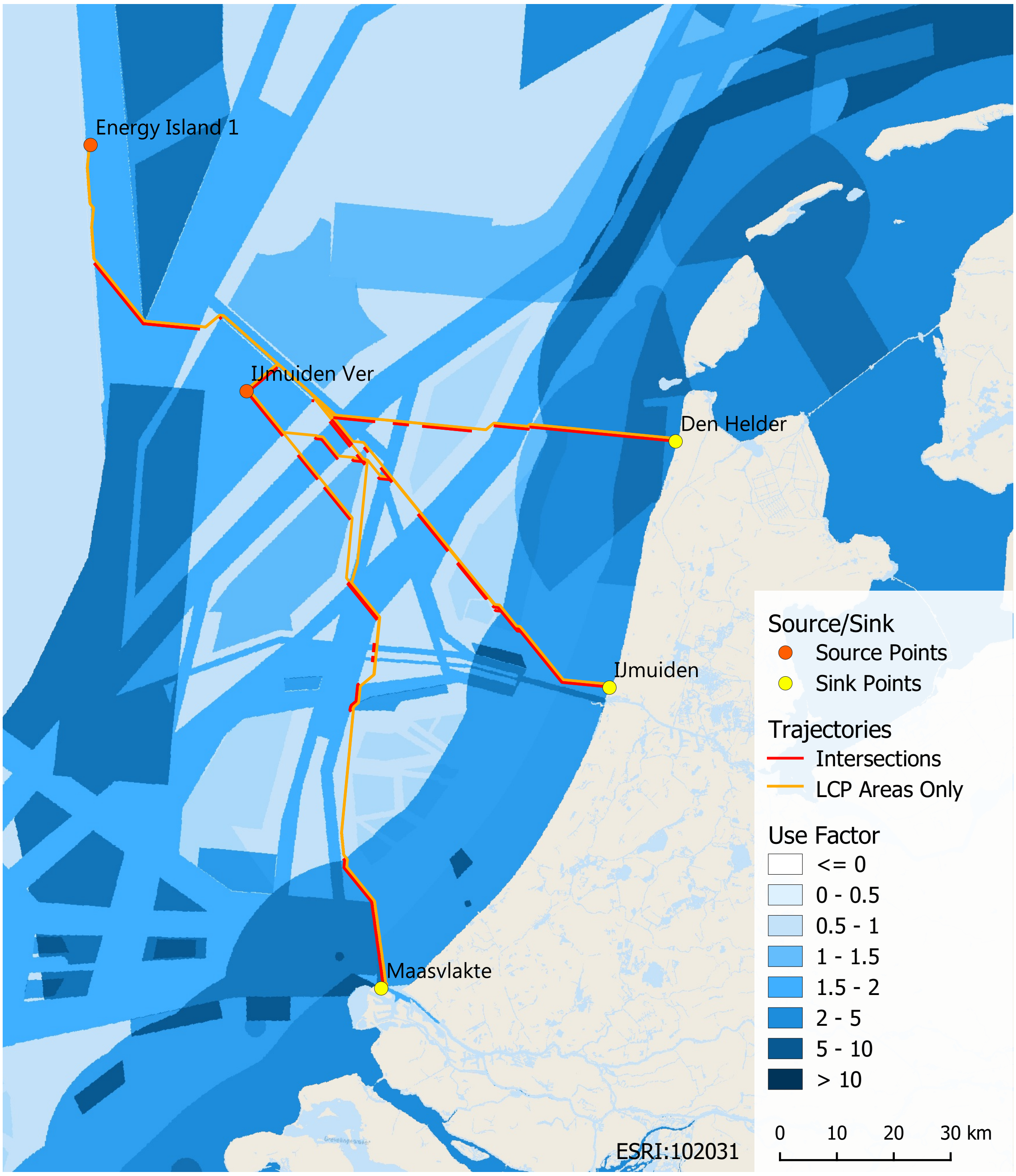


Figure 4.1: Example of an LCP Trajectory Set with intersections using the Area only factor raster and the maximum shipping lanes use factor of 2.0.

to the UK to function as a corridor, which is not directly available for pipeline reuse. The more extensive corridor network thus provides more options for the LCP to 'choose' from.

4.3 Model Sensitivity

Similar to the main scenarios, the changes in use factor values also cause the LCPs to take different routes. In Figure 4.3, the resulting LCPs running over the surface rasters with min, mean and max factor values for each separate scenario are shown. When comparing

A, B and C, it can be stated that the min and max trajectories of the Area Only scenario (A) deviate less from its mean trajectory compared to the Corridor and Reuse scenarios (B and C). To improve readability, in Figure 4.4 some examples are enlarged. In Figure 4.4A it is shown that with a higher shipping lanes factor, the LCP waits longer to start crossing the shipping lane. In Figure 4.4B it is shown that with a lower corridor factor (yellow line), the LCP will almost directly run to the closest corridor, even when this means crossing an area with a higher factor. This signifies that if the objective is to cross as little use areas as possible while still taking into account corridors, the corridor factor should not be set too low. On the left side of Figure 4.4C it is shown that shipping lanes are crossed perpendicularly where possible and on the right side of the figure it is visible that a lower Reuse factor value will cause the LCP to take more detours, hence the three different trajectories reaching IJmuiden from different sides. In Figure B and C also the corridor and reuse trajectories resulting from the raster product are clearly visible as light-colored lines.

Figure 4.2: LCP trajectory results of the three scenarios using the mean factors.

