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Map out renewable energy in the Greater North Sea

Suitable wind turbine locations based on open data

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“Maps are power.
Either you will map or you will be mapped.”
- Nietschmann, 1997

Abstract

The main objective for this research is "Mapping the suitability for wind turbines in the Greater North Sea by making use of the available open data". The Greater North Sea is bordered by Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden, and the United Kingdom (England and Scotland). All have their own rules and regulations regarding this vast marine area, influencing the suitability to locate wind turbines. Besides differences in rules and regulations, a suitability analysis is often influenced by the profession of the planner and social developments. Therefore, this research takes as many influencing factors as possible into account from a wind farming point of view. These are activities, protected areas or objects that influence the suitability of an area to locate wind turbines.

During this research, 30 influencing factors were determined, which can be grouped into 13 main categories. Namely aquaculture, fishery, military, mineral extraction and aggregates, nature protection, renewable energy production, oil and gas exploitation, scientific research, shipping and ports, submarine cables and pipelines, tourism, underwater cultural heritage and other. Open data on the influencing factors is sought via open data portals. Resulting in 37 datasets for Belgium, 35 for the Netherlands, 34 for Denmark and Germany, 32 for the United Kingdom, 31 for France and Norway and 26 for Sweden, out of the 46 datasets searched.

After pre-processing the collected data, all influencing factors were weighted equally and subtracted from the study area, leaving the 'suitable areas for wind turbines' as an output. Suitable areas, in this case, are areas with no activities, objects or protected status. Based on this approach, a total of 103 202 square kilometres is suitable for locating wind turbines. Most of the suitable areas are in the waters of Norway (49%) and the United Kingdom (34%). When taking the rules and regulations of countries into account, the suitable space becomes 129 495 square kilometres. In both cases, sufficient suitable space is available to locate enough wind turbines to reach the climate goals.

When comparing the current and planned wind turbine farms to the suitable areas, only 23% of the current wind turbine farms and 13% of the planned wind turbine farms are located on suitable areas. The most overlap is with the categories nature protection (66% of the current wind turbine farms – 74% of the planned wind turbine farms), fishery (21% - 26%) and other (26% - 17%), which means that countries do consider areas with influencing factors to locate (new) wind turbine farms.

Overall, it can be stated that it is possible to map the suitability for wind turbines in the Greater North Sea by making use of the open data available. However, not all countries have open data available on all influencing factors. Making the results of the current model less accurate. Furthermore, it is recommended to refine the modelling by focussing on weighted classes.

Keywords: Wind turbines, Marine Spatial Planning, Greater North Sea, Open data.

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Suzan Jans

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List of terms and abbreviations

Categories – All influencing factors can be grouped into 13 main categories. The categories are aquaculture, fishery, military, mineral extraction/aggregate, nature protection, renewable energy production, oil and gas exploitation, scientific research, shipping and ports, submarine cables and pipelines, tourism, underwater cultural heritage, and other (Ehler & Douvre, 2009). One category consists of one or more influencing factors.

Exclusive Economic Zone or EEZ – The borders of the countries within the waters. The EEZ is part of the country, giving it the rights for exploring, conserving and managing the natural resources of the waters and seabed (United Nations, n.d.).

EMODnet – The European Marine Observation and Data Network. A consortium of organisations assembling European marine data (EMODnet, N.d.).

Greater North Sea – The study area for this research (Figure 1 paragraph 3.1). The waters of Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden, and the United Kingdom (England and Scotland).

International Council for the Exploration of the Sea or ICES – An intergovernmental marine science organisation performing research on seas and oceans. All countries bordering the Greater North Sea are members of the ICES (ICES CIEM, n.d.).

Influencing factors – a component of a category that influences the planning of wind turbines. This can be activities, objects or protected areas. Influencing factors can be grouped into categories. Each influencing factor consists of one or more datasets.

Open data – Data that anyone can access, use, and share, it becomes usable when made available in a common machine-readable format. A license determines whether data is open data, the license must permit people to use the data in any way they want (European Commission, n.d.). Within this research, open data refers to open **geospatial** data, which means that the open data has a spatial component, such as a location or coordinates.

Suitable areas – During this research, an area becomes suitable for wind turbine planning when there are no influencing factors in that area.

The 8 bordering countries or all countries bordering the Greater North Sea – The countries bordering the project area (Figure 1 paragraph 3.1). The 8 bordering countries are Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden, and the United Kingdom (England and Scotland).

Web Feature Service or WFS – A WFS allows users to request geospatial data from a service in a vector format. Since the service is hosted, the user does not have to download this information. Due to the return being a vector, the user can work with the returned data similarly to a downloaded file (Michaelis & Ames, 2008).

1. Introduction

1.1 Context and background

The climate is changing, and the average temperature on earth is rising. According to the Intergovernmental Panel on Climate Change (IPCC), the global temperature has risen with 1°C since 1880. They predict a temperature rise of 1.5 to 2 °C in 2040 (IPCC, 2018). Studies show effects such as sea-level rise, extreme weather conditions, a decrease in biodiversity, acidification of the waters and an increased chance of the spread of diseases. The more the temperature rises, the more extreme the effects (Arnell et al., 2019; IPCC, 2018; Loarie et al., 2009). The Paris agreement (a legally binding international treaty on climate change) forces the 196 signing parties to limit global warming with a maximum of +1.5°C, compared to the pre-industrial levels (UNFCCC, 2015). The more recent Glasgow Climate Change Conference emphasised the seriousness of the situation. And resulted in more agreements and regulations to limit global warming (UNFCCC Authors, 2021).

In order to try and limit global warming, the 28 members of the European Union have agreed to reduce their CO_2 levels by 40% by 2030 (Rijksoverheid, 2020). The European Union plans on becoming climate neutral by 2050 (European Commission, 2016). One way to limit CO_2 emissions is by making use of renewable energy. Renewable energy can originate from different sources such as bioenergy, hydropower, wind energy, solar energy, or geothermal energy. Using the energy of the wind by making use of wind turbines, can save up to 229g C/kWH (Gram carbon per kilowatt-hour) compared to a conventional pulverised coal-fired power plant (Sims, 2004). Making wind turbines one of the suitable ways to limit CO_2 emissions. This research focuses solemnly on wind turbines since they can be located on waters such as the Greater North Sea, which is the research area of this research (Figure 1).

Changing to wind turbines reduces CO_2 levels and can therefore help to reach the climate goals and limit global warming (Razmjoo et al., 2021). Finding a place to locate wind turbines, however, can be quite challenging. Many people acknowledge the benefits of renewable energy. However, they don’t want wind turbines located near them because of the noise, landscape pollution (visual impacts) and impact on the wildlife (Kondili & Kaldellis, 2012). If wind turbines are located over 7 kilometres away or on an invisible spot (e.g., behind a mountain), they are accepted quicker. Therefore, the sea is often referred to as an excellent location to locate wind turbines (Kondili & Kaldellis, 2012) since wind turbines are then out of sight for most people.

Whereas locating wind turbines at sea might seem like an optimal solution for citizens, this cannot easily be done. Several factors such as environmental factors, biotic factors, anthropogenic factors, sea use, and administrative borders should be considered when locating wind turbines on the water (Ansong et al., 2017; Schaefer & Barale, 2011). Since the Greater North Sea is a unique area with unique animals and habitats, locating wind turbines is impactful (Ducrotoy et al., 2000). So, several factors should be considered whilst planning wind turbines. On the other hand, installing wind turbines also has positive side effects on biodiversity since the wind turbines can function as artificial reefs and no-fishing zones (Petersen & Malm, 2006).

Besides considering several influencing factors whilst planning wind turbines, the process is complicated by the division of the Greater North Sea. All 8 bordering countries (Belgium, Denmark, France, Germany, the Netherlands, Norway, Sweden and the United Kingdom – England and Scotland) with an economic zone within the Greater North Sea make their own plans, have their own rules and regulations, and find other factors important whilst determining where to locate wind turbines. The withdrawal of the UK from the European Union complicates this process even further (European Commission, 2020). There are plans to reinforce cooperation for marine spatial planning within the EU (COM, 2020; European Commission, 2020). However, they are not yet in use, and countries still use their own rules and regulations.

Therefore, this research aims to develop an overview of areas that are suitable to locate wind turbines by making use of the open data that is available. Whilst taking and not taking the rules and regulations of the countries into account. With as underlaying goal to obtain more insights into the complexity of marine spatial planning within the waters of the Greater North Sea. Influencing factors, rules and regulations, data, and sensitivity will be taken into account from the wind farming perspective. Making sure that the suitable areas are not influenced by professions or opinions but based on the open data.

1.2 Problem Definition

There are three main problems defined for this research. Those main problems are, determining the influencing factors that should be taken into account whilst planning for wind turbines on the Greater North Sea, differences in rules and regulations of the bordering countries and the availability of open data.

First of all, determining the influencing factors. There are a lot of different factors influencing marine spatial planning, making it a complicated process. For instance, whilst planning for wind turbines on waters, an area might seem suitable because there is nothing at the water's surface. However, there are chances of the area being essential to the wildlife, which is not visible directly. With that, it increases the chances of birds getting killed by the rotor blades of wind turbines (Drewitt & Langston, 2006) or disturbing the communication of mammals due to the underwater noise of wind turbines (Kondili & Kaldellis, 2012; Thomsen et al., 2006). Furthermore, there might be other activities or objects that are not directly visible such as cables or explosives at the bottom of the sea or an area that is used for exploitation or fishery. So, there are many influencing factors to consider, which are not only visible objects.

Studies often focus on modelling only a part of the influencing factors and do not take them all in consideration. For example, there is research that shows the influence of solemnly the costs on offshore wind turbine planning (Jay, 2012; Kondili & Kaldellis, 2012; Punt et al., 2009). There are models calculating the costs (Resoft, 2008; Kooijman et al., 2001), and models focus solemnly on wildlife (Garthe & Hüppop, 2004; Tucker, 1996). However, none of those research combines multiple influencing factors, such as wildlife and cost. There are planning systems developed indicating effects that should be considered. However, these are just systems, and they don't make use of geospatial data (Punt et al., 2009; Elliott, 2002). Furthermore, choices made during those researches often depend on the profession or opinion of the planner. So, if he thinks wildlife is very important and fishery is not the areas with fishery have higher chances of being transformed to wind turbine farms.

Secondly, all eight bordering countries with an economic zone within the Greater North Sea can make their own rules and regulations for offshore wind turbine planning in their waters. Therefore, they consider different influencing factors whilst planning wind turbine farms. This complicates the process of defining suitable areas since there isn't a single definition of a suitable area. Research on the differences between countries has already been performed (Jones et al., 2016; Olsen et al., 2014; Qiu & Jones, 2013). Because of the differences, the European Union has developed ten key principles to make a more uniform way of wind turbine planning. However, there are still big differences since the principles are just guidelines (Qiu & Jones, 2013; Schaefer & Barale, 2011). On top of that, not all countries are members of the European Union.

Thirdly, it is unclear what open data is available for marine spatial planning and with that the planning of wind turbine farms on the waters. Most of the previously mentioned studies and models only focus on a small part of the Great North Sea due to the data availability. The lack of open data and open data standards is referred to as problematic whilst performing marine planning more often (Depellegrin et al., 2021). If there is data available, this is often not open data, or the data is incomplete (Zhang et al., 2021). The European Union has made it obligatory for countries to make data publicly available. However, countries collect data in different ways and on different topics. All countries have different rules on sharing and collecting data, so there is no single uniform dataset for all countries. It is important to get an overview of the available data to get insights into what data is missing and how different the data from countries is. To make people aware of the opportunities of geospatial data in the process of wind turbine planning. For the Baltic Sea, a study on the availability of open data has already been performed (Frias et al., 2018). It showed that there are differences in data availability per country and per influencing factor. However, no such study has been performed for the Greater North Sea. So, it remains unclear what data is available and where this is stored. Since the Greater North Sea is one of the most crowded marine areas globally (Jentoft & Knol, 2014), the planning for wind turbine farms is complex. Because fishing areas, overarching protected marine areas, oil industry, shipping, military and recreation areas of all countries should be considered (Jentoft & Knol, 2014; Madsen et al., 2011). To take all influencing factors into account, data on all influencing factors should be available for all countries. This emphasises the importance of open data for planning wind turbines on the Greater North Sea.

1.3 Main objective and research questions

As stated within the problem statement, there are three main problems resulting in the objective of this study. Being: no studies consider all influencing factors, there are different rules and regulations per country, and it is unclear what open data is available.

So, it can be stated that there are no EEZ overarching studies regarding wind turbines within the Greater North Sea. At the same time, there seems to be a need to consider the total marine system to overcome issues that may disturb fundamental marine processes. Due to there being many different users in the waters of the Greater North Sea, this study looks at the Greater North Sea from a wind farming point of view. All this has resulted in the research objective.

“Mapping the suitability for wind turbines in the Greater North Sea by making use of the available open data.”

This main objective will be answered by the following research questions.

Research question 1: “What are important influencing factors for offshore wind turbine planning? And what influencing factors do countries consider whilst planning?”

Research question 2: “For which influencing factors is open data available to support offshore wind turbine planning?”

Research question 3: “What areas would be deemed suitable if only open data would be used for wind turbine planning? And how do those areas change when taking countries rules and regulations into account?”

Research question 4: “Are current and planned wind turbine farms on suitable areas according to the open data available?”

2. Review

2.1 Wind turbines

Using the power of the wind has already been done for decades. At first, it was used to sail across the oceans and later, the power of the wind was used for mills to grind grain and pump water. Nowadays, the power of the wind is used to generate energy. It is seen as one of the main sources of renewable energy since no depleting resources are used for the production of the energy. Using wind energy can save carbon and, with that, help with reaching the climate goals. Wind energy can save up to 229g C/kWH (Gram carbon per kilowatt-hour) compared to a conventional pulverised coal-fired power plant (Sims, 2004). Besides limiting carbon emission, it also limits the amount of water used to produce electricity. Wind energy uses 0.004 l/kwh (litre per kilowatt-hour), which is less than coal 1.90 l/kwh or nuclear energy 2.30 l/kwh (Saidur et al., 2011).

The first wind turbine to generate energy was constructed in 1890 in Denmark. This wind turbine was nothing compared to the wind turbines developed nowadays. Back in 1890, the wind turbine generated 12kW (Mathew, 2006). Nowadays, the newest offshore wind turbines can generate up to 10 MW, which is almost 1000 times more (Hu et al., 2021; Liserre et al., 2011). The 10 MW offshore wind turbines are one of the newest in a long line of developments. Due to critical views on onshore wind turbine development, offshore wind turbines became more important in 1990. Nowadays, 4.8% (35 GW) of the global wind capacity is generated offshore, which will increase over the coming years (Joyce & Feng, 2021).

Offshore wind turbines are remotely the same as the wind turbines installed on land. The main differences occur because of natural factors. First of all, offshore wind turbines are often larger. This has to do with the fact that there are higher average wind speeds on open waters, so there is the ability to power bigger rotor blades. Furthermore, other technologies are used on the exterior due to higher chances of corrosion coming from the salt water. Due to those harsh conditions, the design has a lifetime of approximately 25 years (Joyce & Feng, 2021). The last difference is within the foundation of the wind turbine (Breeze, 2016). There are 5 basic types of foundations, monopile structures, tripod structures, lattice structures, jacket foundations and floating structures (Sánchez et al., 2019; Fu, 2018).

Approximately 80% of the European offshore wind turbines make use of a monopile foundation. However, this is expected to decrease due to new developments (WindEurope Business Intelligence, 2020). A monopile foundation is a steel tube driven in a shallow to moderate seabed. The diameter of the tube is dependent on the size of the wind turbine (Malekjafarian et al., 2021; Doherty & Gavin, 2012). Monopiles can be used for depths up to 30 meters. In waters ranging from 20 to 80 meters, tripod or other multipole structures are used, which also make use of tubes (Khare et al., 2020; Breeze, 2016). Floating platforms are still at an early stage of development but will soon take over since they can be used for depts ranging from 40 to 900 meters and not just the shallow to moderate depths (Hu et al., 2021; Khare et al., 2020).

It should be noted that offshore wind turbines are more expensive to construct than onshore wind turbines. This has to do with the fact that extra costs have to be made for transportation, more complicated construction, larger wind turbines, and underwater electrical infrastructure. The highest cost is within the foundation of the wind turbines (Oh et al., 2018). Furthermore, the maintenance of offshore wind turbines is more expensive because of their remote locations (Sánchez et al., 2019; Esteban et al., 2009). By the end of 2018, the average distance from the wind turbine farms to the coast within the Greater North Sea in 2019 was 30 kilometres (Sánchez et al., 2019).

So, in general, it can be stated that offshore wind turbines can be installed in waters with a depth ranging from 0 to 900 meters. However, they are most commonly installed in depths till 40 meters (Sánchez et al., 2019). This is changing towards the deeper waters now the size of the wind turbines is increasing, and there is more awareness of visual and environmental impacts (Bishop, 2019). The most commonly used foundation is the monopile foundation, this has to do with the fact that this can easily be installed in shallow waters.

2.2 Goals

The members of the European Union have agreed to reduce their CO_2 levels with 40% by 2030 (Rijksoverheid, 2020) and be climate-neutral by 2050 (European Commission, 2016). So, new wind turbine farms are needed. Europe's total electricity consumption was 2 562 TWh in 2019. The 8 countries bordering the Greater North Sea together consumed 1 736 TWh. Only 34.6% of the grossed energy came from renewable sources (Eurostat, 2021).

The Commission of the European Union plans on having half of Europe's electricity generated by wind and the other half by other renewable sources by 2050. So, before 2050 a total of 600 GW on wind turbines needs to be installed. This can produce over 2 015 TWh which is half of the assumed consumed electricity in 2050. From the 600 GW, approximately 250 GW will be installed onshore, and 350 GW will be installed offshore (European Wind Energy Association, 2009). When including the needs of the UK and Norway, the Greater North Sea countries need to construct 450GW on offshore wind turbine farms (Freeman et al., 2019).

Due to the high average wind speed, most wind turbines per square kilometre are planned to be constructed within the Greater North Sea (Rodrigues et al., 2015). It is planned to construct 212GW within the waters of the Greater North Sea, leaving 238GW for the Atlantic Ocean, the Baltic Sea and the Southern European waters (Freeman et al., 2019).

Assuming the average offshore wind turbine currently generates 0.008 GW, approximately 26 500 wind turbines will end up within the Greater North Sea (WindEurope Business Intelligence, 2020; NVDE, 2018; Elbersen et al., 2005). With a compact and tactical way of constructing, this is approximately 20 000 square kilometres for the construction of all wind turbines and accompanying platforms (Bulder et al., 2018; Elbersen et al., 2005; Rijksoverheid, n.d.). However, the bordering countries plan on needing 90 000 square kilometres for constructing all wind turbines. Based on an average density of offshore wind of 5MW per square kilometre. This way, multiple use can be ensured (Freeman et al., 2019).

3. Methodology

3.1 Study area

During this research, the borders of the Greater North Sea are as defined within the International Council for the Exploration of the Sea (ICES) Ecoregions (Figure 1**)** (ICES, 2015). The ICES is an intergovernmental marine science organisation performing research on seas and oceans. Since all countries bordering the Greater North Sea are a member of the ICES, their defined area is used (ICES CIEM, n.d.). According to the dataset used during this research, the Greater North Sea has a size of 671 202.55 km2 (ICES, 2015).

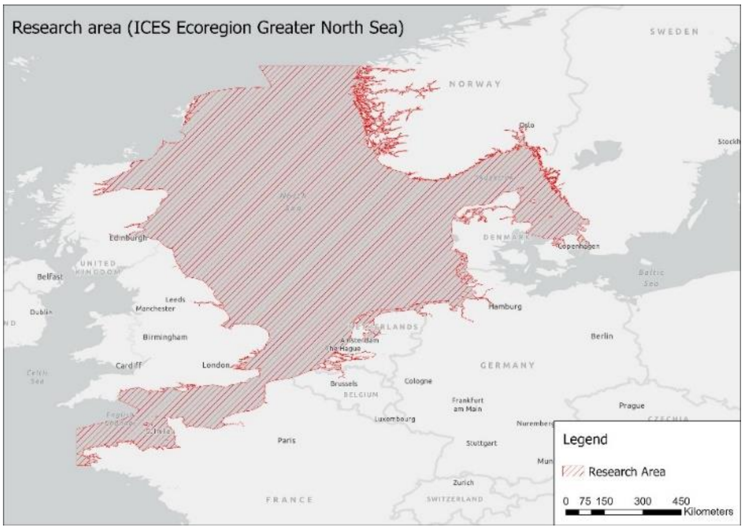


Figure 1 The Greater North Sea as defined by the ICES ecoregions.

3.2 Determining influencing factors and rules and regulations per country

For research question one, "What are important influencing factors for offshore wind turbine planning? And what influencing factors do countries consider whilst planning?" influencing factors had to be determined. An influencing factor is an activity, object or protected area that influences the planning of wind turbines. The determination was based on five categories: Rules and requirements, environmental factors, biotic factors, abiotic factors, and human factors. Literature research has been performed to find as many influencing factors as possible. This literature research was done according to the following steps. First of all, general information on the Greater North Sea was sought. The first three articles that showed on Google Scholar, Scopus, and Web of Science with the words 'Greater North Sea' have been read, and important influencing factors of the Greater North Sea were listed. If the articles showed other useful articles, the snowball effect is used (University of Groningen, n.d.). The first article is then seen as a key document, and the bibliography is used to find other relevant articles. This was repeated with the following terms: 'Marine Spatial Planning', 'Wind turbines on water', 'Offshore wind turbines', 'Offshore wind turbine planning' and 'Influencing factors wind turbines on water'. This way, as many influencing factors as possible, was sought. If more information on a specific influencing factor was needed, the term combined with 'wind turbines', 'marine spatial planning' or 'on water' was used to obtain more information.

To define what influencing factors a country takes into account whilst performing marine spatial planning, the European MSP platform (European Marine Spatial Planning) was used. This website contains information on marine spatial planning for all countries bordering the Greater North Sea (European MSP Platform, 2021).

3.3 Data collection

For the second research question, "For which influencing factors is open data available to support offshore wind turbine planning?" open geospatial data was searched. It should be noted that a single influencing factor can consist of multiple datasets.

Open data is data that is freely available on the internet. Geospatial data is data containing locations. Since the data is used for performing analysis and not just for showing maps, not all formats could be used. A Web Map Service (WMS), for instance, could not be used because this is just a projection of the data. Therefore, only WFS, Shapefiles, Geodatabases and GeoTIFFs were searched. The open data is searched according to the following steps.

1. Find data of the Greater North Sea on EMODnet[1]. EMODnet is a network of over 120 organisations supported by the EU's integrated maritime policy. They observe the sea, collect and process data and make this freely available with as goal to create an overview of reliable and accurate marine data, rather than the fragmented collected and stored data currently. Their main aim is to address threats and understand trends of the marine environment (EMODnet, N.d.).
2. Find data via the INSPIRE Geoportal. This is the European access point to geospatial data provided by the EU Member States and some EFTA countries. It has data available for all countries that are a part of this research except for the United Kingdom. The INSPIRE Geoportal makes the data provided publicly available via several themes. Often the data can be downloaded, or a WFS can be obtained. Another possibility is that a different website containing the data is linked to the INSPIRE portal (Inspire Geoportal, n.d.).
3. Next up, the Open Geodata portals of the 8 countries were checked on all influencing factors (Appendix II**)**.
4. After that, previous research on an influencing factor was searched. With previously carried out research, data often gets described or added. If a source was shared, the data from this source was collected.
5. Lastly, a google search was done. This search contained the influencing factor in English together with ‘WFS’ or ‘Shapefile’. If this did not result in any datasets, data was searched in the native language of the country. This was done by searching the native word of the influencing factor together with ‘WFS’ or ‘Shapefile’.

The EMODnet website contains data of all countries bordering the Greater North Sea. However, per influencing factor, it differed on the countries that shared their data. A country might share something on one influencing factor but not on another influencing factor. So, it can be that there is data available for some countries but missing for others. The missing data of countries was then searched via the other portals (Step 2 onwards). From step 2 onwards, data was searched for all 8 countries bordering the Greater North Sea independently.

If no data was found after performing all five steps, it is assumed this data is not available as open data. Therefore, no further search was performed. If data did exist, but it was not openly available, so a purchase had to be made, this data is seen as not available. Because this research solemnly focuses on the open data available. So, this research focussed on the findability, how easy it was to obtain data and on the completeness of the open data, does a dataset represent reality or do different datasets show different areas.

3.4 Creating a suitability model

An initial state of an MCA has been created to answer the third research question: “What areas would be deemed suitable if only open data would be used for wind turbine planning? And how

[1] “Data used in this master thesis was made available by the EMODnet project, https://emodnet.ec.europa.eu/en/portals funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were collected by Suzan Jans”

do those areas change when taking countries rules and regulations into account?” An MCA (Multi-Criteria Analysis) or MCDA (Multi-Criteria Decision Analysis) transforms and combines geographic data and preferences into a map. Making it possible to find optimal locations for specific situations (Malczewski & Rinner, 2015). The procedure used was as initiated by Saaty (1987), select the criteria (Research question 1), standardise the criteria, weight the criteria and aggregate the criteria. For this research, there are as many variables as there is data found for the influencing factors within research question one

Standardise the criteria - There are two condition classes, being 0/1. If data on an influencing factor is found, it is classed as 1, making the area completely unsuitable. Weighted values are often influenced by professions and the opinions of planners, which can’t be done when using this strategy. Binary values are chosen because it makes everything equally important.

Weight the criteria - The weight for all criteria (influencing factors) is the same. Meaning that, when looking at Saaty’ analytic hierarchy process, the intensity of importance on an absolute scale is 1 out of 10 for all activities. Scale one means, “Two activities contribute equally to the objective” (Saaty, 1987). This is because all influencing factors are more important than wind turbine farms. The interdependence of all influencing factors is equal, meaning that no influencing factor is more important. This way, the importance of influencing factors was not influenced by the profession of the planner. Figure 3 shows how the weights are assigned.

Aggregate the criteria - A negative condition is used rather than a positive condition, meaning that if there is data available on an influencing factor, this is seen as an unsuitable area rather than a suitable area.

For this research, it can be stated that an intersection over union is performed. All unsuitable areas are overlayed with another, creating one big unsuitable area. This area is then subtracted from the entire Greater North Sea. This results in the areas that do not have any other activities taking place which are assumed to be suitable for wind turbine planning. An intersection over union is chosen, so all influencing factors are weighted equally and were not influenced by the interests of researchers. This is also called a Binary overlay method with Boolean logic (Abudeif et al., 2015). The most well-known effort of this was conducted by McHarg and Mumford (1969). They created a manual technique with overlaying good and bad areas of different factors. With that, the High-Risk approach, the AND operator, was used to determine the suitable areas, which means that no matter how good a site is for other layers, if one layer has a ‘bad’ value, the area gets eliminated (McHarg, 1969). Overall, it can be stated that the following formula was used for every location within the study area.

$$S = \sum_{W=1} F_{(n)} W$$

$$S \neq 0 \; results\ in\ Unsuitable\ area$$

S = Suitability

F = Influencing factor

W = Weight of unsuitability

The analysis was performed over the entire area of the Greater North Sea. Zooming in on the EEZs when taking into account the rules and regulations. During this research, FME is used as a software package. The FME model created is provided with the data of this research (Appendix I). Screenshots of the model and further elaboration are provided in appendices III, IV and V.

3.4.1 Data pre-processing

After data on the influencing factors was found and collected (Research question 2), all data had to be pre-processed to generate a suitability overview. In general, the pre-processing steps, as shown in figure 2, were taken. Per influencing factor, more specific steps are presented in appendix III and in the FME file attached with the data of this research (Appendix I).

In general, it can be stated that data pre-processing is done according to the following steps (Figure 2). First, inactive objects are removed from the dataset (for instance, oil and gas platforms that are no longer in use). In the case of a CSV file, the data is converted to spatial data by using the coordinates. All data is reprojected to EPSG23031 because this projection is central within the project area. It has a 1-meter accuracy for the Norwegian waters and a 2-meter accuracy for the French waters. The standard unit is in meters rather than degrees, making it easier to calculate the results (MapTiler Team, 2009). After reprojecting the data, it is clipped to the project area. For point data, the average size of polygons of the same influencing factor was calculated and used as a buffer. If no polygon data was available, research has determined the buffer of the area (Appendix III). For the raster data, the grid was resampled to 1km x 1km and converted to polygons. The attribute values of the polygons are rounded. Based on the rounded values, the polygons were dissolved into bigger polygons. The points of the CSV files are converted to grids by overlaying the points with a grid and summing the occurrences.

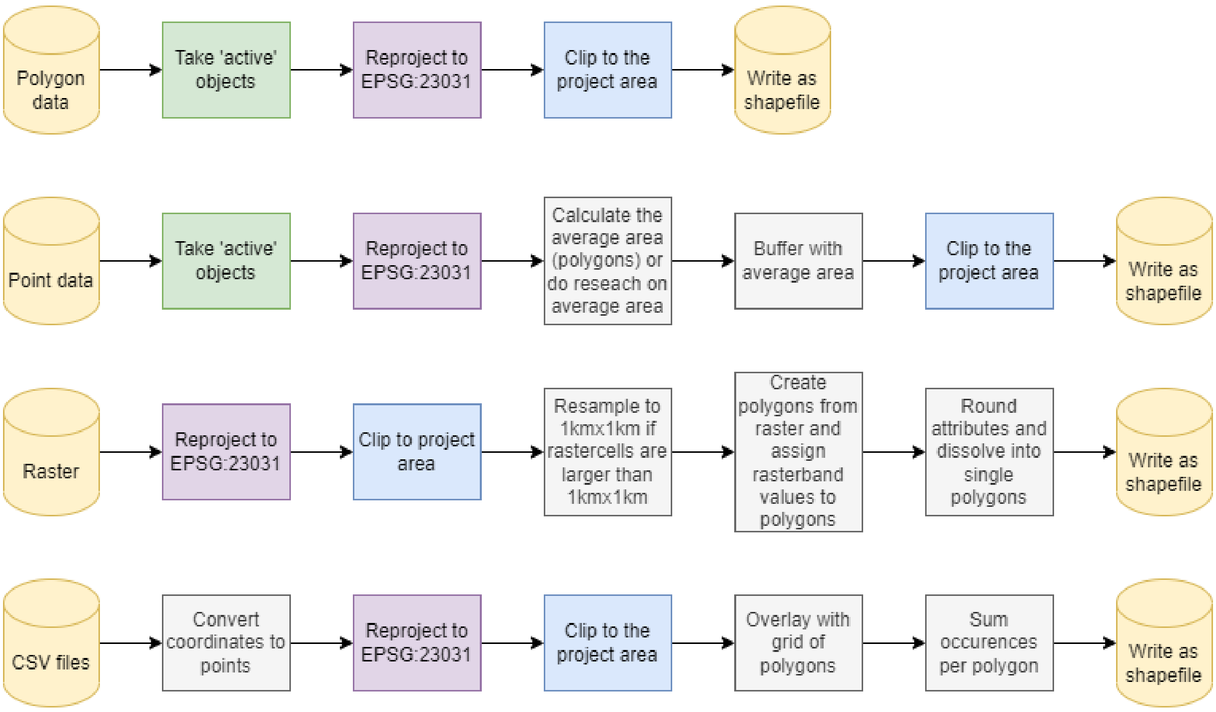


Figure 2 General pre-processing steps per file type. Appendix III or the FME model (Appendix I) for a more detailed version of the pre-processing.

During the pre-processing of the data, some assumptions had to be made since not all data was available or not all data was available in the right type. The main assumptions were:

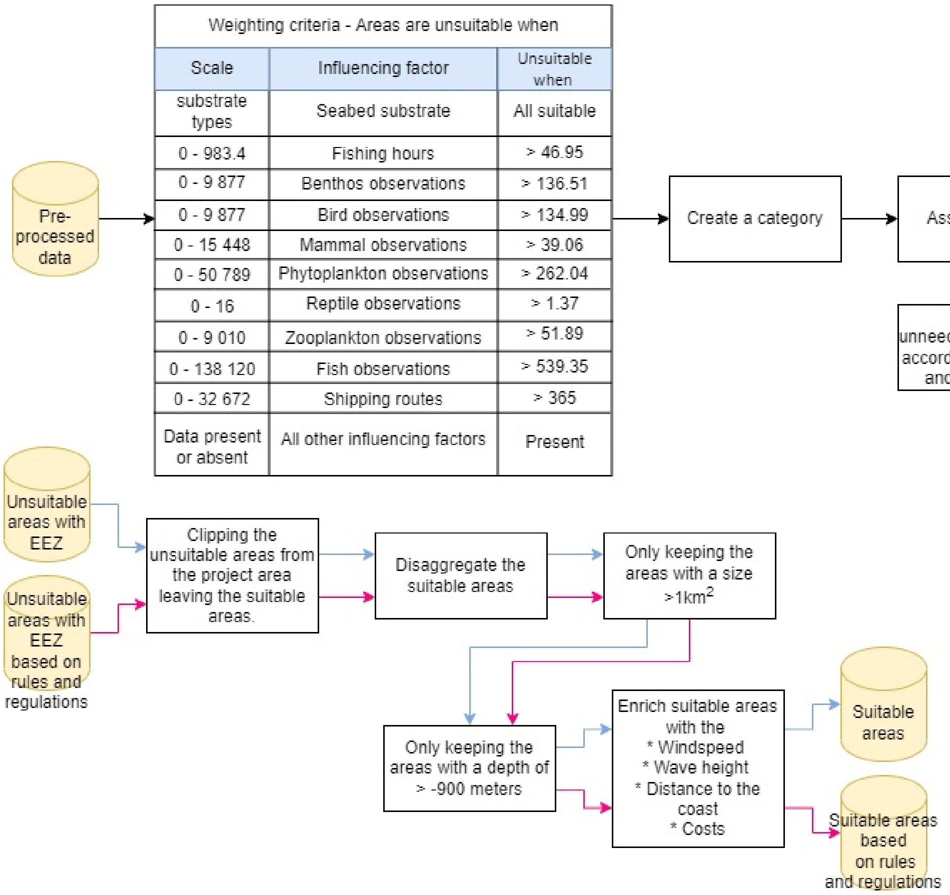
- 'Inactive' objects (objects that are no longer in use, for instance, old oil and gas platforms) can be removed from the waters to make room for wind turbines. Therefore, those areas can be seen as 'suitable' and available for wind turbine planning. If it is unknown whether an object is active or inactive, it is assumed that it is active;
- If only point data is available, a buffer represents the 'unsuitable' area (Appendix III);

- The 'average 16' resampling technique was used when resampling grid cells to cells of 1kilometre by 1kilometre since it calculates a simple average from the sixteen nearest cells and can be used for numeric raster files.

For specific assumptions per influencing factor or an exact reproduction of this research, refer to appendix III here the settings and processing steps are explained more elaborate.

3.4.2 Calculating suitable areas

After pre-processing the data, the unsuitable areas were used to calculate the suitable areas (Figure 3). Appendix IV and the FME file attached with the data of this research (Appendix 1) contains a more elaborate version of this process to make exact reproduction possible.



Weighting criteria - Areas are unsuitable when

Scale	Influencing factor	Unsuitable when
substrate types	Seabed substrate	All suitable
0 - 983.4	Fishing hours	> 46.95
0 - 9 877	Benthos observations	> 136.51
0 - 9 877	Bird observations	> 134.99
0 - 15 448	Mammal observations	> 39.06
0 - 50 789	Phytoplankton observations	> 262.04
0 - 16	Reptile observations	> 1.37
0 - 9 010	Zooplankton observations	> 51.89
0 - 138 120	Fish observations	> 539.35
0 - 32 672	Shipping routes	> 365
Data present or absent	All other influencing factors	Present

Figure 3 The pre-processing steps of calculating the suitable areas. Appendix VI or the FME model (Appendix I) for a more detailed version of the pre-processing.

In general, the following steps were taken to calculate the suitable areas. First, the pre-processed data was weighted to fit the standardized classes (0-suitable, 1-unsuitable) with the following assumptions:

- Only the areas with above-average fishing hours are deemed unsuitable. Areas with average and below-average fishing hours are seen as suitable since multiple-use can take place;
- For the observation data of benthos, birds, mammals, phytoplankton, reptiles, zooplankton, and fish, it is assumed that areas with an above-average number of observations are unsuitable. Areas with a below-average number of observations are suitable for wind turbine planning. Since observations are done throughout the entire Greater North Sea, it is impossible to make every area with an observation unsuitable;

- For shipping movements, it is assumed that areas with less than a single ship a day (<365 ships a year) can relocate the route and with that are suitable for wind turbine planning. This way, only major routes are kept (Ruijgrok et al., 2019).

After applying the assumptions, a category was assigned based on the UNESCO guidelines (Ehler & Douvre, 2009). If something could not be categorised, it was added to the category No. A category can consist of one or multiple influencing factors. There are 13 main categories aquaculture, fishery, military, mineral extraction/aggregate, nature protection, renewable energy production, oil and gas exploitation, scientific research, shipping and ports, submarine cables and pipelines, tourism, underwater cultural heritage and other.

Then the influencing factors were overlayed with the EEZs. The suitable areas were determined in two ways. The first one is based on all available data, and the second is when taking rules and regulations into account. These are the rules and regulations as found in research question 1 (Paragraph 3.2). The data was split into a dataset with all data and a dataset when taking rules and regulations into account. For the latter, data from a category a country does not consider was removed.

Subsequently, all 'unsuitable areas', so areas where an activity takes place, were subtracted from the project area, leaving only the suitable areas. So, an intersection over union is performed based on the unsuitable areas. This means that all unsuitable areas were overlayed with one another and subtracted from the project area. This was done for the dataset with all data available as well as for the dataset with the unsuitable areas based on the rules and regulations.

For both datasets, the suitable areas are disaggregated into single areas and areas smaller than a square kilometre were removed. Areas with a minimal size of 1 km^2 are seen as suitable. Too few wind turbines can be installed for smaller areas, so they were seen as unsuitable (Rodrigues et al., 2015). After this, the suitable areas were overlayed with the depth, and areas deeper than 900 meters were considered unsuitable. This is because 900 meters is the maximum depth for installing wind turbines (Hu et al., 2021). As a final data on windspeed, wave height distance to the coast and the costs were overlayed with the suitable areas. Adding the values to the attributes. For the cost, a relation between the costs of wind turbine construction, the distance from the coast and the water depth is assumed (Table 1) (Green & Vasilakos, 2011; Swart et al., 2009). If areas were deeper or the distance was further, an 'unknown' value was assigned as a cost factor.

Table 1 The cost factor assigned to the suitable areas (Swart et al., 2009).

Water Depth (m)	**Distance from shore (km)**							
	0-10	10-20	20-30	30-40	40-50	50-100	100-200	>200
10-20	1	1.02	1.04	1.07	1.09	1.18	1.41	1.60
20-30	1.07	1.09	1.11	1.14	1.16	1.26	1.50	1.71
30-40	1.14	1.26	1.29	1.32	1.34	1.46	1.74	1.98
40-50	1.40	1.43	1.46	1.49	1.52	1.65	1.97	2.23

3.5 Current and planned wind turbine farms

In order to evaluate the model and see how the open data and model differ from the techniques that countries use to plan wind turbine farms, research question four has been answered, "Are current and planned wind turbine farms on suitable areas according to the open data available?". For this research question, it should be noted that the plans are not the actual plans of the countries but rather the plans according to the available open data. This research question compared the current and planned wind turbine farms (Appendix XI) to the model with all available data (Appendix IX). Since there is no dataset containing all wind turbines installed (Zhang et al., 2021), the wind turbine farms are based on the open data found for research question 2.

In order to answer research question four, the steps shown in figure 4 were taken. Appendix V contains a more elaborate explanation for the exact reproduction of this research question. The 'Unsuitable areas with EEZ' are used as an input (pre-processing of paragraph 3.4).

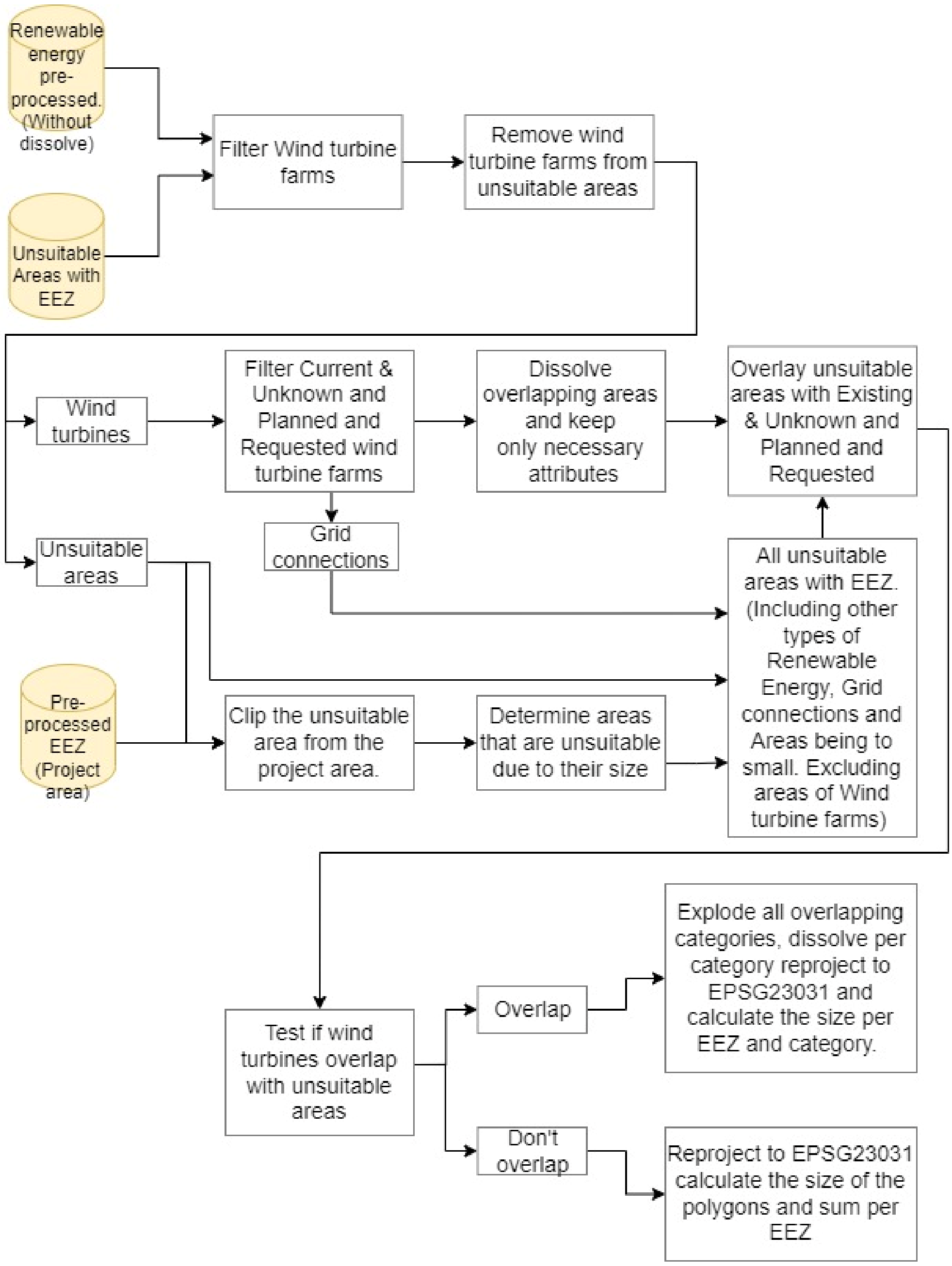


Figure 4 The processing of the data to answer research question 4.

In order to answer research question 4, the wind turbine farms were removed from the unsuitable areas (Figure 4). The current and planned wind turbine farms were separated from each other and dissolved per current and planned. They were then overlayed with the unsuitable areas. Consisting of all categories except the renewable energy category but including the grid connections from the renewable energy category. The size of the suitable areas was calculated, and areas smaller than one square kilometre were deemed unsuitable. Spatial overlap between unsuitable areas and the current and planned wind turbine farms was checked. In case of overlap with influencing factors, the influencing factors were dissolved per category and reprojected to EPSG:23031. Then the sizes of the current and planned wind turbine farms with overlap were calculated per category. For the planned or current wind turbine farms that did not overlap with suitable areas, the data was projected to EPSG:23031, the sizes were calculated and summed per EEZ.

4. Results

This chapter shows the results of the research. Research question 1 is answered within paragraphs 4.1 and 4.2. After this, every research question is covered in a single paragraph.

4.1 Influencing factors

When constructing offshore wind turbine farms, multiple influencing factors should be considered because they influence the suitability of the installation of a wind turbine at a location. During this research, they are divided into 6 different topics; The general rules and requirements talk about the installation of wind turbines and rules and regulations that affect this. Environmental factors tell something about the Greater North Sea itself, for instance, the depth. The biotic factors are based on the animals and vegetation living within the Greater North Sea. The anthropogenic factors explain the manmade objects within the Greater North Sea. Lastly, there are human factors which are activities that are taking place and should be considered whilst planning wind turbines.

All countries bordering the Greater North Sea have their own Exclusive Economic Zone (EEZ). Within the EEZ, a country has rights for exploring, conserving and managing the natural resources of the waters and seabed (United Nations, n.d.). Therefore, all countries can decide for themselves whether and where they want to construct wind turbines (Rodrigues et al., 2015). So, the EEZs are important whilst planning for wind turbines and influence the factors that are taken into account.

4.1.1 Rules and requirements

Wind turbine farms are generally purely for generating energy. However, certain other activities are allowed to take place. For instance, ships are allowed to pass through, and fishing is allowed within designated areas. In order to let other activities take place, a minimum distance of 50 meters around a wind turbine should be kept. The minimum distance around a platform accompanying wind turbines is 500 meters (Rijksoverheid, n.d.).

Besides keeping a distance from the installed wind turbines whilst carrying out other activities, there is also a distance between the wind turbines themselves (Esteban et al., 2009). This distance should be kept in mind whilst planning wind turbines. If wind turbines are located too close to one another, this may cause damage to the habitats of the wildlife of the Greater North Sea (elaborated in paragraph 4.1.3) or insufficient power generation due to catching each other's winds. However, if wind turbines are located very far from another, this may cause extra costs for installation because more cables are needed. So, the distance in between wind turbines is essential. However, there is no set rule of the minimum distance to keep. Literature shows minimum distances between wind turbines ranging from 1 kilometre (Rijksoverheid, n.d) to 1.5 kilometres (Salomon et al., 2020) or six times the diameter of the wind turbine (Elkinton et al., 2006), depending on the technology of the wind turbines. Due to technological developments, rules and regulations for the minimum distances are up to change within the upcoming years (Rijksoverheid, n.d.).

The distance that has to be kept between wind turbines can make suitable areas unsuitable due to an area being too small to install a sufficient amount of wind turbines (Salomon et al., 2020). Therefore it is important to determine and evaluate the minimum suitable available space (Rodrigues et al., 2015). If an area can only locate a single wind turbine, this area is not suitable. Because the costs for constructing a single wind turbine and the costs for maintenance will be too high compared to the power generated by the wind turbine. Often a minimum of 40 wind turbines is located within a wind turbine farm (WindEurope Business Intelligence, 2020).

There are multiple factors influencing the cost of wind turbine construction (Elkinton et al., 2006; Kooijman et al., 2001). Further away from the coast or greater depths cause more expensive wind turbine farms due to increased costs for foundations, installations and grid connections (Rodrigues et al., 2015). On the other hand, the farther away from the coast, the bigger the wind turbines can be due to the wind speed. Larger wind turbines can generate more power, so fewer turbines are needed limiting the construction costs. So, sometimes an area farther away from the coast can be more suitable (Sánchez et al., 2019). Figure 5 shows the influence of the distance to shore on the costs and capacity of European offshore wind turbine farms (Rodrigues et al., 2015).

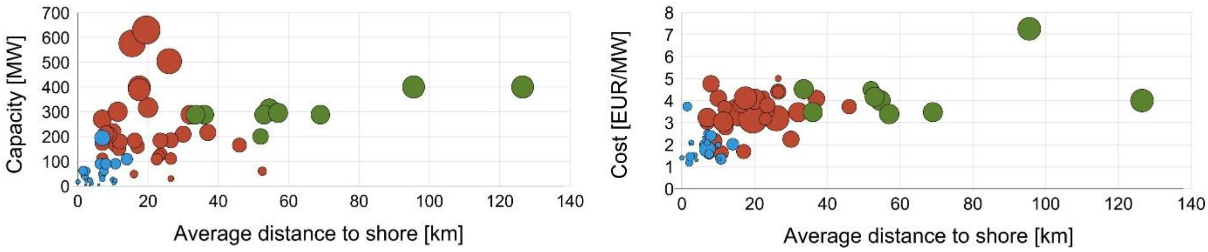


Figure 5 The influence of the distance to shore on capacity and costs for European wind turbine farms projects. The bubble represents the installed capacity of the offshore wind turbine farms (Colours not of importance for this research) (Rodrigues et al., 2015).

To limit the costs, it is important to know the grid connections of other wind turbines. This way, it might not be necessary to create entirely new structures. However, often there is no existing electrical infrastructure close to the location of a new wind turbine farm. Or the maximum capacity of the electricity structure is already reached. Then a new structure must be created, which complicates installation and increases the costs (Sánchez et al., 2019). The type of wind turbine influences the costs for construction as well as the seafloor depth, wave height, seabed and unexpected phenomena (Paragraph 4.2.1) (Sánchez et al., 2019).

Due to the awareness of visual and environmental impacts and the fact that people are less bothered when wind turbines are over 7 kilometres away, a position further from the coast is more suitable (Bishop, 2019; Kondili & Kaldellis, 2012). Therefore, an area of at least 7 kilometres from shore should not be used to locate wind turbines. This distance is often expanded to the 12-mile zone (19.3 kilometres). Since this area is considered a breeding area for birds, a living area for mammals and a tourism zone, it is recommended not to consider this area for wind turbine planning. There are however no restrictions for the use of the area (Elbersen et al., 2005; Kooijman et al., 2001).

4.1.2 Environmental factors

The Greater North Sea consists of several different soil types and types of sediments. Because the Greater North Sea is formed during the Holocene, different types of sedimentation and erosion, have taken place (Ducrotoy et al., 2000). Wind turbines can be installed on soils with the predominant types: Chalk, Clay, Clay/Bedrock, Clay/Gravel, Sand, Sand/Bedrock, Sand/Chalk, Sand/Clay, Sand/Gravel, and Silt. The soil of the Greater North Sea mainly consists of sand and gravel. (Sánchez et al., 2019; Oh et al., 2018). It should be noted that installing wind turbines makes the seabed more prone to erosion since the foundation causes a change in the water flow. However, this is not a problem for most locations within the Greater North Sea (Esteban et al., 2011).

Wind turbines are most commonly installed in waters with depths till 40 meters (Sánchez et al., 2019). However, they can be installed in waters up to 900 meters deep (Hu et al., 2021; Khare et al., 2020). Due to the Greater North Sea having an average depth of 90 meters, it can be assumed that there will be sufficient locations for installing wind turbines (Ducrotoy et al., 2000). Greater depths are associated with higher costs and more complex technologies. Therefore the depth remains an important factor to consider whilst planning for wind turbines within the Greater North Sea. (Dolores Esteban et al., 2015; Rodrigues et al., 2015; Punt et al., 2009; Kooijman et al., 2001).

Another important factor is wave height. This influences the difficulty of installation and maintenance. The higher the waves, the more complex the installation and maintenance becomes (Sánchez et al., 2019; Bredmose & Jacobsen, 2010). A 50-year return period of the wave height is often used when working with the wave height, providing insight into what is considered a normal wave height for an area (Kooijman et al., 2001).

Furthermore, a high and steady wind speed is important to generate the most electricity with a wind turbine. The further away from the coast, the higher and steadier the average wind speed. Due to waters being large continuous areas with no or little disturbance or objects blocking the wind. The higher the wind speed, the bigger the wind turbines can be. So, wind speed is an essential factor whilst determining the optimal location (Sánchez et al., 2019; Eichhorn et al., 2017; Rodrigues et al., 2015; Punt et al., 2009.; Kooijman et al., 2001; Ducrotoy et al., 2000).

Natural phenomena, such as earthquakes, tsunamis or extreme events, should also be taken into account (Sánchez et al., 2019; Esteban et al., 2009). Earthquakes can cause severe damage to wind turbines, especially if this happens whilst in operation (Mo et al., 2017). It is relatively unknown what seismic values a wind turbine can handle. Since this is dependent on the type of wind turbine, different soil layers, the material of the wind turbine and the motion of the water (Kim et al., 2014). Extreme events have the same influences as earthquakes. It is not needed to account for tsunamis within the Greater North Sea since the last record of a notable tsunami was over 8 000 years ago (Chacón-Barrantes et al., 2013).

4.1.3 Biotic factors

The first biotic factors to consider are birds, their habitats, feeding areas, breeding areas, and migration corridors. There are chances of birds getting killed by the rotor blades of wind turbines. There are approximately 0.02-0.6 fatal collisions per wind turbine per year when using careful planning strategies (Mathew, 2006). Raptors have the highest chances of being killed by a wind turbine due to their slow manoeuvring (S. Wang & Wang, 2015). Avoiding well-known bird locations sites is of importance whilst planning wind turbines (Mathew, 2006). Besides fatal collisions, there are also chances of the disappearance of the birds due to habitat loss or drastic change of the habitat (Drewitt & Langston, 2006). Since it is complicated to know the exact habitats of animals, and habitats are prone to change, a distance function is often used as a criterion. Distance is then used as an indicator to avoid conflicts. So, the further away from a known breeding or living area, the better (Eichhorn et al., 2017).

Another factor to keep in mind are bats. Even though it is often forgotten, bats fly above the Greater North Sea (Arnett et al., 2016). Similar to birds, there are chances of fatal collisions. The chances of bats having a mortal collision with a wind turbine are higher than for birds, especially whilst the bats are migrating (Eichhorn et al., 2017; S. Wang & Wang, 2015). To limit the mortal collusions with bats, Dutch and Belgian offshore wind turbines are only allowed to rotate twice per minute during the night within the migration season, from 15 March till 30 June and from 15 August until 30 October. However, this is not the most optimal solution since bats are considered to be active during the entire season at the coast (Lagerveld et al., 2017).

Installing wind turbines also has effects on mammals and fish. The construction of wind turbines causes for the behaviour of marine mammals and fish to change over several kilometres distance (Kondili & Kaldellis, 2012). Not only the installation affects the fish and mammals. After installation, there will be more underwater noise coming from the rotation of the blades, making it harder for mammals to communicate via their acoustic signals and damaging their hearing (Kondili & Kaldellis, 2012; Thomsen et al., 2006). The electromagnetic fields from the cables may influence the fishes capabilities to orientate correctly (Öhman et al., 2007).

Therefore, the most important living areas of mammals and fish should be avoided as much as possible.

Vegetation is also an important factor to keep in mind whilst performing offshore spatial planning. Different kinds of seaweed are prone to extinction and therefore should be protected. However, there are also a lot of alien seaweeds introduced over the past years, which are not specifically to be protected for seafloor disruption (Ducrotoy et al., 2000).

The last biotic factor to keep in mind is plankton. Plankton is the basis of the food network within the Greater North Sea. Fish consume plankton as their primary source of food within the shallow waters (Ducrotoy et al., 2000). The Continuous Plankton Recorder (CPR) has been observing the amount of plankton within the Greater North Sea for a long time and states that due to climate change, plankton is disappearing (CPR, n.d.). Wind turbines account for their disappearance even further since a wind turbine affects the plankton over approximately 10 to 20 kilometres due to the interaction between turbulence and the growth of plankton (T. Wang et al., 2018; Carpenter et al., 2016; van der Molen et al., 2014).

Areas with unique nature or where unique animals live are protected by law and, therefore, unsuitable for wind turbines (Ehler & Douvre, 2009; Rijksoverheid, n.d.). The European Union has created protected areas, more commonly known as the Natura2000 framework. Those areas are valuable and vulnerable (Eichhorn et al., 2017). The Natura2000 areas are based on the EU Habitat and Bird Directives. It also covers the Particularly Sensitive Sea Areas (PSSA), like the Wadden Sea. The PASSA are formulated by the International Maritime Organisation and are officially protected areas (Suárez de Vivero et al., 2009). Furthermore, countries can assign other nature and species conservation sites and protected areas themselves (European Union, 2014). Wind turbines can’t be located in any of the protected areas (Jentoft & Knol, 2014).

Besides all negative influences, wind turbines can have a rather limited positive influence on nature within the Greater North Sea. They can function as artificial reefs and no-fishing zones and with that being suitable areas for mussels to grow and protecting fishes from the fishery. With that, wildlife can be enriched and wind turbines have a positive effect on biodiversity (Petersen & Malm, 2006).

4.1.4 Anthropogenic factors

First of all, there are already existing offshore wind turbines and other types of renewable energy parks (Rodrigues et al., 2015). According to UNESCO's offshore spatial planning rules (Ehler & Douvre, 2009), all other types of renewable energy sources are deemed unsuitable to combine with new wind turbine farms. Meaning that if there is already a type of renewable energy at a location, new sources can’t be added. However, old structures of monopiles can be used for constructing new (more substantial) rotor parts.

Furthermore, protected archaeological areas and submerged archaeological sites should be taken into account (Ehler & Douvre, 2009). These are areas with shipwrecks, unexploded ordnance (Rodrigues et al., 2015) or types of cultural heritage (European Union, 2014). Which, due to their status or danger, cannot be combined with the construction of offshore wind turbines (Ehler & Douvre, 2009).

Lastly, cables and pipes have been installed in the Greater North Sea’s seabed. Those cables and pipes are, for instance, coming from other wind turbine farms or oil platforms. Areas with cables and pipes cannot be used for locating wind turbines due to possible damaging (European Union, 2014; Rijksoverheid, n.d).

4.1.5 Human factors

Shipping routes are essential for the economics of a country. The Greater North Sea contains one of the most intense shipping routes in the world since it navigates to major ports such as

Humber complex, Le Havre, Rotterdam and Hamburg (Ducrotoy et al., 2000). The shipping routes cannot be relocated due to water depth or locations of harbours. Therefore, they should be taken into account whilst planning wind turbines. Similar to the harbour entrances or other harbour activities. Since it is impossible to relocate an entire harbour, the areas are unsuitable for wind turbine planning (Sánchez et al., 2019; Kooijman et al., 2001 Rijksoverheid, n.d.;).

Another important and well-known activity is fishing. There are different kinds of commercial and recreational fishing taking place within the Greater North Sea. All kinds of fishing are classified as unsuitable in combination with offshore wind turbines by the spatial planning guidelines of UNESCO (Ehler & Douvre, 2009). The Greater North Sea has one of the most active fisheries in the world. The European Union has made rules and regulations to limit the number of fishery removals. Fishing is only allowed within the designated areas, managed by the Food and Agriculture Organisation (FAO) and the ICES (Suárez de Vivero et al., 2009). Even though those areas may change over time and areas within wind farms can be used for fishing when multi-use is assumed. It is important to keep the current boundaries into account whilst planning for new wind turbines (Rodrigues et al., 2015; European Union, 2014; Kooijman et al., 2001; Ducrotoy et al., 2000).

Besides fishing, aquaculture takes place (European Union, 2014). A minor activity compared to fishing with Norway, Scotland, France, and the Netherlands as the main performing countries. The primary cultivations are shellfish, salmon, trout, oysters, scallops, and blue mussels. Besides fish, there is also aquaculture taking place for seaweeds (Ducrotoy et al., 2000). Seaweed farming is an example of an upcoming profession, with a current production of 1 500 tonnes (Van den Burg et al., 2021).

Furthermore, there are military activity zones, with activities such as training, flying or other military operations. It is not allowed to perform other activities within those areas due to safety reasons. Therefore, they can´t be used to construct wind turbines (Rodrigues et al., 2015; European Union, 2014; Kooijman et al., 2001).

Other than that, there are installations and infrastructures for the exploration, exploitation and extraction of oil and gas, sand lease, concession areas or other types of raw material extraction areas. Over the past years, infrastructures have been created to extract materials from the Greater North Sea. Some of them are temporary or floating, and others have a permanent function. Areas that are used for extraction cannot be used for locating wind turbines (Rodrigues et al., 2015; European Union, 2014; Ducrotoy et al., 2000).

Within the Greater North Sea, there are also scientific research areas. The areas can vary over time, but there are also stationary research areas. The stationary research areas should be considered whilst planning for wind turbines (European Union, 2014; Ehler & Douvre, 2009).

The second last activities are tourism and recreation, which are important for the economics of a country. Due to danger, all locations near offshore wind turbine farms are deemed unsuitable for tourism according to UNESCO's marine spatial planning rules. Therefore, it is important to avoid areas with tourism and recreation whilst planning wind turbines (Ehler & Douvre, 2009). The most common locations of tourism and recreation are within the 12-mile zone of a country or at beaches. So, a minimum distance of 12 miles (19.3 kilometres) from shore can’t be used for constructing wind turbines (European Union, 2014; Ducrotoy et al., 2000).

Lastly, there are limited numbers of religious areas that should be taken into account whilst planning for wind turbines. These are ceremonial sites, sites for collecting materials for ceremonies and taboo areas which have to be avoided (Ehler & Douvre, 2009).

4.2 Plans, rules, and regulations

All countries have different plans, rules and regulations on the amount of wind energy they want to produce onshore and offshore. Table 2 shows the differences in planned production for the countries in 2050[2]. The United Kingdom plans the highest generation offshore wind turbines and only limited generation onshore (Table 2). Germany, on the other hand, has planned most power generation onshore. Overall, the most limited power generation is planned by Belgium because it has the fewest inhabitants and it is a small country with limited space at sea. A total of 600GW of wind turbines need to be installed to produce 2 015 TWh, which is half of the assumed consumed electricity in 2050 (Paragraph 2.2). Other renewable energy sources will generate the remaining 2 015 TWh.

Table 2 Onshore & offshore wind turbine planning plan 2050 (onshore Nghiem & Pineda, 2017, offshore Freeman et al., 2019).

	Onshore[3]	Offshore[4]	Total capacity	Percentage offshore
North Sea[5]		212 GW		
European plans[6]	250 GW	450 GW	700 GW	64.3 %
Belgium	4.4 GW	6 GW	10.4 GW	57.7 %
Denmark	5 GW	35 GW	40 GW	87.5 %
France	36.4 GW	57 GW	93.4 GW	61.0 %
Germany	70 GW	36 GW	106 GW	34.0 %
Norway	10 GW	30 GW	40 GW	75.0 %
Sweden	12 GW	20 GW	32 GW	62.5 %
The Netherlands	8 GW	60 GW	68 GW	88.2 %
United Kingdom[7]	15 GW	80 GW	95 GW	84.2 %

Countries are allowed to make their own rules and regulations regarding wind turbine planning. But the European Union has made a roadmap indicating how to perform marine spatial planning, based on the 12 main categories from UNESCO (Schaefer & Barale, 2011; Ehler & Douvre, 2009). Countries can decide whether they want to consider a category whilst planning wind turbines or not (Table 3). When looking at the different categories countries take into account (Table 3), it **s**hows a difference between the countries that are a member of the European Union and the countries that are not (England, Norway, and Scotland). Countries that are not a member of the European Union account fewer influencing categories (Freeman et al., 2019).

[2] Based on the Wind Europe Scenario for 2030, since the European 2050 scenarios only specify offshore wind turbines per country. However, the 2030 Wind Europe Scenario Central assumes similar onshore wind turbine generation in 2030 (253GW) as the European scenario in 2050 (250GW) (Nghiem & Pineda, 2017).

[3] The total amount of wind energy listed for the Greater North Sea countries (160.8GW) does not add up to a similar value as the European plans (250GW). This is because the plans are for all European countries and not just the countries bordering the Greater North Sea.

[4] The offshore generation of energy does not add up to the planned 212GW but results in a total of 324. Because Freeman et al., (2019) makes use of the North Sea borders. Excluding Sweden, France and Denmark.

[5] Plan for offshore wind turbine generation for just the waters of the North Sea (Freeman et al., 2019).

[6] European plans for generation of wind energy by 2050 (Freeman et al., 2019)

[7] England & Scotland

Table 3 Overview of the designated uses that are taken into account whilst doing marine planning per bordering Greater North Sea country[8].

	Aquaculture	Fishery	Military	Mineral extraction/Aggregates	Nature protection	Renewable energy production	Oil and gas exploitation	Scientific research	Shipping & Ports	Submarine cables and pipelines	Tourism	Underwater cultural heritage
European Union	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Belgium	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Denmark	✓	✓		✓	✓	✓	✓		✓	✓	✓	
United Kingdom	✓	✓	✓	✓	✓	✓	✓		✓	✓		
France	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Germany	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Netherlands	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
Norway		✓			✓	✓			✓	✓		
Scotland	✓	✓	✓	✓		✓	✓		✓	✓	✓	
Sweden	✓	✓		✓	✓	✓	✓		✓	✓	✓	

4.3 Available Data

Paragraph 4.1 provides a list of influencing factors to take into account whilst planning wind turbines in the Greater North Sea. The influencing factors influence the suitability of an area to locate wind turbines. Open geospatial data is searched to take all influencing factors into account whilst modelling the suitable areas.

Table 4 provides an overview of the available data per country. A check means data is found, the data can consist of different or multiple datasets (Appendix VI). Data on most influencing factors is found for Belgium (37), followed by the Netherlands (35), Denmark (34), Germany (34), The United Kingdom (England and Scotland both 32), France (31), Norway (31) and fewest datasets were found for Sweden (26) (Table 4). There is no difference between countries that are a member of the European Union and countries that are not.

[8] Sources; Belgium, Germany, England, Scotland and The Netherlands (Countries page on; European MSP Platform, 2021), Denmark (Danish Maritime Authority, n.d.), France (Ministere De La Transition Ecologique, 2017) Europe and Norway (Scheidweiler & Grundmann, 2019)

Table 4 Overview of the datasets found per bordering Greater North Sea country [9].

	Category[9]	Belgium	Denmark	France	Germany	Netherlands	Norway	Sweden	UK – England	UK - Scotland
Datasets available (out of 46 influencing factors)		37	34	31	34	35	31	26	32	32
Borders of the Greater North Sea	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Exclusive Economic Zones (EEZ)	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
12-Mile zone	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Soil type	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Seafloor depth	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Wave height	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Windspeed	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Earthquakes	-	✓								
Aquaculture (Finfish)	A	✓	✓				✓			✓
Aquaculture (Shellfish)	A	✓	✓	✓		✓	✓	✓	✓	✓
Aquaculture (Plants)	A									
Fishing hours	F	✓	✓	✓	✓	✓	✓	✓	✓	✓
Military activities	M	✓			✓	✓				
Unexploded ordnance (Munition)	M	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dredging (spoil disposal sites)	MEA	✓	✓	✓	✓	✓	✓	✓	✓	✓
Aggregates	MEA	✓	✓	✓	✓	✓			✓	✓
Sand and gravel extraction	MEA	✓		✓		✓				
Marine protected areas	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Unique habitats	N	✓	✓	✓	✓	✓	✓	✓	✓	✓

[9] Based on the list of twelve categories from UNESCO and the European Union (Schaefer & Barale, 2011; Ehler & Douvre, 2009). With the options Aquaculture (A), Fishery (F), Military (M), Mineral extraction/aggregates (MEA), Nature protection (N), Renewable energy production (REP), Oil and gas exploitation (OGE), Scientific research (SR), Shipping & ports (SP), Submarine cables and pipelines (SCP), Tourism (T) and lastly underwater cultural heritage (CH). No indicates that there is no category available.

Benthos	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Birds	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mammals	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Phytoplankton	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reptiles	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Zooplankton	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fish	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Vegetation (Seagrass)	N	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bats	N									
Offshore energy (wind)	REP	✓	✓	✓	✓	✓	✓	✓	✓	✓
Offshore energy (other)	REP								✓	✓
Grid connections (landing stations)	REP	✓	✓	✓	✓	✓	✓	✓	✓	✓
Oil and gas platforms	OGE		✓		✓	✓	✓		✓	✓
Exploitation licences	OGE		✓	✓	✓	✓	✓		✓	✓
Fossil fuel resources	OGE		✓			✓				
Scientific research areas	SR									
Measuring location	SR	✓						✓		
Shipping routes	SP	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ports	SP	✓	✓	✓	✓	✓	✓	✓	✓	✓
Power Cables	SCP	✓		✓	✓	✓	✓			
Telecommunication cables	SCP	✓		✓	✓	✓	✓			
Pipelines	SCP	✓	✓		✓	✓	✓		✓	✓
Tourism	T									
Shipwrecks	CH	✓	✓	✓					✓	
Cultural heritage	CH		✓							
Religious areas	CH									
Lighthouses	No	✓	✓		✓	✓			✓	✓
Radar tower	No	✓								

When looking at the datasets obtained, it shows that the findability was best for the borders and administrative factors (Table 4). This has to do with the fact that those areas are defined with all countries together and data is shared by at least one of the countries. The findability was lower on specific influencing factors for a country, such as cultural heritage or military areas. Since not all countries collect this data or are willing to share it. There are also influencing factors such as scientific research areas or religious areas that do not have a defined border therefore, no data is available.

Appendix VI contains a more detailed overview of the acquired data with sources, dates, and type of dataset. It shows that most sources, a total of 35, are available as a WFS. Since working with a WFS does not require a download, WFS data was searched first. There are 9 datasets consisting of CSV files containing coordinates, 8 Shapefiles, 5 Geodatabases, 2 GeoTIFFs and 1 ASC file. One source can consist of multiple data types and multiple influencing factors. There are a total of 25 polygon datasets, 28 point datasets, 6 line datasets and 4 grids.

Appendix VII explains why certain datasets are used, providing the following results. Open data is not always as precise as other datasets. For some datasets, there was more precise data available. However, this data was paid or did not overlap the entire study area, but less precise data did. It also shows that sometimes data does exist but is not freely available. For instance, when it was used during research or governmental project or created by a company. In some cases, data was available on a website, but it was not possible to download. Once the source was requested for download or use, it did not work or did not provide the correct data. Lastly, it shows that the trustworthiness of open data remains doubtful. When multiple datasets were obtained, they showed different areas for the same influencing factor, in some cases, which means that some of the datasets are incorrect, but it remains unsure which are correct and which are not.

4.4 Suitable areas

For the third research question, "What areas would be deemed suitable if only open data would be used for wind turbine planning? And how do those areas change when taking countries rules and regulations into account?" the suitable areas are determined. This is done with all available data (Paragraph 4.4.1) and whilst taking the rules and regulations (Table 3) into account[10] (Paragraph 4.4.2).

The suitable areas are determined by performing an intersection over union with all influencing factors (Paragraph 3.3), assuming that the presence of an influencing factor results in the area becoming unsuitable. This results in the area consumption per category, as shown in table 5. It should be noted that there is overlap with the space consumption of the categories. It can be stated that Nature Protection is by far the biggest category that influences the suitability for wind turbines in the Greater North Sea based on the open data available. Scientific research is the smallest category due to a lack of data. Appendix VIII contains maps of how all categories are spread throughout the Greater North Sea.

There is a difference of 26 300 square kilometres in space consumption when taking or not taking the rules and regulations into account (Table 5). The differences are within the categories of military, mineral extraction/aggregates, oil and gas exploitation, scientific research and cultural heritage. Oil and gas exploitation has a big difference because Norway does not take this into account whilst performing marine spatial planning (Table 3), and the area for Norway is 41 601 square kilometres (Appendix VIII).

[10] Not all countries take all categories into account, so when focussing on the rules and regulations a larger area becomes suitable.

Table 5 Area consumption per category, based on the open data available. With or without taking the rules and regulations of table 4 into account.

Category	**Space consumption (Km^2)[11]**	**Space consumption (Km^2) with rules and regulations[11]**
Study area	671 202	671 202
Aquaculture	2759	2759
Fishery	188 871	188 871
Military	15 469	15 425
Mineral extraction/aggregates	23 001	22 990
Nature protection	395 859	395 859
Renewable energy production	32 519	32 519
Oil and gas exploitation	129 291	87 690
Scientific research	0.4	0.002
Shipping and ports	130 863	130 863
Submarine cables and pipelines	11 849	11 849
Cultural heritage	164	17
No category[12]	193 471	193 471
All categories combined[13]	**567 759**	**541 469**
Available space	**103 443**	**129 733**

4.4.1 Suitable areas with all available data

When looking at the suitable areas for wind turbines using all open data obtained (Table 4), 103 202[14] square kilometres is available for wind turbine planning (Figure 6 or Appendix IX). Most of the available spaces are in the Northern parts of the Greater North Sea, especially the water of Norway has a lot of available space (Figure 6). For the centre of the Greater North Sea, the water of the United Kingdom has the most space available for wind turbine planning.

The waters of Denmark, Sweden, the Netherlands, and Belgium only leave for a very limited amount of suitable space (Table 6). Belgium, France, Germany, Sweden and the Netherlands do not have sufficient suitable space available to locate all planned wind turbine farms[15] (Table 6). The total available space is sufficient to reach the renewable enery goals. So, when countries would collaborate, it is possible to reach all renewable energy goals.

[11] Whilst considering the available data of a certain category (Table 4), the assumptions of paragraph 3.4 and rules and regulations (Table 3).
[12] Lighthouses, Radar Towers, Earthquakes and the 12-Mile zone.
[13] All categories dissolved into a single area and then calculated. So, not all categories summed.
[14] This is 241 km^2 less than mentioned within table 5. Since later (as explained within the methodology of paragraph 3.4.2) areas of <1km^2, and areas that are too deep are deemed unsuitable.
[15] It should be noted that some of the plans for offshore wind turbine planning have already been performed. Those areas have been deemed 'unsuitable' because there is already data in the category 'renewable energy'. So, it is possible that a country has already reached (part of its) goals so, not all space that stated is still needed.

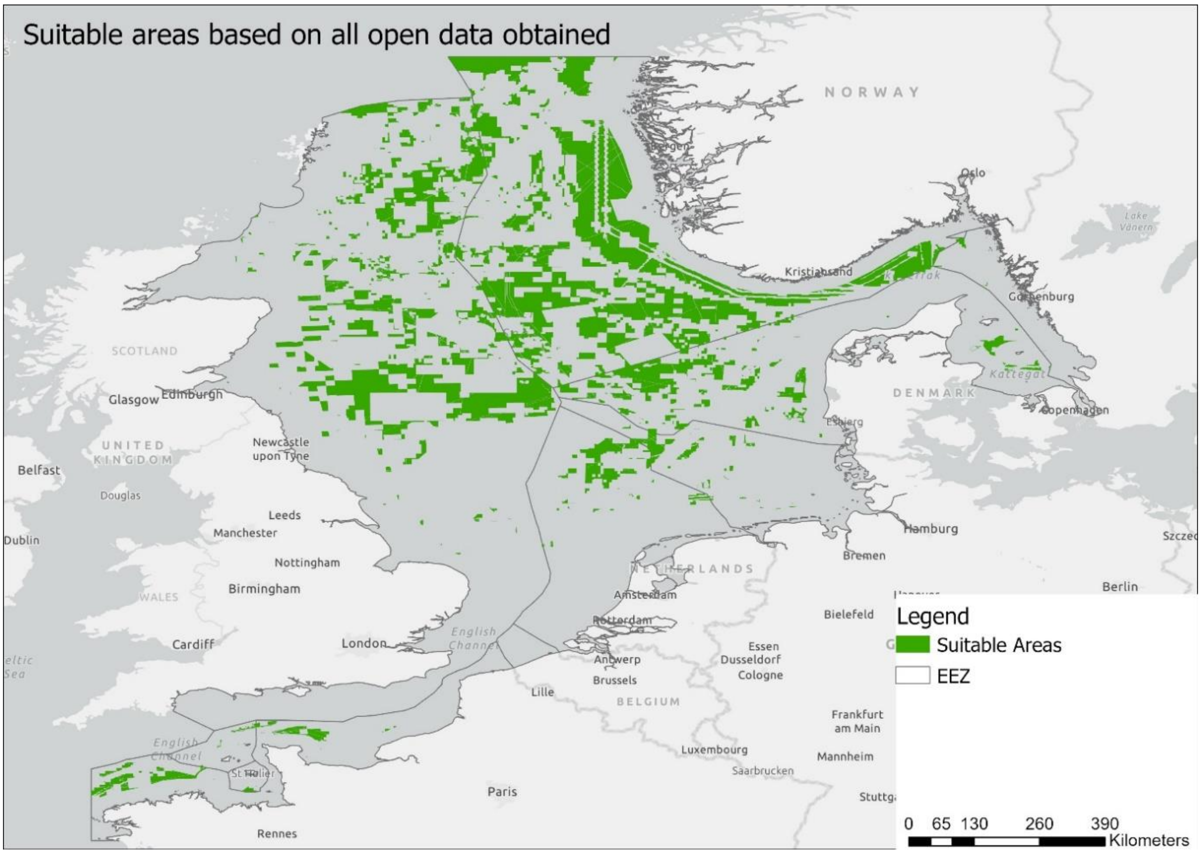


Figure 6 Map of the suitable areas based on all open data available. (Enlarged in Appendix IX)

Table 6 The available space per EEZ, when taking all available data into account [16].

EEZ	Total space EEZ (KM^2)	Available Space (Km^2)[17]	Planned space (KM^2)[18]
North Sea[19]	671 202	103 203	33 125 (212 GW)
Belgium	3 492	0	938 (6 GW)
Denmark	76 398	9 379	5 469 (35 GW)
France	41 598	3 158	8 906 (57 GW)
Germany	41 296	1 650	5 625 (36 GW)
Norway	155 836	50 350	4 688 (30 GW)
Sweden	14 186	112	3 125 (20 GW)
The Netherlands	64 292	3 350	9 375 (60 GW)
United Kingdom[20]	273 962	35 203	12 500 (80 GW)

[16] It should be noted that some of the plans for offshore wind turbine planning have already been performed. Those areas have been deemed 'unsuitable' because there is already data in the category 'renewable energy'. So, it is possible that a country has already reached (part of its) goals so, not all space that stated is still needed.
[17] Within the EEZ of a country, based on the available open data.
[18] Space calculated by multiplying the GW with 1000 and dividing by 6.4MW/km^2 (Ruijgrok et al., 2019). Planned space is based on research of Freeman et al., (2019).
[19] Plan for offshore wind turbine generation for just the waters of the North Sea not the Greater North Sea (Freeman et al., 2019).
[20] England & Scotland.

The seafloor depth, wave height, windspeed and costs are also important influencing factors for determining the suitability of an area (Paragraph 4.1). Appendix X shows maps of the suitable areas enriched with data on those topics. It shows that most of the suitable areas are at the deeper waters, the Norwegian part of the Greater North Sea. However, research showed that waters with a depth of 900meters can be used for wind turbines (Hu et al., 2021; Khare et al., 2020). None of the suitable areas are deeper than 900meters. The suitable spaces in front of the French and Danish coast have high higher levels of kinetic energy but lower installation costs. The centre of the Greater North Sea has the highest wind speed making it most suitable based on that factor, but it has higher installation costs due to the distance to the coast (Appendix X).

4.4.2 Suitable areas when taking rules and regulations into account

When taking the rules and regulations of the countries (Table 3) into account, 129 495 km^2 is available for wind turbine planning[21]. So, an extra 26 293 km^2 becomes suitable because not all countries consider all categories whilst planning for wind turbines. The differences are within the waters of Norway (26 291 km^2) and Denmark (2 km^2) (Table 7).

The extra suitable space in the waters of Norway is spread over the West and central side of the waters (Figure 7). The fact that more space becomes available in Norway might have to do with the fact that Norway is not a member of the European Union and therefore uses other categories to plan for wind turbine farms. The differences of Denmark are minor and therefore not clearly visible on the map. They have to do with the fact that underwater cultural heritage and military activities are not taken into account. Since no areas with military activities are found as open data for Denmark (Table 4) and the cultural heritage areas are minimal (Appendix VIII), the differences do not show.

For the other countries, the excluded categories do either overlap with other categories that are still taken into account or no data was found on the excluded categories, so no more space becomes available. For this research question, it should be noted that the suitable areas would've been different when data on all influencing factors were found (Table 4). There are countries not taking all categories into account (Table 3), but if no data was obtained for a category, this difference will not show since there is no data available to make the area unsuitable in the first place.

[21] This is 2 233 square kilometres less than previously mentioned in table 5. Because later areas of <1km^2 and areas that are too deep are deemed unsuitable (Paragraph 3.4).