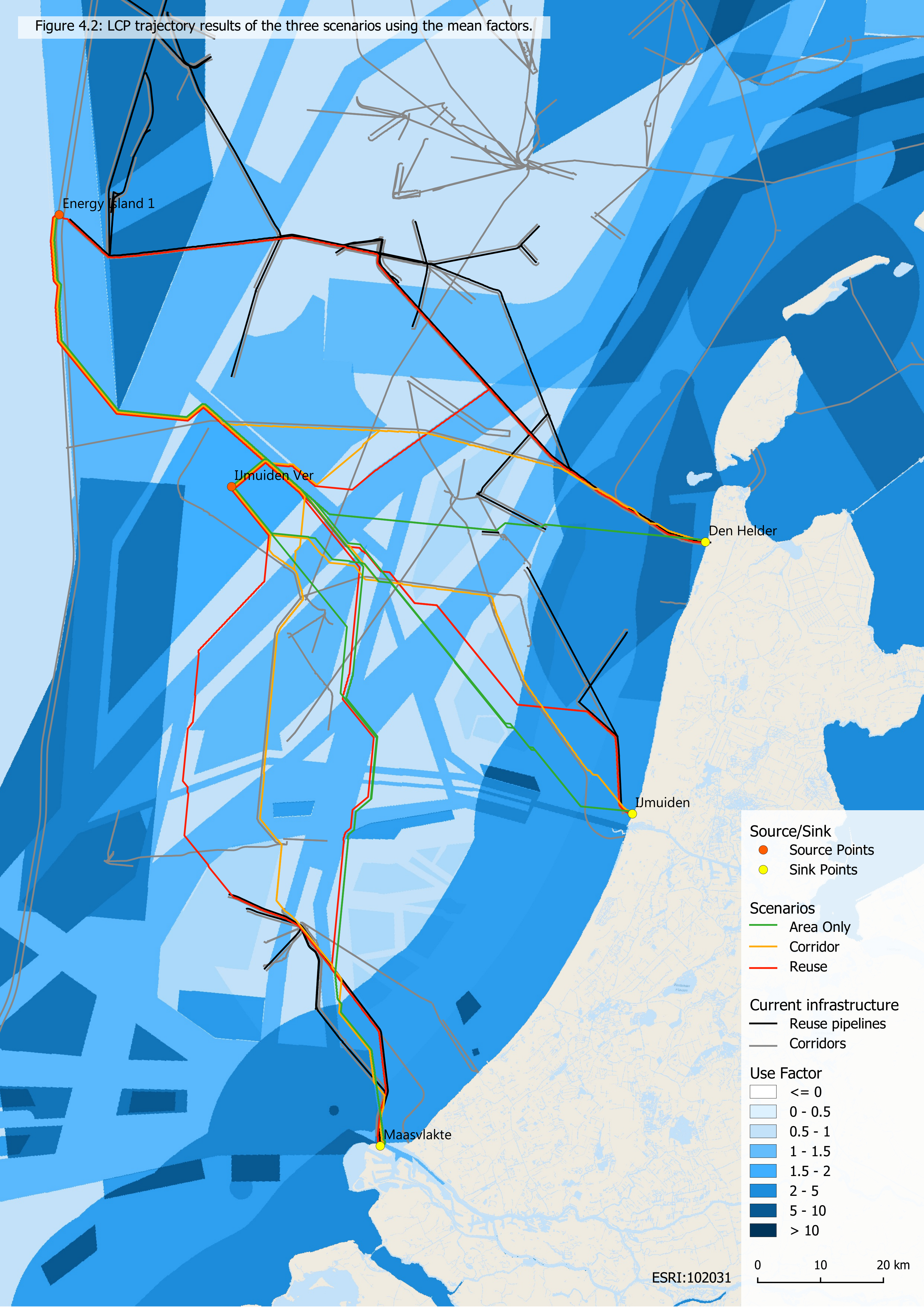


Figure 4.3: LCP trajectory results for each separate scenario; varying in surface raster (A, B, C) as well as factor set (min, mean, max). In all three maps, the mean Use Factor raster is displayed.

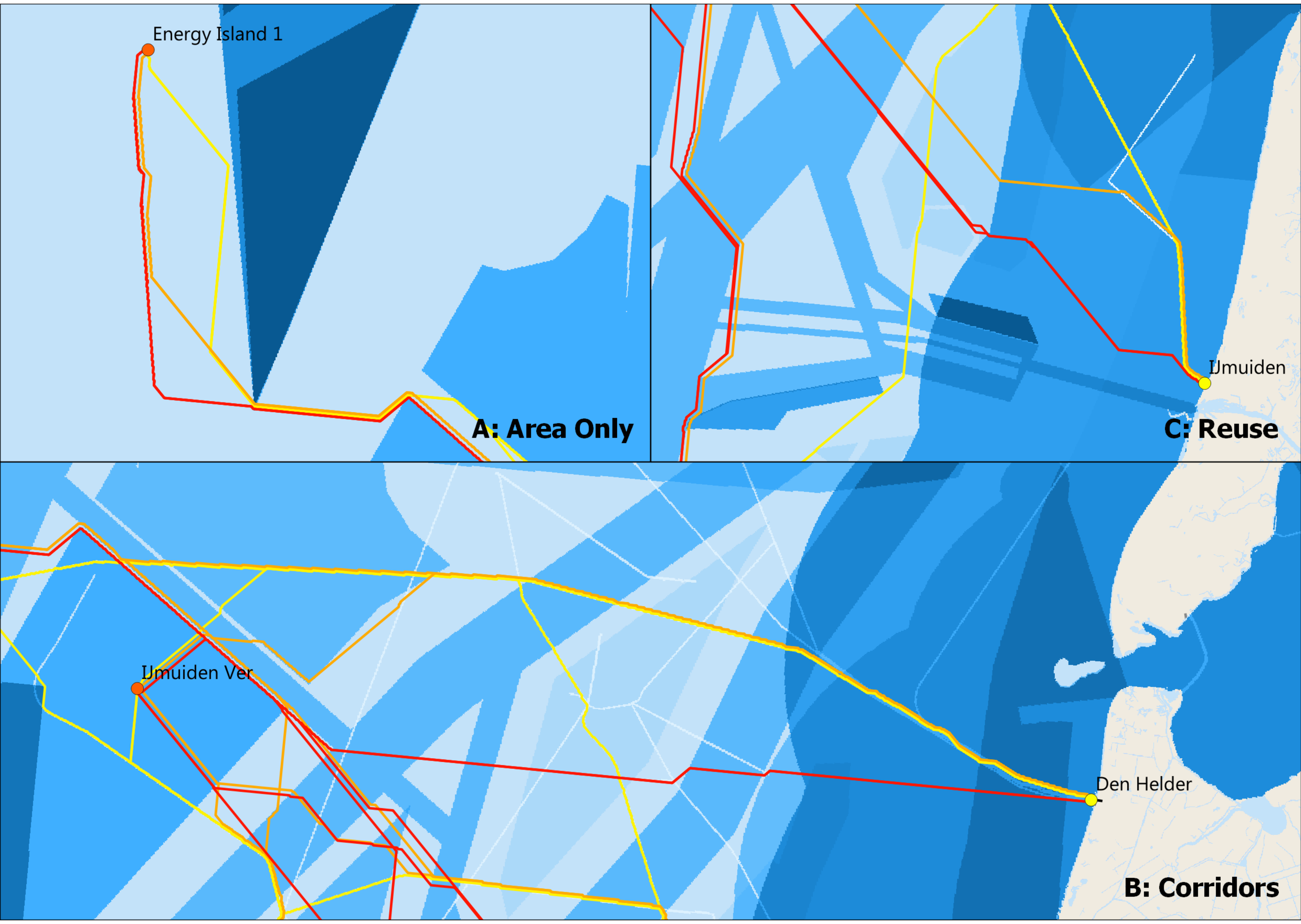


Figure 4.4: Example differences between model runs with min, mean and max values [5].

[5]It should be noted that when two lines run closely parallel to each other, they are actually following the same trajectory. The lines have been offset in order to improve readability.

4.4 Length Differences

The resulting trajectory lengths for each scenario are shown in Figure 4.5 together with the percentage difference of these lengths to the total reference euclidean distance of 674,4 km (the sum of all six straight lines). As expected, the length increases for each trajectory set compared to the euclidean distance; for example the total trajectory length of the Area Only scenario increases with 94,8 km (14,06%) compared to the straight lines.

When comparing the mean results of the three main scenarios, the Area only scenario has the shortest trajectory length, followed by the Corridor scenario and the Reuse scenario respectively. This corresponds to the observed trajectories in Section 4.2. The total length difference between the Area only scenario and Reuse scenario is 29,8 km for six LCP trajectories, which comes down to an average of around 5km per LCP. The area only raster with the minimum shipping lanes factor resulted in the smallest trajectory length increase. In this scenario, the shipping lanes are appointed a value of 1.00, which is identical to not crossing a use function. Also, the lengths of the mean area only and maximum Corridor scenarios are identical. This is due to the maximum corridor factor value of 1.00, which cancels out the effect of the lower corridor costs. The largest increase is seen at the minimum value of the Reuse scenario. In this scenario, the benefit of pipeline reuse has reached a level that the algorithm will almost always choose to follow a reuse trajectory over going in the direction of the landing point.