Table 7 Overview of the difference of taking rules and regulations into account per country. (The area becomes larger due to not all countries considering all activities whilst performing marine spatial planning table 3)

	Total space EEZ (KM^2)	**Suitable area based on available data (Km^2)**	**Suitable area with rules and regulations (Km^2)**
North Sea	671 202	103 202	127 500
Belgium	3 492	0	0
Denmark	76 398	9 379	9 381
France	41 598	3 158	3 158
Germany	41 296	1 650	1 650
Norway	155 836	50 350	76 641
Sweden	14 186	112	112
The Netherlands	64 292	3 350	3 350
The United Kingdom	273 962	35 203	35 203

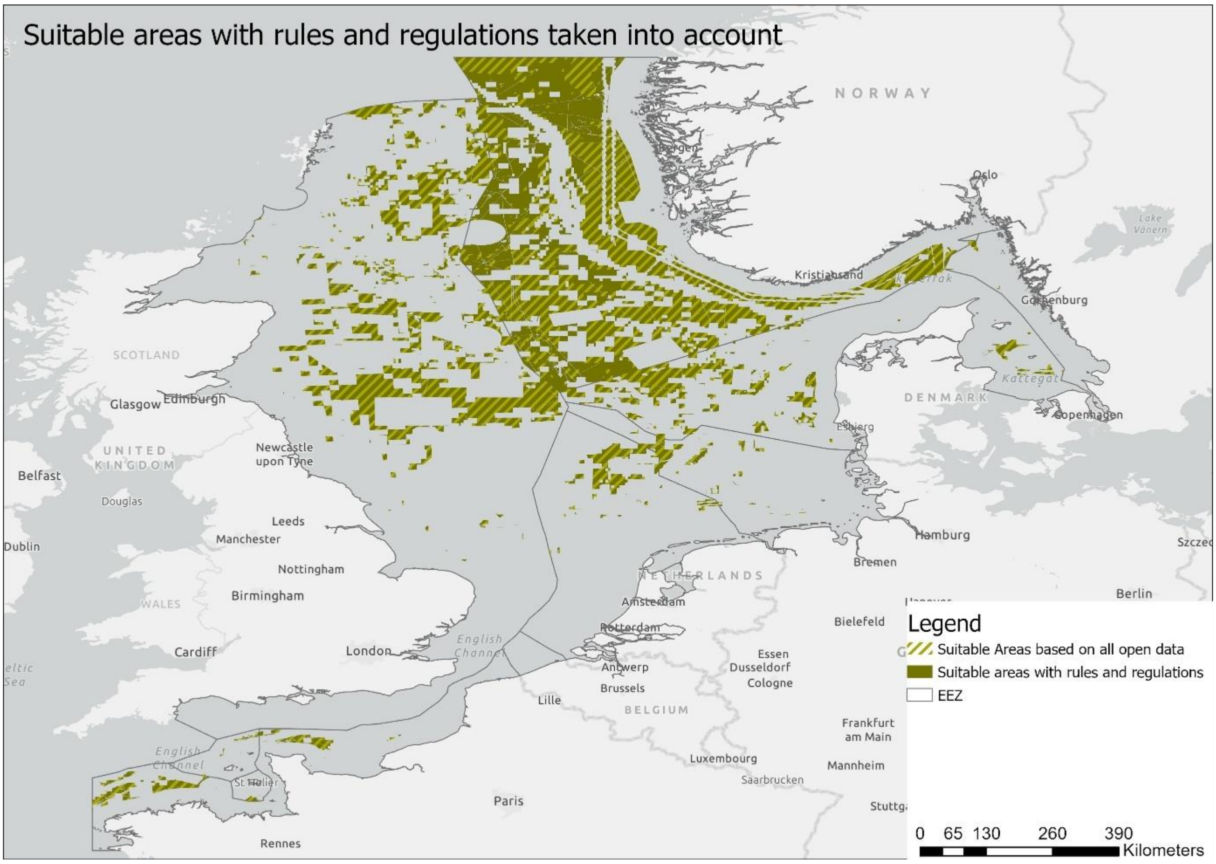


Figure 7 The Suitable areas when taking the rules and regulations into account (table 3). In green, the suitable areas when taking the rules and regulations into account, overlined with the suitable areas based on all open data available.

4.5 Suitability for the current and planned wind turbine farms

Research question four, "Are current and planned wind turbine farms on suitable areas according to the open data available?" is answered to check how the created model relates to the models that countries use to plan wind turbine farms. Data from current and planned wind turbine farms was overlayed with data from the unsuitable areas.

The overlay performed results in an overview of wind turbine farms and the categories they overlap with. This paragraph is split into two parts. First, the overlap of influencing factors with current wind turbine farms is shown. Next, the overlap of influencing factors with planned wind turbine farms is elaborated. For this research question, it should be noted that multiple datasets (Appendix VI) gave different values of current or planned to the same wind turbine farms. Since correctness of the data is assumed, a single wind turbine farm can be within both categories, current and planned (Appendix XI).

4.5.1 Current wind turbine farms

When comparing the current wind turbine farms[22] to the unsuitable areas, according to all data obtained during this research, it has the following results. Most of the current wind turbine farms (77%) are on unsuitable areas (Table 8), according to the current assumptions of the model that if there is an influencing factor located, an area becomes unsuitable.

According to the data, there is a total of 16 062.1 square kilometre wind turbine farms currently in use. Only 3 704 square kilometres (23%) of those wind turbine farms are on suitable areas (Table 8). Belgium, Sweden and the Netherlands do not have any of their current wind turbine farms on suitable areas. Norway performs best by having 64% of its current wind turbine farms on suitable areas. For France, no data on current wind turbine farms was obtained.

Table 8 Comparing the current wind turbine farms[23] to the unsuitable areas according to the open data available.

Country	Size current wind turbine farm (Km^2)[23]	Km^2 on suitable area	Km^2 on unsuitable area
Belgium	194	-	194
Denmark	312	104	208
France [24]	-	-	-
Germany	897	2	895
Norway	5 146	3 293	1 853
Sweden	0.1	-	0.1
The Netherlands	196	-	196
United Kingdom	9 317	303	9 014
Total	16 062.1	3 704	12 358.1

When looking at the categories, the current wind turbine farms overlap with most, nature protection is in the highest-scoring categories for all countries except Denmark (Table 9). It should be noted that a wind turbine farm can overlap with multiple categories since multiple activities can take place within a single area. Besides that, overlap can also come from multi-use with wind turbine farms. In that case, wind turbines are constructed in a way to ensure that

[22] The current wind turbine farms based on the open-data available and obtained during this research (Table 4).
[23] The current wind turbine farms based on the open-data available and obtained during this research.
[24] According to the data France does currently not have any wind turbines within the waters of the Greater North Sea. They do have areas planned for wind turbine development.

other activities can take place. For instance, shipping can take place if wind turbines have sufficient space in between.

Another category with a high level of overlap is the category other (Table 9). This category contains light houses, radar towers, earthquakes and the 12-mile zone. Especially with the 12-mile zone, there is overlap with current wind turbine farms. This is because installing wind turbines closer to the coast is cheaper, and older technologies do not allow for installation in deeper waters.

Table 9 How much the current wind turbine farms overlap with the data of a category. In bold are the three categories with the most overlap.

Category (Km^2)	**Belgium**	**Denmark**	**Germany**	**Norway**	**Sweden**	**The Netherlands**	**United Kingdom**
Aquaculture	50	-	-	-	-	-	0.05
Fishery	**194**	-	154	10	-	33	**3027**
Military	0.05	-	141	-	-	-	0.3
Mineral extraction/aggregates	0.3	-	**892**	-	**0.1**	59	68
Nature protection	**194**	**7**	**680**	**960**	**0.1**	**196**	**8632**
Renewable energy production	-	-	-	-	-	-	-
Oil and gas exploitation	-	0.05	2	**266**	-	59	1932
Scientific research	-	-	-	-	-	-	-
Shipping & ports	**187**	**71**	**495**	146	**0.1**	**70**	1251
Submarine cables and pipelines	9	0.01	56	21	-	40	82
Tourism	-	-	-	-	-	-	-
Cultural heritage	-	0.3	-	-	-	-	-
Other	104	**181**	9	**799**	**0.1**	**101**	**2910**

4.5.2 Planned wind turbine farms

According to the data obtained[25] , 21 073.8 square kilometres of wind turbine farms is planned. Of this, 2 765.2 square kilometres (13%) is planned on suitable areas (Table 10), which means that 18 308.6 square kilometre (87%) of the planned wind turbine farms is on unsuitable areas. For Belgium, Sweden, and the Netherlands, this percentage is even 100%. The United Kingdom scores best with only 85% of the planned wind turbine farms on unsuitable areas.

[25] Only for the wind turbine farms for which data was obtained during this research. If no open data was available a plan is not taken into account.

Table 10 Overview of the overlap of planned wind turbine farms with suitable and unsuitable areas according to all open data available.

Country	Planned wind turbine farms (Km^2)[26]	Km^2 on suitable area	Km^2 on unsuitable area	Percentage on unsuitable areas
Belgium	85.2	-	85.2	100%
Denmark	419.8	39.1	380.7	91%
France	454.4	0.004	454.4	100%
Germany	1 173.5	14.0	1 159.5	99%
Norway	574.1	82.7	491.4	86%
Sweden	82.5	-	82.5	100%
The Netherlands	661.3	-	661.3	100%
United Kingdom	17 623.0	2 629.4	14 993.6	85%
Total	**21 073.8**	**2 765.2**	**18 308.6**	**87%**

When looking at the different categories the planned wind turbine farms overlap with[27], the most overlap is with the categories fishery, nature protection and other (Table 11). If all plans are executed, fishers have a problem because their working area will be limited, and nature will be damaged because of the installation of wind turbine farms. When comparing this to the current wind turbine farms (Table 8), unsuitable overlapping categories are similar (Nature protection, Fishery and Other), which means that a similar planning strategy is used for both the current and the planned wind turbine farms.

[26] Plans according to the available open data, not the actual plans of a country.
[27] It should be noted that a wind turbine farm can overlap with multiple categories, since multiple activities can take place within a single area. Besides multiple use with wind turbine farms can take place. So, wind turbine farms might be constructed in a way to ensure that other activities, like shipping, can take place.

Table 11 Overlapping categories of the planned wind turbine farms per country[28]. In bold are the three categories with the most overlap.

Category (Km^2)	Belgium	Denmark	France	Germany	Norway	Sweden	The Netherlands	United Kingdom
Aquaculture	-	-	-	-	38.8	-	-	-
Fishery	**85.2**	25.3	**245.3**	**828.1**	-	0.4	**562.8**	**3651.5**
Military	0.02	-	-	38.2	-	-	28.7	0.4
Mineral extraction/aggregates	0.2	10.7	-	**271.5**	-	-	**544.0**	0.7
Nature protection	**85.2**	**145.6**	**241.5**	**771.6**	**185.6**	**78.3**	**597.0**	**13458.6**
Renewable energy production	-	-	-	-	-	-	-	-
Oil and gas exploitation	-	-	-	0.6	34.0	-	172.0	**4786.2**
Scientific research	-	<0.1	-	-	-	<0.1	-	-
Shipping & ports	**84.9**	**59.4**	125.4	157.0	**210.0**	**28.0**	368.5	852.8
Submarine cables and pipelines	5.6	6.2	2.8	47.1	5.0	-	44.9	79.0
Tourism	-	-	-	-	-	-	-	-
Cultural heritage	-	0.6	<0.1	-	-	<0.1	-	-
Other	43.9	**371.9**	**454.0**	0.5	**465.9**	**25.1**	188.8	1935.2

[28] Plans according to the available open data, not the actual plans of a country. It should be noted that a wind turbine farm can overlap with multiple categories, since multiple activities can take place within a single area. Besides multiple use with wind turbine farms can take place. So, wind turbine farms might be constructed in a way to ensure that other activities can take place. For instance, shipping can take place is wind turbines have sufficient space in between.

5. Discussion

The suitable areas are determined based on the available open data. However, it remains unknown whether the areas that are deemed suitable or unsuitable are classified correctly. Therefore, there are some points of discussion that need to be addressed. First, the chosen study area is up for discussion. After that, the points of discussion are ordered per research question. As a final, there are some general points of discussion addressed.

5.1 Study area

There are different definitions of the Greater North Sea. Making the conclusion that it is possible to reach the climate goals by only using suitable areas when countries collaborate unsure. The current research and research of Ductroy et al., (2000) use the definition of the ICES (ICES, 2015) as the definition of the Greater North Sea. Research of Jentoft and Knol, (2014) on marine spatial planning within the Greater North Sea excludes Sweden. Research from Wind Europe on offshore wind energy performed by Freeman et al., (2019) excludes Sweden as well as France. Research by Ruijgrok et al., (2019) on 'Cost Evaluation of North Sea offshore wind post 2030' defines the North Sea as the EEZs of Norway, the United Kingdom, The Netherlands, Denmark, and Germany. Leaving Belgium, France, and Sweden outside the scope of their research. Research from Gusatu et al., (2020) does not consider France. Lastly, the research of Scheidweiler and Grundmann (2019) leaves both Denmark and France outside the scope.

A different definition of the Greater North Sea makes differences in the total summed available suitable space. Since some countries have more space available than others (Table 6), it also makes differences for the needed power generation (Table 2), which influences the conclusions on the possibility to reach the climate goals. Furthermore, it influences the conclusions on the available open data. Since some countries have more data available than others. So, the definition of the study area influences the outcome of the research. However, it does not influence the areas that are deemed suitable since this is determined per country. Since the current research makes use of a larger research area than most researches, it was possible to obtain new insights into how a collaboration of all countries would result in the possibility to research the goals for the production of renewable energy. Creating an added value for the scientific field.

5.2 Influencing factors and rules and regulations per country

Thorough research has been performed on the different influencing factors. Providing an overview of influencing factors from a wind farming point of view rather than a point of view of a single profession. Which is different from other researchers that often base the influencing factors on their profession or the of the planner. This is a way the current research contributes to the scientific field. Even though thorough research has been performed, it can be the case that there are influencing factors missing. If an influencing factor was not a result of the literature research, open data for this influencing factor was not searched. With that, the influencing factor is not taken into account whilst modelling the suitable areas. Since an intersection over union is performed with all data obtained during the research, an influencing factor that was not the result of the literature search is currently not taken into account. Because of that, a suitable area might therefore be classified incorrectly. Since it is seen as suitable because there is no influencing factor but might be unsuitable because an influencing factor was missing during the literature search and, therefore, the data search.

Within the current research, categories are used to group the influencing factors (Table 4). Since the guidelines of UNESCO (Ehler & Douvre, 2009) and research of Gusatu et al., (2019) both used the same categories. However, the research of Gusatu et al. (2019) only defines the 12-mile zones, shipping routes, Natura 2000 areas, oil and gas platforms, cables and pipelines, military areas, and extraction areas for aggregates as unsuitable. Rather than all categories as with the current research, which makes major differences in the outcome of the research since the categories are seen as unsuitable areas. If the same categories as Gusatu et al., (2019) were used for the current research, the suitable areas would increase by several thousand square kilometres (Table 5). The difference in used categories shows that the areas that are categorised as unsuitable are, therefore, up for discussion.

During the current research, costs are not seen as an important influencing factor since they are not used to determine whether or not an area is suitable. However, a lot of research has been performed on the costs of locations for wind turbine farms (Bosch et al., 2019; Green & Vasilakos, 2011). Because costs are important for the planners of turbine farms and the companies constructing them, it is important to include them in feasibility studies. Since the current research focuses on suitable areas and open data, a simple cost model is used because costs do not influence suitability.

5.3 Data collection

The biggest uncertainty of the current research is within the open data. Whilst searching open data it was not possible to find data on all influencing for all countries. As stated within the methodology (Paragraph 3.3), if data is not found according to the search procedure described it was assumed that data was not available. For Sweden only 26 datasets have been found, which is the lowest number of datasets, Belgium had the most datasets with 36. However, data was searched on 46 influencing factors. Because it was not possible to obtain data on all influencing factors for any of the countries there are areas without data but presumably with activities. Areas without any data are currently classified as suitable, assuming that there is no influencing factor at a location. However, influencing factors can be at a location but if there is no data available this influencing factor is not accounted for. This would make the classification of ‘suitable area’ then incorrect, having major influences on the outcome of the current research. The consequence of the lack of open data is that most probably less than 103 202 square kilometres is suitable for wind turbine planning.

Frias et al., (2018) performed research on the data needs and availability for the Baltic Sea. Which is comparable to the current research since the same categories are used. The differences are within the research area and the people performing the research. For the research of Frias et al., (2018) multiple researchers from multiple different nationalities searched open data. Because the researchers had different nationalities it was easier for them to find sources. Due to the researchers having different native languages, making a local search or in-depth read of the description easier. During the current research data was sought by a single person with a Dutch nationality. Making the findability best for data of the Netherlands and Belgium and a little more complex for the United Kingdom and Germany. The findability for data of Norway, Sweden, Denmark, and France was the most complex due to language difficulties. Performing research with people from different countries, with different native languages, would presumably result in more open data. This would benefit the research because more open data makes a more trustworthy model. However, the number of datasets obtained during the research of Frias et al., (2018) does not differ largely from the number of datasets obtained during the current research. The difference in the study area is one of the main contributions to the scientific field of the current research since no research on identifying the data availability for the Greater North Sea had been performed.

Furthermore, it had to be assumed that the available open data is correct and complete. If a dataset on an influencing factor was found the assumption was that the data was correct. However, it often remains unsure if this is the case. Countries and organizations can share incorrect or incomplete data by incidence or because no other data is available. Areas are then classified as suitable or unsuitable incorrectly because of an incomplete or not up-to-date dataset. The incompleteness of data is something that showed up during the current research with some influencing factors (Appendix VII). For instance, on the factor of renewable energy production, the data shared via EMODnet was not complete, when using datasets of other sources, it turned out that there were more wind turbine farms than shared via EMODnet. Furthermore, not all open data was correct since different datasets showed different areas of the current and planned wind turbine farms (Appendix XI). Because it was not always possible to find multiple datasets for an influencing factor. It was assumed that the open data found was complete and correct, but it can be that objects are missing within the dataset. Therefore, areas might have been classified as suitable, whereas this is not the case. Causing severe insecurity of the classified suitable areas.

There were also cases of data that was found during the research but not being available as open data. As such the data may be labelled for internal organisational or governmental use only. The current research focuses on open data. However, if all existing data could be used this would've resulted in different areas being classified as suitable. Since more data would result in more unsuitable areas due to the intersection over union, leaving less suitable areas.

5.4 Suitability model

When modelling the suitable and unsuitable areas the following assumptions were made.

- Inactive objects (for example old oil and gas platforms) can be removed and are therefore suitable for wind turbine planning;
- If only a centre point of an object is available a buffer of the average polygon size represents the unsuitable area (Appendix III);
- Shipping corridors with less than one ship a day can be relocated;
- Areas with above-average fishing hours or above-average wildlife observations are deemed unsuitable, other areas remain suitable;
- Areas with a size of less than one square kilometre are unsuitable;
- Areas deeper than -900 meters are unsuitable for wind turbine planning;
- Grid cells can be resampled to 1kmx1km by using the average 16 resampling technique because it can be used for numeric raster values and produces higher quality images than bilinear and nearest neighbour.

Those assumptions influence what areas are deemed suitable and what areas are not. A sensitivity study can be performed to show the differences per assumption. If other assumptions were made, other areas would have been suitable. Therefore, it must be stated that there is some inaccuracy and uncertainty with the modelling of the unsuitable areas and with that the result of the suitable areas.

Furthermore, it is currently assumed that areas in which other activities take place are completely unsuitable. So, if there is data available on an influencing factor this area is seen as unsuitable. However, there are opportunities of shared spaces with influencing factors and wind turbines, this is called multi-use. An area is then suitable for wind turbines even though other activities are taking place. When creating a MCA values in a range from 0 'suitable' and 1 'unsuitable' can be used to define areas where multi-use can take place. This makes the model less harsh on defining the unsuitable areas. Making use of multiple values rather than suitable (0) and unsuitable (1), will result in different suitable areas.

A recent study by Gusatu et al., (2020) does assume multi-use and with that weights the criteria. They defined multiple scenarios that assume different types of multi-use. The current research does not account for multi-use, if an area is occupied by an influencing factor no wind turbines can be located at that location, an intersection over union is performed. This is done because a weighted MCA is often influenced by the profession or opinion of the researcher. A determination of multi-use and weights of the importance of influencing factors was outside the scope of the current research. Because the potential of multi-use should be researched for all influencing factors from a wind farming point of view which was not possible within the time limitations and because not much research is performed from a wind farming point of view. Furthermore, it requires more knowledge on the positioning, capacity, and density of wind farms with multi-use and on the influence of wind turbines on the categories. Besides, weighted criteria are also influenced by the rules and regulations of different countries. These are formulated differently because not all bordering countries use the same policy and planning strategy. Research of Scheidweiler and Grundmann, (2019) shows differences in planning strategies per country. So, when making weighted criteria all rules and regulations should be taken into account. As research by Schiedweiler and Grundman (2019) shows, not all countries divide categories similarly and make use of the same categories. Making the determination of weighted categories even more complex. It is less reliable and realistic to make an entire area unsuitable when an influencing factor is present as done with the current research. Since for instance, ships are able to navigate between the wind turbines. So, it has to be concluded that more research on multi-use and creating weighted factors for the categories will improve the outcome of the current research.

Another point that is up for discussion with the modelling of the suitable areas is the fact that not all categories have the same number of datasets. For the current research, a non-weighted approach with categories is chosen. However, not all categories have the same number of influencing factors (Table 4), so the number of datasets is not equal. For instance, nature has 10 different datasets and cultural heritage only has 1. Making the non-weighted approach not entirely non-weighted because the input is not equal for all categories. This influences the outcome of the model since the data determines the suitable areas. However, the current research looks from a wind farming point of view and not from a profession. Making the differences in categories less relevant since all categories used do influence wind turbines. For the fourth research question, the results are influenced majorly. Because here the categories are used to check overlap with current and planned wind turbine farms, and the categories are not equal.

When comparing the suitable areas of the current research (Appendix IX) to the results of Freeman et al., (2019) (Appendix XII) there are some outstanding differences and similarities. The similarities are coming from the excluded 12-mile zone, excluded nature protected areas, excluded shipping routes, and excluded cables and pipelines. However, the maps also show differences in suitable space. The current research leaves more suitable space around the Norwegian border. Most probably due to the lack of open data from this country. Freeman et al., (2019) found more suitable space near the coast of the United Kingdom. The area in the centre of the Greater North Sea seems to be more suitable according to the research of Freeman et al., (2019). This is due to the fact that other categories are used to determine the suitability. Looking at the results of Freeman et al., (2019) this also shows a cost factor. Comparing this cost factor to the cost factor used within the current research (Appendix X). It shows that the current cost calculation can be done more detailed and accurate. Because a different approach was used with the current research, no costs could be calculated for the deeper areas. Making use of the same data and techniques as Freeman et al., (2019) would have resulted in a more accurate costs and costs for the entire area. However, the exact technique of Freeman et al., (2019) is not explained within their report. Furthermore, costs are not the main facet of the current research so there was no focus on creating the optimal cost model (Paragraph 3.4).

When comparing the suitable areas of the current research (Appendix IX) to the results of Ruijgrok et al., (2019) (Appendix XII), a couple of things are shown. First of all, Ruijgrok et al., (2019) defines more specific and smaller suitable areas. Besides, there are areas close to the shore deemed suitable within their research. This is not possible within the current research since the 12-mile zone is used as a minimal distance from the shore. Furthermore, Ruijgrok et al., (2019) defines more areas suitable within the waters of the Netherlands and fewer within the Norwegian waters and the waters of the United Kingdom. Ruijgrok et al., (2019) takes the influencing factors oil and gas platforms, fisheries, cables and pipelines, sand mining, military zones, sea mammals, birds, bats, habitats, and shipping routes into account. This is similar to the current research, however for the current research data on 36 influencing factors is obtained. Ruijgrok et al., (2019) collected data on the influencing factors bats and birds which was sought but not obtained during the current research. This might have to do with the fact that a different study area was used or with the fact that data was not found by the search procedure of the current research. A major difference between the research of Ruijgrok et al., (2019) and the current research is the fact that costs and adaptability are taken into account. Using costs and adaptability results in a more specific and reliable outcome, with smaller areas. Within the current research, this has not been taken into account because it focussed more on the findability and possibilities of open data.

The fact that the current study differs from the studies of Freeman et al., (2019) and Ruijgrok et al., (2019) is part of its scientific benefit. The current study views the influencing factors from a wind farming point of view, taking all categories into account. The studies of Freeman et al., (2019) and Ruijgrok et al., (2019) are more influenced by professions and don’t take as many influencing factors into account.

5.5 Current and planned wind turbine farms

In order to evaluate the current and planned wind turbine farms, datasets obtained during a search for open data have been used. These are not the official plans for all countries, since most of them could only be found as images in written reports and not as datasets. Zhang et al., (2021) already showed that there is no global offshore wind turbine dataset. The current research emphasizes the importance of creating this once again. The collected datasets have different areas classified as planned and current (Appendix XI) making the areas unsure. This is a major influence on the results of the current research. Since it remains unsure if the complete and correct wind turbine farms are used to evaluate with the overlapping categories.

The current research showed that some of the planned and currently in use wind turbine farms are on unsuitable areas. However, countries themselves can decide where they want to locate new wind turbine farms. With this decision as many of the stakeholders, nature, costs and other processes are taken into account. Marine spatial planning is a complicated process so sometimes less suitable areas must be used. The current research showed that current and planned wind turbine farms are on ‘unsuitable’ locations. However, throughout research of the countries is performed for example within the ‘Beleidsnota Noordzee’ (Rijksoverheid, 2015) or the ‘Marien Ruimtelijk Plan 2020-2026’ (Federale overheidsdienst, 2019). So, it should be assumed that the current and planned wind farms are thoroughly researched and therefore are on the most suitable areas possible. Therefore, it has to be assumed that weighted factors or other analysis tools are used to determine the locations of wind turbines rather than an intersection over union of influencing factors. This is lacking within the current research because it is complicated to determine the weight of the influencing factors from a wind farming point of view. Since weighted factors are often influenced by the profession or stakeholders. Due to a non-weighted approach being used there are differences in the suitable areas according to the plans of countries and the current research.

The current research is meant to perform a non-weighted approach (Paragraph 3.3). Since not all categories have an equal number of datasets, there are 10 different datasets for Nature and only 1 for cultural heritage, the approach is not entirely non-weighted. Influencing the results of the fourth research question a lot. Because this research question looks at the categories that overlap most with the current and planned wind turbine farms. Since not all categories have equal inputs (Table 4) the chances of overlap with a category are not equal. Therefore, the comparison between the categories is unfair. However, the current research focuses on all influencing factors of wind turbine farms. It is true that the influencing factors do overlap with a wind turbine farm. So, comparing unique influencing factors rather than categories is something that can be done.

5.6 General points of discussion

This report focuses solemnly on wind turbines. However tidal energy or floating solar panels can also be used for generating renewable energy on waters such as the Greater North Sea. For those types of renewable energy other influencing factors determine whether or not an area is suitable. By making use of other types of renewable energy current unsuitable areas might become suitable. This implies that it gives countries the opportunities to reach their renewable energy goals, by using other types of renewable energy rather than using wind turbines.

For the current research, it is assumed that the rules and regulations differ per country (Table 3). However, the fact that some countries do not take certain categories into account is questionable. If activities or objects are within an area the area will be less suitable. A country can prioritise wind turbines over certain activities. However, not accounting for cultural heritage (as most countries) is a noticeable fact. Furthermore, the categories are based on guidelines of the European Union and UNESCO (Schaefer & Barale, 2011; Ehler & Douvre, 2009). Since not all countries are a member of the European Union this influences the outcome of the results.

6. Conclusion

Based on the results of this research, a couple of conclusions can be drawn. The conclusions are ordered per research question, at last, a general conclusion based on the objective of this research is drawn.

Overall, it can be stated that this research contributes to the scientific field by creating an initial state of an MCA from a wind farming point of view, rather than from the point of view of a profession which is commonly done. Therefore, as many different influencing factors as possible were defined and all taken into account. Furthermore, it provides insights into the availability and findability of open data for the waters of the Greater North Sea, which was not researched within other studies.

6.1 Influencing factors and rules and regulations per country

"What are important influencing factors for offshore wind turbine planning? And what influencing factors do countries consider whilst planning?"

This research defines a total of 30 different influencing factors that influence offshore wind turbine planning. The influencing factors are a minimum distance to keep, a distance between wind turbines, a minimum of available space, costs, seabed, water depth, wave height, windspeed, natural phenomena such as earthquakes or tsunamis, birds, bats, mammals, fish, vegetation, plankton, other renewable energy farms, areas with cultural heritage, cables and pipelines, shipping routes, ports, fishing areas, aquaculture, military activity zones, mineral extraction, scientific research, tourism, religious areas, EEZs, distance from the coast and protected nature areas. Those influencing factors can be classified into 12 main categories. Those categories are aquaculture, fishery, military, mineral extraction and aggregates, nature protection, oil and gas exploitation, scientific research, shipping and ports, submarine cables and pipelines, tourism, underwater cultural heritage and other.

Research showed that all countries can make their own rules and regulations within their EEZs. Therefore, none of the countries take all 12 main categories into account whilst performing marine spatial planning. Underwater cultural heritage and scientific research are often not taken into account. Renewable energy production, fishery, shipping and ports and submarine cables and pipelines, on the other hand, are taken into account by all countries. It should be noted that the categories are defined by the European Union and UNESCO, and therefore, Norway and the United Kingdom do have slightly different categories.

6.2 Data collection

"For which influencing factors is open data is available to support offshore wind turbine planning?"

When searching open data on the defined influencing factors for the 8 bordering countries of the Greater North Sea, it turned out that there is a much data available, but also a lot of data still is missing or not available as open data. During this research, 46 different datasets were searched for all countries. The data had to be open data, so freely available, and the format could be either a WFS, a shapefile, a geodatabase, or a CSV file with coordinates. This resulted in the most available datasets for Belgium, with 37 of the 46 datasets. Followed by the Netherlands 35 datasets, Denmark and Germany both 34 datasets, the United Kingdom (England and Scotland) 32 datasets, France and Norway both 31 datasets. Sweden has the most limited number of datasets available, with only 26 datasets out of 46. Data on general influencing factors such as borders could easily be obtained, for more specific topics such as scientific research or cultural herritage there was not always data available. Overall, it can be concluded that sharing open data is something that needs to be improved for all countries. Furthermore, open data should become more accessible and easier to find.

6.3 Suitability model

"What areas would be deemed suitable if only open data would be used for wind turbine planning? And how do those areas change when taking countries rules and regulations into account?"

With the available data, it is possible to create maps determining the 'suitable' areas for wind turbine planning. The suitable areas are defined as areas with no influencing factors, so an *intersection over union* of all influencing factors and the Greater North Sea is performed. Areas with influencing factors according to the open data obtained are classified as unsuitable. Overall, there are 103 202 km^2 suitable for wind turbines within the Greater North Sea, 50 350km^2 of this is in the waters of Norway. The 103 202km^2 is more than the 33 125km^2 necessary to reach the European goals and become climate neutral by 2050. However, if all countries want to plan the wind turbines for themselves, only using their own waters for constructing wind turbines, Belgium, France, Germany, Sweden, and the Netherlands will not have sufficient space available, according to this way of modelling. If multi-use and weighted criteria are assumed, the available suitable space will change and might be sufficient.

When taking the rules and regulations of the different countries into account, an even larger area of 129 459 km^2 becomes suitable for wind turbine planning. Most of the 'extra' suitable space is within the waters of Norway (26 291 km^2). Belgium, France, Germany, Sweden, and the Netherlands still have insufficient suitable space to install a sufficient amount of wind turbines to reach their goals. So, it is important that countries collaborate to generate enough wind energy to reach the climate goals.

6.4 Current and planned wind turbine farms

"Are current and planned wind turbine farms on suitable areas according to the open data available?"

Based on the data available for the current wind turbine farms, it can be concluded that 23% (3 704 km^2) of the current wind turbine farms is on suitable areas. Most of the current wind turbine farms on unsuitable areas overlap with the categories nature protection and other. Meaning that the current wind turbine farms have a lot of influence on nature. For the category nature, global protected, local protected, unique areas, and areas with above-average observations are considered.

For the planned wind turbine farms, 13% (2 765.2 km2) is on suitable areas according to all data available. For Belgium, France, Sweden, and the Netherlands, all planned wind turbine farms are on unsuitable areas, which means that according to this data and model, they should consider other areas. The planned wind turbine farms mainly overlap with the categories nature protection, fishery and other.

It can be concluded that with the current wind turbine farms as well as with the planned wind turbine farms, there is a lot of overlap with influencing factors according to the available data. This is due to concessions that have to be made whilst planning wind turbine farms. However, according to this research, there are also suitable areas with no overlap of influencing factors. So, it remains unknown whether the concessions really had to be made or if there were better opportunities to locate wind turbine farms in the first place.

6.5 Overall conclusion

"Mapping the suitability for wind turbines in the Greater North Sea by making use of the available open data."

Overall, it can be concluded that it is possible to map suitable areas for wind turbines within the Greater North Sea based on open data. However, the suitability of the maps that are currently created remains questionable. This has to do with the fact that there is data missing on multiple influencing factors and because several assumptions had to be made whilst modelling. The MCA currently assumes that an area where an influencing factor is located becomes unsuitable, so the lack of data influences the outcome of the suitable areas. Furthermore, multi-use might be possible for some of the influencing factors, which is currently not assumed. The current model only creates suitable and unsuitable areas because an area over union is used rather than weighted criterion, whereas multi-use might be an opportunity with some categories. For this, the categories have to get weighted values without taking professions or preferences of planners into account. Therefore, future research on the available open data and research on weighted suitability from a wind farming point of view for modelling is recommended.

7. Recommendations

Based on the results and the discussion, several recommendations can be made. This chapter shows recommendations ordered per research question. Based on the recommendations, future research can be formulated. At last, some general recommendations are given, resulting from this research but not resulting in future research.

7.1 Influencing factors and rules and regulations per country

Determining influencing factors from as many perspectives as possible but focussing on the wind turbine point of view was a big part of this research resulting in 30 influencing factors. However, it is recommended to do more research on the influencing factors and with that find other influencing factors. It is recommended to interview people from multiple different professions and ask questions on what influencing factors they would consider. During those interviews, new influencing factors might arise. Besides that, new influencing factors will be found in research over time, like with the bats, and should then be taken into account. So, for future research, it is recommended to do additional research on the influencing factors to make the model more reliable.

Furthermore, it is recommended to do more research on the different categories that are used within this research. Currently, the categories of the European Union and UNESCO (Schaefer & Barale, 2011; Ehler & Douvre, 2009) were used to group the different influencing factors. However, Norway and the United Kingdom are not a part of the European Union. On top of that, not all categories have an equal number of influencing factors and, therefore, datasets. Making some categories unintentionally more important. Therefore, it is recommended to do more research on the best way to group the different influencing factors.

For the rules and regulations, it is recommended to do more in-depth research on what influencing factors countries consider. Currently, this was done by a literature search based on the categories. However, whether this represents all rules and regulations a country considers whilst performing marine spatial planning is unknown. So, it is recommended to perform more research on local rules and regulations for future research. Besides, it is recommended to interview local marine spatial planners or the people who write the policies. This will result in more knowledge on rules, regulations and planning strategies and therefore will lead to more reliable results.

7.2 Data collection

During this research, open data was searched to find information on the locations of the influencing factors. However, open data could be obtained for all influencing factors and not for all countries. For future research, it is recommended to do more research on the open data available. When more time is invested in this, there are chances of more data being found and a more reliable model can be created. It is recommended to perform this research with a native speaker for all countries. Since data is often stored in the native language of a country, it can be complicated for a foreigner to find all data needed. Furthermore, locals often know other data portals, data searches or websites containing the data needed. Increasing the chances of finding the open data needed, since currently, only the countries open data portals are used.

7.3 Suitability model

The most important recommendation is for the suitability model. Making changes within the model will improve the results of this research. So, when future research is performed, the focus should be on improving the model. However, following up on the other recommendations is necessary to make it worth improving the model.

Currently, the model only assumes suitable and unsuitable areas resulting in 103 202 km^2 classified as suitable area. If an influencing factor is located within the area, an area becomes unsuitable. However, with some influencing factors, multi-use can take place. Therefore, it is recommended to do more research on the influencing factors and the possibility of multi-use. The influencing factors should then be weighted with values between 0 (multi-use perfectly possible) and 1 (multi-use not possible). It is recommended to perform research on how influencing factors should be weighted from a wind farming point of view. Besides that, it is important to perform research on what should change, for instance, in the layout of a wind turbine farm, to make the multi-use possible. If influencing factors get weighted, it becomes possible to determine the suitability of the areas. So, it is recommended to perform further research on multi-use and weighted values and incorporate this with the model.

On top of that, it is recommended to perform research on how a profession influences the outcome of wind turbine planning. When the model contains the weighted values, it becomes possible to let people of different professions change the weights according to how they view a category or influencing factor. The results of the different professions can then be compared. This is recommended because it shows how differences in opinions and professions make differences in results. So, it can show citizens why it is of importance to be involved with wind turbine planning at sea even though it seems like something that is far away.

7.4 Current and planned wind turbine farms

For the current and planned wind turbine farms, creating a single and complete dataset is recommended. The current research emphasizes what Zhang et al., (2021) already showed, a lot of data is lacking on wind turbine farms at sea. It is recommended to obtain more data on wind turbine farms or, ideally, to create a single dataset. The maps of written reports of countries should be converted to datasets for more accurate data and reliable results. Furthermore, it is recommended to perform research on why countries plan wind turbines in areas with influencing factors, whereas this is not necessary because there are areas with no influencing factors.

7.5 General recommendations

In general, it is recommended for all countries to start collaborating and share data via a single data portal. During this research, EMODnet and INSPIRE were used as primary sources. Neither of them contained data on all influencing factors. Data often could only be found on a single data portal. In some cases, both data portals contained different datasets on a single influencing factor for a single country. To make the use of open data easier it is recommended to share all data via a single location. That way, it can be updated when needed, and data can easily be obtained. If all data gets shared via a single portal, the individual portals of the countries would no longer be necessary, avoiding duplication of datasets.

Besides that, it is recommended for countries to make more data openly available. For some influencing factors, no data could be obtained, or it was only findable for only some countries. A country needs to share as much data as possible because citizens often pay for the collection of the data. On top of that, sharing data is good for development. Once data is shared, more research can be performed, and more knowledge will be obtained. With that, better recommendations can be made, which has a positive influence on a country. When making more data available, it is crucial to make the correct data available. Currently, polygons often get replaced by a centre point. So, the data lacks information, and assumptions must be made. When data is shared as polygons, the actual area rather than an assumption represents the area. That way, more accurate analysis can be done.

For renewable energy and reaching the sustainable goals, it is recommended for countries to collaborate. Currently, all countries plan their own wind turbine farms. They determine what areas are suitable within their own waters. However, when countries would collaborate, it can be that more suitable areas in the waters of other countries can be found. If the formal agreements are made for this, collaboration results in less space consumption and less disruption of the Greater North Sea. Besides that, the current model showed that there is insufficient space available for some countries. Collaboration can result in all countries reaching their goals and becoming climate neutral without using unsuitable areas because the suitable areas of other countries can be used.

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9. Appendix

Appendix I	**-**	Table of Content of zip file that accompanies the thesis report
Appendix II	**-**	Overview of the open data portals of all countries
Appendix III	**-**	Pre-Processing steps & assumptions made whilst pre-processing
Appendix IV	**-**	Processing suitable areas
Appendix V	**-**	Processing current and planned wind turbine farms
Appendix VI	**-**	Open data sources
Appendix VII	**-**	Explanation on used datasets
Appendix VIII	**-**	Unsuitable area per category
Appendix IX	**-**	Enlarged map of the suitable areas
Appendix X	**-**	Suitable areas with depth, wave height, wind speed and costs
Appendix XI	**-**	Map of current and planned wind turbine farms
Appendix XII	**-**	Results of Comparable studies

Appendix I – Table of contents of the zip file that accompanies the thesis report

Table 12 contains an overview of the documents that are within the zip file that accompanies the thesis report. When referred to the model, the FME model within the zip file is meant.

Table 12 Table of contents of the zip file that accompanies the thesis report.

Document	Format	Folder structure
Documentation of what is where in the zip file	Word	Thesis Suzan Jans > Documentation zip file.doc
Thesis proposal	PDF	Thesis Suzan Jans > Proposal > Thesis Proposal Suzan Jans.pdf
Midterm presentation	PPTX	Thesis Suzan Jans > Midterm presentation > Midterm Presentation Suzan Jans.pptx
Thesis report	PFD	Thesis Suzan Jans > Thesis report > GRS Thesis Suzan Jans (1049747).pdf
Final presentation	PPTX	Thesis Suzan Jans > Final presentation > Final presentation Suzan Jans.pptx
Model	FMW	Thesis Suzan Jans > Model > Initial state of MCA to determine suitable areas for wind turbines in Greater North Sea.fmw In order to be able to work with the model, an FME licence, as well as an ArcGIS licence, is necessary. For just opening the model, only FME is required (a free student licence can be obtained via the safe software website) Important notice, for the model to work, the readers and writers' folder structure should be changed to the correct input and output locations. When the folder is saved to **C:\Thesis Suzan Jans** the model should run without making changes.
Source data	Multiple file types	Thesis Suzan Jans > Data > 1. Source Data > name of factor
Pre-processed data	Multiple shapefiles	Thesis Suzan Jans > Data > 2. Pre-processed > name of category > name of category.shp
Data of unsuitable areas	Multiple shapefiles	Thesis Suzan Jans > Data > 3. Unsuitable areas > kind of area.shp
Suitable areas with extra information	Multiple shapefiles	Thesis Suzan Jans > Data > 4. Suitable areas with extra information > type of suitable area.shp
Exports of created maps	JPEG	Thesis Suzan Jans > Maps > name of map.jpg
Feedback peer students	Word	Thesis Suzan Jans > Feedback peer students > PeerFeedback Marlot van Balveren and Reint Jansen – By Suzan Jans.doc

Appendix II – Overview of the open data portals of all countries

Table 13 contains an overview of the used open data portals of the countries bordering the Greater North Sea.

Table 13 Overview of the used open data portals of the countries.