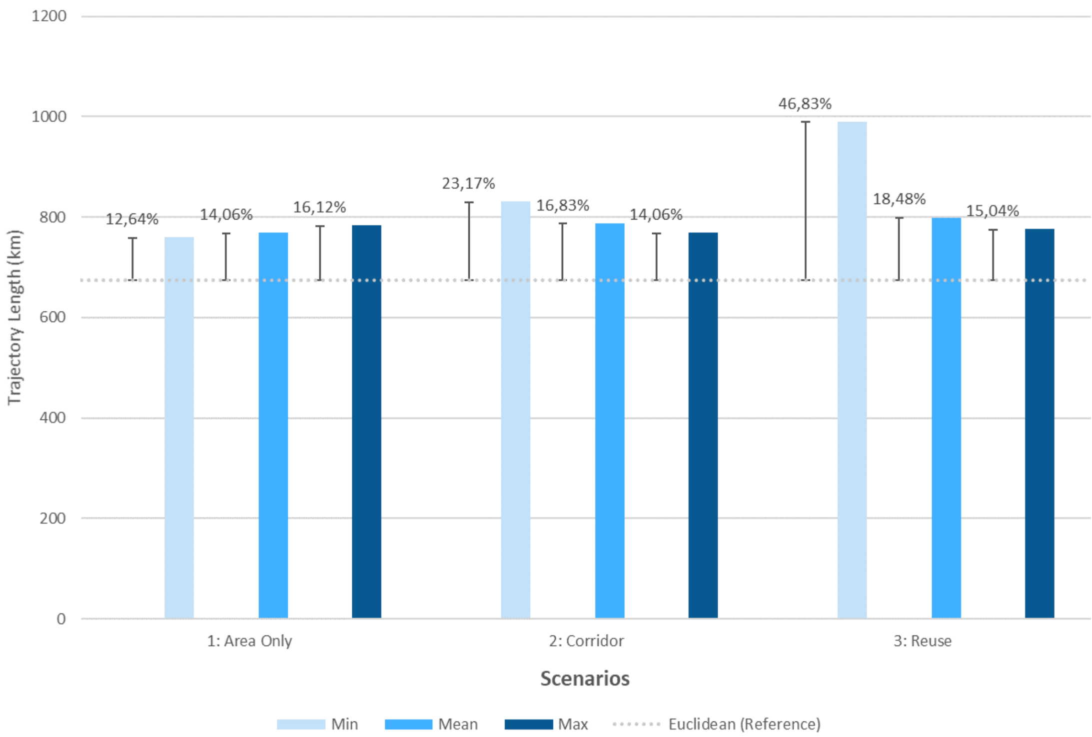


Figure 4.5: Comparison of length results for each scenario and the Euclidean distance.

4.5 Intersected Use Functions

In Figure 4.6 the resulting differences in intersect percentages are shown. Predictably, each model run resulted in a decrease of intersect percentage ranging from -5,11% for the Corridor scenario with the minimum factor value to -38,77% for the Area only scenario with the maximum factor value. When comparing the mean results of the three main scenarios, the Area only scenario has the lowest intersect percentage followed by the Reuse and Corridor scenarios respectively. In contrast to the length difference, the Corridor scenario has a smaller % intersect decrease compared to the Reuse scenario. All scenarios with minimum values have a relatively high intersect rate due to the tendency to ignore use functions by following lower corridor and reuse factors. From these, the Area only and Corridor minimum factor runs have higher percentages compared to the Reuse run. This is due to the higher overall trajectory length of the Reuse run (See Figure 4.5). The reason for the Area only scenario with the minimum factor value to be so high is the fact that in this scenario the shipping lanes factor are set to 1,00, which causes the LCP algorithm to run across these areas without hindrance. However, since the shipping lanes are still included in the overlay layer that is used in the intersect algorithm, they still are counted as intersections.

The lowest intersection values are reached when the maximum factors are used. The differences between these values and the mean values are relatively small compared to the differences between the mean and minimum values. This can be due to certain threshold values which will cause an LCP to choose for taking a longer, more cost-effective route.

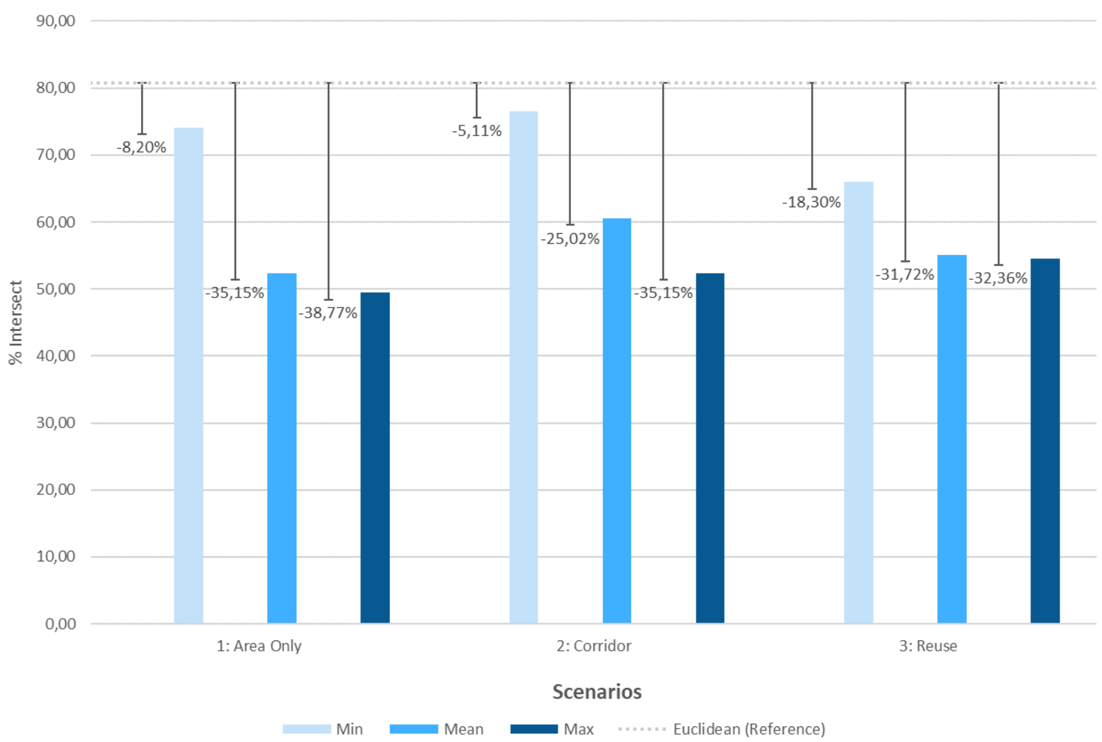


Figure 4.6: Comparison of intersect lengths for each scenario and the Euclidean distance.

4.6 Cost Impact

In Figure 4.7 the resulting differences in total costs are shown. The total cost should be seen as a measure of the product of all the use factors encountered by an LCP and the distance, hereby taking into account LCPs crossing a multitude of use functions at a single raster cell. The Figure shows that in each scenario, the increased length is canceled out by the decrease in mean cost. As can be expected, the minimum factor runs yield the lowest costs. Of these, the lowest costs result from the Reuse scenario; a 73% decrease compared to the straight line costs. Meanwhile, the most conservative scenario, the Area only scenario with maximum factor value, yields a total cost decrease of about 14%. When looking at the mean results of the three main scenarios, the Reuse scenario also results in the most cost-efficient trajectories followed by the Corridor scenario and Area Only scenario respectively.

To give an idea of the costs that are involved in projects of this scale, an example of a cost window for an increased pipeline length has been calculated. As discussed in Section 3.5.2, hydrogen pipelines with a minimum diameter of 14 inches are assumed. Following Nogepa (2009), this diameter results in costs of 0.42-0.98 MEur/km. If this value is multiplied with the length difference of for example the Mean Area only scenario (Section 4.4), the extra length of 94,8 km results in extra costs of 39,8 - 92,9 MEuro compared to straight lines. When looking at a single LCP from this scenario, for example the one running from IJmuiden Ver to IJmuiden, the 5,31 km of extra length results in extra costs of 2,23-5,20 MEuro compared to the corresponding straight line.

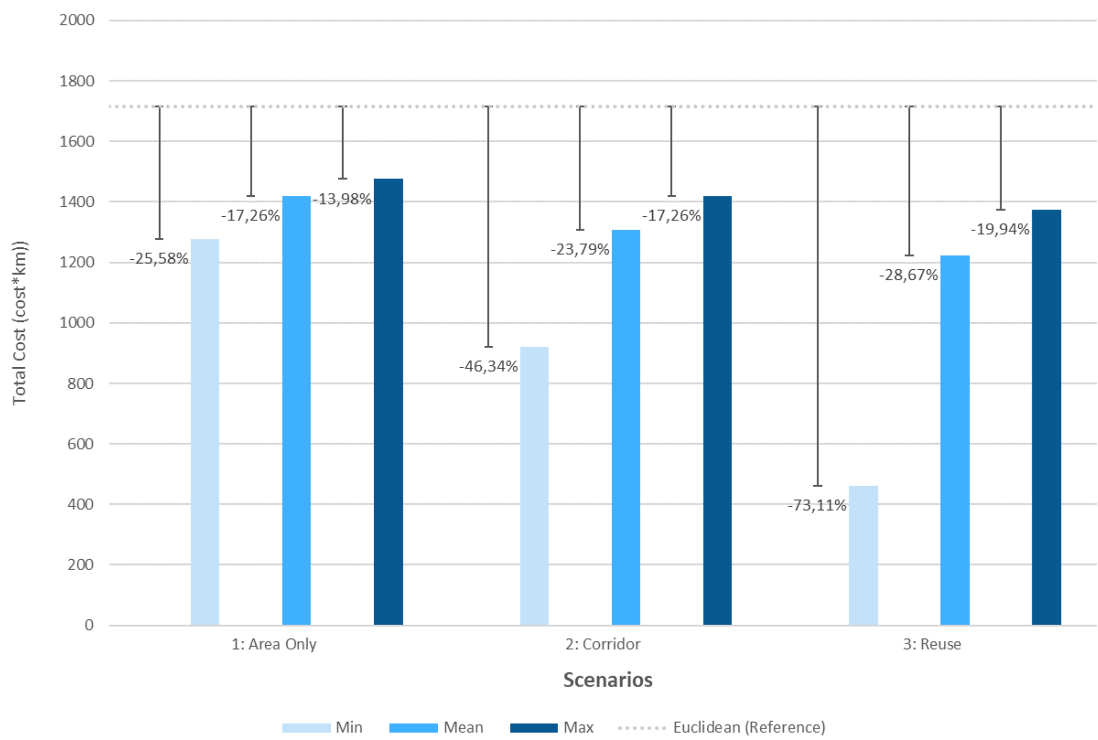


Figure 4.7: Comparison of Total Cost results for each scenario and the Euclidean distance.

4.7 Join Results

In order to see which cables, pipelines and surface uses are crossed by certain LCPs a join module was added to the model. Although for this research the full functional potential of the join module has not been exploited yet, the algorithm already has been integrated into the Python code. An example of a resulting attribute table has been included below in Figure 3. Tables like this can be used to acquire knowledge about the total amount of function areas or cables/pipelines crossed. This can be useful information, since each of these crossings can incur additional costs.

fid	layer	path	Object ID_	LayerName
1	LCP3-1-3Geom	C:/Users/thoonser	1	WindFarm
2	LCP3-1-3Geom	C:/Users/thoonser	13	WindFarm
3	LCP3-1-3Geom	C:/Users/thoonser	2	ZD_Clearwa
4	LCP3-1-1Geom	C:/Users/thoonser	4	ZD_Clearwa
5	LCP3-1-3Geom	C:/Users/thoonser	4	ZD_Clearwa
6	LCP3-1-1Geom	C:/Users/thoonser	10	ZD_Clearwa
7	LCP3-1-1Geom	C:/Users/thoonser	42	ZD_Clearwa
8	LCP3-1-1Geom	C:/Users/thoonser	47	ZD_Clearwa
9	LCP3-1-3Geom	C:/Users/thoonser	47	ZD_Clearwa
10	LCP3-1-4Geom	C:/Users/thoonser	47	ZD_Clearwa
11	LCP3-1-1Geom	C:/Users/thoonser	53	ZD_Clearwa
12	LCP3-1-1Geom	C:/Users/thoonser	55	ZD_Clearwa
13	LCP3-1-4Geom	C:/Users/thoonser	60	ZD_Clearwa
14	LCP3-1-1Geom	C:/Users/thoonser	2	WindArea
15	LCP3-1-3Geom	C:/Users/thoonser	2	WindArea
16	LCP3-1-4Geom	C:/Users/thoonser	2	WindArea
17	LCP3-1-1Geom	C:/Users/thoonser	3	WindArea
18	LCP3-1-3Geom	C:/Users/thoonser	3	WindArea
19	LCP3-1-4Geom	C:/Users/thoonser	4	WindArea
20	LCP3-1-3Geom	C:/Users/thoonser	5	WindArea
21	LCP3-1-1Geom	C:/Users/thoonser	13	ShiprouteZone
22	LCP3-1-1Geom	C:/Users/thoonser	14	ShiprouteZone
23	LCP3-1-4Geom	C:/Users/thoonser	20	ShiprouteZone
24	LCP3-1-1Geom	C:/Users/thoonser	53	ShiprouteZone
25	LCP3-1-1Geom	C:/Users/thoonser	57	ShiprouteZone
26	LCP3-1-4Geom	C:/Users/thoonser	57	MilitaryAr
27	LCP3-1-4Geom	C:/Users/thoonser	120	MilitaryAr
28	LCP3-1-4Geom	C:/Users/thoonser	121	MilitaryAr
29	LCP3-1-4Geom	C:/Users/thoonser	122	MilitaryAr
30	LCP3-1-4Geom	C:/Users/thoonser	135	Nat2000
31	LCP3-1-1Geom	C:/Users/thoonser	7	EcoArea
32	LCP3-1-3Geom	C:/Users/thoonser	7	EcoArea

Table 3: Join table of an LCP set (layer column) with use function areas (LayerName column).

5 Discussion

In this section some of the main limitations of this research are discussed and compared to the benefits of the model. By doing this, conclusions can be drawn about the suitability of the methodology for this type of application, therefore providing an answer to subquestion 6. The discussion is divided into four subcategories; Input, Model, Results and Applications.

5.1 Input

As is shown in the results section, a change in input variables can have significant impact on the model results. First of all, altering the input factors for use functions can cause the trajectory of the LCPs to vary (See Figure 4.3). This variation was shown to be the largest when the input factor of the Reuse scenario was changed. However, it must be mentioned that the input difference between the mean and the min and max values also differs; the minimum Reuse input factor is 0.1 compared to a mean of 0.58, while the minimum shipping lane factor is 1.00, compared to a mean factor of 1.66 (Table 2). As mentioned in Section 3.3, at present it is not possible to extract unambiguous costs/km from literature. For this reason, experts from within TNO were asked to fill in a form (Appendix A) to estimate the use factors. In this form, also an explanation or comment is requested for each separate use. From these comments it was clear that use factors are not exact. Therefore, these extreme values were chosen to ascertain what difference they would have on the outcome.

Next to that, also the believed relative importance of nature, shipping, (wind)energy and military were examined in the use factor assessment form. From these, the energy was found to be most important, followed by nature, shipping and military respectively. This indicates a slight bias of the experts towards energy and nature, which might be reflected in the use factor ratings; someone who finds nature important might assign higher use factors to nature use functions, although it must be stated that this effect is not proven. For the purpose of this model this bias might be beneficial, since the results should encourage discussions between users with different viewpoints.

Next to the input factors, the choice of source and sink points can also have significant impact on the model results. The current points were chosen, because of their relatively high likelihood to be included in a future hydrogen network. However, since this research should be considered as a proof of concept of the methodology, it is not within the scope of this research to test the effect of source/sink location. Potential future tests of the model, using sources and sinks on different locations and distances will demonstrate their actual impact.

5.2 Model

In accordance with the equation of van den Broek et al. (2010), this research has assumed use factors that were multiplied to produce the total cost at a certain location. Hereby a raster product algorithm is used to combine the raster layers that contain the use factors.

This approach therefore assumes that the use functions have a multiplicative nature, so having multiple use functions for one specific place makes it less desirable to build a pipe at that location. This is in part intuitive/natural, and in part an assumption. Another assumption would be a linear approach, adding up all the use factors that are larger than 1 , e.g. shipping routes, and multiplying them by the use factor that is smaller than 1, e.g. pipeline reuse. Hereby first adding a value of 1 to represent areas that are not covered by use functions. For this approach, a linear set of use functions terms should be put together by experts. When comparing both approaches, the total cost values of the quadratic approach are inflated at areas with high-factor use functions laying on top of each other, while total cost values are lower for this approach at locations with low-factor use functions. Considering the current qualitative characteristic of the model and its function as a proof of concept, the difference in total cost this brings is not expected to greatly change the overall appearance of the outcomes; the model works well to compare different pipeline trajectories. However, it is conceivable that the differences in results can become less pronounced. It is advised to first obtain a better understanding of these approaches before starting a more quantitative research using this model.