Country	Open data portal
Belgium	https://data.gov.be/en https://www.geo.be/
Denmark	https://www.opendata.dk/ https://eng.gst.dk/
England	https://data.gov.uk/ https://naturalengland-defra.opendata.arcgis.com/
France	https://geo.data.gouv.fr/ https://www.data.gouv.fr/
Germany	https://www.geoportal.de/ https://www.govdata.de/ https://www.bsh.de/
Netherlands	https://www.nationaalgeoregister.nl/ https://www.pdok.nl/ https://data.overheid.nl/ https://opendatanederland.org/
Norway	https://www.geonorge.no/ (https://kartkatalog.geonorge.no/) https://data.norge.no/
Scotland	https://spatialdata.gov.scot/ https://statistics.gov.scot/
Sweden	https://www.dataportal.se/en https://www.lantmateriet.se/

Appendix III – Pre-Processing Steps & Assumptions made whilst pre-processing

In general, the pre-processing of the data takes place in the first green box of the FME workbench (Figure 8), all the way to the left. Within the small green box to the left (within the pre-processing box) the project area is created. After this pre-processing is done for all the different datasets found. The steps taken will be explained in this appendix. Refer to the .fmw file attached to this project folder documents (Appendix I) for the created model, the settings of the transformers and an explanation of the transformers used.

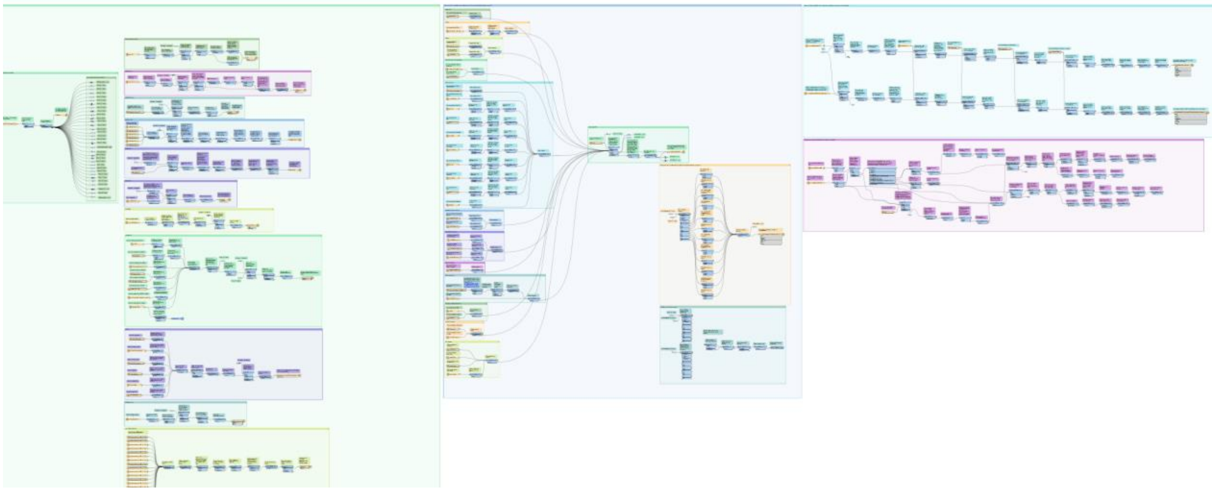

Figure 8 The entire model created during this research. This is the same as the .fmw file attached (Appendix I).

First, the project area is created from the ICES dataset (Figure 9). The source is read and the Greater North Sea area is filtered. This is then reprojected to EPSG:23031 and written to a shapefile, the data is also used for a lot of different clips to other data, as (partly) shown within the dark green box (right side of figure 9).

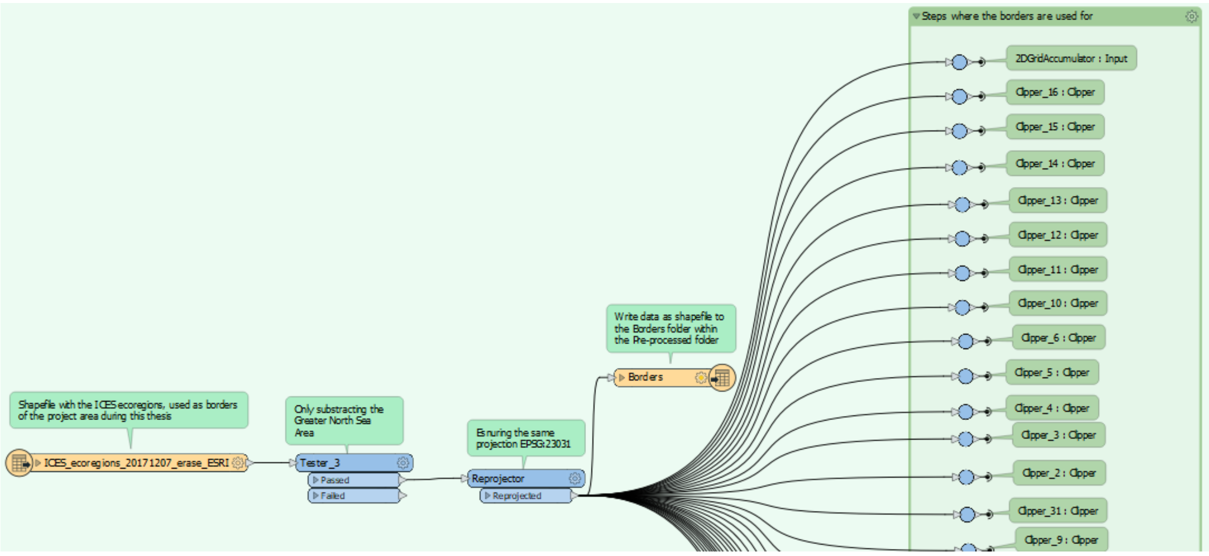

Figure 9 Pre-processing of the project area.

After this, the part to the right (right side of the first big green box in figure 8) is pre-processed. This is done per influencing factor. Starting with the Exclusive Economic Zones (Figure 10). First, the data is read, then the EEZs of countries are selected. They are reprojected to EPSG:23031 and clipped to the project area. The EEZs of Jersey and Guernsey are aggregated into a single EEZ of the United Kingdom (containing England, Scotland, Jersey and Guernsey). After this, all EEZs within the Greater North Sea are written to a single shapefile.

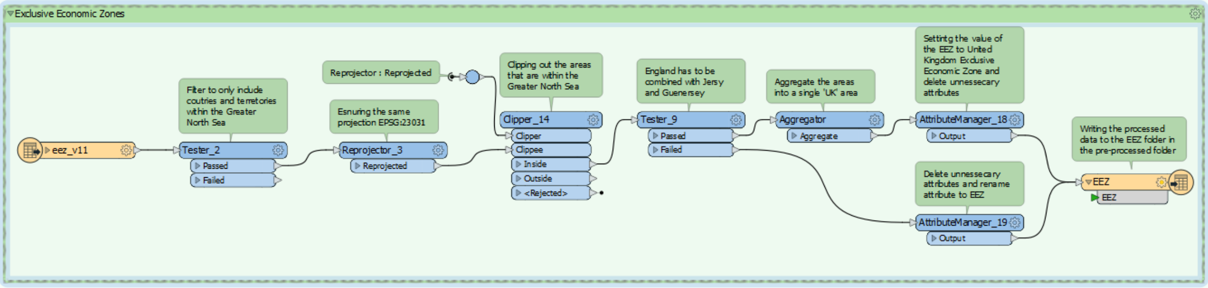

Figure 10 Pre-processing of the Exclusive Economic Zones.

This is followed by pre-processing the 12-mile zone (Figure 11). First, the data is read, then the zones of the countries bordering the Greater North Sea are selected. This is reprojected to EPSG23031 and clipped to the project area. The 12-mile zone is just a single line and not a polygon connected to the coasts. Therefore, the area in between the borders of the project area and the 12-mile zone is created by clipping the 12-mile zone from the project area. This output is disaggregated into single polygons, assigned with unique numbers and the numbers from the coasts to the 12-mile line are kept. This is then aggregated with the original 12-mile zone to create a polygon from the coast to 12-miles within the waters. After this, unnecessary attributes are removed, and the data is written to a shapefile.

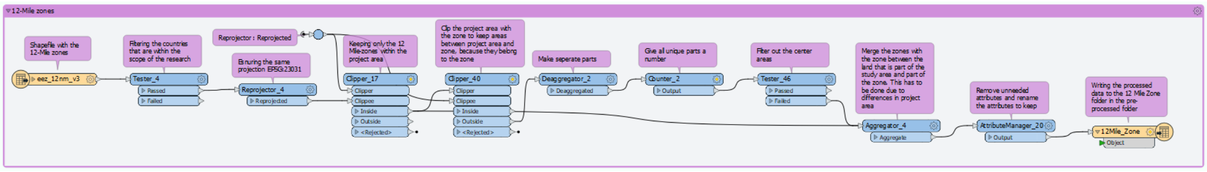

Figure 11 Pre-processing of the 12-Mile zones.

Then the seabed substrate is pre-processed (Figure 12). First, the data is read, reprojected to EPSG23031, and clipped to the project area. After this, unnecessary attributes are removed. The suitable substrates are then filtered based on their suitability, the unsuitable areas are written to a shapefile. In this case, no data is filtered because all sediments within the Greater North Sea are suitable for wind turbine farms. However, if this changes at one point the unsuitable areas can be used within the process of determining the suitable areas.

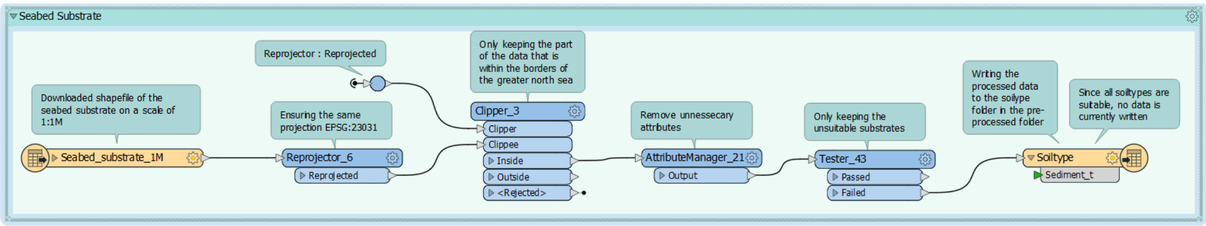

Figure 12 Pre-processing of the seabed substrate.

Next in line is the bathymetry or seafloor depth (Figure 13). The data consists of six different Asci files. They are all read and reprojected to the EPSG23031 and clipped to the project area, to limit the size. The raster files are resampled to a 1kmx1km grid, since more detailed information is not necessary. This is done with an average-16 interpolation type. A single raster is created out of the six separate raster files. The cells of this raster are converted to polygons and the value of the raster bands are set as a value of the polygons. The values are rounded to the closest number with 0 decimals. The areas with the same depth are dissolved into single polygons. Those polygons are written to a shapefile.

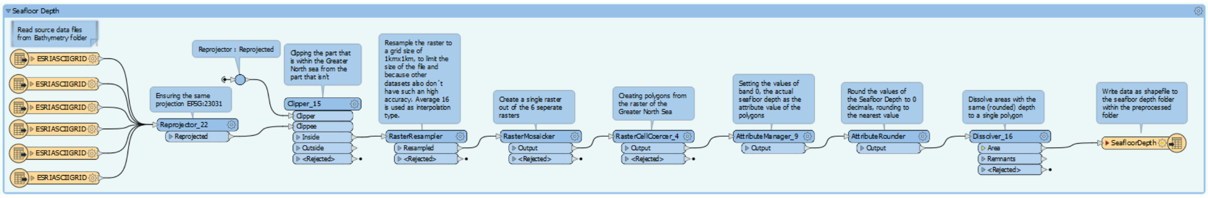

Figure 13 Pre-processing of the bathymetry or Seafloor depth.

For the wave heights, a similar approach is taken (Figure 14). However, there are some minor differences due to the differences in the data. First, the raster file is read, this time no conversion is done. Because the wave heights dataset covers areas far outside of the projection area, therefore, the project area is converted to WGS84 (like the raster file), the raster is then clipped to the project area. After this, the raster is reprojected to the EPSG23031 projection. The raster cells are resampled to 1kmx1km with an average16 interpolation. Because more precision is not necessary and the other datasets also have this precision. After this, polygons are created from the raster cells and the raster band values are assigned to those polygons. The values of the kinetic energy are rounded to the nearest whole number. Based on the kinetic Energy the areas are dissolved into single polygons. Lastly, this data is written to a shapefile.

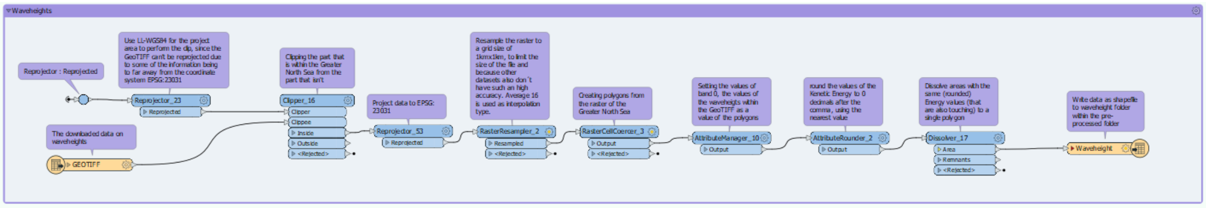

Figure 14 Pre-processing of the wave heights.

The pre-processing of the wind speed data is also done in the most basic way (Figure 15). First, the data is read and only the attribute containing the average annual wind speed value is kept. This is clipped to the project area with the WGS84 projection. Because some of the windspeed areas can't be reprojected to EPSG23031, since they are too far away from the projection area. After the clip with the project area, the data is reprojected to EPSG23031, and the unnecessary attributes are removed. The data is then written to a shapefile.

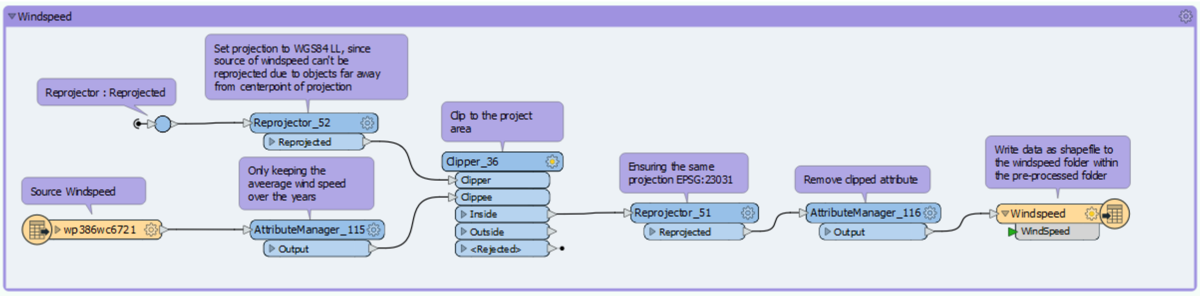

Figure 15 Pre-processing of the wind speed.

The earthquake data consists of just points. So, the pre-processing is according to the following steps (Figure 16). First, the data is read and reprojected to EPSG23031. Then the areas with a magnitude of above 0 or no value are selected. A buffer value is created based on the magnitude of an earthquake, a value of 35 if the magnitude is over 5, 25 if the magnitude is between 5 and 4, 15 if the magnitude is in between 3 and 4, 10 if the magnitude is in between 3 and 2 and 7 if the magnitude is less than 2 or unknown (Bhattacharya et al., 2021). After this, the point is buffered with the assigned buffer value in kilometres. The buffered areas are clipped to the project area. This clip is performed after buffering since some epicentres might be outside of the project area but the project area might be influenced by it. Before writing the data as a shapefile the unnecessary attributes are removed.

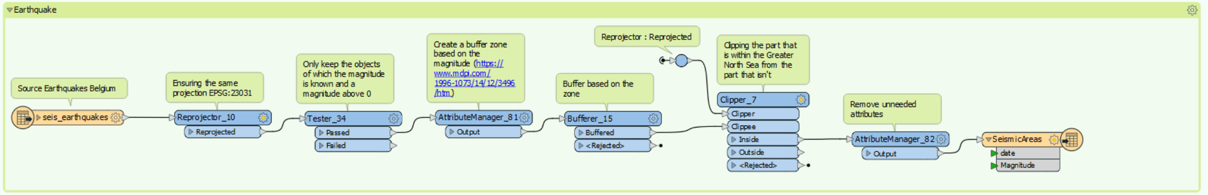

Figure 16 Pre-processing of the Earthquake data.

Then the pre-processing of the aquaculture takes place (Figure 17). Since there are a lot of different sources, different steps have to be taken. As first only the active, or unknown if active sites are kept. The inactive sites are not taken into account. Next unnecessary attributes are removed and the type of aquaculture (e.g., finfish, shellfish) is assigned. All the data is reprojected to EPGS23031. Then point data needs to be buffered. Since there are polygons available for the Norwegian dataset, the average length of those polygons is calculated (Belgium also has polygon data but they are not used to calculate the length because it is a planned area and not the actual aquaculture areas). The points (all data except the Norwegian and Belgian data) is buffered with 1108 meters, the average length of the Norwegian polygons. The buffer is done in a square rather than a circle since most Norwegian aquaculture areas were squared. All data, the buffered points and the polygons are clipped to the project area. This is done after the buffer because a centre point might be outside of the project area but once the point is buffered to an area it can be inside the project area. The overlapping aquaculture areas are then dissolved into a single area and the unnecessary attributes are removed. The data is written to a shapefile.

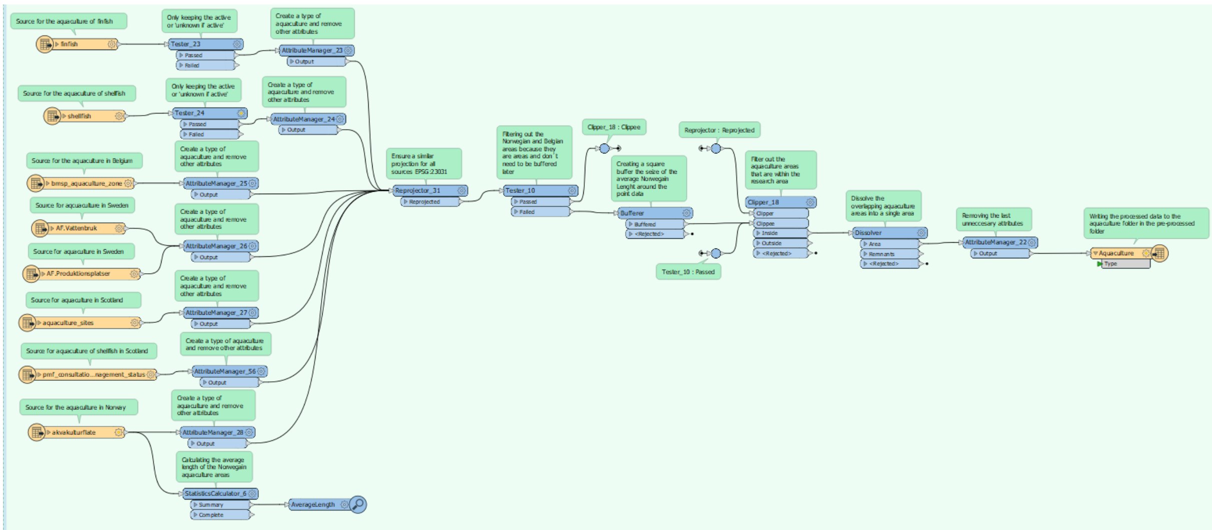

Figure 17 Pre-processing the aquaculture areas and points.

Then the data for the fishery is pre-processed (Figure 18). There are six different sources, representing different types of fisheries. Since all data is coming from the same source, they all have similar values and make use of the same raster, making the pre-processing simultaneous pre-processing possible. As a first step, the unnecessary attributes are removed and the attribute containing the Mw fishing hours is renamed with the type of fishing that is being performed. The data is then reprojected to the EPGS23031 projection. After that an overlay is performed, with this overlay, the different datasets are merged into a single dataset. Since not all polygons will have values in all Mw categories the empty categories are set to a value of 0. The attributes are summed to a single value rather than all values within a single category. Creating a single attribute with MW fishing hours for a single polygon. The data is clipped to the project area. Unnecessary attributes are removed, and the data is written to a shapefile.

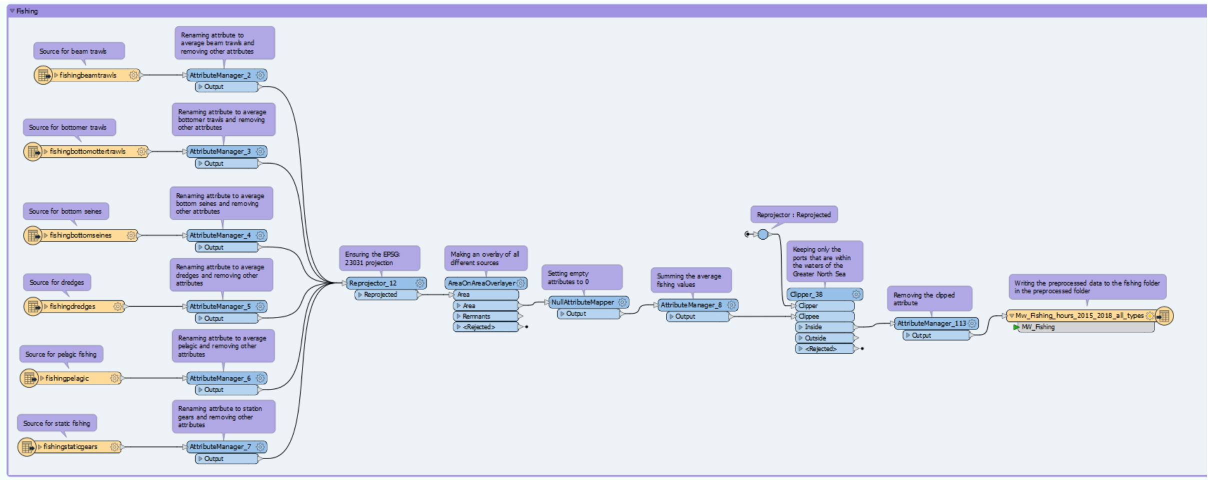

Figure 18 Pre-processing of the fishery sources.

Next up the data for the military areas are pre-processed (Figure 19). First, the data is reprojected to EPSG23031, then areas with as attribute active or 'unknown' are selected. They are clipped to the project area, to only keep the data within the Greater North Sea. The overlapping polygons are dissolved into single areas and all unnecessary attributes are removed. The remaining polygons are written to a shapefile.

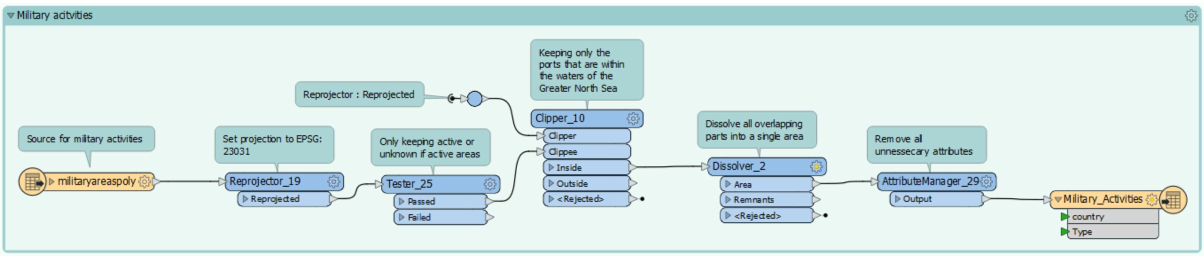

Figure 19 Pre-processing of the military areas.

This is followed by the pre-processing of the unexploded ordnance (Figure 20). These are multiple different sources since it is the data from 1999 till 2019. At first, all data is reprojected to EPGS2303. Since there are a lot of different datasets, they all have different attributes. So, a single attribute for the attribute Action is created and other attributes are removed. Then all objects with the attribute 'exploded' are filtered out, since it is sure they are not at the location anymore, for the others it is unknown, so their locations will be unsuitable for wind turbine planning. Since it is data of multiple years there might be overlapping ordnance. Therefore, the geometries are extracted, and duplicate geometry is removed. A buffer of 50 meters is added to the points to comply for the inaccuracy of the data. Overlapping polygons are dissolved and the data is written to a shapefile.

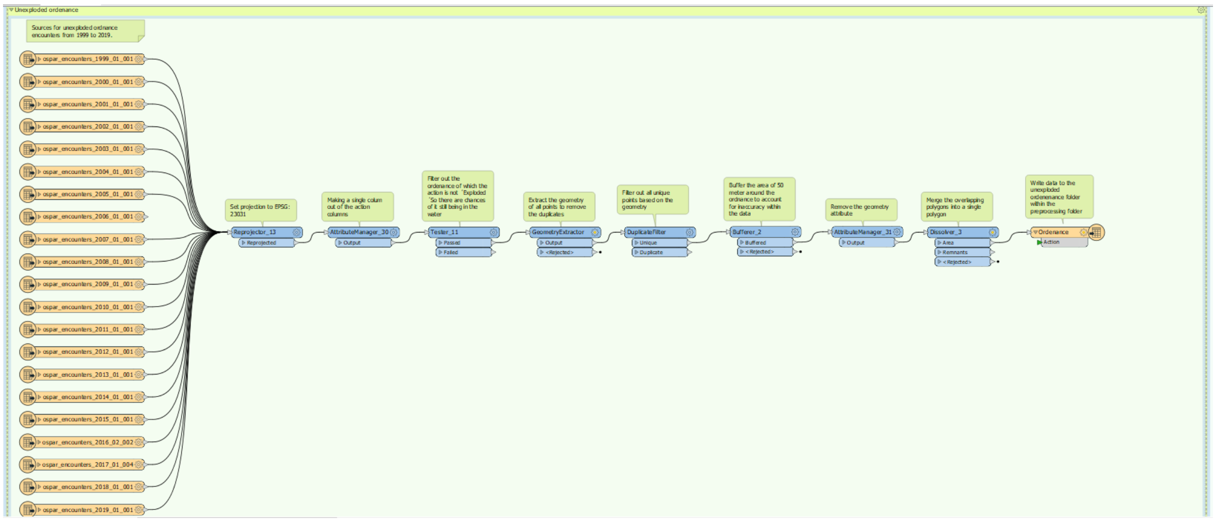

Figure 20 Pre-processing of the unexploded ordnance.

Next up is the pre-processing of the dredging (soil disposal) sites (Figure 21). There are two different datasets available for this an OSPAR dataset and a Scottish dataset. Both will in the end be written into a single shapefile. Since the Scottish dataset consists of polygons this will be explained first. The Scottish dataset (Bottom figure 21) is first filtered in ‘open’ sides and not open sides. Only the open sides will be considered. They are reprojected and dissolved into single areas when they overlap. They are then overlayed with the Waters of the Greater North Sea and removed if they are outside of the study area. The average size of the areas is calculated to use as a buffer for the OSPAR dataset. The OSPAR dataset is read (Top figure 21) and reprojected to EPSG23031. The activity deposit is filtered and kept, the other data is used with the extraction zones (Figure 22). A buffer around the points is created. This buffer is 541 meters, from the average size of the Scottish disposal sites (the average Scottish size is converted to a radius which results in 541). The areas are dissolved into a single area if they overlap and after that, they are overlayed with the project area. If the data is within the project area it is kept. The datasets are merged, an activity attribute is created, and other attributes are removed. The data is written to a shapefile.

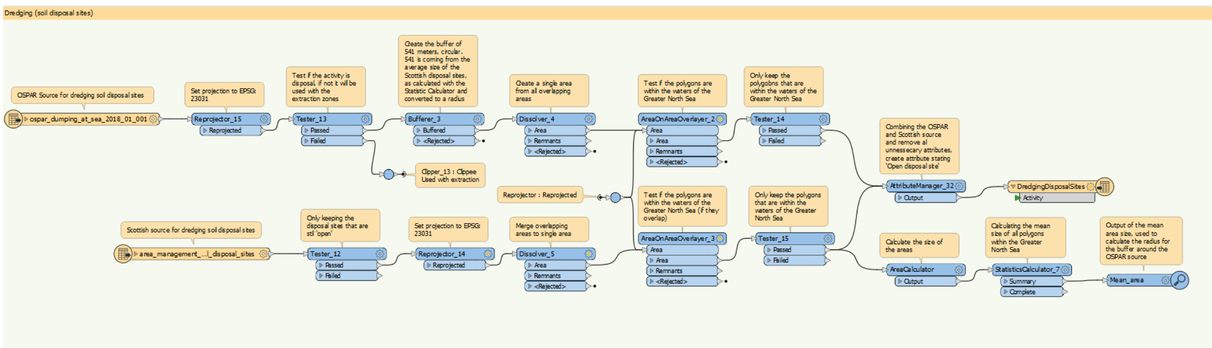

Figure 21 Pre-processing of the dredging (soil disposal sites).

The next influencing factor are the extraction zones (Figure 22). Since there are 4 different datasets the pre-processing is a little more complex. The AZTI (Far left figure 22) data is of a larger area than just the Greater North Sea. For this data first the 'active' and 'unknown' objects are kept. The data is reprojected to EPSG23031 and clipped to the project area. It is merged with the reprojected Belgian and German data and unnecessary attributes are removed. There is also OSPAR data available as points (filtered from the dredging step), for this data it is first tested if it is within the project area. Only the points that overlap with the project area are kept. For the points that overlap with polygons of other datasets, the size of the polygons is calculated to later use as a buffer for the other points. Resulting in a buffer value of 1950 meters (the average area of the polygons overlapping points) with which all points are buffered. Overlapping polygons are dissolved into a single polygon and clipped to the Greater North Sea study area. Then the buffered points that overlap with a polygon from a different dataset are removed, to make sure no unnecessary areas are deemed unsuitable due to the buffers. Finally, the buffered points are merged with the polygons from the other datasets. Unnecessary data is removed, and the data is written as a shapefile.

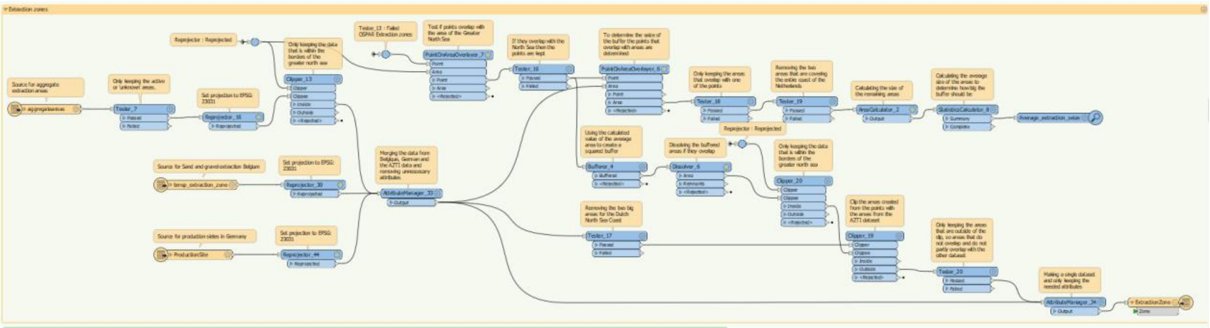

Figure 22 Pre-processing of the extraction zones.

As shown within figure 23 the pre-processing of the marine protected areas is according to the standard processing steps (Figure 2). First, the data is read, and a selection is made on the needed areas. This data is reprojected to EPSG23031 and clipped to the project area. Only the objects with the status 'Designated' are kept. It is assumed that the other data is not needed. After that, unnecessary attributes are removed, and the data is written to a shapefile.

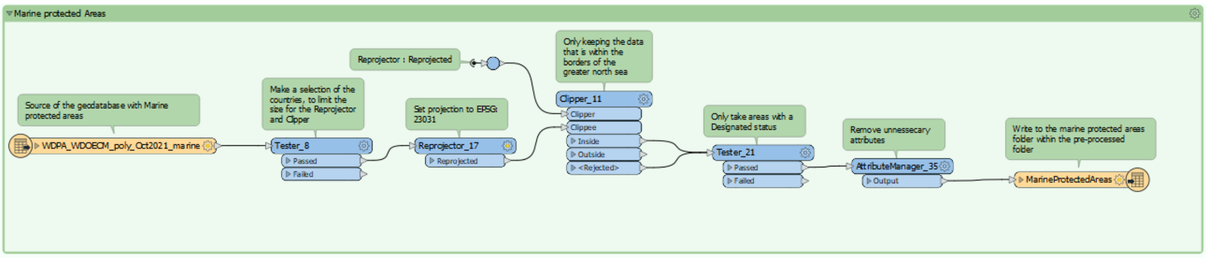

Figure 23 Pre-processing of the marine protected areas.

For the pre-processing of the unique habitats (Figure 24) the standard process is used as well (Figure 2). First, the overlapping parts of all seven sources are aggregated and reprojected to EPSG23031. The overlapping parts can be aggregated before reprojecting because the data is from the same source. Only the areas within the project area are kept, by clipping the data with the project area. The unnecessary attributes are removed, and the data is written as a shapefile.

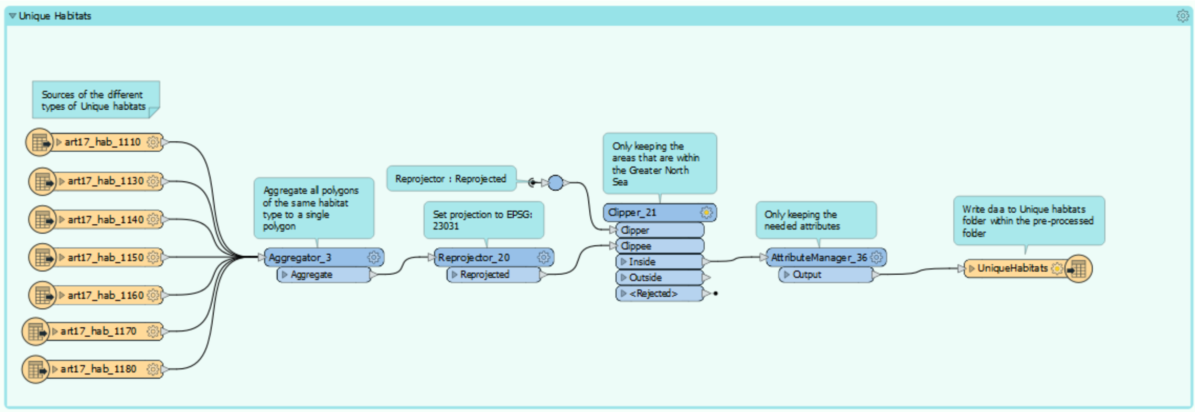

Figure 24 Pre-processing of the unique habitats.

The pre-processing of the wildlife factor seems complicated (Figure 25). However, it is the same process repeated seven times for the different sources. When zooming in on the reptiles (but can be any other source as well) this consists of the following steps (Figure 26).

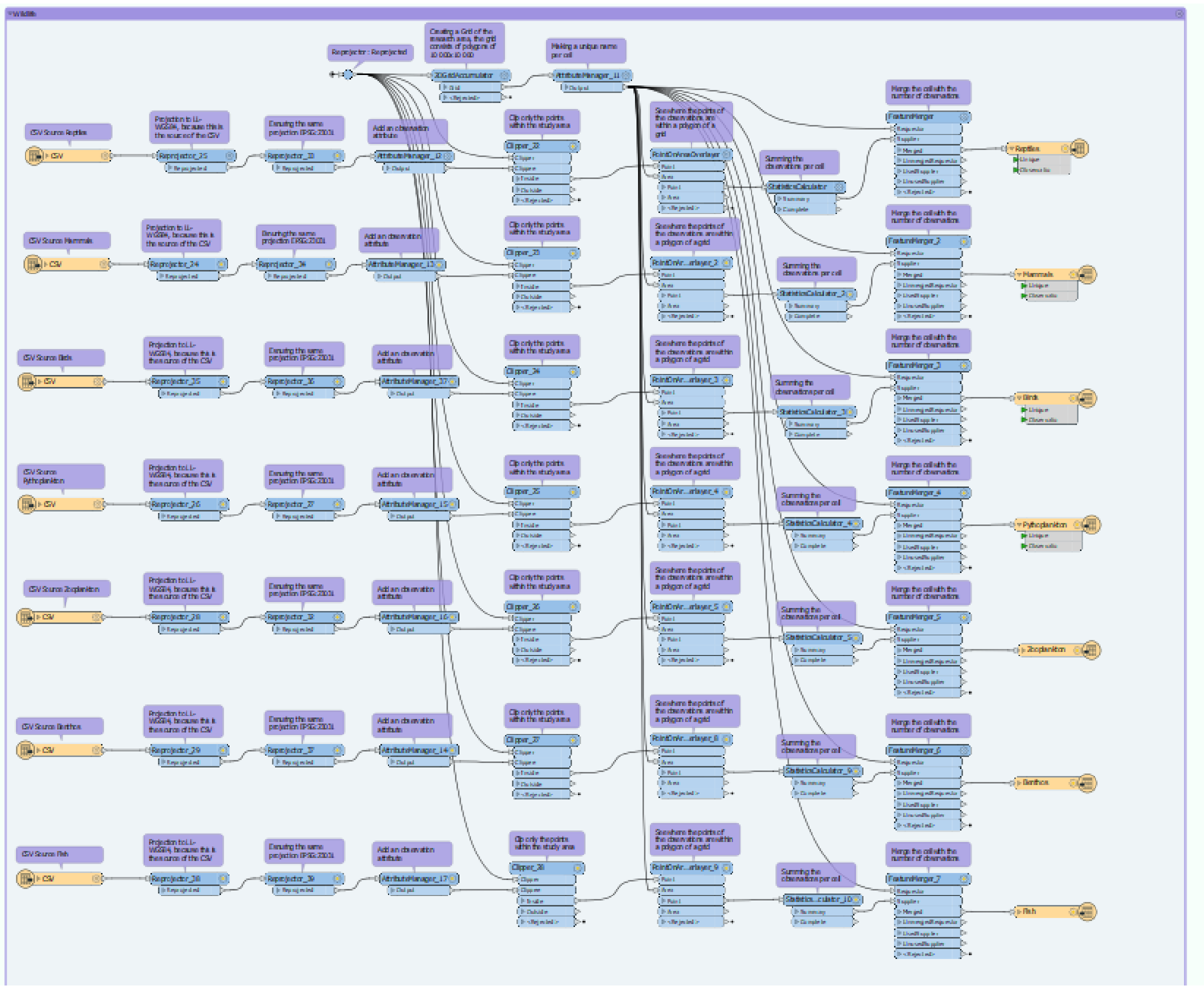

Figure 25 Overview of the pre-processing of the wildlife factor.

First, the CSV source is read, the columns of x and y are assigned to latitude and longitude, the data is reprojected to EPSG23031. An observation attribute with the value of 1 is created for all observations. Since every point represents a single observation. The data is clipped to the project area to only keep the points that are within the Greater North Sea. Then the project area is gridded into cells of 1kmx1km, and unique values are assigned to the grid cells. The points are overlayed with the grid cells, assigning the unique value of the grid to an observation. The number of observations per grid cell is summed, based on the unique observations. Because of this, the geographical shapes are lost. So, the summed observations grouped per unique value are merged with the unique values of grid cells again, to make the data spatial. The spatial grids are written to a shapefile, this is done for all wildlife datasets collected.

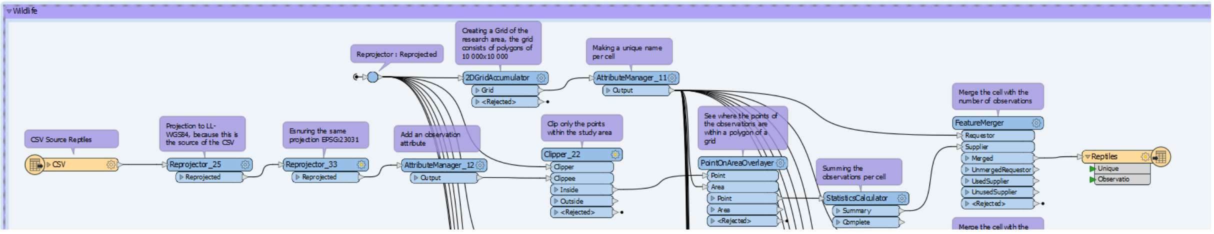

Figure 26 Zoomed in on reptiles for explaining the pre-processing of all wildlife factors.

For Seagrass there are just two different sources (Figure 27). One with polygons and one with points. Both datasets are first converted to EPSG23031. The point dataset is then buffered with squares of 20 meters since seagrass is often sampled in grids of 20 meters (Dolch; et al., 2017). Both datasets are simultaneously clipped to the project area, to only keep the data within the Greater North Sea. Unnecessary attributes are removed and overlapping polygons are dissolved into a single polygon. This data is written to a shapefile.

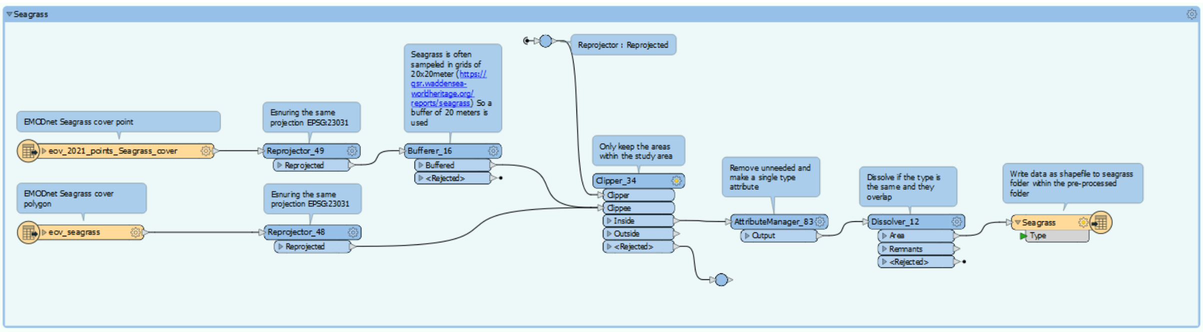

Figure 27 Pre-processing of seagrass.

The pre-processing of the renewable energy data can be classified into two separate categories. One for polygon data (Top part) and one for point data (Bottom part), divided by the block in figure 28. Except for the Belgian points, which are single wind turbine points of a single wind turbine farm. So, a hull around the points is created and the area is then treated as a polygon. For the polygons (including the Belgian), the unnecessary attributes are removed, the projection is set to EPSG23031, and a single uniform status attribute is created. The areas are clipped to the project area and an average area of the polygons is calculated to use as a buffer for the point datasets. The data is then merged with the point data. Before the merge with the point data, the unnecessary attributes of the points are removed, and the projection is set to EPSG23031. The points are clipped to the study area and uniform status attribute is created. It is checked if a point is already within a polygon (which has a buffer of 500 meters due to differences in the data). Only the points that are not within the polygons are kept and buffered with 5400 meters as a square (the average of all polygons). This is merged with the other polygons the overlap and clip attributes are removed and the data is then written to a shapefile to use with research question 4. Other unnecessary attributes are removed, overlapping areas are dissolved and the data is written to a shapefile.

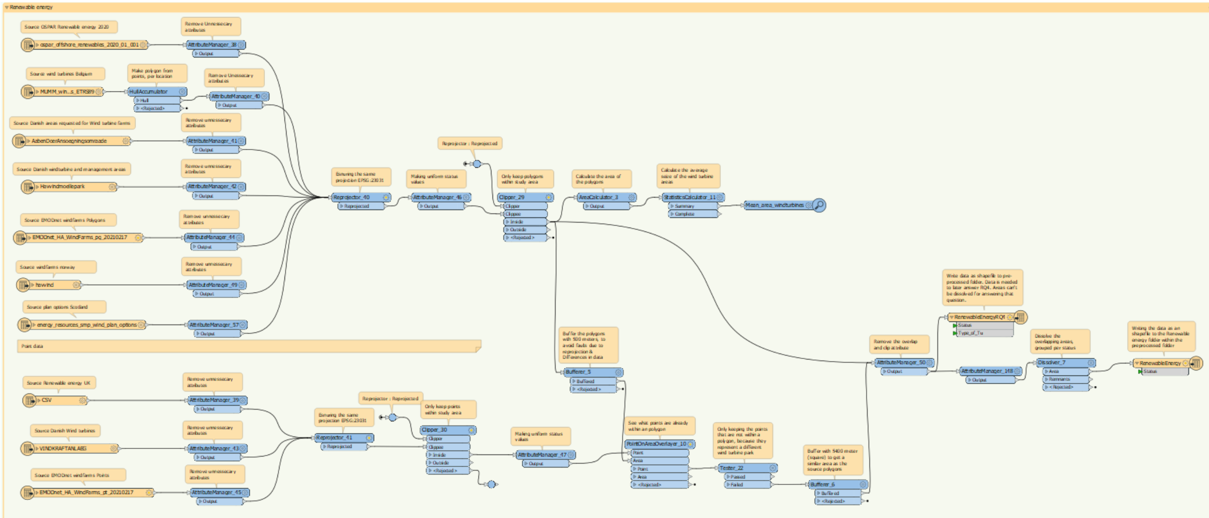

Figure 28 Pre-processing of the renewable energy data. Part of the image above the block (top) are areas and the bottom part are points.

The pre-processing of the grid connections (Figure 29) is similar to the general pre-processing (Figure 2). First, the data is read, reprojected to EPSG23031, and clipped to the project area. However, this time the project area is buffered with 25 kilometres because not all grid connections are within the waters. Then the unnecessary attributes of the grid connections are removed and the grid connections are buffered with 20 meters (Scheidweiler & Grundmann, 2019).

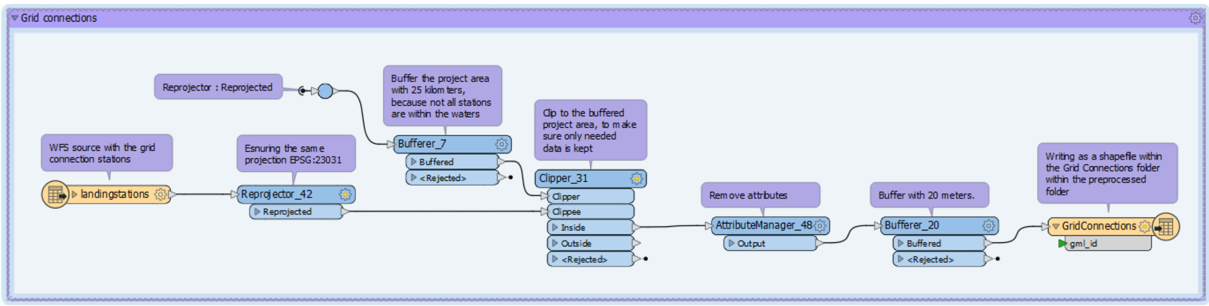

Figure 29 Pre-processing of grid connections

This is followed by the pre-processing of oil and gas platforms (Figure 30). This data consists of two different sources one is the platforms dataset and one is filtered from the German dataset of cables and pipelines (Explained with cables and pipelines). First, both datasets are reprojected to EPSG23031, then the decommissioned, derogated and shutdown platforms are removed because it is assumed they can be removed for a wind turbine farm. The left-over points are then clipped from the project area, so only the points within the project area are kept. Then unnecessary attributes are removed, and the points are buffered with 125meters, in a square. This is because platforms are more than just a point. The 125 meters is based on the Troll A platform, the largest platform of the Greater North Sea. It has a size of 250 meters, so a buffer of 125 meters on both sides (Andrei, 2015). Since this is the largest platform, other platforms can't be larger, so the buffer should account for all platforms.

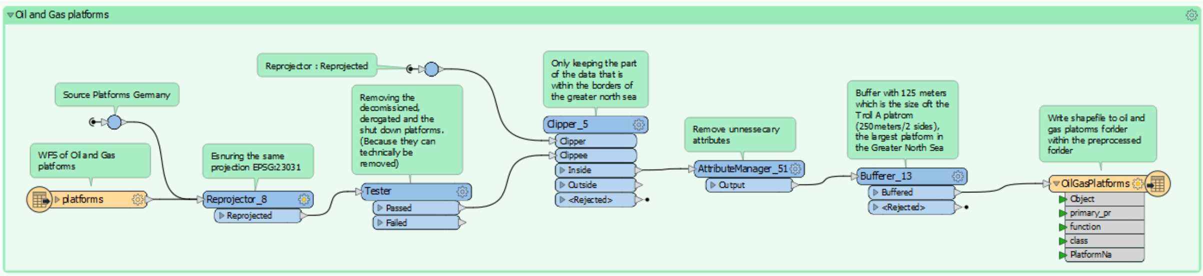

Figure 30 Pre-processing of the oil and gas platforms.

The pre-processing of the exploitation data is as shown in figure 31. First, the data is reprojected to EPSG23031. Then only the exploitation areas are selected and not the exploration areas. This is done since exploration areas are not yet active. Next up, only the licences with an active date are selected. So, if the end-year is bigger than 2021 or if there is no year added. Then the areas within the project area are clipped. The unnecessary attributes are removed, and the data is written to a shapefile.

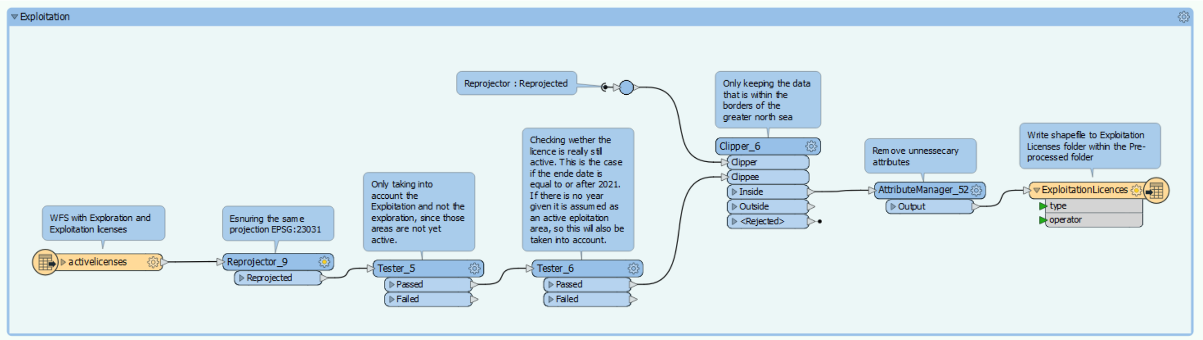

Figure 31 Pre-processing of the exploitation data.

For fossil fuel resources the pre-processing (Figure 32) is similar to the general pre-processing steps (Figure 2). First, the data of the two different sources are read and unnecessary attributes are removed. A value called type is created to store the type of fossil fuel. The data is then reprojected to EPSG23031 and clipped to the project area. The clip attribute is removed and the data is written to a shapefile.

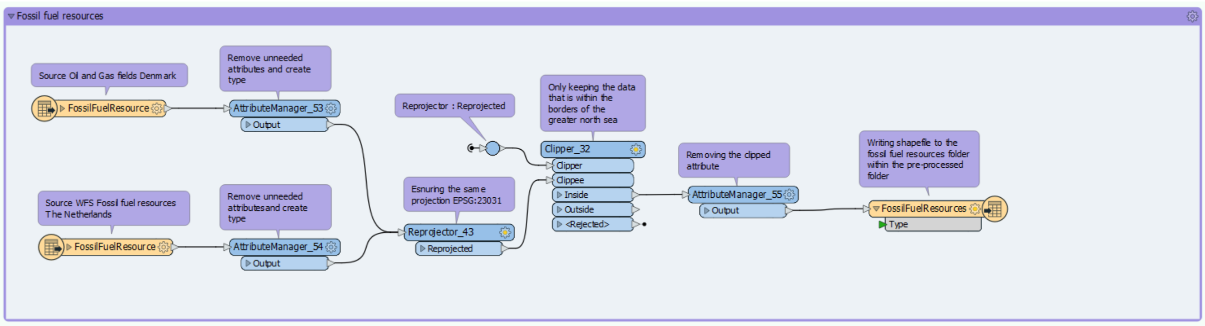

Figure 32 Pre-processing of the fossil fuel resources.

Leaving just 10 influencing factors for the pre-processing. Fossil fuel resources are followed by measuring locations (Figure 33). First, the source data is read. For Sweden there is an attribute indicating if sites are still active, only the data with no 'end of lifespan' value are kept. The active data is combined with the Belgian source and reprojected to EPSG23031. The data is clipped to the project area, to only keep the sites within the project area. After this, sites are buffered with 12 meters (circular). This is because the size of weather buoys ranges from 1 to 12 meters (University of Rhode Island, 2010). All unneeded attributes are removed and attribute with the value 'measuring pole' is added. The data is then written to a shapefile.

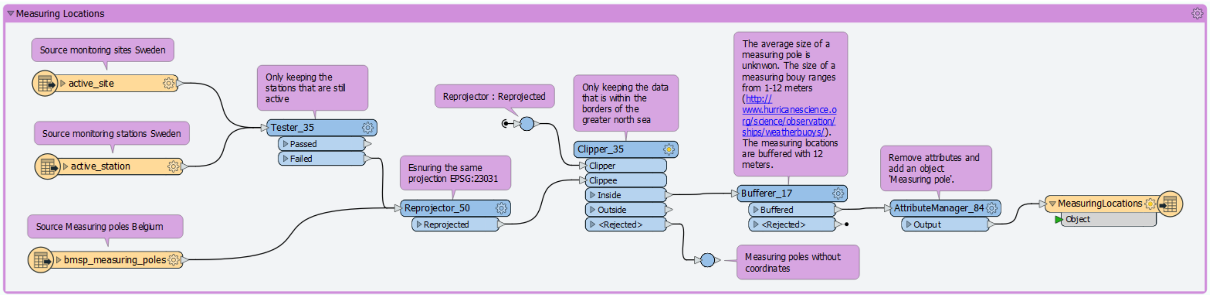

Figure 33 The pre-processing of measuring locations.

Next up are the shipping routes (Figure 34). Having a relatively simple pre-processing process. First, the Geo TIFF is read, and the data is reprojected to EPSG23031. The data is clipped to the project area, leaving only the raster cells within the project area. The raster cells are then converted to polygons and the values of band 0, the shipping movements, are set as attributes to the polygons. The data is written in a shapefile as polygons.

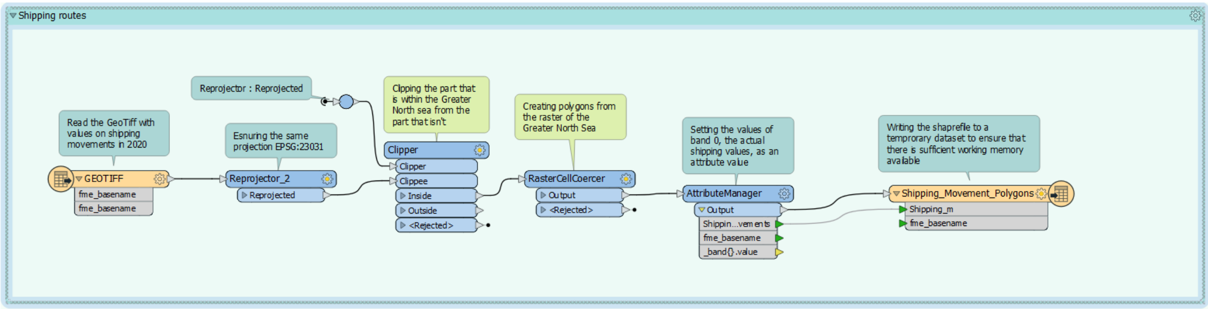

Figure 34 Pre-processing of the shipping routes.

Then the pre-processing of the ports is performed. Since only point data is available extra steps are needed (Figure 35). First, the data is reprojected to EPSG23031. The points are buffered this is done with 5 kilometres circular. This value is based on the average area of the largest ports within the research area (73square kilometres) converted to a radius (Sinha, 2021). This data is clipped to the project data. The clip is done after the buffer because it might be that a point is outside the project area, but the buffer is inside the project area. Then the overlapping ports are dissolved, and unneeded attributes are removed. The data is then written to a shapefile.

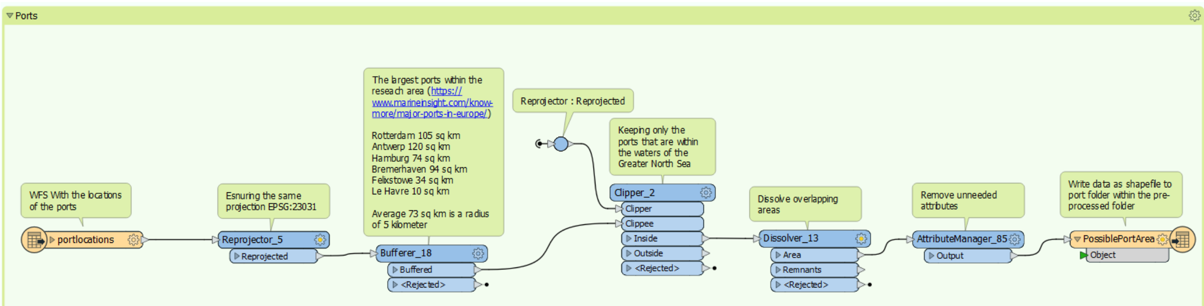

Figure 35 Pre-processing of the ports.

Next up are the power and communication cables, which are multiple sources (Figure 36). If there is an attribute indicating whether the cables are active or inactive, a selection is made and the active cables or cables without a value are filtered and kept. Then the unneeded attributes are removed. This is for all sources except the German source, which contains the cables as well as platforms and pipelines. For the German source, the platforms and pipelines are filtered out before the unnecessary attributes are removed. Then the data is combined within the buffer transformer. The cables are buffered with 100 meters on both sides since cables have a volume and there is a safety zone (Frias et al., 2018). The cables are clipped to the project area, which is set to an LL-WGS84 projection first. Because some of the cables are too far from the EPSG23031 projection so it causes an error when reprojecting. Once the data is clipped to the project area, the data is reprojected to EPSG23031. Overlapping cables are dissolved, this is done per type (so telecommunication cables and power cables separate). Unnecessary attributes are removed, and the data is written to a shapefile.

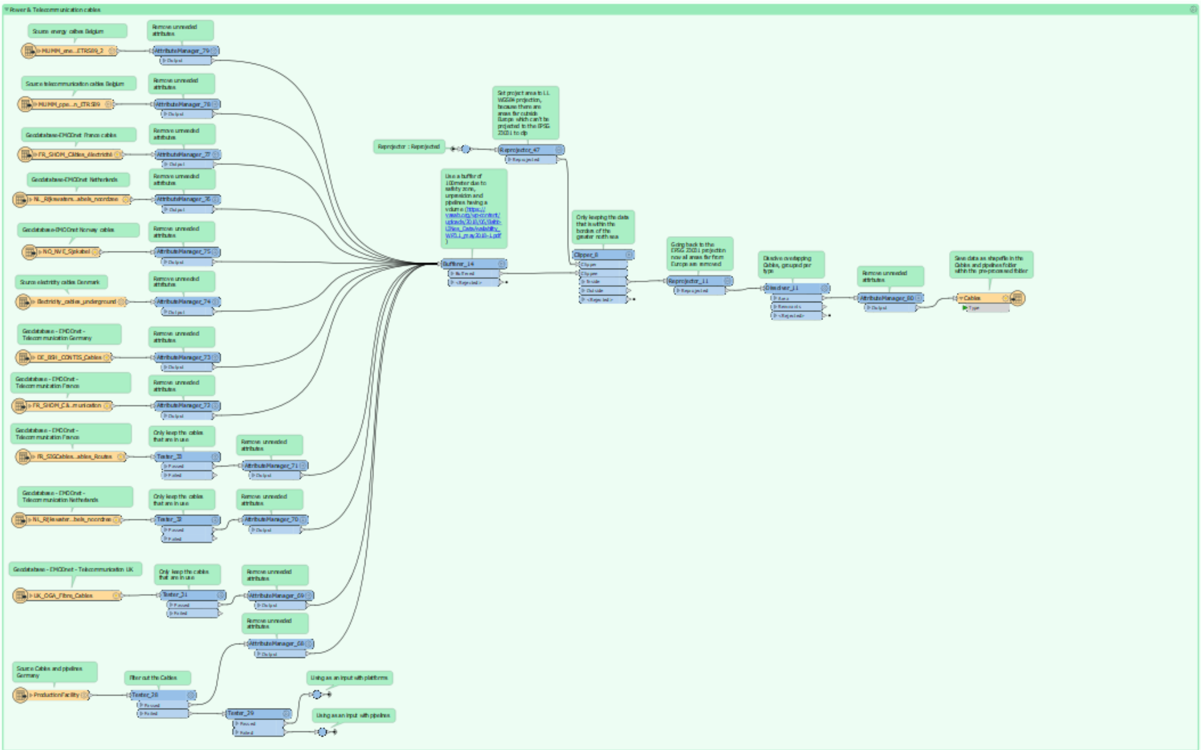

Figure 36 Pre-processing of the power and communication data.

The pre-processing for pipelines is similar to the pre-processing of the cables. The pipelines have 3 different sources (Figure 37). The source at the top is the data coming from the German source, the selected pipelines within the cables pre-processing. The others are coming from EMODnet and Belgium. All data is projected to EPSG23031. Followed by applying a buffer of 100 meters, since cables have a volume and there is a safety zone (Frias et al., 2018). The buffered pipelines are clipped to the project area, to only keep the data inside of the project area. Overlapping pipelines are dissolved into a single area and unnecessary attributes are removed. The data is written to a shapefile.

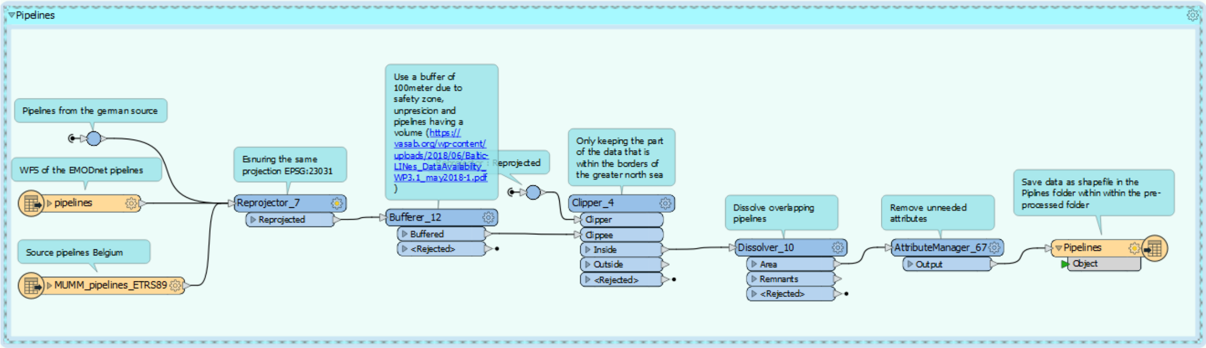

Figure 37 Pre-processing of the pipelines.

The pre-processing of the shipwrecks (Figure 38) is up next. There are 4 different shipwreck datasets, of which the French and English data have size values. The Danish and Belgian don't. First, all unnecessary attributes of the dataset are removed. For the English data, the polygons are replaced with a centre point because all polygons are circles of the same size. Then the data is tested, if the data has a value within the size attribute no action is taken. If data doesn't have this a size of 53 is set because this is the average size of the French and English data. This is calculated with the statistics calculator (Top of figure 38). Then a buffer is performed based on the size attributes. So, if a shipwreck already had a size this value is used as a buffer value, otherwise, a buffer value of 53 is used. After this, the data is clipped to the project area. Overlapping shipwrecks are dissolved and the unnecessary attributes are removed. The data is written to a shapefile.

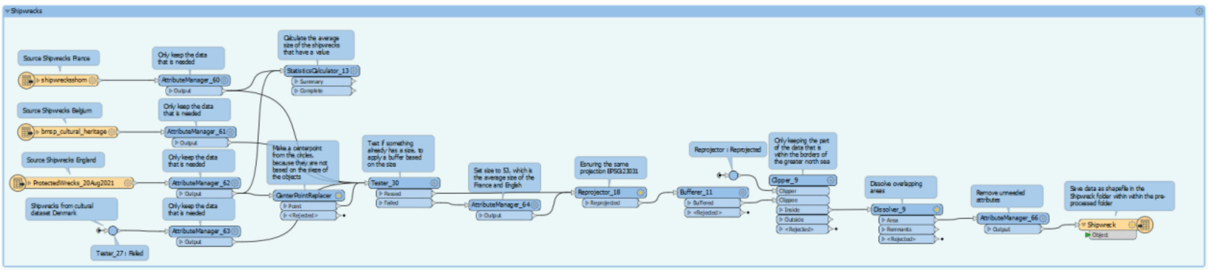

Figure 38 Pre-processing of the shipwreck data.

Next up is the pre-processing of the cultural heritage data (Figure 39). The input data consist of 3 different Danish datasets. One has polygons (Top part of figure 39) of which the average size is calculated as first. One has lines and the last one are points. Out of the point dataset, the shipwrecks are filtered first (the shipwrecks were used with the pre-processing of shipwrecks figure 38) the remaining data is buffered with 137 meters, to get the size area as the average of the areas. Then all data is combined and reprojected. The data is clipped to the project area and dissolved when overlapping. The line data is buffered with 100 meters, otherwise, it is not possible to write it as a polygon. After this, all unnecessary attributes are removed, and the data is written to a shapefile.

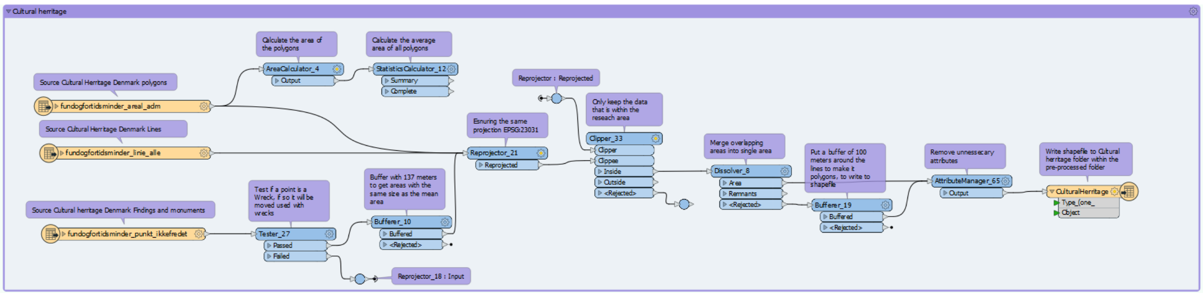

Figure 39 Pre-processing of the cultural heritage data.

The pre-processing of the lighthouses (Figure 40) is similar to the general pre-processing steps (Figure 2). First, the data is read and reprojected to EPSG23031. Only the active towers are kept and buffered with 15,3 meters (Cligan, 2019). Since it is unknown to what side the lighthouses are located all sides are buffered with 15.3 meters. The data is clipped to the project area, unnecessary data is removed, and the data is written to a shapefile.

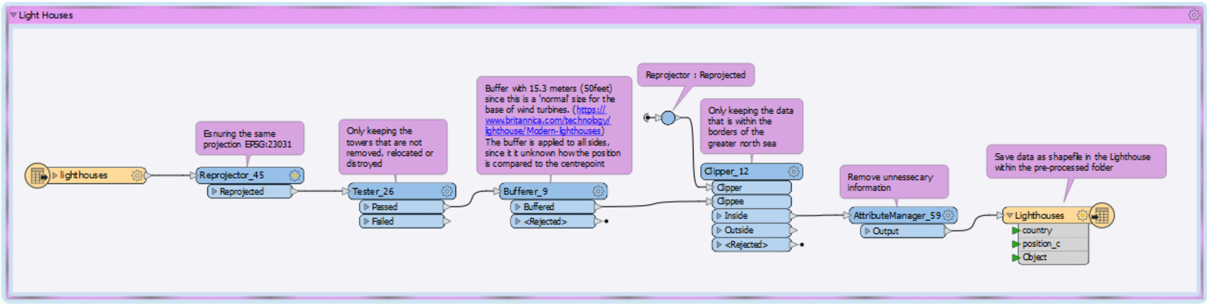

Figure 40 Pre-processing of lighthouses.

Next up is the pre-processing of radar towers (Figure 41). First, the projection is changed to EPSG23031. Then a buffer of 95 meters is applied since the tower is 95x14 meters. It is unknown to what direction it is located, so all sides are buffered with 95 meters. Next up, unnecessary attributes are removed, and the data is written to a shapefile.

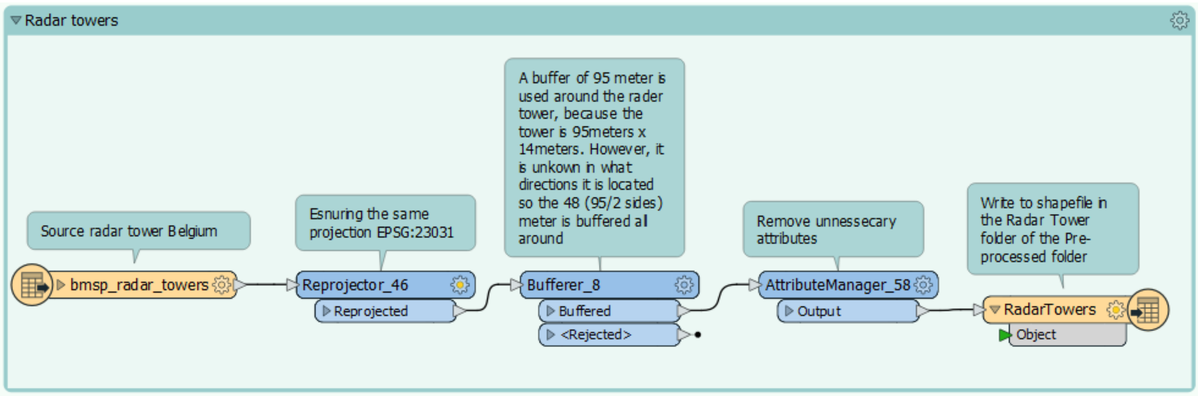

Figure 41 Pre-processing of the radar tower data.

Lastly, a shapefile with the distance to the coast is created (Figure 42). First, a bounding box is created around the study area, then the study area is clipped from the bounding box. You then get the borders of the study areas as a result. Which is needed because it is not possible to buffer inwards. Then the buffer zones are created, so a buffer of 10, 20, 30, 40, 50, 100, 200 and 350 kilometres is applied. The buffers are then clipped to the project area because all sides were buffered, so also the outsides of the bounding box. The different distances are filtered. A distance is overlayed with the distance underneath it, to only keep a zone and not from the coast to the maximum distance. The non-overlapping distances are kept, and new distance values are set within the attributes. Once this is done for all distances they are combined, and the unnecessary attributes are removed. The data is then written to a shapefile.

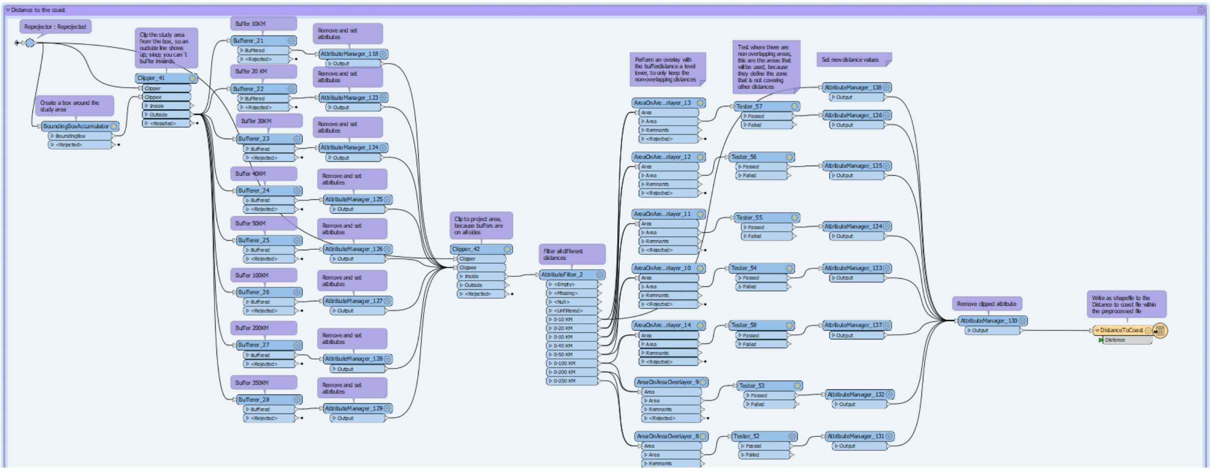

Figure 42 Creating a shapefile with the distance to the coast as a pre-processing step.

Appendix IV – Processing suitable areas

The processing of the suitable areas is done in two steps (Figure 3). Within the FME model this looks like figure 43. In the big dark blue box (Left of figure 43) the first steps are taken and in the big light blue box (Right of figure 43) the final steps are taken. Both boxes will be explained within this appendix and with that, the processing of the suitable areas is explained.

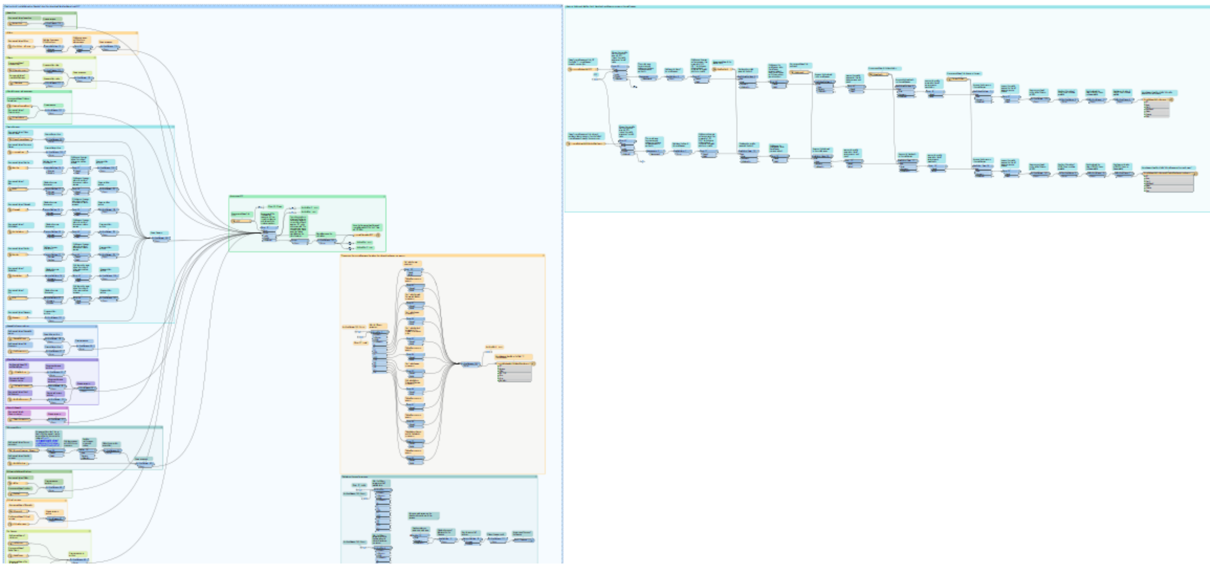

Figure 43 Processing of the suitable areas.

On the left of the left dark blue box (Figure 43) all categories are within their own boxes. All data is first per category before they are all combined within the little green box in the centre of the big dark blue box to the left (Figure 43). First, the categories will be explained, followed by the green box in the centre and then the two boxes underneath the green box. After that, the big light blue box to the right (Figure 43) will be explained.

For the different categories, there are three basic processing possibilities, before being used in the green centre box. The first one is just adding a category. This is done for the categories aquaculture, mineral extraction and aggregates, scientific research, cables and pipelines and cultural heritage. For those categories, the pre-processed data is read. A category value is created, and the 'object' attribute is kept (Example figure 44). For those categories, the presence of the data results in an area being unsuitable (Figure 3).

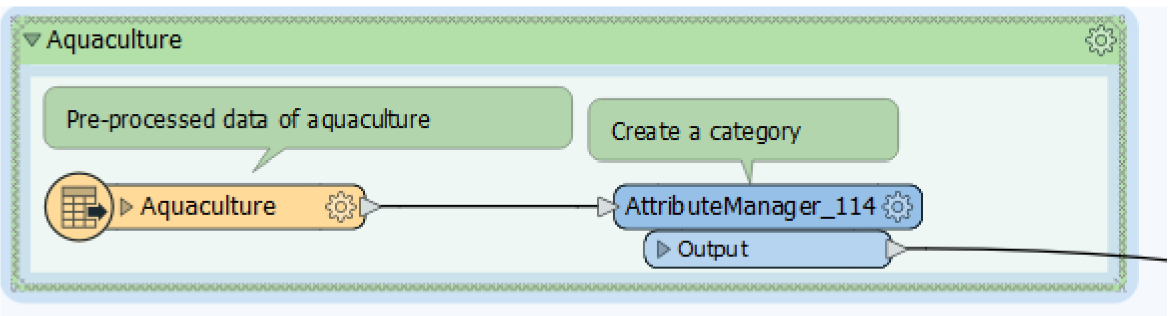

Figure 44 Example of what adding a category looks like within the workbench. This is done for the categories of aquaculture, mineral extraction and aggregates, scientific research, cables and pipelines and cultural heritage.

The second processing possibility is creating a category and an object attribute. If data does not have an object attribute yet, or if multiple sources have to be combined into a single category an object attribute was created. This object explains what the objects within the data are. This is done for the categories military, renewable energy production, oil and gas exploitation and no category (Example figure 45). So, what happens is that first the pre-processed data of a category is read. Then an object value is created, explaining what the object is if necessary unneeded attributes are removed. After this, the data is combined and a category is created. For those categories, similar as to the previously mentioned categories, the presence of the data results in an area becoming unsuitable (Figure 3)

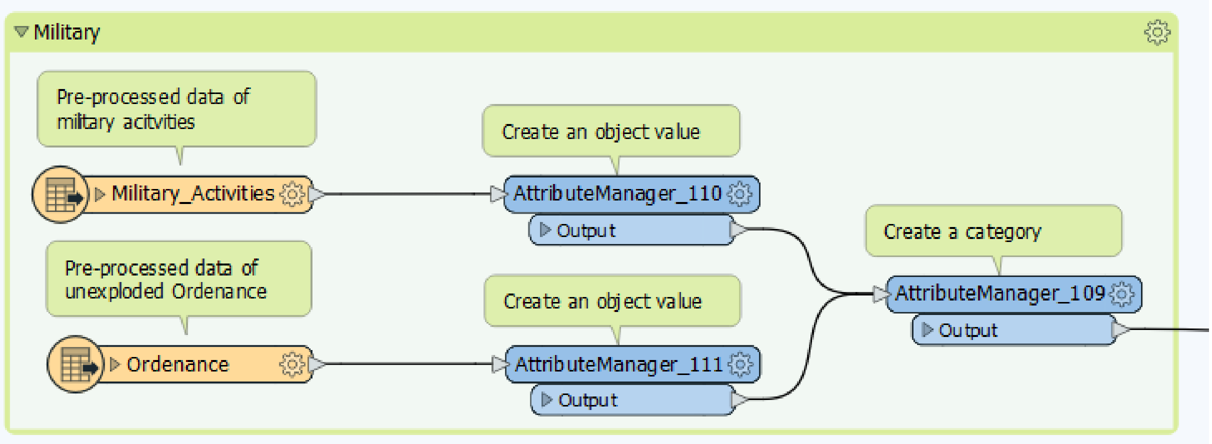

Figure 45 Example of what adding an object and a category looks like within the workbench. This is done for the categories military, renewable energy production, oil and gas exploitation and no category.

The third processing possibility is that there is more processing necessary before the data can be used. This is the case for fishery, nature protection and shipping and ports. For those categories, unsuitability is not determined by the presence of data (Figure 3). They will all be explained separately.

Figure 46 shows the processing of the fishery. The average fishing hours are calculated first. If a polygon has an above-average number of fishing hours this is kept as an 'unsuitable' area otherwise it is seen as suitable. This is because fishing takes place throughout the entire Greater North Sea if all locations where fishery takes place would be seen as unsuitable, there would be no space within the Greater North Sea for wind turbines. Since it is possible to perform multi-use with fishing and wind turbines only locations with above-average fishing hours are kept. Since those areas are seen as the main areas for the activities, for locations with less activity multi-use can be assumed. To the remaining polygons, a category value is assigned.

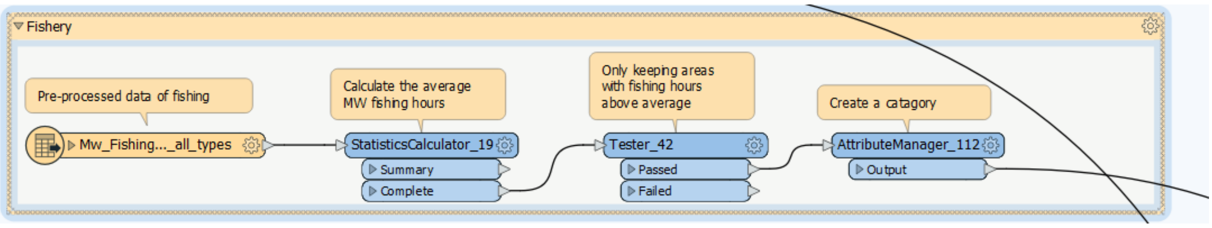

Figure 46 Processing of the fishery data.

For nature protection, there are multiple pre-processed sources available (Figure 47). For the marine protected areas, unique habitats, and seagrass areas only an object attribute is created. For the observations of benthos, birds, mammals, phytoplankton, reptiles, zooplankton, and fish the process is similar to fishery. The average number of observations per polygon is calculated. If a polygon has an above-average number of observations the area is seen as 'unsuitable' otherwise it is seen as suitable. This is done because observations are done throughout the entire Greater North Sea. Areas with an above-average number of observations are seen as unique and important for wildlife. So, wind turbines installation would disturb wildlife in those areas. Therefore, those areas are seen as unsuitable. All polygons with an above-average number of observations are combined with the marine protected areas, unique areas and seagrass areas and a category attribute is added.