There are several things that can be improved concerning efficiency and usability of the model. For example, at the moment the user is not able to vary in input layers and amounts of input layers. This can be implemented by adding a for-loop with the rasterize and reclassify modules and making the amount of iterations equal to the amount of input vector layers. When looking at the run time of the model, the following should be considered; if the spatial extent becomes larger, e.g. the complete North Sea, the run time will increase drastically. The average run time per LCP was about 3,5 min, so if for each source and sink a new LCP has to be computed, the total run time will increase exponentially. On top of that, the lengths of each LCP will become much larger which also has a similarly large effect on run time. Furthermore, in this case the amount of required storage space will also increase drastically. The model and all of the results now take up about 7 GB of space.

Taking a larger raster size however will help mitigate both these issues, although this can also have a negative effect on the precision of the resulting trajectories. If this model has to be run as time-efficient as possible, some tests should be run to investigate which raster size results in the lowest model run-time, while preserving plausible outcomes. Next to that, other efforts can be made to decrease run time of the model: a programming expert can for example further investigate options for programming efficiency, parallelization of programming tasks or running the model on computers with larger processing power. However, at this moment it is unsure how much of this is possible considering potential limitations of running a model in QGIS.

Next, with the current LCP algorithm, the path can only move in 8 different directions. Due to the relatively high homogeneity of the cumulative cost raster, the path will strictly follow the horizontal, vertical or diagonal directions. This skews the outcome of the total pipeline distance significantly. Some algorithms include a 'knights move' option to increase the directions in which the cost raster grows from 8 to 16 (Awaida & Westervelt, 2013). However, this algorithm was not used for this research due to the unavailability of a corresponding path algorithm (r.path) in the current QGIS version. This might be implementable in a next version. As a consequence, processing time also will most likely increase drastically when this method is used. To overcome this, the radial method described by Tomlin (2010) could be used. Implementing this method however is outside the scope of this particular research.

The effect of this limitation is the most evident in the Area Only scenario; when comparing Figure 4.3 A to Figure 4.3 B and C, it is clear that the trajectories of the model in the Area Only scenario are affected most by the directional limitations. Also, when comparing these results with the results of van den Broek et al. (2010), it can be clearly seen that the results from that study are not as straight as the ones from the Area Only scenario. It might be questioned whether the Area Only scenario or scenarios without a lot of spatial variability are therefore as relevant as the other scenarios at this point; In other studies, LCP algorithms are most often used in conjunction with layers with high spatial variability or other limiting factors such as height or slope.

Lastly, the model is currently only able to calculate one network type; point-to-point connections. However, as shown in Section 2.2.3 there are other network types, like a hub-spoke or mature transport network, that can become more viable when the network becomes more extensive. It can be beneficial to attempt to implement these options into the model in the future. For now, the resulting trajectories can provide an idea about these types of networks, since the model can visualise where the highest density of pipelines are located when use functions are considered.

5.3 Results

When looking at the results in Figures 4.5 to 4.7 it can be said that when using this model, overall the length will increase, while the amount of intersected use functions will decrease together with the hypothetical costs. If the goal is to intersect as little use functions as possible and disregard the total costs, the Area Only scenario should be used, followed by the Reuse scenario and Corridor scenario. The smaller % intersect value of the Reuse scenario is due to the tendency of the model to follow the corridor and reuse networks. And since the corridor network is more extensive, the LCP will as a result follow a larger part of the network which does not take into account use functions.

As discussed in Section 4.2, this larger network also provides the LCP with more options. It can be argued that the model is better suited for a case with a multitude of options, because the potentially crossed use functions are compared more equally; when only a single reuse pipeline is present, the LCP will almost always follow its trajectory if its use factor is low enough. However, when multiple corridors are present, the most cost-efficient one will be chosen. This changes the trajectory criterion from 'Is there a reuse/corridor route available?' to 'What is the most cost-efficient reuse/corridor route?'. Therefore, it might be beneficial to use the model in combination with a network that is as extensive as possible, which can for example be attained by combining the reuse and corridor networks.

At the moment, the cost figures provide a clear measure of the use factors that are encountered by an LCP. The questions that arise now regarding the calculated cost figures are the following: *Is the decrease in total cost worth the added length?* and *To what extend can actual cost estimations be made using this model?* As of now, it will be up to the user to decide whether the potential decrease in costs weighs up to the increase in trajectory length. Since the use factors are not based on true costs, a true value cannot be assigned yet to these figures. However, some effort can be made in order to make the use factors more precise and give the best possible picture. For this it will be of importance to carry out a more in-depth research about the use factors. This might be done by collecting resulting costs from projects with pipelines crossing use functions and making an estimation of the cost share related to use function conflicts. From these estimations, the use factor for each function could be derived inductively.

A similar investigation can be done about benefits of using corridors or reusing pipelines. When these benefits become more clear and the factors become more accurate, or at least proportionally correct compared to the area factors, then this model and methodology can ultimately help in giving ideas about where to use corridors or decommissioned pipelines. In that case, other properties can also be taken into account. For example, the problem of linking new pipelines to decommissioned pipelines or pipelines that are still in use. This tieback in other pipelines might be possible, however it might prove to be less costly to outright start a new pipeline from a platform.

5.4 Applications

Although at this moment some conclusions can be drawn from the results, it can also be concluded from Section 5.2 and Section 5.3 that a lot of modelling uncertainties remain. These uncertainties, together with the uncertainties of the large dependence on market and location for hydrogen pipelines when using these kinds of scales and the reference year of 2050, signify that at this moment no unambiguous cost estimate can be made using this model. Therefore, the model fits better in earlier stages of planning as support for stakeholders. Here it can be of use in risk assessment, since the model can outline areas with a possible high density of pipelines. In these areas, every conflict in space can be a potential risk.

As explained before, the ability of stakeholders to fill in use factors themselves can lead to a wide range of possibly biased values. However, this variability can also have its benefits; the focus does not have to lay on costs, but can also lay on other input factors, like risk management or the application of certain hypothetical scenarios. In addition, this methodology could possibly be applied to the planning of electricity cable trajectories and CO_2 pipelines, which would require a different set of input factors. As mentioned before, this model can also be applied on a larger scale (a network covering the entire North Sea) or a smaller scale (cable trajectories from a certain OWF to an energy hub). A requirement for acquiring the best results is that either the algorithm is able to move in more directions or the use factor raster has a high spatial variability. In the smaller scale case, also geohazards could be taken into account. A few examples of geohazards are; Pockmarks (depressions in the seabed), Rocks, UXOs (Unexploded Ordnances) and shipwrecks.

These examples indicate the potential of the methodology to be used as a support for stakeholders in an early phase of plan-making. This potential, combined with the relatively short development time of this research, show that a lot can be gained by approaching these kind of problems from a spatial perspective.

6 Conclusion

Within the framework of the NSE program, this research attempted to answer the question on how to optimize the routing of hydrogen pipelines considering current use functions and existing infrastructure. This question was answered by developing a model to compare straight pipeline trajectories with trajectories that take into account spatial use function and infrastructure reuse potential on the North Sea. The reference year was hereby set to the year 2050. The objective of developing the model was subdivided into seven sub-questions which will be answered below.

1. *What are the use functions that influence the construction costs of hydrogen pipelines?* As is shown in Section 2.1, the use functions of the North Sea can be divided into; wind energy, nature reserves, oil and gas infrastructure, shipping lanes, sand extraction areas, military areas and fishery & aquaculture areas. Due to the expected growing spatial demands for both energy and nature, the multiple use of space will become increasingly important.
2. *How to assess the influence of these use functions?* An attempt was made to derive the cost factors from existing literature and models. However, the literature proved to be not conclusive enough. A consult also showed that assigning generic cost factors does not do justice to the complexity and specific conditions of realistic projects. Since this study is in an earlier project phase, and input for the model was required, a form was developed and sent to a selection of experts within the organisation of TNO. From this form, mean use factors were derived.
3. *What is the impact on the route when the model is making use of corridors or decommissioned pipelines?* The LCPs of the Corridor and Reuse scenarios tend to follow the current infrastructure and thereby take larger detours compared to the Area Only scenario. It can be argued that the model is better suited for a more extensive corridor or reuse network, because the potentially crossed use functions are compared more equally. The Area Only scenario predominantly follows horizontal, diagonal or vertical directions. These directional limitations are due to limitations inherent in the LCP algorithm.
4. *What are the length differences when comparing the calculated routes to the currently used straight lines?* The Area Only scenario resulted in the shortest merged trajectory length; 769,3 km, a length increase of about 14,1% compared to the straight line reference. The Corridor and Reuse scenarios resulted in length increases of about 16,8% and 18,5% respectively.
5. *What are the differences in amounts of intersected land-use compared to straight lines?* The percentages of intersected use functions decreased for all scenarios; ranging from -25% for the Corridor scenario to -35,1% for the Area Only scenario.
6. *What are the estimated differences in costs when comparing straight lengths to the lengths that result from this model?* The (hypothetical) costs decreased with: -17,3% for Area Only, -23,8% for Corridor and -28,7% for the Reuse scenario.
7. *How suitable is the developed model for this type of application?* The model still has some shortcomings and limitations, like the imprecise input factors and limited

directions of movement of the LCP. Also, the dependence on market and location for hydrogen pipelines is too high to be able to provide a reliable cost estimate using this model. Therefore, the model and methodology shows greater potential in earlier stages of planning as a supporting tool for stakeholders.

To summarize, when comparing the scenarios to straight line trajectories, in each scenario the length has increased, while the hypothetical costs have decreased to various extents. The relative differences of these results are dependent on the use factor, which are set by the user. From this, the following can be concluded; in the case of the routing of hydrogen pipelines, a sacrifice will have to be made either in the length, or in the amount of crossed use functions, depending on which is more important for the user. Next to that, the potential in application of the model combined with the relatively short development time of this research, show that a lot can be gained by approaching these kind of problems from a spatial perspective.

7 Research Opportunities/Recommendations

In this section some suggestions for research opportunities are listed.

1. **Improving functionality:** As a next step, new functionalities could be added, like coordinate input by clicking the map canvas or the further development of the join functionality. These functionalities can be relevant in a future implementation of the model into the North Sea Energy Atlas.
2. **Web Processing Service (WPS):** The final product of this research could potentially be developed into a Web Processing Service, which in turn can be implemented into the North Sea Energy Atlas. In this WPS, a user is able to drag in their own infrastructural elements after which the processing service would process the pipelines. If this processing is done externally on a computer with a large computing power, this way the user will be able to quickly process LCPs.
3. **Upscaling of the model and International collaboration:** As mentioned in Section 3.4.2, this research does not include the Delfzijl and Sloe demand centers. Moreover, this research focuses on the Dutch continental shelf, because for the Netherlands most of the required data is already available for TNO. When this research is continued, data of other countries surrounding the North Sea can be included to be able to support in planning mature hydrogen networks across EEZ borders.
4. **Including a minimum bend radius:** According to personal communication with Boskalis and according to Kang and Lee (2017) pipelines have a minimum bend radius of about 1km to ensure that the stresses in the pipe wall do not exceed the allowable limits. To implement this in the pipeline route, a Laplacian smoothing algorithm can be used. This algorithm however has not been integrated into QGIS yet.

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Appendices

A Expert use factor assessment form

NSE Hydrogen Pipeline: Factor of Impediment Form

Dear Participant,

Thank you for contributing to this research.

For my MSc thesis I am developing a method to efficiently estimate the spatial distribution and length of future offshore hydrogen pipeline sections. This will be done by applying a Least Cost Path algorithm to a GIS layer with offshore use factors.
An important input for the least cost path algorithm is to assess different use factors and assess their impact on the cost or general impediment for developing an offshore pipeline. With a stakeholder consultation I am gathering expert input on the application and values of the use factors to test the methodology. For this I am requesting your expert input.
The results of this form will be used as input values for a proof of concept and serve as an example on how a group of stakeholders could assess the use factors. It is at this stage not the goal to come to accurate values or consensus on these use factors. The inputs will be used anonymous. Filling in the form shouldn't take more than 8 minutes.

Please fill in the form by answering the following question:
If you would guesstimate the factor of impediment of crossing one of the following uses of the North Sea with a hydrogen pipeline, what would this factor be? This factor should include costs/km, but can also include a personal preference (see example 4 below). If desired, an explanation of your answer can be given after each question.

A few examples:
1. If you estimate crossing a shipping lane with a pipeline will cause the costs/km to increase with a factor 1.6, please fill in 1.6;
2. If you estimate that the cost/km will not change when crossing the land use, the factor will be 1;
3. If you estimate re-using decommissioned pipelines will cause the costs/km to decrease with 50%. Please fill in a factor of 0.5;
4. If you estimate the cost factor of crossing a Natura2000 area will be 1.4, but you think the protection of these areas is of high importance, you could for example increase the factor to 1.6.

Thanks in advance!
* Required

Shipping Lanes & Anchor Areas

1. How would you rate the factor of impediment for Shipping lanes? (shown in grey on the map) *

2. Explanation:

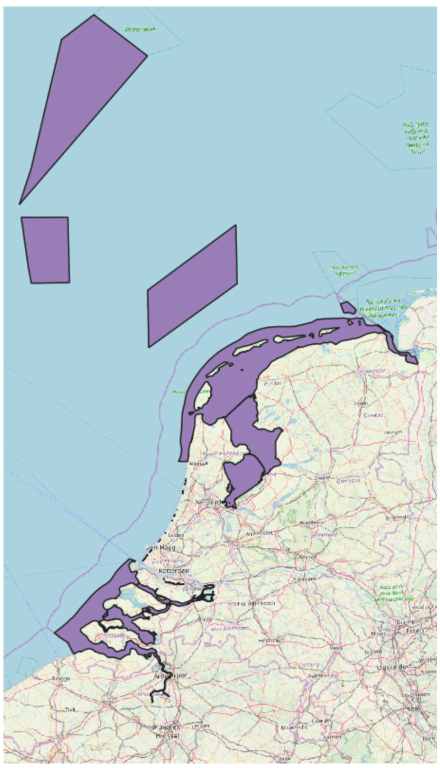
3. How would you rate the factor of impediment for Anchor Areas for ships? (shown in green on the map) *

4. Explanation:

Natura 2000

Currently protected areas.

5. How would you rate the factor of impediment for Natura 2000 areas? (shown in purple on the map) *



6. Explanation:

Nature Network

Nature network areas are included in scenarios II and IV of the PBL and consist of planned protected areas to improve biodiversity.

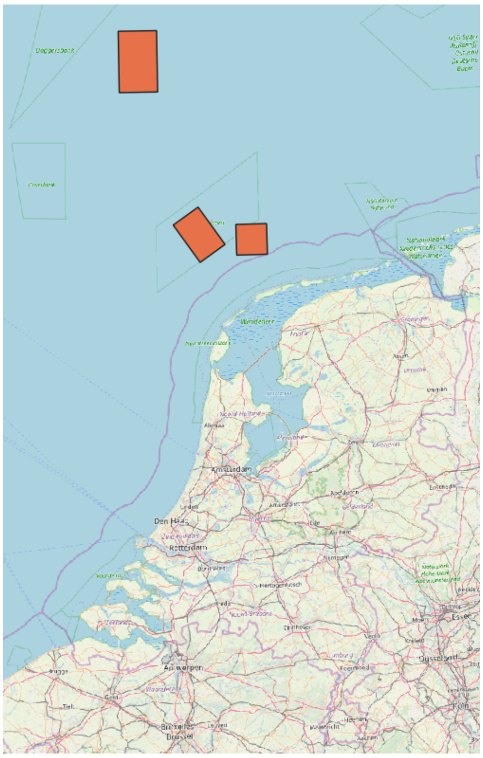
7. How would you rate the factor of impediment for Nature Network areas? (the scenario IV areas are shown in red on the map) *

8. Explanation:

Oyster Fields

Used as artificial reefs and nature.