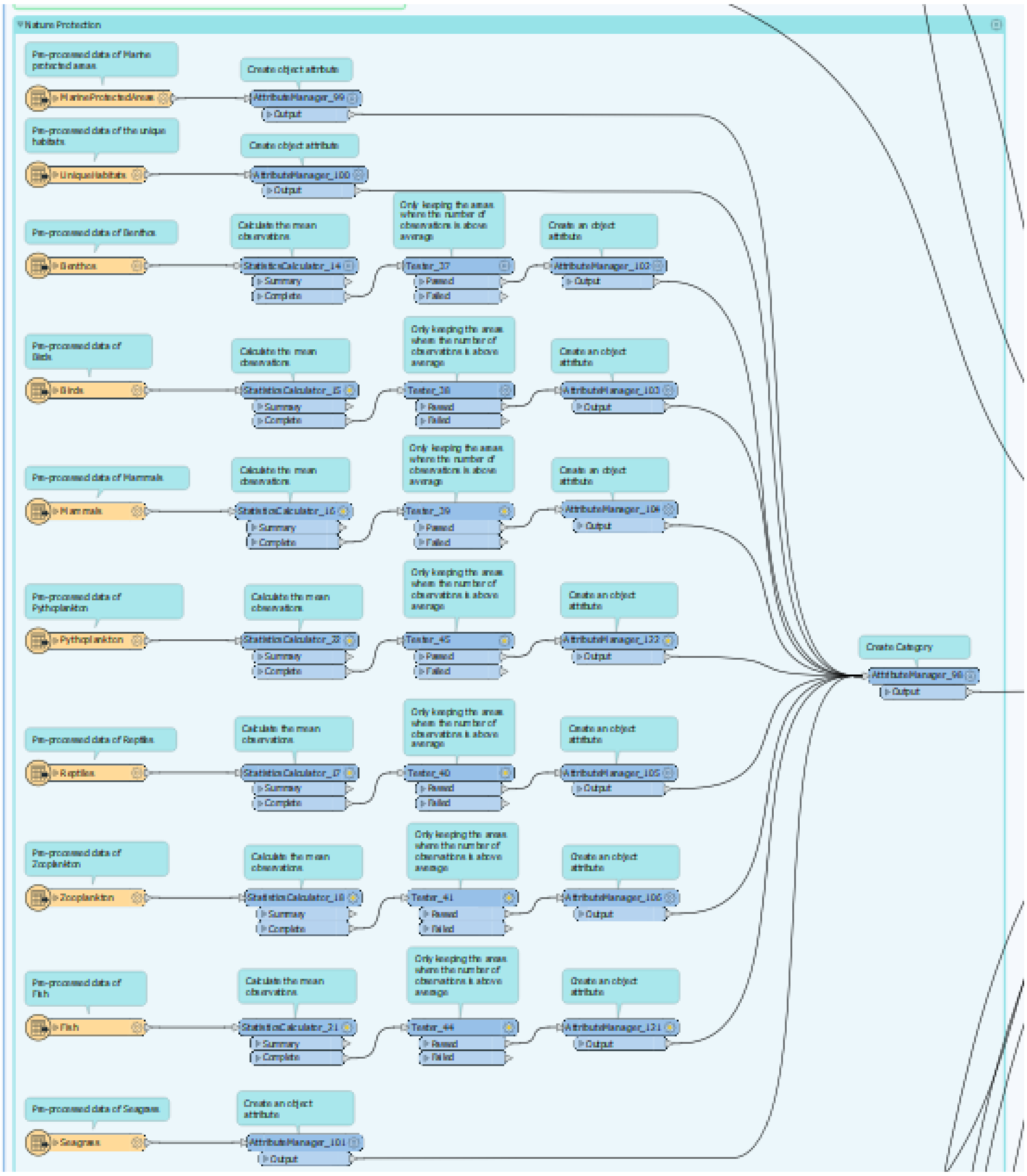

Figure 47Processing of nature protection.

For shipping and ports, the processing is shown in figure 48. On the shipping movement, more processing was needed. It is first tested if there are over 365 shipping movements within a polygon. If so, the area is seen as unsuitable. Otherwise, the area is seen as suitable, because the shipping lanes can quite possibly be relocated (Ruijgrok et al., 2019). After this, the data of unsuitable shipping areas is combined with the ports and a category is added.

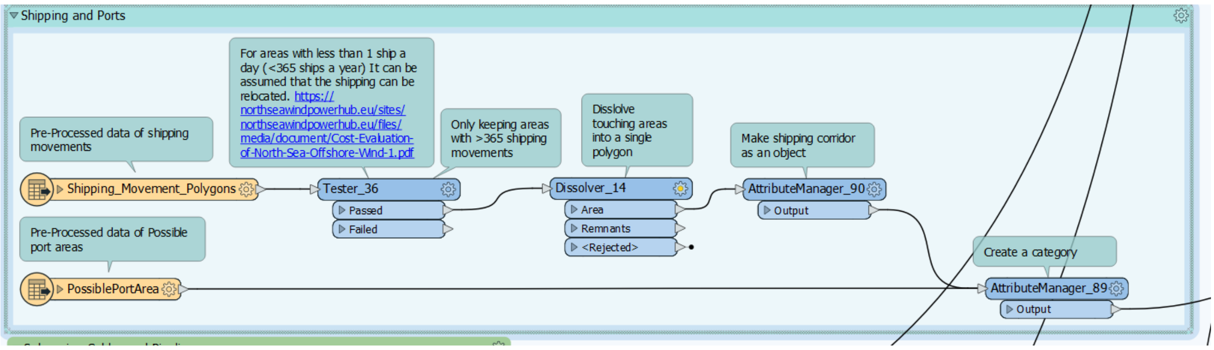

Figure 48 Processing of the shipping data.

This finishes creating the categories, all categories are combined within the bright green box (Centre of figure 43). Within this part of the analysis (Figure 49) the EEZ is assigned to the different datasets. This is done by clipping all the data to the pre-processed EEZ dataset. The attributes are merged during this clip. Some parts can't be clipped, due to the complex structures so the EEZs are assigned manually. The data is then written to a shapefile containing all unsuitable areas with their EEZs.

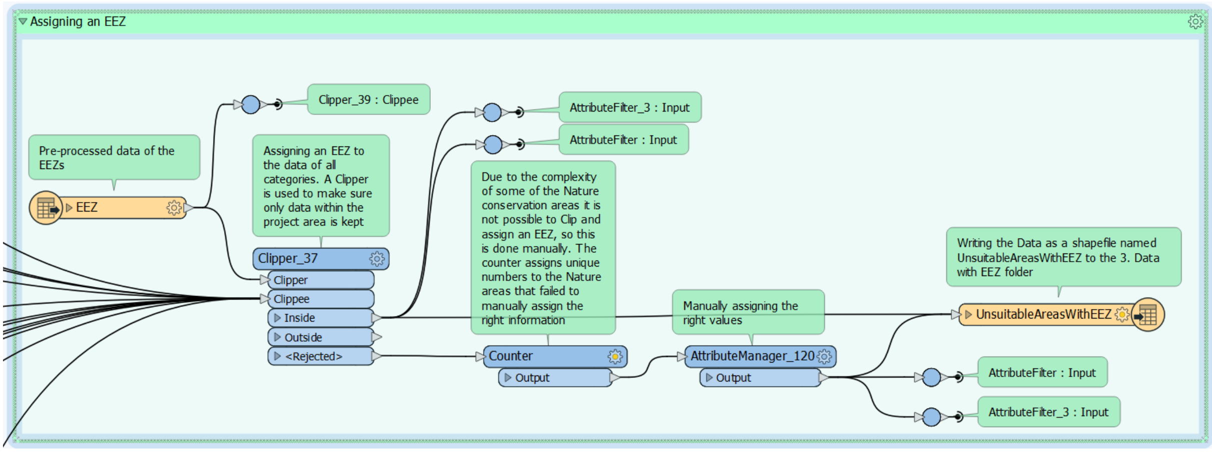

Figure 49 Assigning the EEZ to the data with the categories.

Underneath the green box, there is a big yellow box (Figure 43). Here the unsuitable values based on rules and regulations are determined. First, all data is filtered per category. Then per category, a test is done, only keeping the countries that take the category into account whilst doing marine spatial planning (Table 3). The filter is based on the EEZ that is assigned (Figure 49). Then unnecessary attributes are removed, and the data is written to a shapefile. This shapefile contains all unsuitable areas when taking the rules and regulations into account.

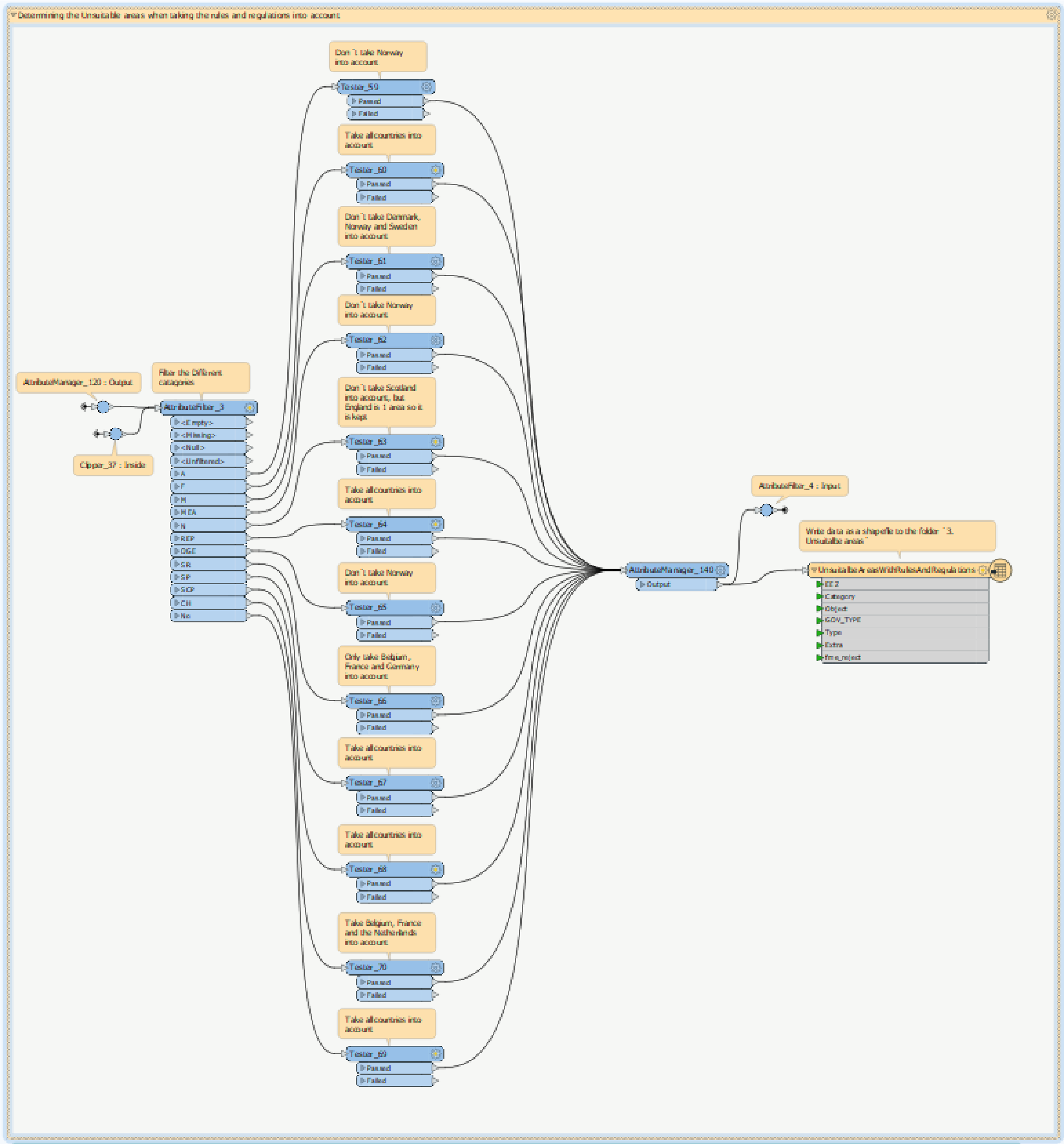

Figure 50 determining the unsuitable areas when taking the rules and regulations into account.

The last part of the dark blue box (Left side of figure 43) is calculating the sizes of the categories (Figure 51). This is done for all unsuitable areas and for the areas when taking the rules and regulations into account. The process for them is similar. First, the data is filtered based on the categories. Then the dissolver can be connected to a certain theme. What happens is that the overlapping areas are dissolved into a single area. The size of the area is calculated, summed for all areas and converted to square kilometres. This output is then shown, but not written to a dataset.

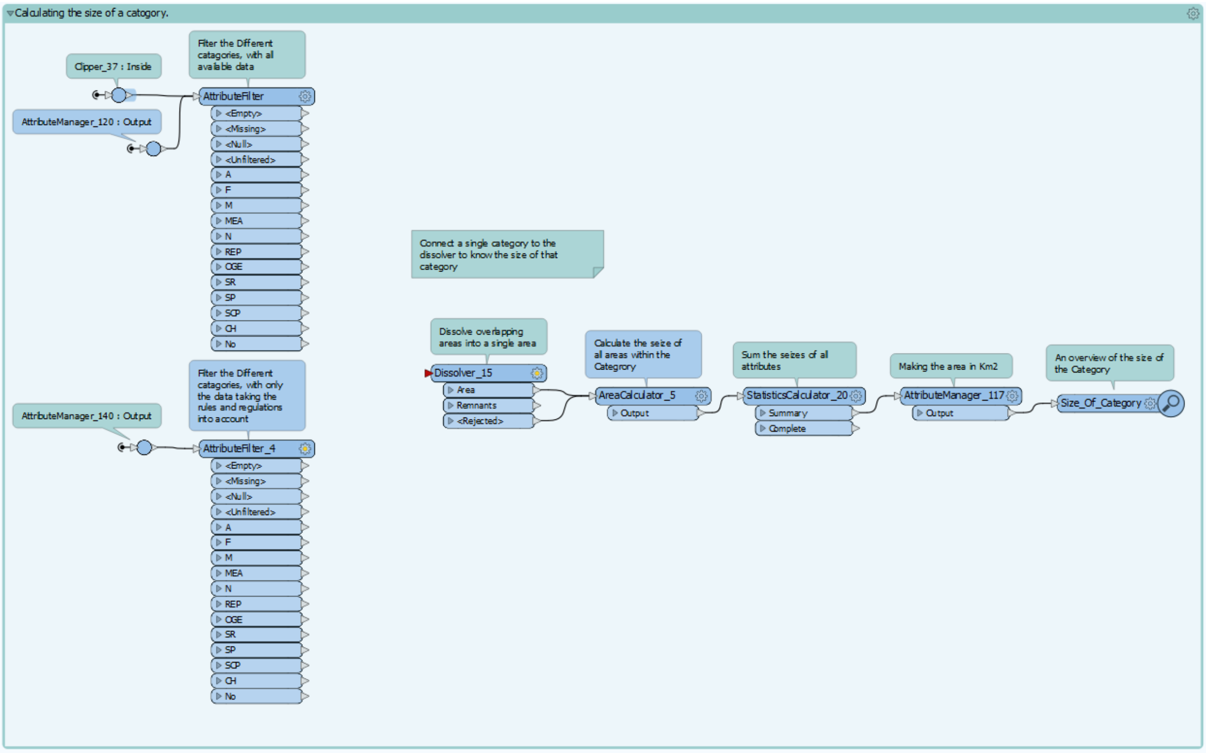

Figure 51 Calculating the size of a category.

In the final part of the workbench, the suitable areas get calculated and enriched with extra data, the big light blue block (Right side of figure 43). Here the suitable areas and the suitable areas with rules and regulations are processed similarly. As an example, the suitable areas for all data are explained.

First, the shapefile written in the previous step, containing all unsuitable areas, their categories and EEZs is read (Figure 52). The unsuitable areas are clipped from the entire project area. The 'outside' areas are the remaining suitable areas. Since this becomes a single polygon, this data is disaggregated, and the sizes of the areas are calculated. Only the 'suitable' areas with a minimal size of 1 km^2 are seen as suitable. Otherwise, too few wind turbines can be installed (Rodrigues et al., 2015). So, the areas that are smaller than one square kilometre are removed from the suitable areas.

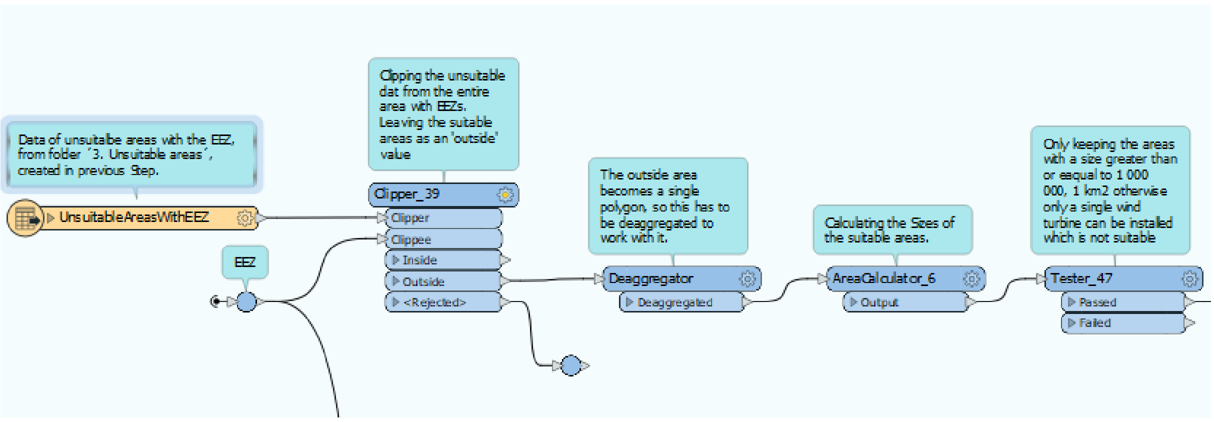

Figure 52 First part of determining suitable areas and enriching with extra information.

The next part of the processing (Figure 53) consists of adding the pre-processed data on the depth, wind speed, wave height and distance to the coast. This is done by overlaying the suitable areas with the polygons containing the information on those factors. With this overlay, the data is merged. Only the suitable areas are kept, and all other data is removed again. Suitable areas with depths deeper than -900 meters are removed since they are unsuitable for wind turbines (Hu et al., 2021).

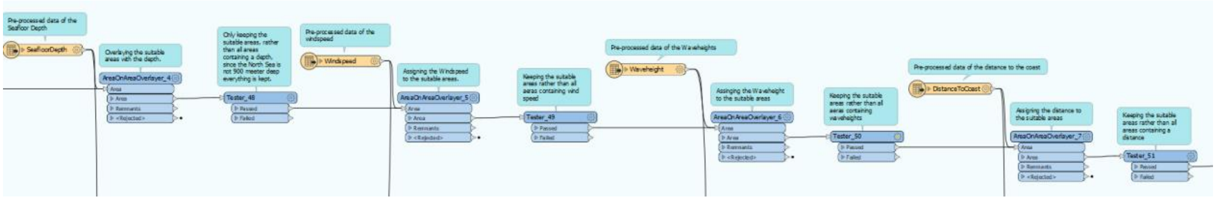

Figure 53 enriching the suitable areas with the pre-processed data on depth, wind speed and wave height.

For the last part (Figure 54) the costs are added. Since no dataset was available for the costs of the wind turbines, this data is created. Based on the distance from shore and the depth (Table 14). If areas were deeper or the distance was over the values shown in the table an 'unknown' value was assigned as a cost factor. After assigning the costs values of 99999 are given if the suitable area does not contain a depth, windspeed or wave height. This is done so the data can be written to a shapefile and used to create maps.

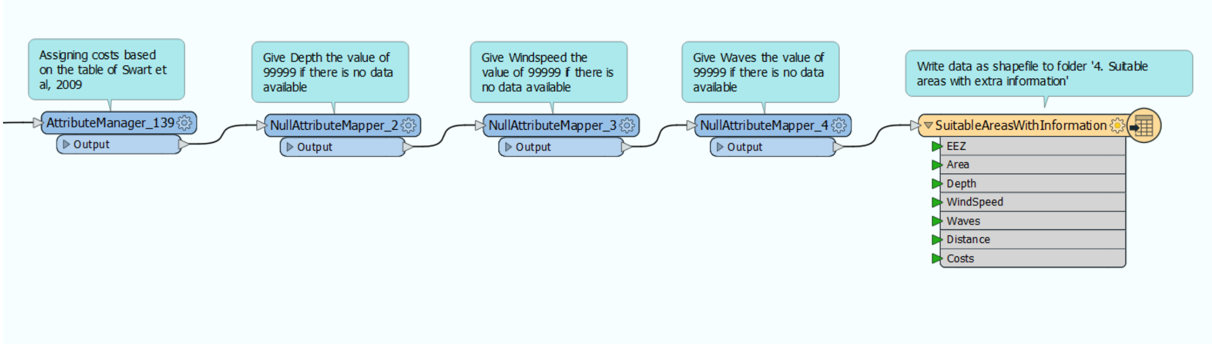

Figure 54 The final processing of the data to determine the suitable areas.

Table 14 The costs assigned to the suitable areas (Swart et al., 2009).

Water Depth (m)	**Distance from shore (km)**							
	0-10	10-20	20-30	30-40	40-50	50-100	100-200	>200
10-20	1	1.02	1.04	1.07	1.09	1.18	1.41	1.60
20-30	1.07	1.09	1.11	1.14	1.16	1.26	1.50	1.71
30-40	1.14	1.26	1.29	1.32	1.34	1.46	1.74	1.98
40-50	1.40	1.43	1.46	1.49	1.52	1.65	1.97	2.23

Appendix V – Processing Current and planned wind turbine farms

The processing of the data to answer the research question "Are current and planned wind turbine farms on suitable areas according to the open data available?" is done as described within this appendix. The big purple box (Bottom right figure 55) contains the processing steps for this research question.

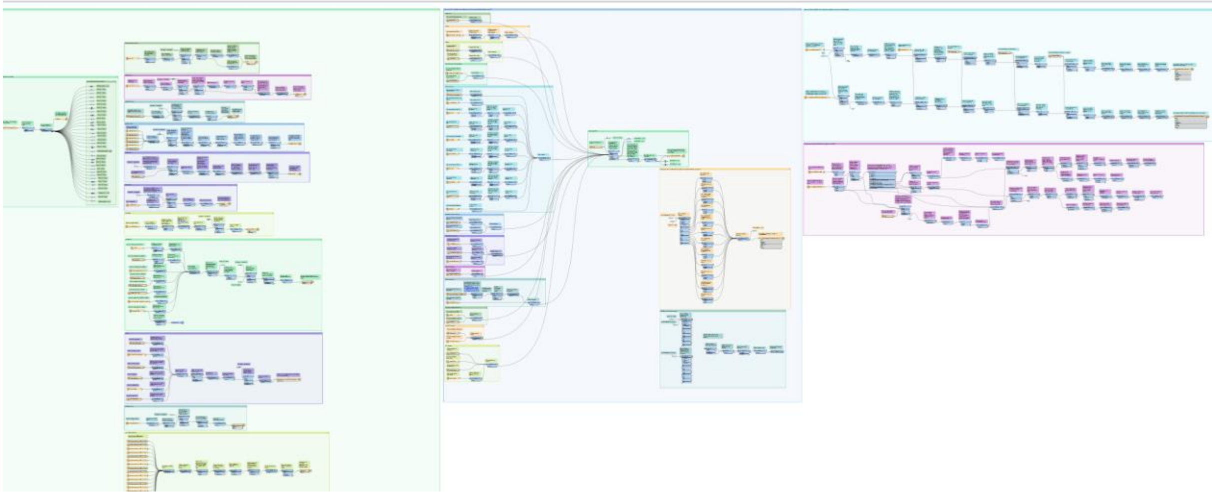

Figure 55 The model created during this research, bottom right the big purple box containing the processing steps to answer the final research question.

Zooming in to the purple box (Figure 56) it shows that there are 3 sources used and that there is no data written as output. However, it shows three different 'ends' of the process. Because the data is not written to a document but the output is used to create tables and overviews.

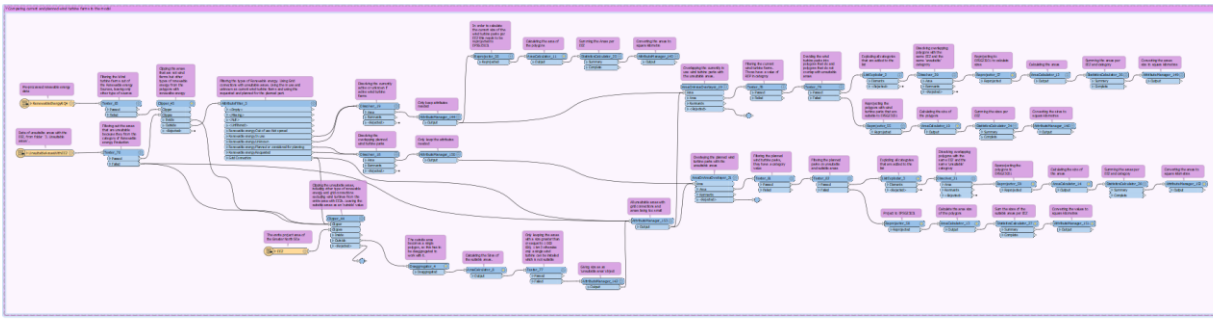

Figure 56 The process to answer the research question. Showing three readers (yellow boxes) but no writers.

At first, the input data is read (Figure 57). The sources for this are the pre-processed renewable energy data (Appendix III). And the unsuitable areas with EEZ (Appendix IV). First, only the wind turbine farms and unknown renewable energy production are filtered out of the renewable energy dataset. Because other types of renewable energy are not relevant for this research. Simultaneously the unsuitable areas from renewable energy production are filtered out of the unsuitable areas' dataset. The areas that are not wind farms or unknown renewable energy production are clipped from the unsuitable areas. This is to get a dataset containing data on wind turbine farms and a dataset containing data on other types of renewable energy production. The data that is classified as 'outside' is used for the filter as explained in figure 58. The data classified 'inside' will be explained with figure 59.

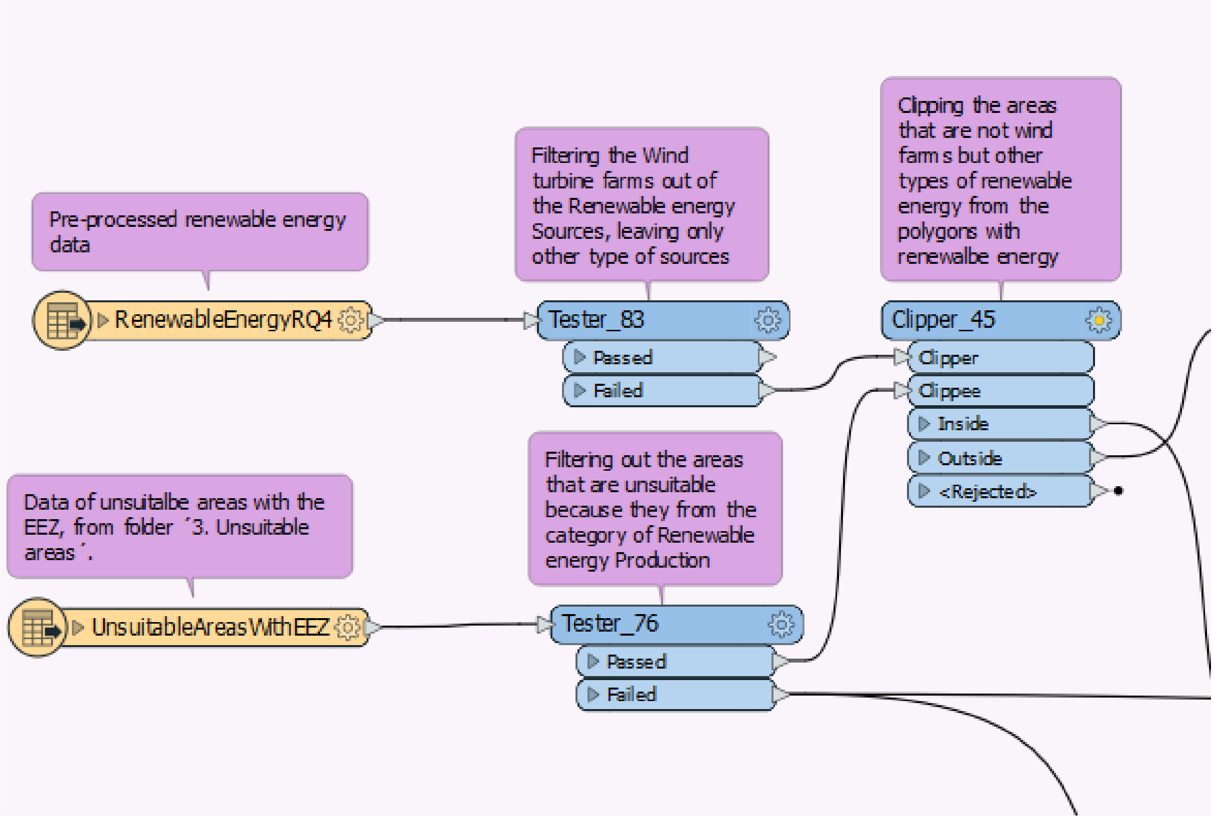

Figure 57 The first processing steps using the renewable energy data and unsuitable areas as an input to filter the wind turbine farms.

The data classified as 'outside' is filtered, the wind turbine farms and unknown types of renewable energy production are used (Figure 57) There are 5 different filters, being 'Renewable energy in use', 'Renewable energy unknown', Renewable energy planned or considered for planning', Renewable energy requested' and Grid Connections (Figure 58). Based on those filters two groups are created. The currently active wind turbine farms consist of the first two filters and the planned wind turbine farms, consisting of the following two filters. The filter for Grid connections is used as input for the unsuitable areas. Per group (Figure 58). the overlapping areas are dissolved, and the necessary attributes are kept. As shown at the far right of figure 58 the data is used with two different area on area overlayers. This will be explained after the other input for this is elaborated.

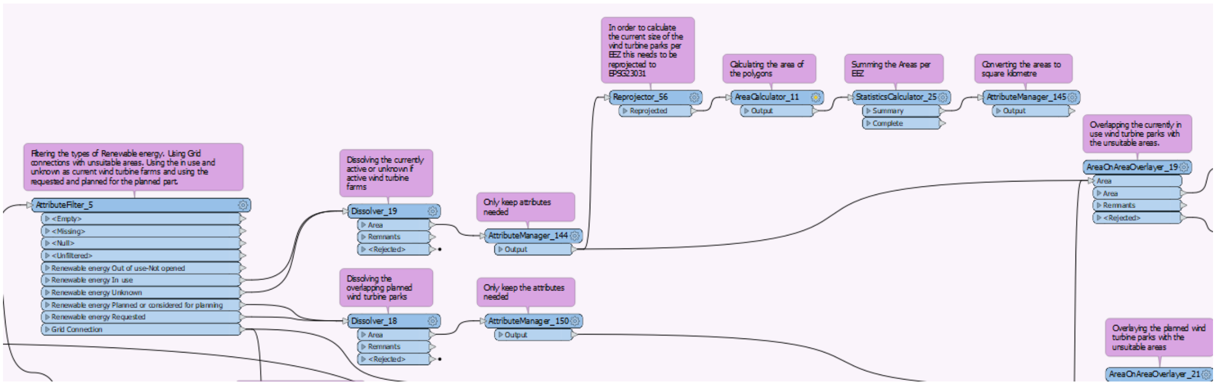

Figure 58 filtering the four different groups and creating two groups, the active and planned wind turbine farms. At the end, the area-on-area overlayer of the final steps is shown. The top part shows the calculation of the size of the wind turbine farms.

The top part of figure 58 shows a row of transformers after the attribute manager of the currently active wind turbine farms. Those transformers calculate the size of the total current wind turbine farms per EEZ. This is done according to the following steps. First, the data is reprojected to EPSG23031 to ensure metres as a unit. Then the sizes of the areas are calculated and summed per EEZ. Lastly, the areas are converted to square kilometres and used as input for the tables.

The area-on-area overlayer has two different inputs (Figure 58). The first input is explained previously, the second input is shown in figure 59. The entire project area of the Greater North Sea is used as input for the clipper. From this, the unsuitable areas are clipped. The unsuitable areas, in this case, are the unsuitable areas that failed in the tester (Figure 57) so that are not the renewable energy production. Plus, the data that is inside from the clipper, so the other types of renewable energy, plus the Grid Connections filtered. The outside of this clip is kept and disaggregated (Like in appendix IV). So, these are 'suitable areas' without renewable energy production being that are classified as unsuitable. The size of the areas are calculated, areas with a size smaller than 1 square kilometre are classified as unsuitable areas, due to them being too small. This is used as an input for the final inputs for the area-on-area overlayer.

Before the data is connected to the area-on-area overlayers, together with the previous data, an attribute manager is used to combine all data used as an input (Far right of figure 59). This attribute manager removes unnecessary attributes and sets the attribute to NameUnsuitable. To divide the unsuitable and suitable areas later. Furthermore, an unsuitable attribute containing Yes is created. The input for this attribute manager is, the areas that are too small, the filtered grid connections and the unsuitable areas minus the wind turbine farms.

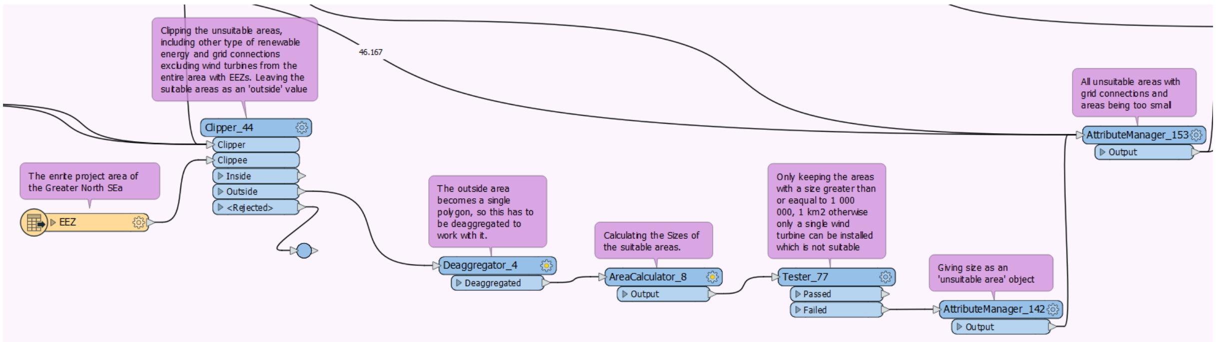

Figure 59 The other input of the area-on-area overlayer. Calculating the unsuitable areas due to size.

The data from 'Current wind turbine farms' and 'Planned wind turbine farms' both get connected to their own area on area overlayer (Figure 56). Figure 60 shows the final process since both processes are identical, only one is shown.

So, the current wind turbine farms or planned wind turbine farms, together with the data from the attribute manager (Figure 59) are connected to the area-on-area overlayer (Figure 60). The wind turbine farms are overlayed with the other data and all information is listed. The wind turbine farms are filtered and divided into areas that overlap with unsuitable areas and areas that do not overlap. If an area does overlap with an unsuitable area (Top row of transformers figure 60) a list of the categories is created. After this, the data is solved per category. The data is reprojected to EPSG23031 to ensure the units of metres. The sizes of the areas are calculated and summed per EEZ and category. The sizes are converted to square kilometres and used as an input for the tables. For the wind turbine farms that do not overlap with unsuitable areas the data is reprojected to EPSG23031, the size of the areas is calculated, summed per EEZ, and converted to square kilometres (Bottom row of transformers figure 60). Similar to the unsuitable areas the output is used as input for the tables within this report.

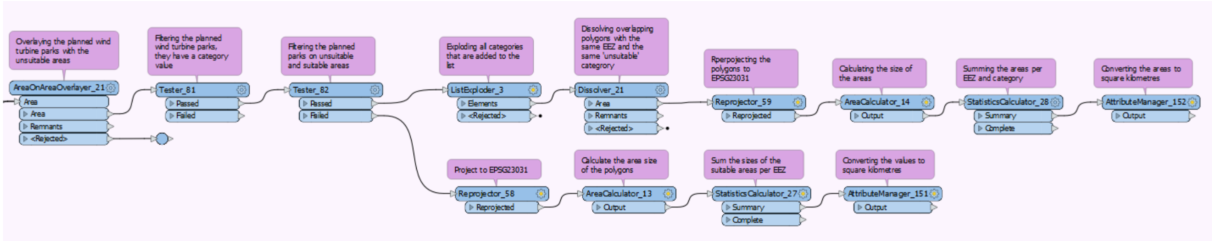

Figure 60 The final steps were the size of the area is calculated and summed per EEZ

Appendix VI – Open Data sources

Table 15 provides an overview of the different data sources that are used during this research. The sources are used to represent an influencing factor. For every source, the data format, the countries that are represented within the source, the geometry type, the publication date, the last update date, the download date and a reference are given. The datasets are grouped per category.

Table 15 Overview of the different data sources used during this research.

	Data format	Country	Geometry type	Publication	Updated	Downloaded	Reference
Zones and boundaries							
Borders of the Greater North Sea	Shape file	All	Polygon	26-04-2009	08-01-2015	22-10-2021	(ICES, 2015)[29]
Exclusive Economic Zones (EEZ)	Shape file	All	Polygon	17-03-2020	17-03-2020	22-10-2021	(Flanders Marine Institute, 2019)
12 Mile zone	Shape file	All	Polygon	30-09-2019	30-09-2019	22-10-2021	(Flanders Marine Institute, 2019)
Seabed							
Soil type Top 25 centimetres	Shape file[30]	All	Polygon	10-2016	09-2021	21-10-2021	(EMODnet, 2016)[31]
Seafloor depth	ASC file (6x)	All	Raster	12-2020	-	26-10-2021	(EMODnet Bathymetry Consortium, 2020)
Wave height[32]	Geo TIFF	All	Raster	10-04-2019	-	26-10-2021	(EMODnet, 2019a)

[29] This is the most recent version available, according to the ICES website.
[30] A download rather than a service is used due to the service not being able to handle the amount of data.
[31] The 1:1 000 000 scale is used, due to other scales not having information on the entire Greater North Sea.
[32] Mean of annual 90th percentile, expressed in kinetic energy.

Windspeed (1983-1993) at 50 meters. (1˚resolution)	Shape file	All	Polygon	2005	-	22-11-2021	(NASA Langley Atmospheric Sciences Data Center, 2005)
Seismic activities	WFS	Belgium	Polygon	-	08-05-2021	-	(Royal Observatory of Belgium, 2021)
Aquaculture & Fisheries							
Average MW fishing hours[33] - Beam trawls - Bottom otter trawls - Bottom seines - Static gears	WFS	All	Raster 0.05 x 0.05 degrees	26-02-2020	26-02-2020	-	(Cogea, 2020b)
Aquaculture Finfish	WFS	Denmark Norway Scotland	Points	09-10-2017	13-09-2021	-	(AND-International, 2017)
Aquaculture Shellfish	WFS	Denmark France Netherlands Norway United Kingdom	Points	01-07-2014	26-11-2019	-	(AND-International, 2014)
Aquaculture	Geodatabase	Norway	Polygon	18-11-2020	18-11-2020	22-10-2021	(Kartverket, 2020)
Aquaculture	WFS	Sweden	Points	16-06-2021	-	-	(Jordbruksverket, 2021)

[33] From the year 2015 till the year 2018, dataset is created in 2020.

Aquaculture and aquaculture shellfish	WFS	Scotland	Points	2020	22-05-2021	-	(Marine Schotland, 2020)
Aquaculture zones	WFS	Belgium	Polygon	22-05-2019	10-12-2020	-	(Royal Belgian Institute for Natural Sciences, 2019a)
Military activities							
Military activities	WFS	Belgium Germany Netherlands	Polygon	2020	01-02-2021	-	(CETMAR, 2021b)
Munition encounters (1999-2017)	WFS	All	Points	09-12-2016	31-12-2021	-	(OSPAR Commission, 2016)
Extraction of materials							
Dredging (Soil disposal site) & Aggregates	Shape file[34]	Belgium Denmark France Germany Netherlands Norway UK (England)	Points	01-01-2018	-	18-11-2021	(OSPAR Commission, 2018)
Dredge spoil disposal sites	WFS	Scotland	Polygon	2020	22-05-2021	-	(Marine Schotland, 2020)
Aggregates	WFS	Belgium Denmark France Germany Netherlands UK	Polygon	19-09-2018	04-08-2020	-	(AZTI, 2020)

[34] A WFS is available as, as mentioned within the APA-reference. However, during the research this source did stop working so a shapefile has been downloaded instead.