9. How would you rate the factor of impediment for Oyster Fields? (shown in orange on the map) *



10. Explanation:

Wind & ...

... Nature Network, Fishery and Aquaculture

11. How would you rate the factor of impediment for Wind parks that are also part of the international nature network? (shown in brown on the map) *

12. Explanation:

13. How would you rate the factor of impediment for Wind parks that can also be used for active fishery? (shown in red on the map)

14. Explanation:

15. How would you rate the factor of impediment for Wind parks that can also be used for aquaculture and passive fishery? (shown in yellow on the map)

16. Explanation:

Military

17. How would you rate the factor of impediment for Military Areas? (shown in green on the map) *

18. Explanation:

Pipeline re-use and corridors

19. How would you rate the factor of impediment for the re-use of decommissioned pipelines? *

20. Explanation:

21. How would you rate the factor of impediment for following pipeline or cable corridors?

22. Explanation:

Relative importance

23. How would you rate the importance of the following subjects compared to the other uses of the North Sea? *

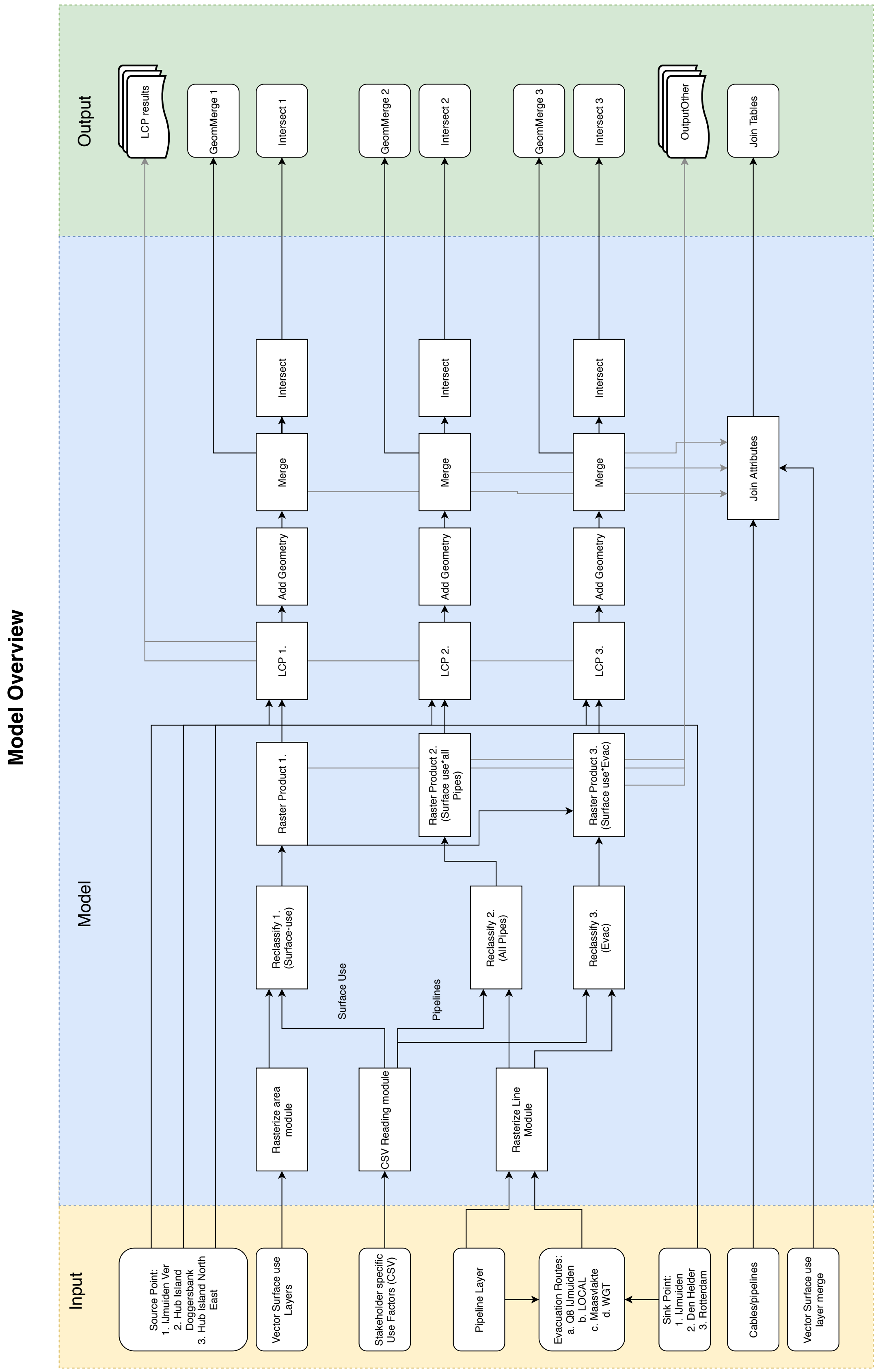
Check all that apply.

	Not important	Less important	Neutral	More important	Very important
Shipping	☐	☐	☐	☐	☐
Nature	☐	☐	☐	☐	☐
(Wind)Energy	☐	☐	☐	☐	☐
Military	☐	☐	☐	☐	☐

Comments/remarks

24. If you have any comments or remarks, feel free to leave them below.

B Algorithm Flow Chart



C Git Readme

Atlas LCP

Least Cost Path project for the North Sea Energy Programme.

Getting started

Prerequisites

The model itself is runs in QGIS 3.10 with GDAL and SAGA. The complete package is downloadable from the OSGEO4W website. Next to that, the Least Cost Path Plugin is required. This plugin can be found in the internal plugin repository.

This model was written in Python 3.7. A version of python should come with QGIS, if not; Python can be downloaded from here. Alternatively, anaconda could be used for this.

Python is also needed for installing pandas through pip. 1. Make sure python is added to the windows path, if not; follow the steps on this website. If python is not on your path, then you can try the instructions in the section below. 2. For upgrading pip and installing pandas, open the commandline.
3. Upgrade pip with:

```
python -m pip install --upgrade pip
```

If you get an `EnvironmentError`, add --user to the statement

4. Install pandas:

```
python -m pip install pandas
```

Pip and pandas should now be successfully installed.

Pycharm is the development environment used for this project.

(Optional) Python not on path

If you don't have python on your path, you can try to access python using the full python executable location. Following the same steps provided above, replace the `python` with the location `C:/Program\ Files/QGIS\ 3.10/apps/Python37/python.exe`. You may need to adjust this path according to your QGIS set up. Here is an example of how you would write step number 3 from above:

```
C:/Program\ Files/QGIS\ 3.10/apps/Python37/python.exe -m pip install --upgrade pip
```

Clone the Repository

To clone this repository to your pc, git has to be downloaded frome here.

1. Open git bash
2. Go to the directory where the repository clone should be stored using `cd the/desired/directory`
3. Copy the https link under the blue clone button in the repository
4. Clone the git repository with:

```
git clone that/copied/url
```

Usage

IMPORTANT: Change the projectpath directory in the AtlasLCP.py file to the directory where the atlas-lcp folder is saved by opening it in a text editor.

Open QGIS 3.10 Set the project Coordinate Reference System (CRS) in QGIS to Europe Equidistant Conic (ESRI:102031). This can be done by clicking on the projection button in the bottom-right corner of the screen. Then search for the CRS using the search bar and select and apply the CRS.

Adjusting input:

Use factor values can be changed by adjusting the values in the Factors file in the InputFactor folder.

Other input layers can be adjusted by opening them in a QGIS project, adjusting them and saving them under the same name in the original folder.

Input surface use layers can either be changed in a QGIS project or other layer files can be selected in the model window.

Running the model:

Make sure you have the Least Cost Path plugin installed. This can be done through:

> Plugins>Manage and Install Plugins> *search for Least-Cost Path in the search bar* >Install Plugin

Optional: *Open the python console using the python logo on the toolbar in the top of your screen. In the python console, the print statements as well as the model running time will be displayed.*

Open the processing toolbox via Processing. Click on the yellow and blue python logo on the top of the toolbox and choose 'Open Existing Script'. Locate the downloaded AtlasLCP folder and open the 'AtlasLCP.py' script in the Bin folder. Click on run (the green arrow at the top of the screen).

Fill in the required parameters:

Select the surface use/reuse/corridor and extent layer files. Select the Factor Set to use. These correspond with the columns in the Factor.csv. Select the scenario rasters over which the LCP will run. If the reuse scenario is selected, select the name of the required evacuation route or all available evacuation routes. Finally enter the required source/sink points. Click Run again.

Results and output:

After the model is finished, the results will be placed in the corresponding output folders:

- GeomMerge: Merged LCPs with added geometry attributes The first number of the LCPGeomMergeFactor files corresponds with the factor set, the second responds to the scenario, so: LCPGeomMergeFactor2-3 are the merged LCPs calculated with the factors of factorset 2 and scenario 3 (Reuse)
    - Intersect: The results of the intersects of the LCP merges with the dissolved overlay layer containing al surface uses
- OutputOther: the products of the intermediate (?) model modules. Here the raster files are stored together with the reclassified and raster product layers divided folders for each Factor set
- LCPResults: All seperate LCPs divided in Factor Set folfers, where the first number corresponds with the scenario (Area Only/Corridors/Reuse), the second number with the source and the third number with the sink

Rerunning the model:

If you want to rerun the model, remove the LCP files in the LCPResults/Factor folder you want to change together with the corresponding GeomMerge and Intersect files and run the model again. If changes are made to the input vector layers, then also the corresponding rasterize and reclassify files in the OutputOther file have to be deleted or moved to another folder. Sometimes QGIS has to be closed first, before the files can be deleted. These files are often marked with -wal and -shm copies.

Tests

To test the model it is wise to start with 1 sink/source point and 1 product raster (scenario).

Future Improvements

- The model often crashes after finishing the run, not sure if fixable or inherent to QGIS
- To make Source/Sink points dependent on the layer, the user has to input the layer first. This makes it impossible to read the source and sink names before the parameter input screen
- To be able to vary in input layers and amounts of input layers, the amount of rasterize and reclassify modules and product layers have to be made variable using for loops

Version history

Authors

- **Cas Thoonsen** - *Main Developer* - TNO
- **Logan Brunner** - *Developer* - TNO

D Least-cost path results table

Scenario		Source	Sink	Length (km)	Total Cost (cost*km)	Mean Cost	Sinuosity
Area	**Min**	IJmuiden Ver	Maasvlakte	117,13	185,4	1,58	1,09
			IJmuiden	88,36	164,4	1,86	1,06
			Den Helder	81,36	210,2	2,58	1,06
		Energy Island 1	Maasvlakte	184,91	240,6	1,30	1,18
			IJmuiden	149,34	215,9	1,45	1,12
			Den Helder	138,55	260,9	1,88	1,19
	Mean	IJmuiden Ver	Maasvlakte	119,25	209,5	1,76	1,11
			IJmuiden	88,42	175,5	1,99	1,06
			Den Helder	82,77	221,5	2,68	1,08
		Energy Island 1	Maasvlakte	188,26	282,0	1,50	1,20
			IJmuiden	149,97	242,9	1,62	1,13
			Den Helder	140,59	288,8	2,05	1,21
	Max	IJmuiden Ver	Maasvlakte	119,17	216,4	1,82	1,11
			IJmuiden	88,40	180,8	2,05	1,06
			Den Helder	82,85	226,7	2,74	1,08
		Energy Island 1	Maasvlakte	192,69	296,2	1,54	1,23
			IJmuiden	154,83	255,4	1,65	1,16
			Den Helder	145,19	301,2	2,07	1,24
Corridor	**Min**	IJmuiden Ver	Maasvlakte	122,85	129,4	1,05	1,14
			IJmuiden	103,01	120,6	1,17	1,24
			Den Helder	87,66	140,8	1,61	1,14
		Energy Island 1	Maasvlakte	190,32	186,6	0,98	1,21
			IJmuiden	175,55	167,9	0,96	1,32
			Den Helder	151,30	176,0	1,16	1,30
	Mean	IJmuiden Ver	Maasvlakte	121,08	184,4	1,52	1,12
			IJmuiden	92,93	163,8	1,76	1,12
			Den Helder	89,75	202,2	2,25	1,17
		Energy Island 1	Maasvlakte	189,07	260,3	1,38	1,20
			IJmuiden	154,54	231,3	1,50	1,16
			Den Helder	140,60	266,2	1,89	1,21
	Max	IJmuiden Ver	Maasvlakte	119,25	209,5	1,76	1,11
			IJmuiden	88,42	175,5	1,99	1,06
			Den Helder	82,77	221,5	2,68	1,08
		Energy Island 1	Maasvlakte	188,26	282,0	1,50	1,20
			IJmuiden	149,97	242,9	1,62	1,13
			Den Helder	140,59	288,8	2,05	1,21
Reuse	**Min**	IJmuiden Ver	Maasvlakte	129,94	108,4	0,83	1,21
			IJmuiden	178,68	70,4	0,39	2,15
			Den Helder	134,58	59,1	0,44	1,75
		Energy Island 1	Maasvlakte	239,28	127,2	0,53	1,52
			IJmuiden	175,93	53,9	0,31	1,32
			Den Helder	131,82	42,6	0,32	1,13
	Mean	IJmuiden Ver	Maasvlakte	129,53	172,1	1,33	1,20
			IJmuiden	97,51	166,4	1,71	1,17
			Den Helder	96,45	172,9	1,79	1,25
		Energy Island 1	Maasvlakte	188,41	247,9	1,32	1,20
			IJmuiden	155,33	233,7	1,50	1,17
			Den Helder	131,82	231,4	1,76	1,13
	Max	IJmuiden Ver	Maasvlakte	119,73	196,9	1,64	1,11
			IJmuiden	88,42	173,7	1,96	1,06
			Den Helder	85,60	213,0	2,49	1,11
		Energy Island 1	Maasvlakte	188,74	269,4	1,43	1,20
			IJmuiden	149,97	241,1	1,61	1,13
			Den Helder	143,42	280,3	1,95	1,23

E Merged results table

	Scenario	#FactorSet	Sum Length	Sum Length (km)	Sum Intersect Length	% Intersect	Sum Total Cost	Mean Sinuosity
Euclidean (Reference)	1: Area	2	674432	674,4315533	544423	80,72	17165,2	1
Min	1: Area Only	7	759651	759,651	562959	74,11	12774	1,116
	2: Corridor	3	830687	830,687	636324	76,60	9211,59	1,225
	3: Reuse	5	990236	990,236	653035	65,95	4615,77	1,514
Mean	1: Area Only	2	769264	769,264	402687	52,35	14201,9	1,123
	2: Corridor	2	787963	787,963	476913	60,52	13081,7	1,163
	3: Reuse	2	799045	799,045	440392	55,11	12244,7	1,188
Max	1: Area Only	8	783128	783,128	387053	49,42	14765,8	1,147
	2: Corridor	4	769264	769,264	402687	52,35	14201,9	1,13
	3: Reuse	6	775873	775,873	423623	54,60	13743,2	1,141