Sand and gravel Extraction	WFS	France Netherlands	Polygon	01-01-2014	-	-	(ICES, 2014)
Sand and gravel extraction zone	WFS	Belgium	Polygon	22-05-2019	10-12-2020	-	(Royal Belgian Institute for Natural Sciences, 2019d)
Nature protected areas							
Marine protected areas[35]	Geodatabase	All	Polygon	-	09-2021	22-09-2021	(UNEP; WCMC; UICN, 2021)
Unique Habitats	WFS	All	Polygon	17-02-2021	08-03-2021	-	(EMODnet, 2021)
Biodiversity[36]							
Benthos	CSV	All	Points	-	2021	1-11-2021	(EMODnet Biology, 2021)
Birds	CSV	All	Points	-	2021	28-10-2021	(EMODnet Biology, 2021)
Fish[37]	CSV	All	Points	-	2021	5-11-2021	(EMODnet Biology, 2021)
Mammals	CSV	All	Points	-	2021	28-10-2021	(EMODnet Biology, 2021)

[35] This dataset contains the European Natura2000 Network (on water) as well as other types of nature protected areas from countries.

[36] The seven first datasets are all coming from the EMODnet Biology source. The data of this source is based on observations that are done throughout time and combined into a big dataset. Meaning there is no publication date available. The absence of data doesn´t mean that there are no animals living there, but an absence of observations. Furthermore, if countries or institutes observe more at certain locations it might seem like more animals are living within a certain area. So, the number of observations is observations is not equal to the number of animals living there and the number of observations is not equal throughout the area.

[37] A selection of the most occurring fish species has been made (Callaway et al., 2002; McGlade, 2002), since it was not possible to download for the trait 'fish'.

Phytoplankton	CSV	All	Points	-	2021	28-10-2021	(EMODnet Biology, 2021)
Reptiles	CSV	All	Points	-	2021	28-10-2021	(EMODnet Biology, 2021)
Zooplankton	CSV	All	Points	-	2021	28-10-2021	(EMODnet Biology, 2021)
Seagrass cover	WFS	All	Polygon & Point	2019	23-09-2021	-	(EMODnet, 2019b)
Existing renewable energy sources							
Wind energy Norway	Shape file	Norway	Polygon	28-11-2016	28-11-2016[38]	22-10-2021	(Norges vassdrags og energidirectorat, 2016)
Windmill locations	WFS	Belgium	Point	10-12-2020	-	-	(Royal Belgian Institute for Natural Sciences, 2020)
Offshore windfarms	WFS	Denmark	Point & Polygon	20-10-2014	25-09-2019	-	(Styrelsen for Dataforsyning of effektivesring, 2014)
Renewable energy sources	CSV	United Kingdom	Points	01-07-2014	06-2021	2-11-2021	(BEIS Renewable, 2021)
Offshore wind energy	GDB	All	Point & Polygon	01-06-2014	17-02-2021	02-11-2021	(CETMAR, 2021a)

[38] Currently the most up-to-date version found.

Renewables	Shape file[39]	Belgium Germany United Kingdom	Polygon	07-07-2021	-	18-11-2021	(OSPAR Commission, 2021)
Landing Stations (Grid connections)	WFS	All	Point	24-08-2014	01-08-2017	-	(EMODnet, 2014)
Oil and Gas							
Oil and gas platforms	WFS	Denmark Germany Netherlands Norway United Kingdom	Point	14-08-2015	21-10-2020	-	(Cogea, 2020c)
Fossil fuel resources	WFS	Denmark	Polygon	27-10-2020	-	-	(Energistyrelsen Klima Energi- og Forsyningsministeriet, 2020)
Fossil fuel resources	WFS	Netherlands	Polygon	30-07-2015	18-06-2021	-	(TNO Geologische Dienst Nederland, 2015)
Exploitation licenses	WFS	Denmark France Germany Netherlands Norway United Kingdom	Polygon	30-06-2014	05-10-2020	-	(Cogea, 2020a)

[39] A WFS is available as a source, as mentioned within the APA-reference. However, during the research this source did stop working so a shapefile has been downloaded instead.

Exploitation areas	WFS	Germany	Polygon	10-09-2020	-	-	(Federaal Maritiemen hydrografisch agentschap, 2020)
Research							
Measuring poles	WFS	Belgium	Points	22-05-2019	10-12-2020	-	(Royal Belgian Institute for Natural Sciences, 2019b)
Measuring locations	WFS	Sweden	Points	-	10-12-2020	-	(Naturvardsverket, 2020)
Shipping							
Shipping routes	Geo Tiff	All	Raster	19-12-2019	09-2021	23-10-2021	(European Maritime Safety Agency, 2020)
Ports	WFS	All	Points	03-05-2014	01-11-2019	-	(Eurofish and Cogea, 2019)
Cables and pipes							
Power Cables	Geodatabase	France Netherlands Norway	Lines	15-01-2015	26-01-2021	21-10-2021	(Cogea, 2015)
Telecommunication cables	Geodatabase	France Netherlands Norway Germany United Kingdom	Lines	15-01-2015	26-01-2021	21-10-2021	(Cogea, 2015)

Pipelines	WFS	Denmark Netherlands Norway United Kingdom	Lines	20-12-2017	20-12-2019	-	(Cogea, 2019)
Electricity cables, Telecommunication cables and Pipelines	WFS	Belgium	Lines	10-08-2018	-	-	(MUMM, 2018)
High voltage cables, data cables and pipelines	WFS	Germany	Lines	10-09-2020	-	-	(Federaal Maritiem en hydrografisch agentschap, 2020)
Electricity cables	WFS	Denmark	Lines	19-10-2020	-	-	(Energinet, 2020)
Archaeological areas							
Shipwrecks	WFS	France	Points	-	09-2020	-	(SHOM, 2020)
Shipwrecks	WFS	Belgium	Points	22-05-2019	22-10-2020	-	(Royal Decree, 2020)
Shipwrecks	WFS	England	Polygon	21-12-2017	20-08-2021	9-11-2021	(National Heritage List for England, 2020)
Preserved Ancient Monuments	WFS	Denmark	Polygon and Points	12-11-2020	-	-	(Slots- og Kulturstyrelsen, 2020)
Other							
Lighthouses	WFS	Belgium Denmark Germany Netherlands UK	Points	13-08-2015	-	-	(ARLS, 2015)

Radar towers	WFS	Belgium	Points	22-05-2019	10-12-2020	-	(Royal Belgian Institute for Natural Sciences, 2019c)

Appendix VII – Explanation on used datasets

This appendix explains the search of the different open data sets used during this research. It elaborates why certain datasets are used and what other datasets were found during the search for open data. The description is given per category (Table 4).

Borders – As indicated within the introduction the borders of the Greater North Sea are as defined within the ICES Ecoregions (ICES, 2015). Data for the shoreline (European Environment Agency, 2016), Exclusive Economic Zones and 12-Mile zone (Flanders Marine Institute, 2019) is based on European standards.

Seabed – For the soil type only a top 25 centimetres dataset is found (EMODnet, 2016). This data is available in several scales. The 1:1 000 000 scale is used during the project since the smaller scale data did not have information on the entire Greater North Sea. So, less accurate data is used than what is available, because of the size of the project area. The data is used as a shapefile since the service could not handle providing data for the entire Greater North Sea. Data of the soil deeper than 25 centimetres could not be obtained anywhere.

EMODnet also provides Seafloor depth data (EMODnet Bathymetry Consortium, 2020). This data needs to be downloaded as ASC files and is not provided as a service. The data for the wave height, in kinetic energy, is also coming from EMODnet and is the mean of the annual 90th percentile (EMODnet, 2019a).

Research shows that it is possible to obtain data on the average 50-year wind speed for the entire Greater North Sea (Geyer et al., 2015). The New European Wind Atlas (NEWA) offers this data. However, via their website, it is not possible to carry out a download or use a service. A dataset containing the monthly and annual average wind data at one degree is available via NASA (NASA Langley Atmospheric Sciences Data Center, 2005). This dataset however contains data from 1983-1993 at a height of 50 meters above the surface. Therefore, it must be assumed that wind speed is a factor that does not change much over time. NASA did have other datasets available, but they could not be obtained.

Aquaculture – For aquaculture several datasets are available. EMODnet provides a dataset with aquaculture locations for finfish (AND-International, 2017) and shellfish (AND-International, 2014). For finfish, data is available for Denmark, Norway, and Scotland and for shellfish for Denmark, France, the Netherlands, Norway, and the United Kingdom. This is just point data and not polygons marking the areas in the water. Extra data is available for Norway (Kartverket, 2020), Sweden (Jordbruksverket, 2021), Scotland (Marine Schotland, 2020) and Belgium (Royal Belgian Institute for Natural Sciences, 2019a). For Germany, INSPIRE has a dataset available that contains data on ‘agriculture and aquaculture’. Since there is no data on aquaculture in this file it is assumed that there is no aquaculture in Germany.

It should be noted that all data is based on the aquaculture of living animals. No data was found on seaweed farming or other types of non-living aquaculture. Seaweed farming however is an upcoming profession, with a current production of 1 500 tonnes (Van den Burg et al., 2021).

Fishery – To obtain insights into where fishery is taking place datasets containing the average MW fishing hours are used. Data is available on beam trawls, bottom otter trawls, bottom seines, and static gears, which are the most common types of fisheries within the Greater North

Sea. These datasets are based on data ranging from the years 2015 to 2018 (Cogea, 2020b). The data is available for the entire Greater North Sea.

Military – Within the category military there are two kinds of datasets available. First of all, there is data available for military activities. These are locations within the waters where military practises are carried out. This data is available for Belgium, Germany, and the Netherlands (CETMAR, 2021b). The other countries do not share this data.

Besides, there is also data available on munition encounters. For munition encounters, there is data available ranging from 1999 to 2017 (OSPAR Commission, 2016). This dataset covers all countries. However, not every country is covered every single year.

Mineral extraction and aggregates – Data is available on dredging and on aggregates. The OSPAR dataset contains data on dredging for all countries except Sweden and Scotland (OSPAR Commission, 2018). For Scotland data on dredge spoil disposal sites was obtained via the open data portal (Marine Schotland, 2020). For aggregates, data is available for Belgium, Denmark, France, Germany, the Netherlands, and the UK (AZTI, 2020). Leaving Norway and Sweden without data sources. On sand and gravel extraction data is available for France, the Netherlands (ICES, 2014) and Belgium (Royal Belgian Institute for Natural Sciences, 2019d).

Nature – A single dataset is available for Marine protected areas (UNEP; WCMC; UICN, 2021). This dataset contains the European Natura2000 Network as well as nature protected areas defined by countries and data on unique habitats (EMODnet, 2021).

Data on the occurrence of species can be obtained from EMODnet (EMODnet Biology, 2021). There is data available on benthos, birds, mammals, phytoplankton, reptiles, and zooplankton. The web viewer shows a grid with occurrences. This data could not be found on the website. The data shared is only available as Comma Separated Value files (CSV). The CSV files contain data on the observations of species, as well as a coordinate of the location where an observation is done.

EMODnet also has data available on the occurrence of fish. However, it is not possible to filter ‘fish’ as a trait for downloading. Therefore, a selection of the most occurring species according to previous research of McGlade and Callaway has been created and used (Callaway et al., 2002; McGlade, 2002). It is assumed that this represents the general fish occurrence.

Data on the occurrence of bats could not be obtained, most probably because research on this is quite new. Therefore, only a limited amount of wind turbines within the Dutch part of the Greater North Sea has the monitoring equipment (Lagerveld et al., 2017). Since research is only done for the Dutch coastline and no interpolation for the entire Greater North Sea has been performed this data is not available. So, it should be assumed that turning off wind turbines within the migration periods during the nights is sufficient to limit the number of fatal collisions (Lagerveld et al., 2017).

Renewable energy production – For renewable energy production, EMODnet has data available on wind turbines (CETMAR, 2021a). On other types of renewable energy production, such as floating solar panels or tidal energy there EMODnet has no data available. For the UK and Germany data on other types of renewable energy production was found (BEIS Renewable, 2021; OSPAR Commission, 2021). For Norway, and Denmark more up-to-date datasets than the EMODnet data are available (Norges vassdrags og energidirectorat, 2016;Styrelsen for Dataforsyning of effektivesring, 2014). It should be noted that for some countries there is only data available as points and not as polygons, a single point represents an entire wind turbine farm. Furthermore, there is data available on landing stations, or grid connections of all countries (EMODnet, 2014).

Oil and gas exploitation – For oil and gas exploitation there are three main datasets. Oil and gas platforms, exploitation licences and resources. The data of oil and gas platforms covers Denmark, Germany, the Netherlands, Norway, and the United Kingdom (Cogea, 2020a). For Germany a more up-to-date dataset is available (Federaal Maritiem en hydrografisch agentschap, 2020). The data for the exploitation licenses covers all countries except Belgium and Sweden. Sweden has a dataset available, but this only covers land and not sea. Resource data is available for Denmark and The Netherlands (Energistyrelsen Klima Energi- og Forsyningsministeriet, 2020; TNO Geologische Dienst Nederland, 2015).

Scientific research – Areas designated for scientific research are not available for any of the countries. So, it must be assumed that scientific research will be carried out throughout the waters and not just at a single set location. There is a dataset containing the measuring poles available for Belgium (Royal Belgian Institute for Natural Sciences, 2019b) and a dataset with observation locations for Sweden (Naturvardsverket, 2020).

Shipping and ports – For shipping routes, a GeoTIFF containing information on all shipping movements within the Greater North Sea is available (European Maritime Safety Agency, 2020). For the ports, a dataset with data for all countries is available on EMODnet (Eurofish and Cogea, 2019).

Submarine cables and pipelines –For submarine cables and pipelines there is a dataset for submarine power cables, one for telecommunication cables (Cogea, 2015) and one for pipelines (Cogea, 2019). The power cables dataset contains data for France the Netherlands and Norway. The telecommunication cables data is available for France, the Netherlands, Norway Germany, and the United Kingdom. For pipelines data for Denmark, the Netherlands, Norway, and the United Kingdom is available. A more elaborate dataset on pipelines is available for Germany (Federaal Maritiem en hydrografisch agentschap, 2020) and on cables for Belgium (MUMM, 2018).

Tourism – Countries can reserve areas for tourism. However, no datasets are available on this influencing factor. Therefore, it must be assumed that tourism only takes place within the 12-Miles zone.

Cultural heritage – On cultural heritage, there is data available on preserved ancient monuments for just Denmark which also contains shipwrecks (Slots- og Kulturstyrelsen, 2020). For Belgium, France and England there is data available on shipwrecks (Royal Decree, 2020; SHOM, 2020; National Heritage List for England, 2020). For other countries, this data does exist, however, this data is paid and not open data.

No category – A web map for earthquakes, landslides and other geological events is available to view via the EMODnet data portal. However, this data is not available for download. A dataset on the occurrences of earthquakes in Belgium from 1350 onwards is available (Royal Observatory of Belgium, 2021). This dataset covers a part of the Greater North Sea.

Lastly, data on lighthouses is obtained for Belgium, Denmark, Germany the Netherlands, and the United Kingdom (ARLS, 2015) and data on radar towers for Belgium (Royal Belgian Institute for Natural Sciences, 2019c). This data is not part of any of the categories, however, it is not possible to construct wind turbines in those areas. Therefore, they are classed as no category.

Appendix VIII – Unsuitable areas per category

To create the map with suitable areas the unsuitable areas are overlayed with the project area. The areas where no influencing factors are located are seen as suitable areas for wind turbine planning. This appendix shows the unsuitable areas for the thirteen main categories aquaculture (Figure 61), fishery (Figure 62), military (Figure 63), mineral extraction and aggregates (Figure 64), nature protection (Figure 65), renewable energy production (Figure 66), oil and gas exploitation (Figure 67), scientific research (Figure 68), shipping and ports (Figure 69), submarine cables and pipelines (Figure 70), tourism (no data obtained), underwater cultural heritage (Figure 71) and other (Figure 72).

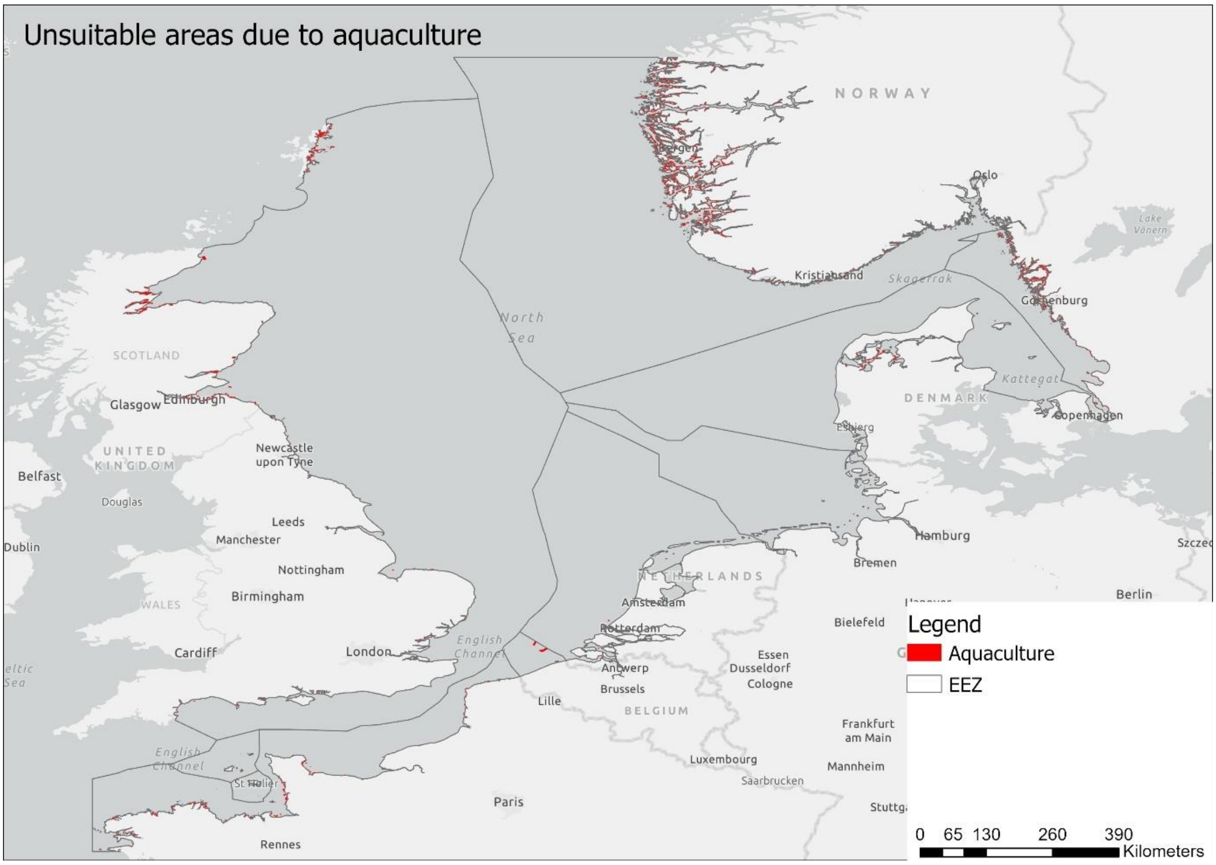

Figure 61 Map of the areas that become unsuitable due to the category aquaculture.

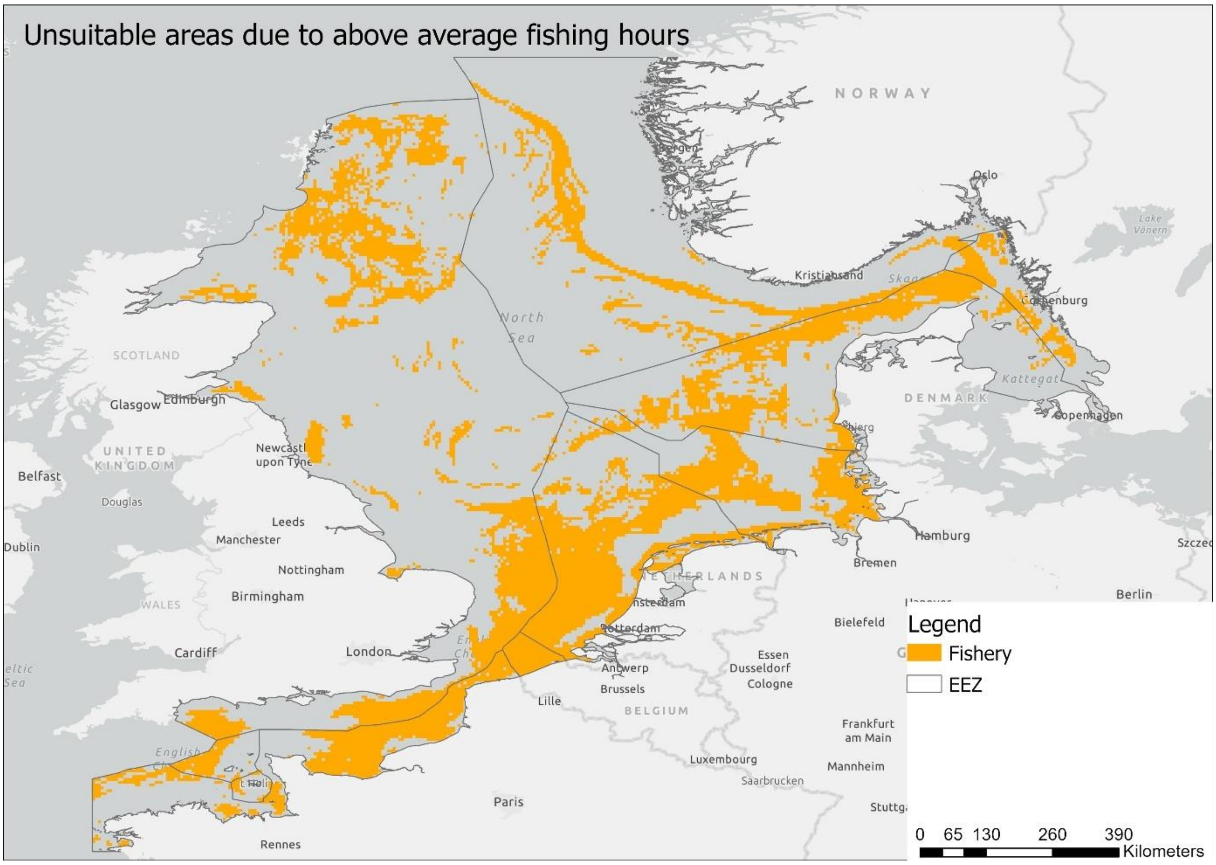

Figure 62 Map of the areas that become unsuitable due to the category fishery.

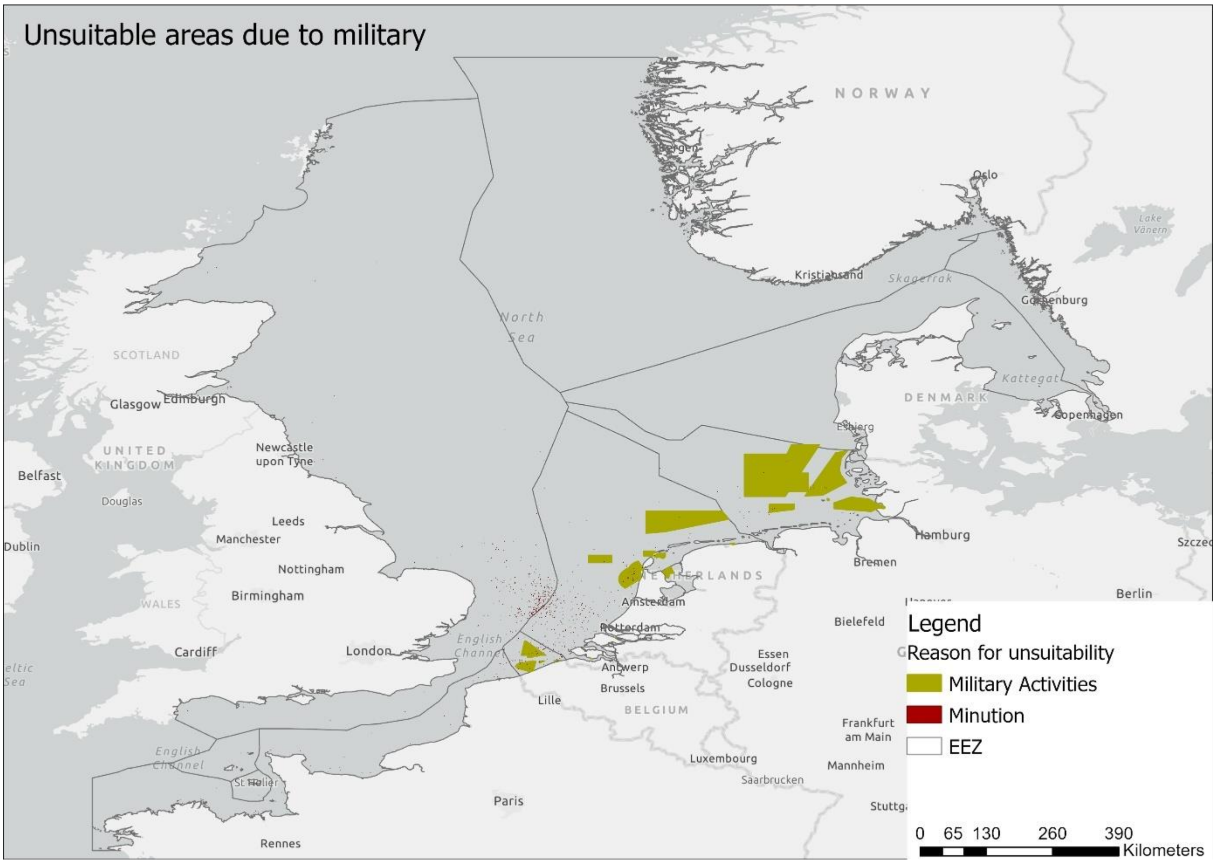

Figure 63 Map of the areas that become unsuitable due to the category military.

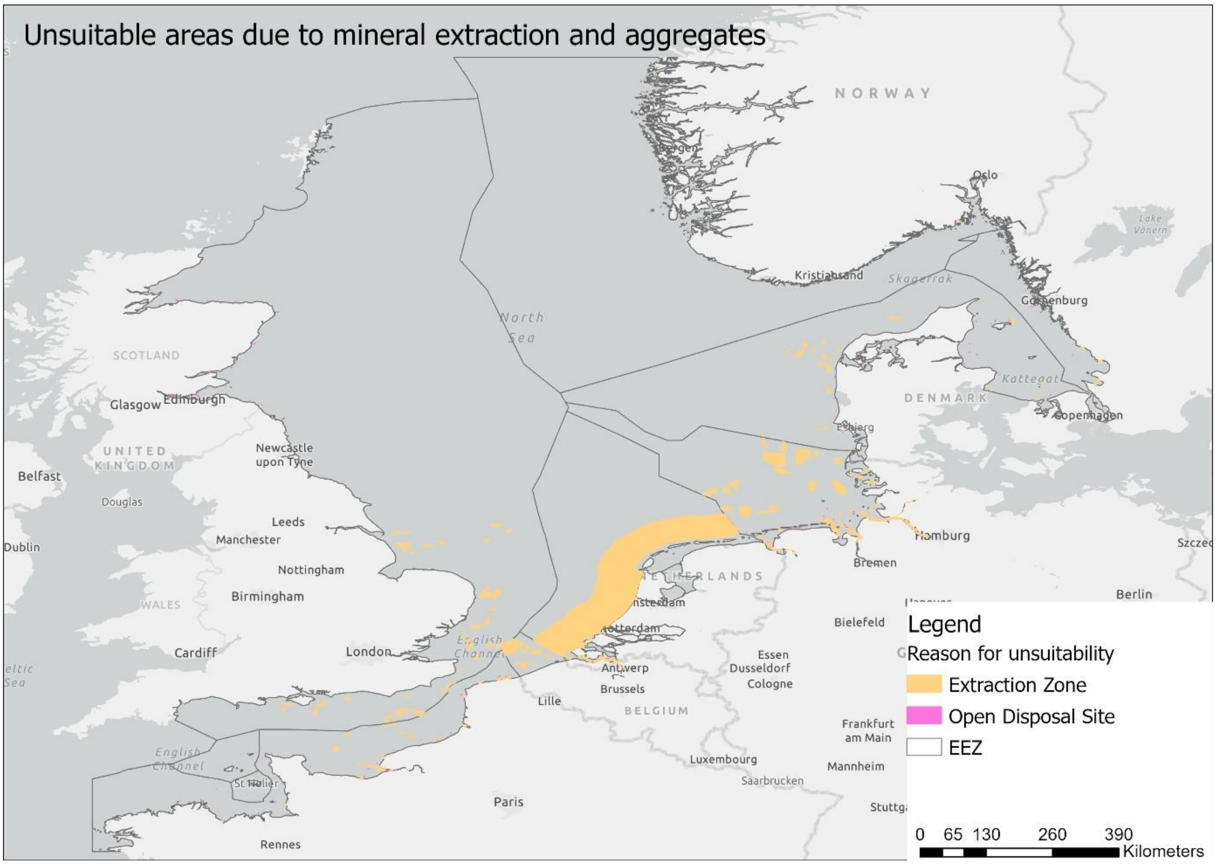

Figure 64 Map of the areas that become unsuitable due to the category mineral extraction and aggregates.

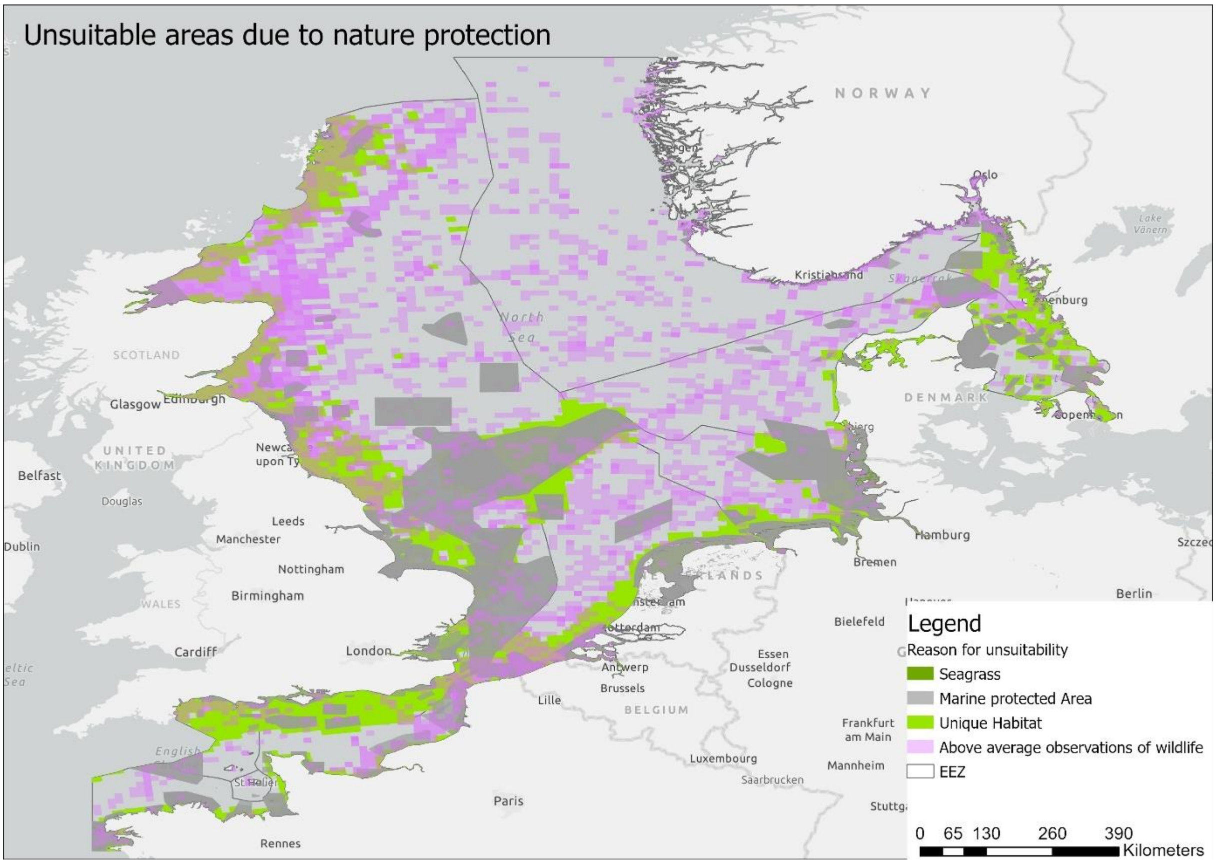

Figure 65 Map of the areas that become unsuitable due to the category nature.

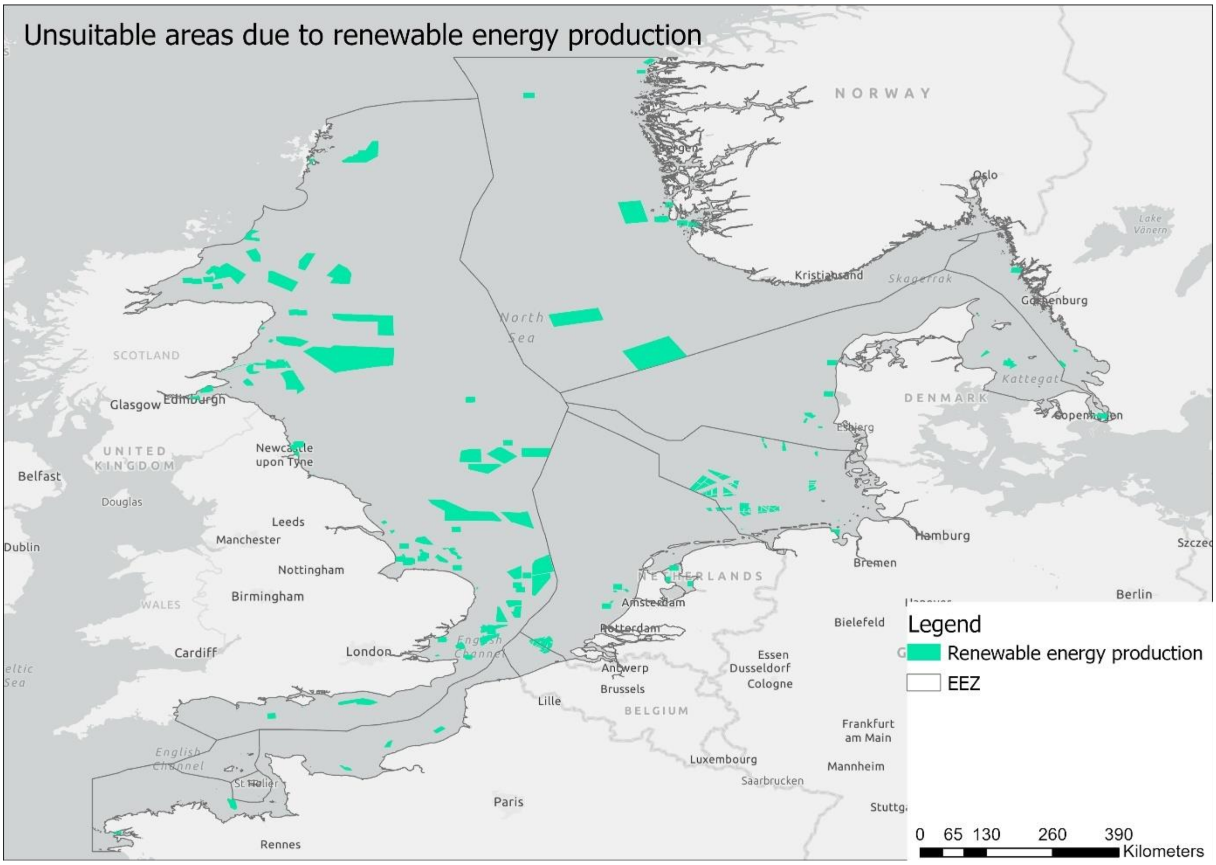

Figure 66 Map of the areas that become unsuitable due to the category renewable energy production.

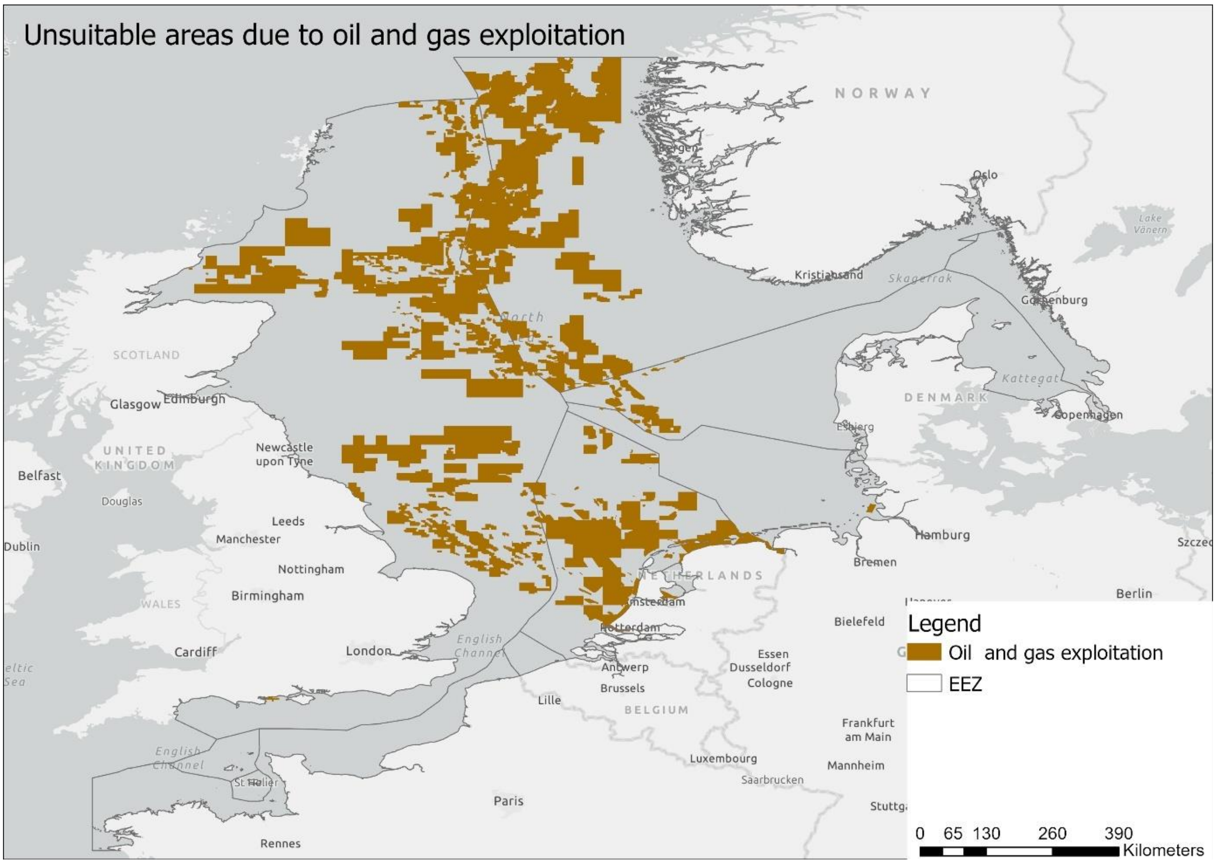

Figure 67 Map of the areas that become unsuitable due to the category oil and gas exploitation.

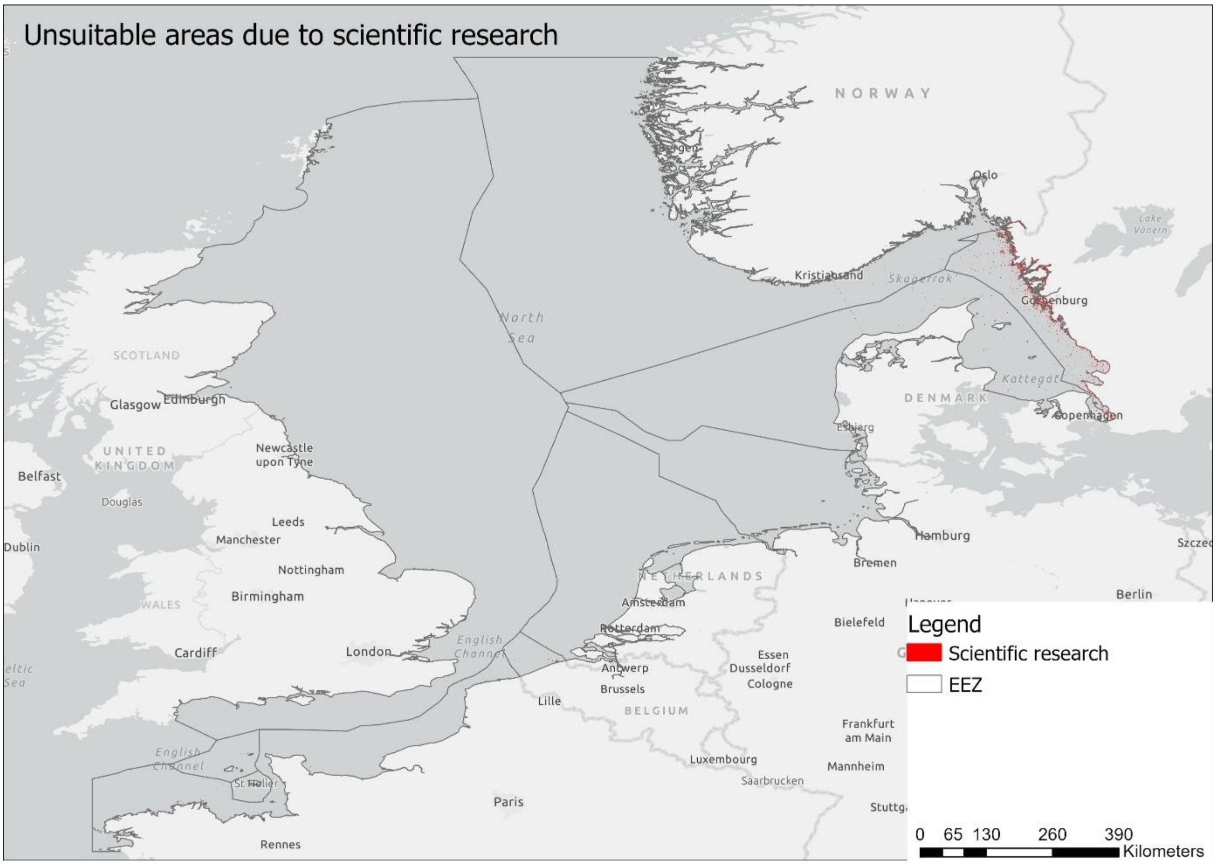

Figure 68 Map of the areas that become unsuitable due to the category scientific research.

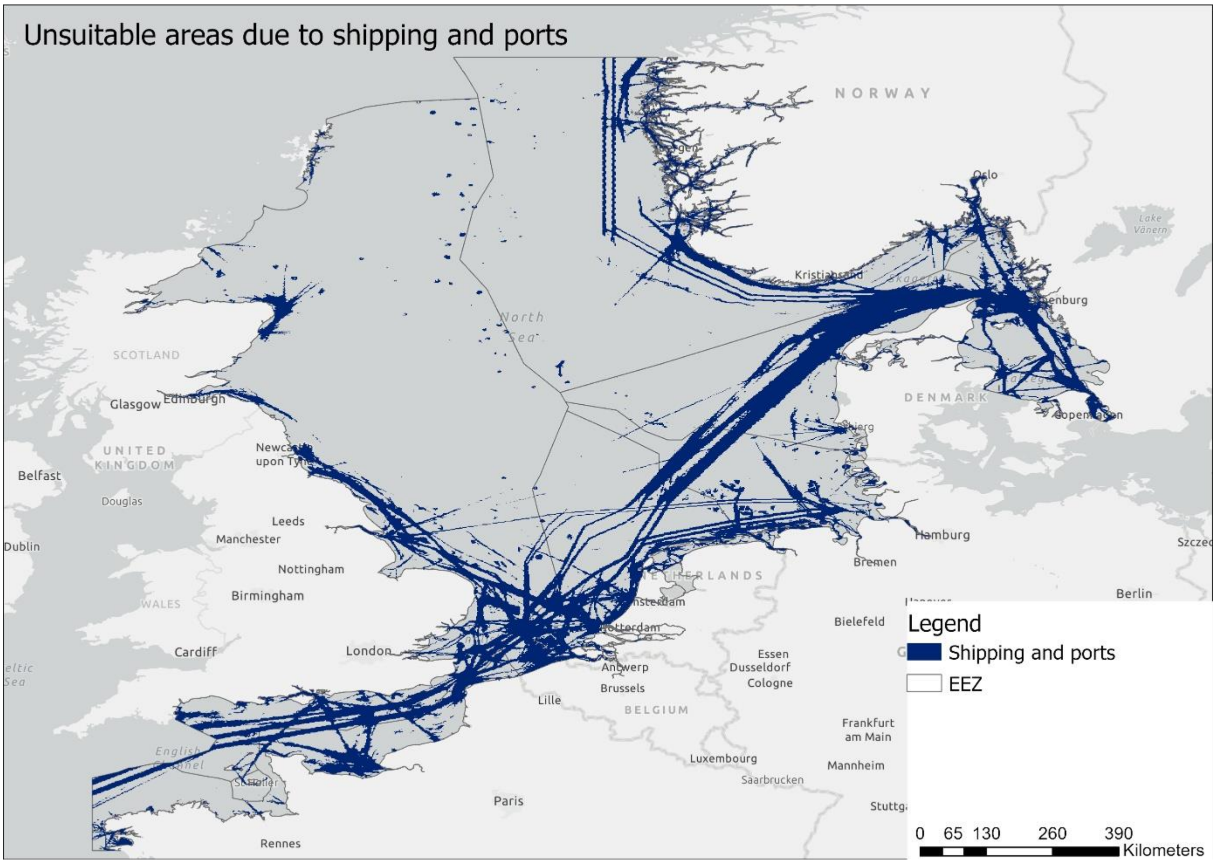

Figure 69 Map of the areas that become unsuitable due to the category shipping and ports.

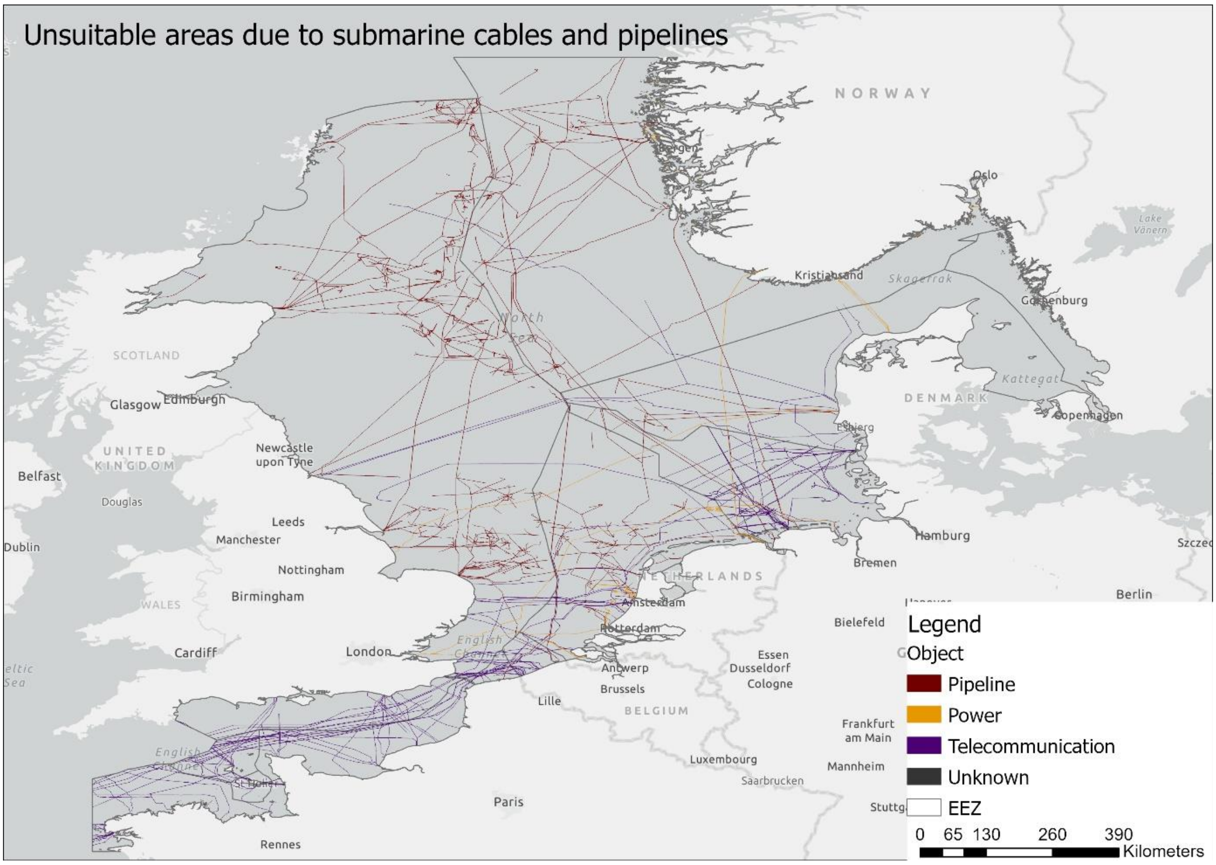

Figure 70 Map of the areas that become unsuitable due to the category submarine cables and pipelines.

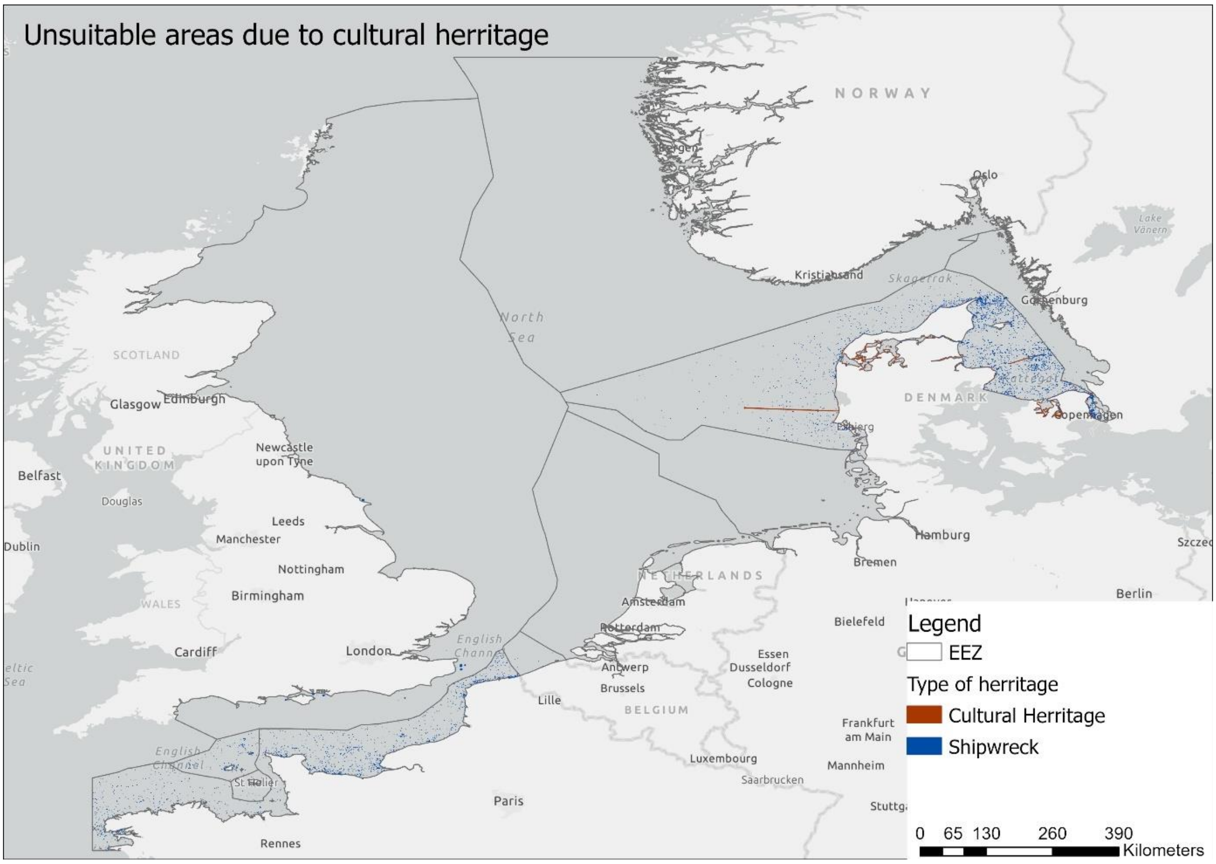

Figure 71 Map of the areas that become unsuitable due to the category cultural heritage.

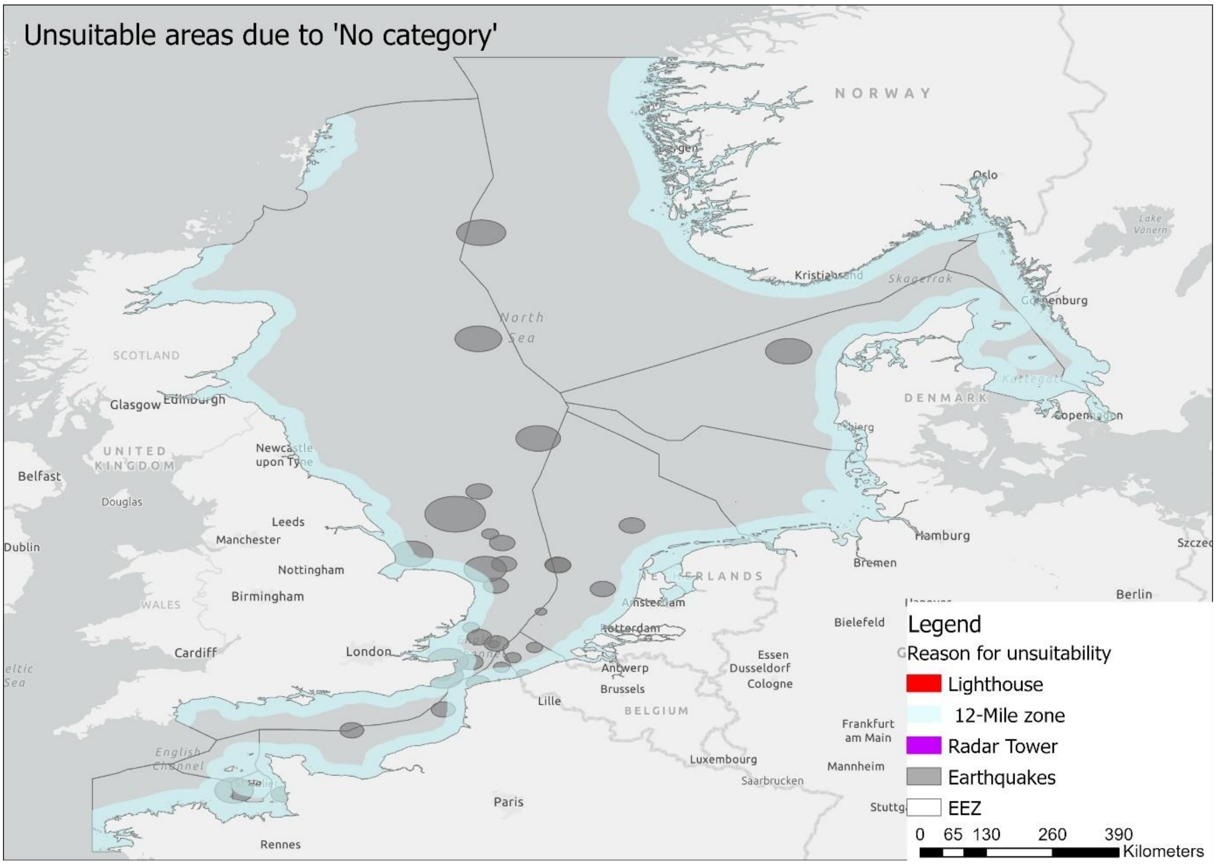

Figure 72 Map of the areas that become unsuitable due to the category other.

Appendix IX – Enlarged map of the suitable areas

Figure 73 provides an enlarged map of the suitable areas. This way the smaller areas are better visible as with the small images.

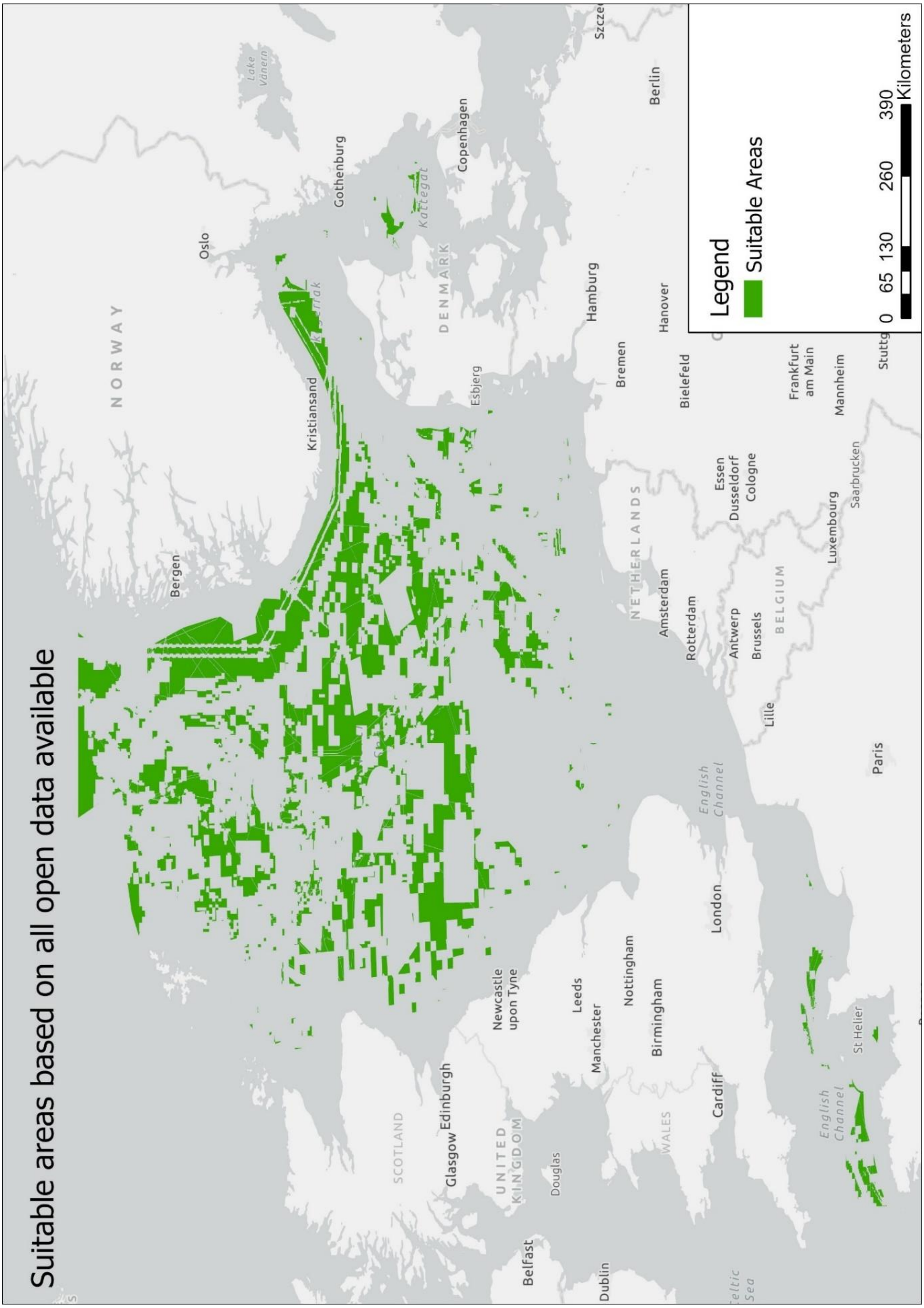

Figure 73 Enlarged map of the suitable areas.

Appendix X – Suitable areas with depth, wave height, wind speed and costs

This appendix contains the suitable areas enriched with the information of depth (Figure 74), wave height (Figure 75), wind speed (Figure 76) and costs (Figure 77).

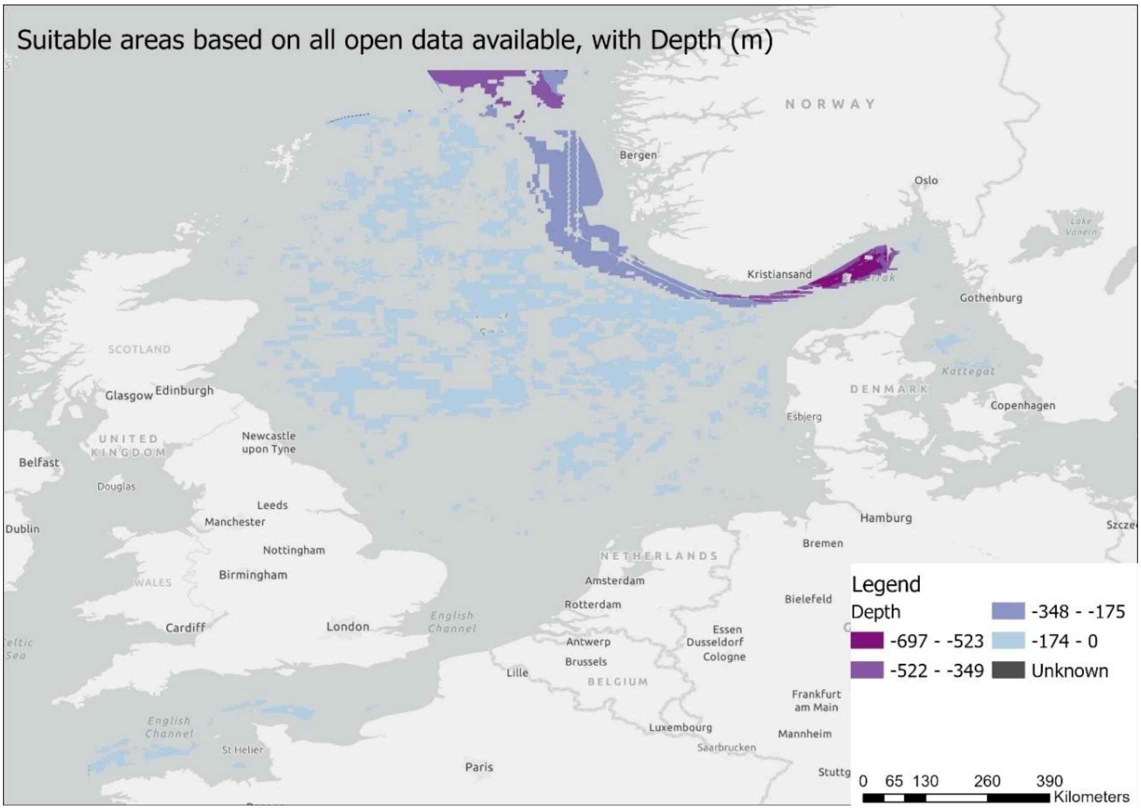

Figure 74 Suitable areas enriched with the depth in meters.

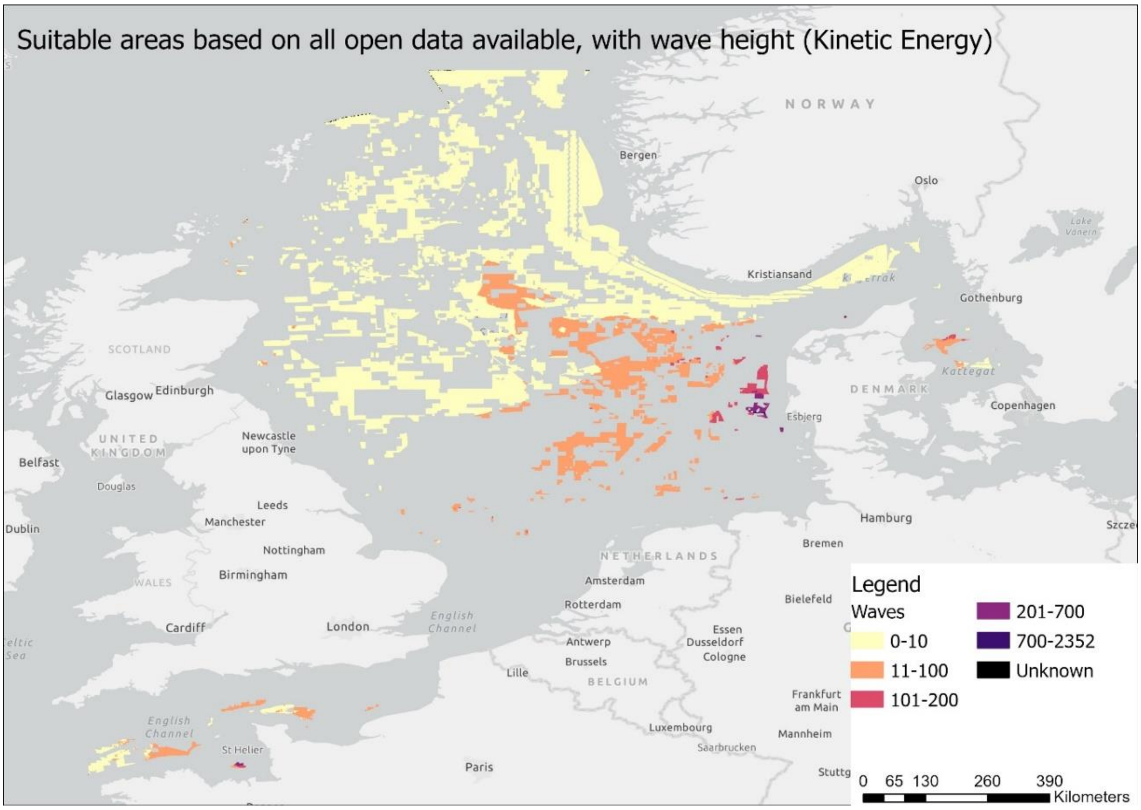

Figure 75 Suitable areas enriched with kinetic energy.

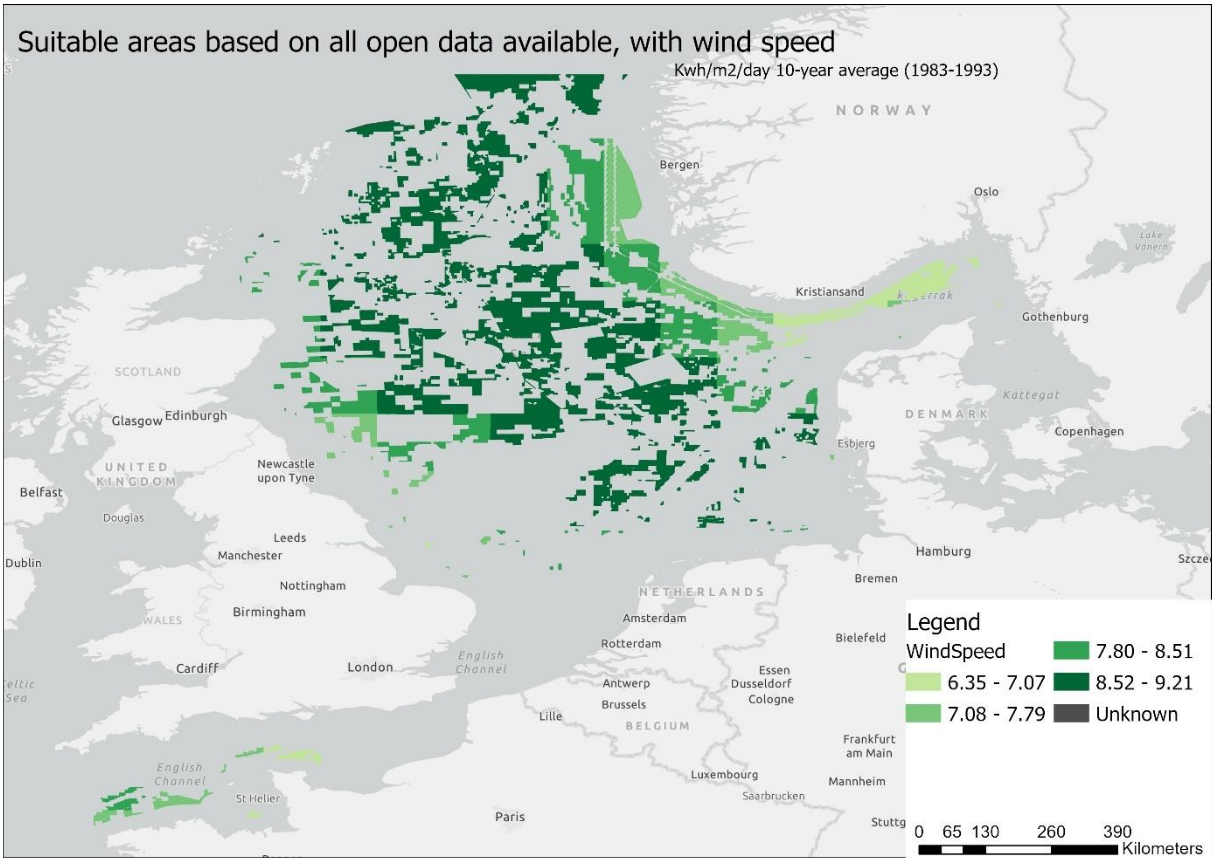

Figure 76 Suitable areas enriched with the 10-year average (1983 – 1993) wind speed in kWh per m2 per day.

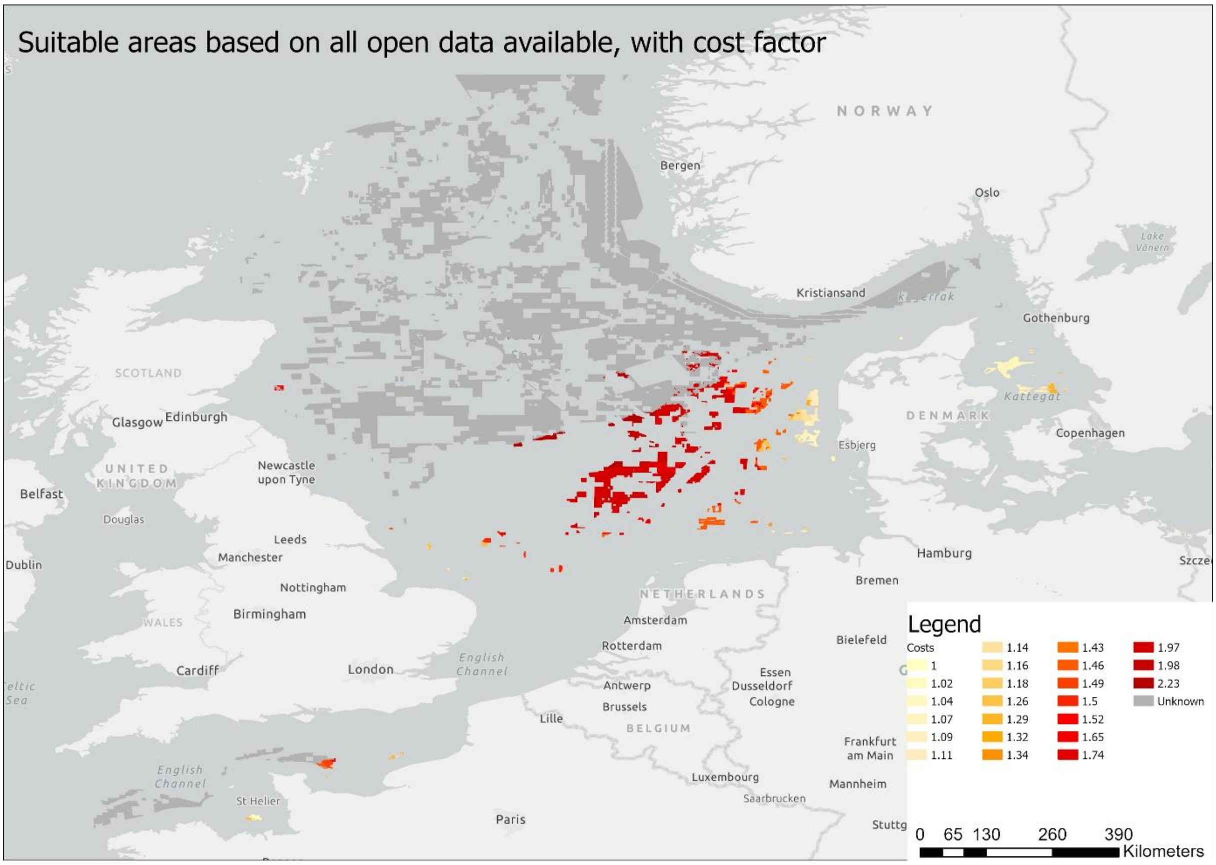

Figure 77 Suitable areas enriched with the cost factor.

Appendix XI – Map of current and planned wind turbine farms

This appendix shows an overview of the planned and current wind turbine farms based on all open data obtained during this research (Figure 78). Because multiple sources were used, giving multiple values for current and overlapping wind turbine farms, a single wind turbine farm can occur multiple times. Since correctness of the data is assumed, the differences are not accounted for. Green represents the current wind turbine farms, grey the planned wind turbine farms, and dark green is shown when multiple values are overlapping (Figure 78).

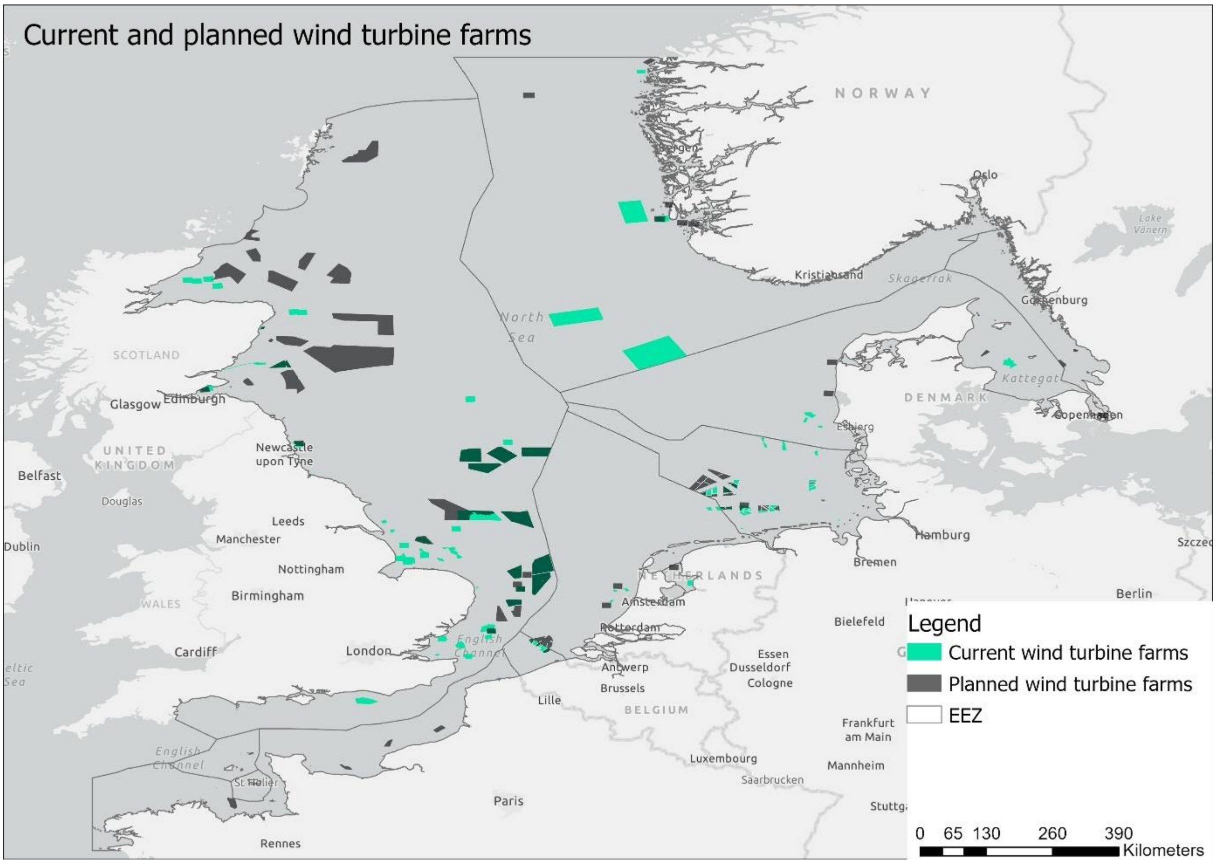

Figure 78 overview of the planned and current wind turbine farms based on the open data obtained.

Appendix XII –Results of comparable studies

This appendix contains the results of comparable studies. The result of the study of Freeman et al., (2019) is shown in figure 79. The result of the study of Ruijgrok et al., (2019) is shown in figure 80.

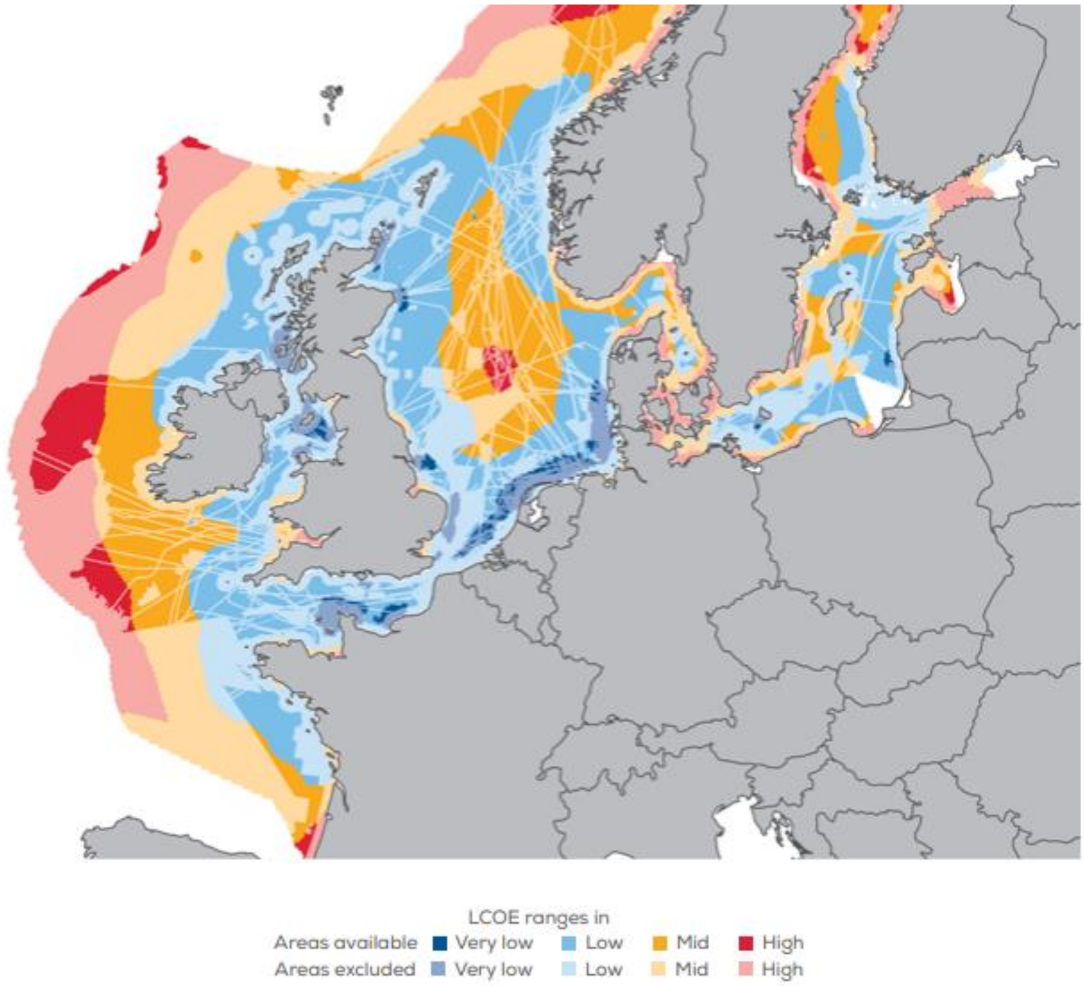

Figure 79 Result of study from Freeman et al., (2019) Showing the suitability of the available and excluded areas.

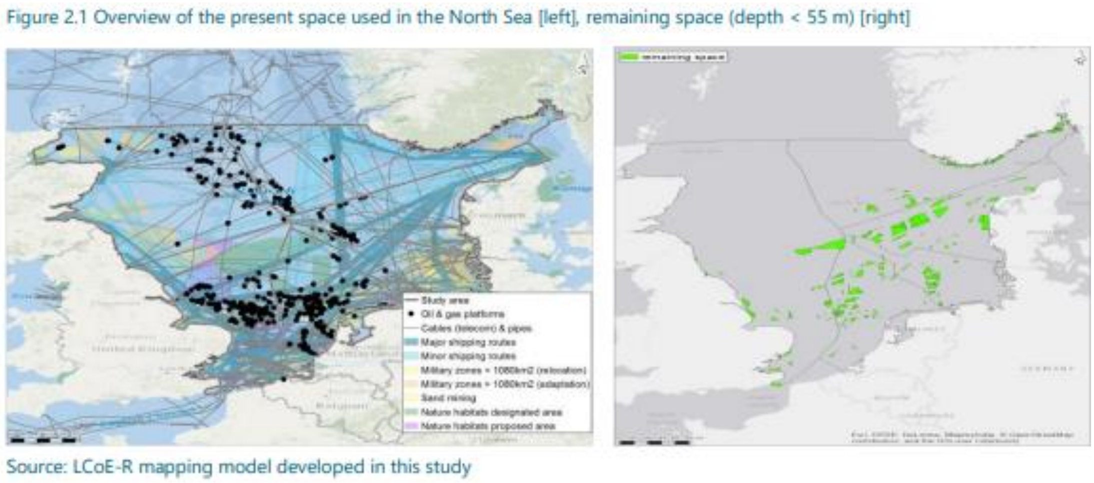

Figure 80 Result of study from Ruigrok et al., (2019)